Project #: E-21-658
Center #: R6336-0A0

Contract#: XL-7-06031-1
Prime #: DE-AC02-83CH10093

Subprojects ?: Y
Main project \\

Project unit: ELEC ENGR  Unit code: 02.010.118
Project director(s): ROHATGI A  ELEC ENGR  (404)894-7692

Sponsor/division names: SOLAR ENERGY RES INST / MIDWEST RESEARCH INSTITUTE
Sponsor/division codes: 240 / 012

Award period: 870601 to 920331 (performance) 930415 (reports)

Sponsor amount
Contract value 0.00  New this change 0.00  Total to date 757,661.00
Funded 0.00  757,661.00

Cost sharing amount 9,555.00

Title: HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THINFILM SOLAR CELLS

PROJECT ADMINISTRATION DATA

OCA contact: Mildred S. Heyser 894-4820
Sponsor technical contact RICK MITCHELL (303)231-379
Sponsor issuing office NANCY S. GARDNER (303)231-1471
SOLAR ENERGY RESEARCH INSTITUTE 1617 COLE BLVD.
GOLDEN, CO 80401
SOLAR ENERGY RESEARCH INSTITUTE 1617 COLE BLVD.
GOLDEN CO 80401

Security class (U,C,S,TS) : U
 Defense priority rating :
 Equipment title vests with: Sponsor X

Administrative comments - TO REVISE DELIVERABLE SCHEDULE
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 10/23/92

Project No. E-21-658
Project Director ROHATGI A
Center No. R6336-0A0
School/Lab ELEC ENGR

Sponsor NATIONAL RENEWABLE ENERGY LAB/MIDWEST RESEARCH INST
Contract/Grant No. XL-7-06031-1
Contract Entity GTRC
Prime Contract No. DE-AC02-83CH10093

Title HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THINFILM SOLAR CELLS

Effective Completion Date 920331 (Performance) 930415 (Reports)

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Subproject Under Main Project No.
Continues Project No.

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NOTE: Final Patent Questionnaire sent to PDPI.
GEORGIA INSTITUTE OF TECHNOLOGY  
OFFICE OF CONTRACT ADMINISTRATION  

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)  

Closeout Notice Date 10/23/92  

Project No. E-21-658  
Center No. R6336-0A0  

Project Director ROHATGI A  
School/Lab ELEC ENGR  

Sponsor NATIONAL RENEWABLE ENERGY LAB/MIDWEST RESEARCH INST  

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LEGEND  
1. * indicates the project is a subproject.  
2. I indicates the project is active and being updated.  
3. A indicates the project is currently active.  
4. T indicates the project has been terminated.  
5. R indicates a terminated project that is being modified.
July 31, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 6/1/87-7/31/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

cc: Mr. John Benner
1. **Contract Identification:** High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cells

2. **Reporting Period:** 6/1/87 through 7/31/87

3. **Contract Number:** XL-7-06031-1

4. **Contractor Name and Address:**
   Solar Energy Research Institute
   Golden, CO 80401-3393
   1617 Cole Blvd.

5. **Contract Start Date:** 6/1/87

6. **Contract Completion Date:** 5/31/88

7. **Months:**

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8. **FY: Dollars in Thousands:****

   - **a. B&R Numbers:**
   - **b. Planned:** 0
   - **c. Actual:** 0
   - **d. Variance:** 0

9. **Cost Status:**

   - **a. FY:** 6/1/87
   - **b. Cost Plan:** 
   - **c. Planned Costs Prior FYs:** 0
   - **d. Actual Costs Prior FYs:** 0
   - **e. Total Estimated Costs for Contract:** 223,762
   - **f. Total Contract Value:** 223,762
   - **g. Estimated Costs for Subsequent Reporting Period:** 0
   - **h. Unfilled Orders Outstanding:** 0
   - **i. Estimate for Subsequent Reporting Period:** 11,388

10. **Manpower Status (Direct Labor):**

   - **a. Manpower Plan Date:** 6/1/87
   - **b. Planned Manpower for Contract:** 3667
   - **c. Actual Manpower for Contract:** 3667
   - **d. Total Estimated Manpower for Contract:** 3667
   - **e. Total Manpower:** 3667

11. **Major Milestone Status:**

   - **a. Task 1:** 
   - **b. Task 2:** 
   - **c. Task 3:** 
   - **d. Task 4:** 
   - **e. Task 5:** 

12. **Remarks:**

13. **Signature of Contractor's Project Manager and Date:**

14. **Signature of Government Technical Representative and Date:** 7/31/87

---

*Notes:
- h of Window Mat.
- h of CdZnTe and CdMnTe
- g & bg of CdZnTe
- d CdMnTe
- h of P+ Interlayer
- Fab. & Testing
Ms. Margaret Lemke  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 8/1/87-8/30/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors  
Administrative Assistant

pm  
Enclosures

cc: Mr. John Benner
FORM DOE 686

U.S. DEPARTMENT OF ENERGY

CONTRACT MANAGEMENT SUMMARY REPORT

1. Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell
2. Reporting Period: 8/1/87 through 8/30/87
3. Contract Number: XL-7-06031-1

Solar Energy Research Institute
Golden, CO 80401-3393
1617 Cole Blvd.

4. Contractor (Name and Address):

5. Contract Start Date: 6/1/87
6. Contract Completion Date: 5/31/88

7. Months: J J A S O N D J F M A M

8. Dollars in Thousands:

9. Cost Status:

   a. Cost Plan Date: 6/1/87
   b. Costs Prior FYs
   c. Actual Costs Prior FYs
   d. Total Estimated Costs for Contract
   e. Total Contract Value
   f. Unfilled Orders
   g. Estimated for Subsequent Reporting Period

10. Manpower Status (Direct Labor):

   a. Manpower Plan Date: 6/1/87
   b. Planned Manpower
   c. Actual Manpower
   d. Variance

11. Major Milestone Status:

   a. Task 1
   b. Task 2
   c. Task 3
   d. Task 4
   e. Task 5

12. Remarks:

13. Sign and Date:

14. Signature of Government Technical Representative and Date

---

of Window Mat.
of CdZnTe and CdMnTe
& Bg of CdZnTe
of P+ Interlayer Fab. & Testing
November 2, 1987

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 9/1/87-9/30/87 on the above referenced contract.

Please note there were some charges that were incorrectly posted to this project during the month of August. We removed these charges in September which showed negative expenditures for the month.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Administrative Assistant

pm  
Enclosures

cc: Mr. Ken Zweibel
High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell

Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

6/1/87 to 5/31/88

Contract Management Summary Report

Manpower Status (Direct Labor)

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned: 3667

Actual: 3667

Variances: 0

Manpower Status

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

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Manpower

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Variances

Task 1

Task 2

Task 3

Task 4

Task 5

Manpower

Planned

Actual

Variances

Task 1

Task 2

Task 3

Task 4
November 11, 1987

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 10/1/87-10/31/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Enclosures

cc: Mr. Ken Zweibel
**High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cells**

**Contract Management Summary Report**

**1.** Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cells

**2.** Reporting Period: 10/1/87 - 10/31/87

**3.** Contract Number: XL-7-06031-1

**4.** Contract Name and Address:
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

**5.** Contract Completion Date: 5/31/88

**6.** Signature of Government Technical Representative and Date

**7.** Months: J J A S O N D J F M A M

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**8.** Costs

- Planned Costs Prior FYs: 0
- Actual Costs Prior FYs: 0
- Total Estimated Costs for Contract: 223,762

**9.** Hours

- Planned Hours: 3667
- Actual Hours: 3667
- Variance Hours: 0

**10.** Manpower Status (Direct Labor)

- Planned Hours: 0
- Actual Hours: 0
- Variance Hours: 0

**11.** Major Milestones Status

- Task 1
- Task 2
- Task 3
- Task 4
- Task 5

**12.** Remarks

**13.** Signature of Contractor's Project Manager and Date

**14.** Signature of Government Technical Representative and Date
Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 11/1/87-11/30/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosures

cc: Mr. Ken Zweibel
1. Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell
2. Reporting Period: 11/1/87 through 11/30/87
3. Contract Number: XL-7-06031-1
4. Contractor (Name and Address):
   Solar Energy Research Institute, Golden, CO 80401-3393
   1617 Cole Blvd.
5. Contract Start Date: 6/1/87
6. Contract Completion Date: 5/31/88

7. Months

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10. Manpower Status (Direct Labor)

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11. Major Milestone Status

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12. Remarks

of Window Mat. th of CdZnTe and CdMnTe
ng & Bg of CdZnTe nd CdMnTe
th of P+ Interlayer
Fab. & Testing
January 26, 1988

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 12/1/87-12/31/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosures  

cc: Mr. Ken Zweibel
High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cells

Reporting Period: 12/31/87 through 12/31/88

Task 1
- Task 2
- Task 3
- Task 4
- Task 5

Manpower Status (Direct Labor)

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Cost Status

- Dollars in Thousands
- Dollars in
- Dollars in
- Dollars in
- Dollars in

Yearly Costs

- Yearly Costs
- Yearly Costs
- Yearly Costs
- Yearly Costs
- Yearly Costs

Monthly Costs

- Monthly Costs
- Monthly Costs
- Monthly Costs
- Monthly Costs
- Monthly Costs

Total Costs

- Total Costs
- Total Costs
- Total Costs
- Total Costs
- Total Costs

Manpower

- Manpower
- Manpower
- Manpower
- Manpower
- Manpower

Manpower Status (Direct Labor)

- Manpower Status
- Manpower Status
- Manpower Status
- Manpower Status
- Manpower Status

Status of Work

- Status of Work
- Status of Work
- Status of Work
- Status of Work
- Status of Work
Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-ACO2-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 1/1/88-1/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosures

cc: Mr. Ken Zweibel
1. Contract Information
   High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cells
   1/1/88 - 12/31/88

4. Contractor (Name and Address)
   Solar Energy Research Institute
   Golden, CO 80401-3393

5. Contract Start Date
   6/1/87

6. Contract Completion Date
   5/31/88

7. Description of Work
   - Of Window Mat.
   - h of CdZnTe and CdMnTe
   - g & Kg of CdZnTe and CdMnTe
   - h of P+ Interlayer
   - Fab. & Testing

10. Manpower Status
    - Hours
      - Planned: 3667
      - Actual: 3667
      - % Variance: 0%

12. Remarks

14. Signature of Government Technical Representative and Date
March 14, 1988

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Larson:


If you have any questions, please feel free to contact me.

Sincerely,

[Signature]

Research Administrator

Enclosures

cc: Mr. Ken Zweibel
Task | Status | Details
--- | --- | ---
Task 1 | | 
Task 2 | | 
Task 3 | | 
Task 4 | | 
Task 5 | | 

12. Remarks: 

13. Signature of Contractor's Project Manager and Date: 

14. Signature of Government Technical Representative and Date: 

**Notes:**
- Task 1: Description of work.
- Task 2: Description of work.
- Task 3: Description of work.
- Task 4: Description of work.
- Task 5: Description of work.
April 18, 1988

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:


If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosures  

cc: Mr. Ken Zweibel
May 17, 1988

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:


If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

cc: Mr. Ken Zweibel
ev. of Window Mat.
Growth of CdZnTe and
CdMnTe
Growth & Bg of CdZnTe
and CdMnTe
Growth of P+ Interlayer
all Fab. & Testing

1 Task 1
2 Task 2
3 Task 3
4 Task 4
5 Task 5

12 Remarks
June 15, 1988

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
        Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report
for the period 5/1/88-5/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Enclosures

cc: Mr. Ken Zweibel
July 22, 1988

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 6/1/88-6/30/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm
Enclosures

cc: Mr. Ken Zweibel
Contract Management Summary Report

1. Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell

2. Reporting Period: 6/1/88 through 6/30/88

3. Contract Number: XL-7-06031-1

4. Contractor (Name and Address):
   Solar Energy Research Institute
   Golden, CO 80401-3393
   1617 Cole Blvd.

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 6/30/89

7. Months:

   J  J  A  S  O  N  D  J  F  M  A  M  J  J  A

   B  P Y

8. Cost Status:

   a. Dollars
      Thousands:
      459
      450
      400
      350
      300
      250
      200
      150

   b. B&R Numbers:
      250
      200
      150

   c. Planned
   d. Actual
   e. Variance

9. Cost Plan:
   a. Dollars
      Thousands:
      6/1/87

   b. Planned Costs Prior FYs
   c. Actual Costs Prior FYs
   d. Total Estimated Costs for Contract
   e. Total Contract Value
   f. Unfunded Orders Outstanding

10. Manpower Status (Direct Labor):

   6766
   3851

11. Major Milestone Status:

   a. Task 6
   b. Task 7
   c. Task 8
   d. Task 9
   e. Task 10

12. Remarks:

13. Signature of Contractor's Project Manager and Date:

14. Signature of Government Technical Representative and Date:
1. **Contract Identification**: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell

2. **Reporting Period**: through

3. **Contract Number**: XL-7-06031-1

4. **Contractor (Name and Address)**: Solar Energy Research Institute, Golden, CO 80401-3393, 1617 Cole Blvd.

5. **Contract Start Date**: 6/1/87

6. **Contract Completion Date**: 11/30/89

7. **Months**

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8. **FY**

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9. **Cost Status**

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10. **Manpower Status (Direct Labor)**

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11. **Major Milestone Status**

- **Task 6**
- **Task 7**
- **Task 8**
- **Task 9**
- **Task 10**

12. **Remarks**

13. **Signature of Contractor's Project Manager and Date**

14. **Signature of Government Technical Representative and Date**
Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 7/1/88-7/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

cc: Mr. Ken Zweibel
of CdZnTe and Te Solar Cells
Growth of 1.7 eV
gap HgZnTe
ng & Bandgap Tail-7 of HgZnTe
Growth of Trans- it Ohmic Contact Fabrication with Te Films
U.S. DEPARTMENT OF ENERGY
CONTRACT MANAGEMENT SUMMARY REPORT

1. Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell
2. Reporting Period: 6/1/87 through 11/30/89
3. Contract Number: XL-7-06031-1
4. Contractor (Name and Address):
   Solar Energy Research Institute
   Golden, CO 80401-3393
   1617 Cole Blvd.
5. Contract Start Date: 6/1/87
6. Contract Completion Date: 11/30/89
7. Months: [S O N]
8. FY:
9. Cost Status:
   a. Plans:
      - Costs Prior FY:
      - Actual Costs Prior FY:
      - Total Estimated Costs for Contract:
      - Total Contract Value:
      - Unfunded Orders Outstanding:
   b. Approved Costs:
      - Planned:
      - Actual:
      - Variance:
      - Estimate for Subsequent Reporting Period:
10. Manpower Status (Direct Labor):
    a. Plans:
       - Manpower Plan Date:
       - Planned Manpower Prior FY:
       - Actual Manpower Prior FY:
       - Total Estimated Manpower for Contract:
       - Total Contract Manpower:
    b. Actual:
    c. Variance:
11. Major Milestones Status:
   a. Task 6
   b. Task 7
   c. Task 8
   d. Task 9
   e. Task 10
12. Remarks

13. Signature of Contractor's Project Manager and Date
14. Signature of Government Technical Representative and Date
Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393

SUBJECT:     Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
             Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 8/1/88-8/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure  
cc:  Mr. Ken Zweibel
### Contract Management Summary Report

**Contract Identification:** High Efficiency Cadmium & Te Solar Cells

**Reporting Period:** 1/1/88 through 3/31/88

**Contract Number:** XL-7-06031-1

**Contractor (Name and Address):**
Golden, CO 80401-3393
1617 Cole Blvd.

### 7. Months

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### 9. Cost Status

- **Actual Costs:** 459,643
- **Total Contract Value:** 553,613
- **Total Estimated Costs:** 459,643
- **Current Variance:** 91,960,358.9
- **Total Variance:** 6,813

### 10. Manpower Status (Direct Labor)

- **Planned Costs Prior FY:** 3667
- **Total Estimated Manpower:** 3851
- **Total Contract Manpower:** 7333
- **Planned Manpower Prior FY:** 720
- **Actual Manpower:** 720
- **Total Variance:** 523

### Major Milestone Status

- **Task 6**
- **Task 7**
- **Task 8**
- **Task 9**
- **Task 10**
1. Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell  
2. Reporting Period: through  
3. Contract Number: XL-7-06031-1  
4. Contractor (Name and Address):  
   Solar Energy Research Institute  
   Golden, CO 80401-3393  
   1617 Cole Blvd.  

7. Months:  
   | S | O | N | E | FY  
   |---|---|---|---|---  

9. Cost Status:  
   a. Cost Plan:  
   b. Planned Cost Prior FY:  
   c. Actual Cost Prior FY:  
   d. Over/Under Cost:  
   e. Total Contract Value:  
   f. Unliquidated Options:  
   g. Estimated Subcontract Reporting Period:  

10. Manpower Status (Direct Labor):  
   a. Manpower Plan Date:  
   b. Planned Manpower Prior FY:  
   c. Actual Manpower Prior FY:  
   d. Total Estimated Manpower:  
   e. Total Contract Manpower:  

11. Major Milestone Status:  
   a. Task 6  
   b. Task 7  
   c. Task 8  
   d. Task 9  
   e. Task 10  

12. Remarks:  

13. Signature of Contractor's Project Manager and Date:  
14. Signature of Government Technical Representative and Date:  

October 12, 1988

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 9/1/88–9/30/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Ken Zweibel
**Contract Management Summary Report**

1. **Contract Identification**
   - High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cells

2. **Reporting Period**
   - 9/1/88 through 9/30/88

3. **Contract Number**
   - X1-7-00531-1

4. **Contractor (Name and Address)**
   - Solar Energy Research Institute
   - Golden, CO 80401-3393
   - 1617 Cole Blvd.

7. **Months**

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8. **Contracted Costs**

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9. **Manpower Status (Direct Labor)**

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10. **Major Milestones**

- **Task 6**
- **Task 7**
- **Task 8**
- **Task 9**
- **Task 10**

11. **Special Notes**

- Growth of 1.7 eV gap HgZnTe
- Bandgap Tailoring of HgZnTe
- Growth of Transient Ohmic Contact Fabrication with Te Films

---

**Growth of CdZnTe and Te Solar Cells**

---

**Remarks**

---
1. Contract Identification:
High Efficiency Cadmium &
Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address):
Solar Energy Research Institute
Golden, CO 80401-3393
1617 Cole Blvd.

7. Months
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9. Cost Status
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<td>b. Actual Costs Prior FYs</td>
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<td>152,699</td>
<td>459,643</td>
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| 10. Manpower Status (Direct Labor)
| a. Manpower Plan Date | b. Planned Manpower Prior FYs | c. Actual Manpower Prior FYs | d. Estimated Manpower for Contract |
| 6/1/87            | 3667               | 3851               | 7333               |
| e. Total Contract Manpower |
| 7333               |

11. Major Milestone Status
a. Task 6
b. Task 7
c. Task 8
d. Task 9
e. Task 10
November 14, 1988

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 10/1/88-10/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Enclosure

cc: Mr. Ken Zweibel
## Contract Management Summary Report

**Project:** High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell

**Contractors:**
- Solar Energy Research Institute
  - Golden, CO 80401-3393
  - 1617 Cole Blvd.

**Contract Period:**
- 10/1/87 through 10/31/88
- Contract Start Date: 6/1/87
- Contract Completion Date: 11/30/89

## Financial Summary

### 9. Costs

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### 11. Major Progress Status

- **Task 6**: [Progress Bar]
- **Task 7**: [Progress Bar]
- **Task 8**: [Progress Bar]
- **Task 9**: [Progress Bar]
- **Task 10**: [Progress Bar]

### 12. Remarks

- [Remarks]

**Location of CdZnTe and Te Solar Cells**
- Growth of 1.7 eV gap HgZnTe
- Bandgap Tailoring of HgZnTe
- Growth of Transparent Ohmic Contact Fabrication with Te Films

**References**
- [References]

**Signatures**
- [Signature]

(U.S. Department of Energy)

**Contract Management Summary Report**

**Contractor:** Solar Energy Research Institute

**Golden, CO 80401-3393**

**1617 Cole Blvd.**

**Contract Period:** 10/1/87 through 10/31/88

**Contract Start Date:** 6/1/87

**Contract Completion Date:** 11/30/89

**Contract Number:** XL-7-06031-1

**Form Approved:**
- [Form Number]
- [Date]

**Form DOE E31**

**Date:** [Date]

**Contractor:** Solar Energy Research Institute

**Golden, CO 80401-3393**

**1617 Cole Blvd.**

**Contract Period:** 10/1/87 through 10/31/88

**Contract Start Date:** 6/1/87

**Contract Completion Date:** 11/30/89

**Contract Number:** XL-7-06031-1

**Form Approved:**
- [Form Number]
- [Date]
DEPARTMENT OF ENERGY
CONTRACT MANAGEMENT SUMMARY REPORT
FORM ASSIGNED
OMB NO. 3090-0001
1. Contract Identification: High Efficiency Cadmium & Zinc Telluride Based Thin Film Solar Cell
2. Reporting Period: [Insert Date]
3. Contract Number: XL-7-06031-1
5. Contract Start Date: 6/1/87
6. Contract Completion Date: 11/30/89
7. Months: S O N
8. FY:

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10. Manpower Status (Direct Labor):

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11. Major Milestones Status:

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12. Remarks:

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
December 12, 1988

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:


If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Ken Zweibel
CONTRACT MANAGEMENT SUMMARY REPORT

FORM DOE 536

1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Reporting Period: 11/1/88 through 11/30/88

3. Contract Number: XL-7-06031-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

7. Months

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8. Planned Costs Prior FY: 223,762

9. Actual Costs Prior FY: 152,699


11. Total Contract Value: 459,643

12. Unfilled Orders Outstanding: 34,344

13. Estimated for Subsequent Reporting Period: 15,280

14. Variance:

- Task 6: Opt of Solar Cell
- Task 7: MBE Growth 1.7 eV
- Task 8: Dop Bandgap Tail
- Task 9: MBE Growth Transp
- Task 10: Cell Fabric

16. Remarks

17. Signature of Contractor's Project Manager and Date

18. Signature of Government Technical Representative and Date
## Contract Management Summary Report

### 1. Contract Identification
- High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

### 4. Contractor (Name and Address)
- Solar Energy Research Institute
  - 1617 Cole Blvd.
  - Golden, CO 80401-3393

### 5. Contract Start Date
- 6/1/87

### 6. Contract Completion Date
- 11/30/89

### 7. Months

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### 10. Manpower Status (Direct Labor)

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### 11. Major Milestone Status

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### 12. Remarks

---

### 13. Signature of Contractor's Project Manager and Date

### 14. Signature of Government Technical Representative and Date
January 16, 1989

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 12/1/88-12/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure  
cc: Mr. Ken Zweibel
### CONTRACT MANAGEMENT SUMMARY REPORT

**I. Contract Identification**
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

**2. Reporting Period**
12/1/88 through 12/31/88

**3. Contract Number**
XL-7-06031-1

**4. Contractor (Name and Address)**
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

**5. Contract Start Date**
6/1/87

**6. Contract Completion Date**
11/30/89

**7. Months**

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**9. Cost Status**

- **a. Dollars in Thousands**
  - 197
  - 720
  - 523

- **b. B&R Numbers**
  - 300
  - 250
  - 200

**10. Manpower Status (Direct Labor)**

- **a. Planned**
  - 7333
  - 6900
  - 6500
  - 6000
  - 5500
  - 5000
  - 4500
  - 4000
  - 3500
  - 3000
  - 2500
  - 2000
  - 1500
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- **b. Actual**
  - 720
  - 640
  - 369
  - 564
  - 656
  - 544

- **c. Variance**
  - (523)
  - (444)
  - (172)
  - (367)
  - (459)
  - (347)

**11. Major Milestone Status**

- **a. Task 6. Optimization of Solar Cell**
- **b. Task 7. MBE Growth 1.7 eV**
- **c. Task 8. Dopant Bandgap Tail**
- **d. Task 9. MBE Growth Transp**
- **e. Task 10. Cell Fabric.**

**12. Remarks**

**13. Signature of Contractor's Project Manager and Date**

**14. Signature of Government Technical Representative and Date**
1. Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Contractor (Name and Address)
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

3. Contract Number
XL-7-06031-1

4. Contract Start Date
6/1/87

5. Contract Completion Data
11/30/89

### Cost Status

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### Major Milestone Statu

- Task 6
- Task 7
- Task 8
- Task 9
- Task 10
- Task 11
- Task 12
- Task 13
- Task 14

### Remarks

- Signature of Contractor's Project Manager and Date
- Signature of Government Technical Representative and Date
February 16, 1989

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 1/1/89-1/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

\[\text{pm}\]

Pam Majors
Research Administrator

pm
Enclosure

cc: Mr. Ken Zweibel
**FORM DOE 536**  
**CONTRACT MANAGEMENT SUMMARY REPORT**

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March 15, 1989

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:


If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

Enclosure

cc: Mr. Ken Zweibel
### Contract Management Summary Report

**Form Doe 536**

**Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

**Reporting Period:** 2/1/89 through 2/31/89

**Contract Number:** XL-7-06031-1

**Contract Start Date:** 6/1/87

**Contract Completion Date:** 11/30/89

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#### 9. Cost Status

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#### 10. Manpower Status (Direct Labor)

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#### 11. Major Milestone Status

| b. Task 7. MB Growth 1.7 eV |
| c. Task 8. Dop Bandgap Tail |
| d. Task 9. MB Growth Trans |

#### 12. Remarks

---

Form approved
OMB No. 38R-0190

[Graphs and tables are included, showing data and progress on various aspects of the project.]
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address): Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

2. Contract Number: XL-7-06031-1

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

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12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
April 15, 1989

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Larson:


If you have any questions, please feel free to contact me.

Sincerely,

pm
Research Administrator

Enclosure

cc: Mr. Ken Zweibel
1. Contract Identification
   High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Reporting Period
   3/1/89 through 3/31/89

4. Contractor (Name and Address)
   Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

7. Months
   | J | J | A | S | O | N | D | J | F | M | A | M | J | A |

9. Cost Status
   a. Dollars in Thousands
   b. Costs Prior FYs
   c. Planned Costs Prior FYs
   d. Actual Costs Prior FYs
   e. Total Estimated Costs for Contract
   f. Total Contract Value
   g. Estimated for Subsequent Reporting Period

10. Manpower Status (Direct Labor)
   a. Manpower Plan Date
   b. Planned Manpower Prior FYs
   c. Actual Manpower Prior FYs
   d. Total Estimated Manpower for Contract
   e. Total Contract Manpower

11. Major Milestone Status
   b. Task 7. MBE Growth 1.7 eV
   c. Task 8. Dopant Tail
   d. Task 9. MBE Growth Transport
   e. Task 10. Solar Cell Fabrication

12. Remarks
# CONTRACT MANAGEMENT SUMMARY REPORT

## 1. Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

## 4. Contractor (Name and Address)
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

## 5. Contract Start Date
6/1/87

## 6. Contract Completion Date
11/10/89

## 7. Months
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## 11. Major Milestone Status

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## 12. Remarks

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May 15, 1989

Ms. Debbie Larson
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 4/1/89-4/30/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Enclosure

cc: Mr. Ken Zweibel
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Reporting Period: 4/1/89 through 4/30/89

3. Contract Number: X-7-06931-1

4. Contractor (Name and Address): Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

7. Months

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8. Cost Status

9. Cost Status

10. Manpower Status (Direct Labor)

11. Major Milestones Status

12. Remarks

13. Signature of Contractor's Person and Date

14. Signature of Government Technical Representative and Date
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address): Solar Energy Research Institute

1617 Cole Blvd.
Golden, CO 80401-3393

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

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</table>

12. Remarks:

13. Signature of Contractor's Project Manager and Date:

14. Signature of Government Technical Representative and Date:
June 15, 1989

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 5/1/89-5/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure  

cc: Mr. Ken Zweibel
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell
2. Reporting Period: 6/1/87 through 11/30/89
4. Contractor (Name and Address): Solar Energy Research Institute 6/1/87
5. Contract Start Date: 6/1/87
6. Contract Completion Date: 11/30/89
7. Reporting Period: 6/1/87 through 11/30/89
8. Report Number: XL-7-00631-1
9. Contractor IN: Solar Energy Research Institute
10. Contractor Address: 1617 Cole Blvd., Golden, CO 80401-3393
12. Remarks:
13. Signature of Contractor's Project Manager and Date
14. Signature of Government Technical Representative and Date
1. Contract identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address):
   Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

3. Contract Number: XL-7-06031-1

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

7. Months: | S | C | N | M |
|---|---|---|---|

8. Contract Status: (Data Table)

9. Cost Status: (Data Table)

10. Manpower Status (Direct Labor): (Data Table)

11. Major Milestone Status:
   - Task 6
   - Task 7
   - Task 8
   - Task 9
   - Task 10

12. Remarks:

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
July 21, 1989

Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Larson:

Enclosed please find copies of the Monthly Contract Management Report for the period 6/1/89-6/30/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Ken Zweibel
1. Convert Amount

High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Reporting Period

6/1/89 through 6/31/89

3. Contract Number

XL-7-06031-1

4. Contractor (Name and Address)

Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

5. Contract Start Date

6/1/87

6. Contract Completion Date

11/30/89

7. Months

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<th>A</th>
<th>S</th>
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<th>N</th>
<th>D</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
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8. FY

- Dollars in Thousands
- B&R Numbers

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9. Cost Status

- a. Dollars in Thousands
- b. Planned Costs Prior FYs
- c. Actual Costs Prior FYs
- d. Total Estimated Costs for Contract
- e. Total Contract Value

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<td>152,699</td>
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<th>c.</th>
<th>Actual Costs Prior FYs</th>
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<td>152,699</td>
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<th>d.</th>
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</thead>
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<td>459,643</td>
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<thead>
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<th>e.</th>
<th>Total Contract Value</th>
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</thead>
<tbody>
<tr>
<td>459,643</td>
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</table>

10. Manpower Status (Direct Labor)

- a. Manpower Plan Date
- b. Planned Manpower Prior FYs
- c. Actual Manpower Prior FYs
- d. Total Estimated Manpower for Contract
- e. Total Contract Manpower

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11. Major Milestone Status

- b. Task 7. MBE Growth 1.7 eV
- d. Task 9. MBE Growth Transport
- e. Task 10. Cell Fabrication

12. Remarks
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

7. Months | S | O | N |
|---|---|---|---|

8. Cost Status:

| g. Cost Plan Date | 6/1/87 |
| h. Planned Costs Prior FYs | 223,762 |
| i. Actual Costs Prior FYs | 152,699 |
| j. Total Estimated Costs for Contract | 459,643 |

9. Accrued Costs:

| c. Planned | 17.0 |
| d. Actual | 17.0 |
| e. Variance | 17.0 |

10. Manpower Status (Direct Labor):

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11. Major Milestone Status:

| a. Task 6 |
| b. Task 7 |
| c. Task 8 |
| d. Task 9 |
| e. Task 10 |
| f. |
| g. |
| h. |
| i. |

12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
Ms. Debbie Larson  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Larson:  

Enclosed please find copies of the Monthly Contract Management Report for the period 7/1/89-7/31/89 on the above referenced contract.  

If you have any questions, please feel free to contact me.  

Sincerely,  

Pam Majors  
Research Administrator  

pm  
Enclosure  

cc: Mr. Ken Zweibel
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Reporting Period: 7/1/89 through 7/31/89

3. Contract Number: XL-7-06031-1

4. Contractor (Name and Address): Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

7. Months

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8. FY

9. Cost Status

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11. Major Milestone Status

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</tbody>
</table>

12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
## Contract Management Summary Report

### 1. Contract Identification
- High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

### 4. Contractor (Name and Address)
- Solar Energy Research Institute
- 1617 Cole Blvd.
- Golden, CO 80401-3393

### 5. Contract Start Date
- 6/1/87

### 6. Contract Completion Date
- 11/30/89

### 7. Months

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### 9. Cost Status

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<th>a.</th>
<th>b. Cost Plan Date (6/1/87)</th>
<th>c. Planned Costs Prior FYs</th>
<th>d. Actual Costs Prior FYs</th>
<th>e. Total Estimated Costs for Contract</th>
<th>f. Total Contract Value</th>
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<tbody>
<tr>
<td>459</td>
<td>450</td>
<td>400</td>
<td>350</td>
<td>459,643</td>
<td>459,643</td>
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</table>

| a. B&R Numbers |
|---|---|---|---|---|
| 300 | 250 | 200 | 150 |

### 10. Manpower Status (Direct Labor)

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<tr>
<th>a.</th>
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<th>d. Variance</th>
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<td>8500</td>
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### 11. Major Milestone Status

- Task 6
- Task 7
- Task 8
- Task 9
- Task 10

### 12. Remarks

---

**13. Signature of Contractor's Project Manager and Date**

**14. Signature of Government Technical Representative and Date**
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-ACO2-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Gardner:  

Enclosed please find copies of the Monthly Contract Management Report for the period 8/1/89-8/31/89 on the above referenced contract.  

If you have any questions, please feel free to contact me.  

Sincerely,  

Pam Majors  
Research Administrator  

pm  
Enclosure  

cc: Mr. Ken Zweibel
1. **Contract Identification**: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. **Reporting Period**: 8/1/89 through 8/31/89

3. **Contract Number**: XL-7-06031-1

4. **Contractor (Name and Address)**: Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

7. **Months**

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9. **Cost Status**

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<td>152,699</td>
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10. **Manpower Status (Direct Labor)**

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<th>c. Actual Manpower</th>
<th>d. Variance</th>
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11. **Major Milestone Status**

|-------------------------------|-----------------------------|-----------------------------|-----------------------------|------------------------|

12. **Remarks**

13. **Signature of Contractor's Project Manager and Date**

14. **Signature of Government Technical Representative and Date**
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 11/30/89

7. Months: S O N

8. FY:

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<td>i. Total Estimated Costs for Contract</td>
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<tr>
<td>j. Total Contract Value</td>
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10. Manpower Status (Direct Labor):

<table>
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<tr>
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<tbody>
<tr>
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<td>g. Total Estimated Manpower for Contract</td>
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11. Major Milestone Status:

a. Task 6
b. Task 7
c. Task 8
d. Task 9
e. Task 10
f. Task 11

12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 9/1/89-9/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

cc: Mr. Ken Zweibel
1. **Contract Identification**
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. **Reporting Period**
9/1/89 through 9/30/89

3. **Contract Number**
XL-7-06031-1

4. **Contractor (Name and Address)**
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

5. **Contract Start Date**
6/1/87

6. **Contract Completion Date**
11/30/89

7. **Months**
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9. **Manpower Status**

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10. **Manpower Status**

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11. **Major Milestone Status**

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<thead>
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12. **Remarks**

13. **Signature of Contractor's Project Manager and Date**

14. **Signature of Government Technical Representative and Date**
### Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

### Contractor (Name and Address)
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

### Contract Number
XL-7-06033-1

### Contract Start Date
6/1/87

### Contract Completion Date
11/30/89

### Months
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### Cost Status

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<th>B. Actual Costs Prior FYs</th>
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### Major Milestone Status

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<tr>
<td>10</td>
<td>In Progress</td>
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### Remarks

---

13. Signature of Contractor's Project Manager and Date
14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 10/1/89-10/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

Enclosure

cc: Mr. Ken Zweibel
1. **Contract Identification**: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. **Reporting Period**: 10/1/89 through 10/31/89

3. **Contract Number**: XL-7-06031-1

4. **Contractor (Name and Address)**: Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. **Contract Start Date**: 6/1/87

6. **Contract Completion Date**: 11/30/89

7. **Months**

   |---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

8. **Cost Status**

   - **a. Dollars in Thousands**
   - **b. B&R Numbers**
   - **c. Planned Costs Prior FYs**
   - **d. Actual Costs Prior FYs**
   - **e. Total Estimated Costs for Contract**
   - **f. Total Contract Value**
   - **g. Unfilled Orders Outstanding**
   - **h. Estimated for Subsequent Reporting Period**

9. **Manpower Status (Direct Labor)**

   - **a. Manpower**
   - **b. Planned Manpower**
   - **c. Actual Manpower**
   - **d. Variance**

10. **Milestone Status**

   - **b. Task 7. MBE Growth 1.7 eV**
   - **c. Task 8. Dop Bandgap Tail**
   - **d. Task 9. MBE Growth Trans**
   - **e. Task 10. Cell Fabric**

11. **Remarks**

12. **Signatures**

   - Contractor's Project Manager and Date
   - Government Technical Representative and Date
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address):
   Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

5. Contract Start Date: 6/1/87
6. Contract Completion Date: 11/30/89

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9. Cost Status
   a. Cost Plan Date: 6/1/87
   b. Planned Costs Prior FYs
   c. Actual Costs Prior FYs: 152,699
   d. Total Estimated Costs for Contract: 459,643
   e. Total Contract Value: 459,643
   f. Unfilled Orders Outstanding

   a. Planned Costs
      b. Actual Costs
      c. Variance
      d. Cumulative Variance

   a. Planned
      b. Actual
      c. Variance

10. Manpower Status (Direct Labor)
    a. Manpower Plan Date: 6/1/87
    b. Planned Manpower Prior FYs: 3667
    c. Actual Manpower Prior FYs: 3651
    d. Total Estimated Manpower for Contract: 7333
    e. Total Contract Manpower: 7333

   a. Planned
      b. Actual
      c. Variance

11. Major Milestone Status
    a. Task 6
    b. Task 7
    c. Task 8
    d. Task 9
    e. Task 10

12. Remarks

13. Signature of Contractor's Project Manager and Date
14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Gardner:  

Enclosed please find copies of the Monthly Contract Management Report for the period 11/1/89-11/30/89 on the above referenced contract.  

If you have any questions, please feel free to contact me.  

Sincerely,  

Pam Majors  
Research Administrator  

Encl  

cc: Mr. Ken Zweibel
1. **Contract Identification**: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. **Contractor (Name and Address)**: Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

7. **Months**

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11. **Major Milestone Status**
   - Task 6. Opt of Solar Cell
   - Task 7. MBE Growth 1.7 eV
   - Task 8. Dop Bandgap Tail
   - Task 9. MBE Growth Transp
   - Task 10. Cell Fabric

12. **Remarks**
### CONTRACT MANAGEMENT SUMMARY REPORT

**Contract Number:** XL-7-06031-1

#### 1. Contract Identification
- **High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell**

#### 4. Contractor (Name and Address)
- **Solar Energy Research Institute**
  - 1617 Cole Blvd.
  - Golden, CO 80401-3393

#### 5. Cost Status
- **Cost Plan Date:** 6/1/87
- **Planned Costs Prior FYs:**
  - FY 223,762
  - FY 152,699
- **Total Estimated Costs for Contract:** 459,643
- **Total Contract Value:** 459,643
- **Unfilled Orders Outstanding:**

#### 6. Manpower Status (Direct Labor)
- **Manpower Plan Date:** 6/1/87
- **Planned Manpower Prior FYs:**
  - FY 3667
  - FY 3851
- **Total Estimated Manpower for Contract:** 7333
- **Total Contract Manpower:** 7333

### Major Milestones Status

#### Task 6

#### Task 7

#### Task 8

#### Task 9

#### Task 10

### Remarks
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 12/1/89-12/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Ken Zweibel
## Contract Identification

High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

### Reporting Period

6/1/88 through 12/31/89

### Contract Number

XL-7-06031-1

### Contractor (Name and Address)

Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

### Contract Start Date

6/1/87

### Contract Completion Date

11/30/89

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- Dollars
- Thousands

### B&R Numbers

### Unfilled Orders Outstanding

### Manpower Status (Direct Labor)

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- Manpower Plan Date 6/1/87
- Planned Manpower Prior FYs 3667
- Actual Manpower Prior FYs 3851
- Total Estimated Manpower for Contract 7333
- Total Contract Manpower 7333

### Major Milestone Status

- Task 6: Opt of Solar Cell
- Task 7: MBE Growth 1.7 eV
- Task 8: Dop Bandgap Tail
- Task 9: MBE Growth Trans
- Task 10: Cell Fabric

### Remarks

### Signature of Contractor's Project Manager and Date

### Signature of Government Technical Representative and Date
**Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

**Contractor (Name and Address):** Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

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### 12. Remarks

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### 13. Signature of Contractor's Project Manager and Date

---

### 14. Signature of Government Technical Representative and Date

---
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 1/1/90-1/31/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

Enclosure

cc: Mr. Ken Zweibel
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. Contract Number: XL-7-06031-1

3. Contractor (Name and Address): Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

4. Months
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5. Cost Status
   - Dollars in Thousands
   - B&R Numbers
   - Accrued Costs
   - Variance

6. Manpower Status
   - Direct Labor
   - Total Contract Manpower

7. Major Milestone Status
   - Task 6. Opt of Solar Cell
   - Task 7. MBB Growth 1.7 eV
   - Task 8. Dop Bandgap Tail
   - Task 9. MBB Growth Transp
   - Task 10. Cell Fabric

8. Remarks

9. Signature of Contractor's Designee and Date

10. Signature of Government Technical Representative and Date
1. **Contract Identification**

High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

2. **Contract Number**

XL-7-06031-1

3. **Contract Start Date**

6/1/87

4. **Contract Completion Date**

11/30/89

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### 7. Months

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5. **Cost Status**

- **g. Cost Plan Date**: 6/1/87
- **h. Planned Costs Prior FYs**: 223,762
- **i. Actual Costs Prior FYs**: 152,699
- **j. Total Estimated Costs for Contract**: 459,643
- **k. Total Contract Value**: 459,643
- **l. Unfilled Orders Outstanding**: 0

6. **Accrued Costs**

- **c. Planned**: 17.0 17.0 17.0
- **d. Actual**: 16.1 11.2 13.2 11.1 8.9
- **e. Variance**: 0.9 5.8 3.8
- **f. Cum. Variance**: 8.5 89.3 93.1

7. **Manpower Status**

- **a. Manpower Plan Date**: 6/1/87
- **b. Planned Manpower Prior FYs**: 3667
- **c. Actual Manpower Prior FYs**: 3851
- **d. Total Estimated Manpower for Contract**: 7333
- **e. Total Contract Manpower**: 7333

8. **Major Milestone Status**

- **a. Task 6**
- **b. Task 7**
- **c. Task 8**
- **d. Task 9**
- **e. Task 10**

9. **Remarks**

---

13. **Signature of Contractor’s Project Manager and Date**

---

14. **Signature of Government Technical Representative and Date**
March 20, 1990

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:


If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure  

cc: Mr. Ken Zweibel
### Contract Management Summary Report

**Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

**Reporting Period:** 2/1/90 through 2/13/90

**Contract Number:** XI-7-06031-1

**Contract Start Date:** 6/1/87

**Contract Completion Date:** 11/30/89

#### 1. Contract Identification
- High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

#### 2. Reporting Period
- 2/1/90 through 2/13/90

#### 3. Contract Number
- XI-7-06031-1

#### 4. Contractor (Name and Address)
- Solar Energy Research Institute
- 1617 Cole Blvd.
- Golden, CO 80401-3393

#### 5. Contractor Start Date
- 6/1/87

#### 6. Contract Completion Date
- 11/30/89

#### 7. Months

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#### 8. FY

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

#### 9. Cost Status

- **a. Dollars in Thousands**
  - 459
  - 450
  - 400
  - 350
  - 300
  - 250
  - 200
  - 150
  - 100
  - 50
  - 0

- **b. B&R Numbers**
  - 11111

- **c. Planned Costs Prior FYs**
  - 223,762

- **d. Actual Costs Prior FYs**
  - 152,699

- **e. Total Estimated Costs for Contract**
  - 459,643

- **f. Total Contract Value**
  - 459,643

- **g. Estimate for Subsequent Reporting Period**
  - 1112

#### 10. Manpower Status (Direct Labor)

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

- **a. Planned Manpower**
  - 197
  - 197
  - 197
  - 197
  - 197
  - 197
  - 197
  - 197
  - 197
  - 197
  - 197

- **b. Actual Manpower**
  - 720
  - 720
  - 640
  - 365
  - 436
  - 544
  - 806
  - 189
  - 834
  - 420
  - 327
  - 437
  - 421
  - 361

- **c. Variance**
  - (523)
  - (523)
  - (443)
  - (172)
  - (367)
  - (347)
  - (309)
  - 8
  - (45)
  - (223)
  - (140)
  - (140)
  - (224)
  - (164)

- **d. Total Contract Manpower**
  - 7333

#### 11. Major Milestone Status

- **b. Task 7. MBE Growth 1.7 eV**
- **c. Task 8. Dop Bandgap Tail**
- **d. Task 9. MBE Growth Transp /**
- **e. Task 10. Cell Fabric.**

#### 12. Remarks

---

**13. Signature of Contractor's Project Manager and Date**

**14. Signature of Government Technical Representative and Date**
1. Contract Identification
   High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

4. Contractor (Name and Address):
   Solar Energy Research Institute
   1617 Cole Blvd.
   Golden, CO 80401-3393

7. Months

9. Cost Status

10. Manpower Status (Direct Labor)

11. Major Milestone Status

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:


If you have any questions, please feel free to contact me.

Sincerely,

[Signature]

Pam Majors  
Research Administrator

Enclosure

cc: Mr. Ken Zweibel
**Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

**Reporting Period:** 3/1/90 through 3/31/90

**Contract Number:** XL-7-06031-1

**Contractor (Name and Address):**
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

**Contract Start Date:** 6/1/87

**Contract Completion Date:** 11/30/89

### Months

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### Cost Status

- **Dollars in Thousands**
  - a. Planned Costs Prior FYs: 223,762
  - b. Actual Costs Prior FYs: 152,699
  - c. Total Estimated Costs for Contract: 459,643
  - d. Total Contract Value: 459,643
  - e. Unfilled Orders Outstanding

### B&R Numbers

- a. Planned B&R Numbers
- b. Actual B&R Numbers

### Accrual Costs

- a. Planned
- b. Actual
- c. Variance

### Manpower Status (Direct Labor)

- a. Planned Manpower
- b. Actual Manpower
- c. Variance

### Major Milestone Status

- b. Task 7. MBE Growth 1.7 eV
- c. Task 8. Dop Bandgap Tail
- d. Task 9. MBE Growth Transp

### Remarks

---

12. Remarks

---

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cell

3. Contract Number: X1-7-06031-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

6. Contract Completion Date: 11/30/89

7. Months: S O N D J F M

9. Cost Status:

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9a. B&R Numbers:

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11. Major Milestone Status:

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<td>Task 6</td>
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12. Remarks:

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
May 16, 1990

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 4/1/90-4/30/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator  

cc: Mr. Rick Mitchell
# Contract Management Summary Report

**Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

**Reporting Period:** 4/1/90 through 4/30/90

**Contract Number:** XL-7-06031-1

**Contractor Name and Address:**
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

**Contract Start Date:** 6/1/87

**Contract Completion Date:** 3/31/91

## Cost Status

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- a. Dollars in Thousands
- b. S&R Numbers
- c. Planned Costs
- d. Actual Costs
- e. Variance

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## Manpower Status (Direct Labor)

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<td>g. Actual Manpower Prior FYs 13,173</td>
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<td>b. Planned 418</td>
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<td>c. Actual 376</td>
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<td>d. Variance (42)</td>
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## Major Milestone Status

- a. Task 1. MOCVD Growth CdTe
- b. Task 2. MOCVD Growth CdZnTe
- d. Task 4. Def. Characteristics
- e. Task 5. Cell Fabrication
- f. Task 6. MBE Growth CdZnTe

## Remarks

13. Signature of Contractor's Project Manager and Date
14. Signature of Government Technical Representative and Date
May 16, 1990

Mr. Denny Hogge
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XX-0-19145-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Mr. Hogge:

Enclosed please find copies of the Monthly Contract Management Report for the periods 4/1/90-4/30/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

Enclosure

cc: Mr. Bhushan Sopori
**Contract Management Summary Report**

**FORM APPROVED**

OMB NO. 38R-0190

---

**1. Contract Identification**  
Impurity Characterization Support for Silicon

**2. Reporting Period**  
4/1/90 through 4/30/90

**3. Contract Number**  
XX-0-19145-1

**4. Contractor (Name and Address)**  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

**5. Contract Start Date**  
10/23/89

**6. Contract Completion Date**  
10/23/90

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**7. Months**  
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**8. FY 89/90**

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**9. Cost Status**

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**10. Manpower Status (Direct Labor)**

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**11. Major Milestone Status**

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**12. Remarks**

---

**13. Signature of Contractor's Project Manager and Date**

**14. Signature of Government Technical Representative and Date**
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 5/1/90-5/31/90 on the above referenced contract. Also enclosed is a revised cost plan through January 1991.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator  

cc: Mr. Rick Mitchell
### CONTRACT MANAGEMENT SUMMARY REPORT

**1. Contract Identification**
- High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

**2. Reporting Period**
- 5/1/90 through 5/31/90

**3. Contract Number**
- XL-7-06031-1

**4. Contractor (Name and Address)**
- 

**5. Contract Start Date**
- 6-1-87

**6. Contract Completion Date**
- 1-31-91

**7. Months**

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**8. FY**

|     |     |     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|-----|
| g. | Planned Costs Prior FYs | 459,643 |
| i. | Actual Costs Prior FYs | 481,430 |
| j. | Total Estimated Costs for Contract | 607,698 |
| k. | Total Contract Value | 607,698 |
| l. | Unfilled Orders Outstanding | 41.6 |

**9. Cost Status**

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**10. Manpower Status (Direct Labor)**

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**11. Major Milestone Status**

- Task 1. MOCFD
  - Growth CdTe
- Task 2. MOCFD
  - Growth CdZnTe
- Task 3. Chem.
- Heat Treat.
- Task 4. Def.
  - Characterization
- Task 5. Cell
  - Fabrication
- Task 6. MBE
  - Growth CdZnTe

**12. Remarks**

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**13. Signature of Contractor's Project Manager and Date**

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**14. Signature of Government Technical Representative and Date**

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July 25, 1990

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 6/1/90-6/30/90 on the above referenced contract. There were some charges that were incorrectly posted to this account. These charges have been removed and this shows a deficit in expenditures during June.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

Enclosure

cc: Mr. Rick Mitchell
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. Reporting Period: 6/1/90 through 6/31/90

3. Contract Number: XL-7-06031-1

4. Contractor (Name and Address):

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 1/31/91

7. Months: APR MAY JUN JUL AUG SEP OCT NOV DEC JAN

8. FY:

9. Cost Status
   a. Cost Plan Date
   b. Planned Costs Prior FYs
   c. Actual Costs Prior FYs
   d. Total Estimated Costs for Contract
   e. Total Contract Value
   f. Unfilled Orders Outstanding

10. Manpower Status (Direct Labor)
    a. Manpower Plan Data
    b. Planned Manpower Prior FYs
    c. Actual Manpower Prior FYs
    d. Variance

11. Major Milestone Status
    a. Task 1. MOC/D Growth CdTe
    b. Task 2. MOC/D Growth CdZnTe
    d. Task 4. Def Characteristic
    e. Task 5. Cell Fabrication
    f. Task 6. MBE Growth CdZnTe

12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
August 27, 1990

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 7/1/90-7/31/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Rick Mitchell
### Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

### Reporting Period
7/1/90 through 7/31/90

### Contract Number
XL-7-06031-1

### Contract Start Date
6-1-87

### Contract Completion Date
1-31-91

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### Manpower Status (Direct Labor)

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### Major Milestone Status

- Task 1: MOCVD Growth CdTe
- Task 2: MOCVD Growth CdZnTe
- Task 3: Chem. & Heat Treat.
- Task 4: Def. Characteristic
- Task 5: Cell Fabrication
- Task 6: MBE Growth CdZnTe

### Remarks

---

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 8/1/90-8/31/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Rick Mitchell
## Contract Management Summary Report

### 1. Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

### 2. Reporting Period
8/1/90 through 8/31/90

### 3. Contract Number
XL-7-06031-1

### 4. Contractor (Name and Address)

### 5. Contract Start Date
6-1-87

### 6. Contract Completion Date
1-31-91

### 7. Months
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### 9. Cost Status

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### 10. Manpower Status (Direct Labor)

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### 11. Major Milestone Status

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### 12. Remarks

### 13. Signature of Contractor's Project Manager and Date

### 14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Gardner: 

Enclosed please find copies of the Monthly Contract Management Report for the period 9/1/90-9/31/90 on the above referenced contract.  

If you have any questions, please feel free to contact me.  

Sincerely,  

Pam Majors  
Research Administrator  

cc: Mr. Rick Mitchell
CONTRACT MANAGEMENT SUMMARY REPORT

1. Contract Identification
   High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. Reporting Period
   9/1/90 through 9/30/90

3. Contract Number
   XL-7-06031-1

4. Contractor (Name and Address)

5. Contract Start Date
   6-1-87

6. Contract Completion Date
   1-31-91

7. Months
   APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC  JAN

8. FY

9. Cost Status
   a. Planned
   b. Actual
   c. Variance
   d. Variance

10. Manpower Status (Direct Labor)
    a. Planned
    b. Actual
    c. Variance

11. Major Milestone Status
    a. Task 1. MOC
       Growth CdTe
    b. Task 2. MOC
       Growth CdZnTe
       & Heat Treat.
    d. Task 4. Def.
       Characteristic
    e. Task 5. Cell
       Fabrication
    f. Task 6. MBE
       Growth CdZnTe

12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 10/1/90-10/31/90 on the above referenced contract. Actual effort for Dr. Rohatgi was incorrectly charged to the project for the summer quarter. His effort has been corrected which shows a deficit expenditure for the month of October.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Rick Mitchell
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. Reporting Period: 10/1/90 through 10/31/90

3. Contract Number: XL-7-06031-1

4. Contractor (Name and Address):

5. Contract Start Date: 6-1-87

6. Contract Completion Date: 1-31-91

7. Months: APR MAY JUN JUL AUG SEP OCT NOV DEC JAN

8. FY:

9. Cost Status:

a. Planned Costs Prior FY's: 459,643
b. Actual Costs Prior FY's: 481,430
c. Total Estimated Costs for Contract: 607,698
d. Total Contract Value: 607,698

10. Manpower Status (Direct Labor):

a. Planned Manpower Plan Date: 6/1/87
b. Planned Manpower Prior FY's: 7,333
c. Actual Manpower Prior FY's: 13,173
d. Total Estimated Manpower for Contract: 17,337

11. Major Milestone Status:

a. Task 1. MOCVD Growth CdTe:
   - Current Milestone: Complete
b. Task 2. MOCVD Growth CdZnTe:
   - Current Milestone: Complete
c. Task 3. Chem. & Heat Treat:
   - Current Milestone: Complete
d. Task 4. Def. Characteristic:
   - Current Milestone: Complete
e. Task 5. Cell Fabrication:
   - Current Milestone: Complete
f. Task 6. MBE Growth CdZnTe:
   - Current Milestone: Complete

12. Remarks:

13. Signature of Contractor's Project Manager and Date:

14. Signature of Government Technical Representative and Date:

January 2, 1991

Ms. Nancy Gardner
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 11/1/90-11/30/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

cc: Mr. Rick Mitchell
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. Reporting Period: 11/1/90 through 11/31/90

3. Contract Number: XL-7-06031-1

4. Contractor (Name and Address):

5. Contract Start Date: 6/1/87

6. Contract Completion Date: 1/31/91

7. Months

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8. FY

9. Cost Status

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10. Manpower Status (Direct Labor)

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11. Major Milestone Status:

- Task 1: MOCVD Growth CdTe
- Task 2: MOCVD Growth CdZnTe
- Task 3: Chem. & Heat Treat.
- Task 4: Def. Characteristic
- Task 5: Cell Fabrication
- Task 6: MBE Growth CdZnTe

12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
January 18, 1991

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 12/1/90-12/31/90 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Rick Mitchell
## Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

## Reporting Period
12/1/90 through 12/31/90

## Contract Number
XL-7-06031-1

## Contract Start Date
6-1-87

## Contract Completion Date
1-31-91

### 7. Months
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### 9. Cost Status
- a. Cost Plan Date
- b. Planned Costs Prior FYs
- c. Actual Costs Prior FYs
- d. Total Estimated Costs for Contract
- e. Total Contract Value
- f. Unfilled Orders Outstanding

### 10. Manpower Status (Direct Labor)
- a. Manpower Plan Date
- b. Planned Manpower Prior FYs
- c. Actual Manpower Prior FYs
- d. Total Estimated Manpower for Contract
- e. Total Contract Manpower

### 11. Major Milestone Status
- a. Task 1. MOCVD Growth CdTe
- b. Task 2. MOCVD Growth CdZnTe
- d. Task 4. Def. Characteristic
- e. Task 5. Cell Fabrication
- f. Task 6. MBE Growth CdZnTe
- g. 
- h. 
- i. 

### 12. Remarks
February 22, 1991

Ms. Nancy Gardner
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093
         Project Director: A. Rohatgi

Dear Ms. Gardner:

    Enclosed please find copies of the Monthly Contract Management Report for the period
    1/1/91-1/31/91 on the above referenced contract.

    If you have any questions, please feel free to contact me.

    Sincerely,

    Pam Majors
    Research Administrator

pm
Enclosure

cc: Mr. Rick Mitchell
## 1. Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

## 2. Reporting Period
1/1/91 through 12/31/91

## 3. Contract Number
XL-7-06031-1

## 4. Contractor Name and Address

## 5. Contract Start Date
6-1-87

## 6. Contract Completion Date
1-31-91

## 7. Months
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## 8. B&R Numbers

## 9. Cost Status

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## 10. Manpower Status (Direct Labor)

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## 11. Major Milestone Status

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<tbody>
<tr>
<td>Task 1</td>
<td>MOCVD Growth CdTe</td>
</tr>
<tr>
<td>Task 2</td>
<td>MOCVD Growth CdZnTe</td>
</tr>
<tr>
<td>Task 3</td>
<td>Chem. &amp; Heat Treat.</td>
</tr>
<tr>
<td>Task 4</td>
<td>Def. Characteristic</td>
</tr>
<tr>
<td>Task 5</td>
<td>Cell Fabrication</td>
</tr>
<tr>
<td>Task 6</td>
<td>MBE Growth CdZnTe</td>
</tr>
</tbody>
</table>

## 12. Remarks

## 13. Signature of Contractor's Project Manager and Date

## 14. Signature of Government's Technical Representative and Date
March 22, 1991

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
          Project Director: A. Rohatgi

Dear Ms. Gardner:


If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc: Mr. Rick Mitchell
CONTRACT MANAGEMENT SUMMARY REPORT

1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. Reporting Period: 2/1/91 through 2/28/91

3. Contract Number: XL-7-06031-1

4. Contractor [Name and Address]:

5. Months: APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB

6. FY: 1991

7. Cost Status:

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   a. Planned Costs Prior FYs: 459,643
   b. Actual Costs Prior FYs: 481,430
   c. Total Estimated Costs for Contract: 607,698
   d. Total Contract Value: 607,698
   e. Unfilled Orders Outstanding: 0

8. FY: 1990

9. Manpower Status (Direct Labor):

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   a. Planned Manpower: 6/1/87
   b. Planned Manpower Prior FYs: 7,333
   c. Actual Manpower Prior FYs: 13,173
   d. Total Estimated Manpower for Contract: 17,337
   e. Total Contract Manpower: 17,337

10. Major Milestone Status:

   a. Task 1. MOCVD Growth CdTe
   b. Task 2. MOCVD Growth CdZnTe
   d. Heat Treat.
   e. Task 4. Def.
   f. Characteristic
   g. Task 5. Cell
   h. Fabrication
   i. Task 6. MBE Growth CdZnTe
   k. Task 8. Test
   l. Task 9. Installation

11. Remarks:

   a. Remarks:
   b. Remarks:
   c. Remarks:
   d. Remarks:
   e. Remarks:
   f. Remarks:
   g. Remarks:
   h. Remarks:

12. Remarks:

   a. Remarks:
   b. Remarks:
   c. Remarks:
   d. Remarks:
   e. Remarks:
   f. Remarks:
   g. Remarks:
   h. Remarks:

13. Remarks of Contractor's Project Manager and Date:

14. Signature of Government Technical Representative and Date:
April 18, 1991

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 3/1/91-3/31/91 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,


Pam Majors  
Research Administrator  

pm  
Enclosure  

cc: Mr. Rick Mitchell
**1. Contract Identification**
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

**2. Reporting Period**
3/1/91 through 3/31/91

**3. Contract Number**
XL-7-06031-1

**4. Contractor (Name and Address)**

**5. Contract Start Date**
6-1-87

**6. Contract Completion Date**
1-31-91

**7. Months**

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**8. FY**

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**9. Cost Status**

**10. Manpower Status (Direct Labor)**

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<th>b. Planned Manpower Prior FYs</th>
<th>c. Actual Manpower Prior FYs</th>
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**11. Major Milestone Status**

- Task 1: MOCVD Growth CdTe
- Task 2: MOCVD Growth CdZnTe
- Task 3: Chem. & Heat Treat.
- Task 4: Def. Characteristic
- Task 5: Cell Fabrication
- Task 6: MBE Growth CdZnTe

**12. Remarks**

**13. Signature of Contractor's Project Manager and Date**

**14. Signature of Government Technical Representative and Date**
May 23, 1991

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi  

Dear Ms. Gardner:

Enclosed please find copies of the Monthly Contract Management Report for the period 4/1/91-4/30/91 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure  

cc: Mr. Rick Mitchell
# CONTRACT MANAGEMENT SUMMARY REPORT

## 1. Contract Identification
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

## 2. Reporting Period
4/1/91 through 5/31/91

## 3. Contract Number
XL-7-06031-1

## 4. Contractor (Name and Address)

## 5. Contract Start Date
6-1-87

## 6. Contract Completion Date
3-31-92

## 7. Months
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## 8. FY

## 9. Cost Status

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## 10. Manpower Status (Direct Labor)

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## 11. Major Milestone Status

- **b. Task 8. CdS Film Charac.**
- **d. Task 10. Fab. CdZnTe**
- **e. Task 11. Charac. Cells**
- **f.**
- **g.**
- **h.**
- **i.**

## 12. Remarks

## 13. Signature of Contractor's Project Manager and Date

## 14. Signature of Government Technical Representative and Date
June 21, 1991

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393

SUBJECT:  Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
          Project Director:  A. Rohatgi

Dear Ms. Gardner:

    Enclosed please find copies of the Monthly Contract Management Report for the period  
5/1/91-5/31/91 on the above referenced contract.

    If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors  
Research Administrator

pm  
Enclosure

cc:  Mr. Rick Mitchell
1. **Contract Identification**: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. **Reporting Period**: 5/1/91 through 5/31/91

3. **Contract Number**: XL-7-06031-1

4. **Contractor (Name and Address)**: 6-1-87

5. **Contract Completion Date**: 3-31-92

6. **Months**: FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB

7. **Cost Status**:
   - **In Thousands**
   - Planned Costs Prior FYs: 607,698
   - Actual Costs Prior FYs: 582,262
   - Total Estimated Costs for Contract: 757,661
   - Total Contract Value: 757,661
   - Unfilled Orders Outstanding

8. **FY**:
   - Planned Costs Prior FYs: 607,698
   - Actual Costs Prior FYs: 582,262
   - Total Estimated Costs for Contract: 757,661
   - Total Contract Value: 757,661

9. **Manpower Status (Direct Labor)**:
   - Planned Manpower Prior FYs: 17,337
   - Actual Manpower Prior FYs: 16,678
   - Total Estimated Manpower for Contract: 22,278
   - Total Contract Manpower: 22,278

10. **Major Milestone Status**:  
    - Task 7. Invest. CdS
    - Task 8. CdS Film Charac.
    - Task 10. Farbic. CdZnTe
    - Task 11. Charac. Cells

11. **Remarks**

12. **Signature of Contractor's Project Manager and Date**

13. **Signature of Government Technical Representative and Date**
September 23, 1991

Ms. Nancy Gardner  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10093  
Project Director: A. Rohatgi

Dear Ms. Gardner:

Attached, as required by contract, are two (2) copies of subject above. This report includes the months of June, 1991 through August, 1991.

Should you have questions or need additional information, I may be contacted at (404)853-9836.

Sincerely,

Kathy Knighton

Attachments

cc: Mr. Rick Mitchell  
A. Rohatgi  
E21-658 File
# Contract Management Summary Report

**1. Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

**2. Reporting Period:** 6/1/91 through 8/31/91

**3. Contract Number:** XL-7-06031-1

**4. Contractor (Name and Address):**

**5. Contract Start Date:** 6-1-87

**6. Contract Completion Date:** 3-31-92

## 7. Months

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## 9. Cost Status

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## 10. Manpower Status (Direct Labor)

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## 11. Major Milestone Status

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## 12. Remarks

**13. Signature of Contractor's Project Manager and Date:**

**14. Signature of Government Technical Representative and Date:**
November 14, 1991

Mr. Rick Mitchell  
SERI  
1617 Cole Blvd.  
Golden, CO 80401-3393

Re:  Contract Management Summary Report  
September 1 through October 31, 1991  
High Efficiency Cadmium and Zinc  
Telluride Based Thin Film Solar Cells

Dear Mr. Mitchell:

Enclosed please find the September and October reports for the High Efficiency...

..... contract from Dr. A. Rohatgi.

Very sincerely yours,

Rochelle Kraehe

rfk
### CONTRACT MANAGEMENT SUMMARY REPORT

**1. Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

**2. Reporting Period:** 9-1-91 through 10-31-91

**3. Contract Number:** XL-7-06031-1

**4. Contractor (Name and Address):**

**5. Contract Start Date:** 6-1-87

**6. Contract Completion Date:** 3-31-92

### 7. Months

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### 10. Major Milestone Status

- **Task 7. Invest. CdS**
- **Task 8. CdS Film Charac.**
- **Task 9. Farbic. CdTe**
- **Task 10. Fab. CdZnTe**
- **Task 11. Charac. Cells**

### Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
December 19, 1991

Mr. Rick Mitchell  
SERI  
1617 Cole Blvd.  
Golden, CO 80401-3393

Re: CMSP: November 1 through 30, 1991  
High Efficiency Cadmium and Zinc  
Telluride Based Thin Film Solar Cells

Dear Mr. Mitchell:

Enclosed please find the November report for the High Efficiency......Solar Cells from Dr. A. Rohatgi. Effective December 16, 1991, I am the contact person for any questions or information that you wish to retrieve or relay to Dr. Rohatgi.

Very sincerely yours,

Rochelle Kraehe  
rfk  
Attachments
# CONTRACT MANAGEMENT SUMMARY REPORT

**Contract Identification:** High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

**Contract Number:** XL-7-06031-1

**Reporting Period:** 11-1-91 through 11-30-91

### 4. Contractor (Name and Address)

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### 11. Major Milestone Status

- **Task 7**: Invest. CdS
  - b. Task 8: CdS Film Charac.
  - d. Task 10: Fab. CdZnTe
  - e. Task 11: Charac. Cells

### 12. Remarks

13. Signature of Contractor's Project Manager and Date

14. Signature of Government Technical Representative and Date
January 9, 1992

Mr. Rick Mitchell  
SERI  
1617 Cole Blvd.  
Golden, CO 80401-3393

Re: CMSP: December 1 through 31, 1991  
High Efficiency Cadmium and Zinc  
Telluride Based Thin Film Solar Cells

Dear Mr. Mitchell:

Enclosed please find an original and 3 copies of the December CMSR for the above referenced contract.

Very sincerely yours,

Rochelle Kracht

rfk
attachment
1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

2. Renumbering Period: 1-2-91 through 12-31-91

3. Contract Number: 7L-7-06031-1

4. Contractor [Name and Address]:

5. Contract Start Date: 6-1-87

6. Contract Completion Date: 3-31-92

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9. Cost Plan Date: 6-1-87

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11. Major Milestone Status:

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<td>Task 8. Cds Film Charac.</td>
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<td>Task 9. Fabric. CdTe</td>
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<td>Task 10. Feb. CdZnTe</td>
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<td>Task 11. Charac. Cells</td>
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12. Remarks:

13. Signature of Contractor's Project Manager and Date: [Signature]

14. Signature of Government Technical Representative and Date: [Signature]
March 18, 1992

Mr. Rick Mitchell  
NREL  
1617 Cole Blvd  
Golden, CO 80401-3393  

Re: CMSP: Jan 1 to Feb 29, 1992  
High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells

Dear Mr. Mitchell:

Enclosed please find an original and 3 copies of the January and February 1992 CMSRs for the above referenced contract.

Very sincerely yours,

Rochelle Kraehe

rfk  
Encs: CMSRs 1-1 to 2-29-92
CONTRACT MANAGEMENT SUMMARY REPORT

1. Contract Identification: High Efficiency Cadmium and Zinc Telluride Based Thin Film Solar Cells
2. Reporting Period: 12/41-91 through 12/31-91
3. Contract Number: XL-7-06031-1
4. Contractor (Name and Address)
5. Contract Start Date: 6-1-87
6. Contract Completion Date: 3-31-92
7. Months: FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB
8. FY

9. Cost Status
   a. In Thousands
      |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
      | 757 | 750 | 725 | 700 | 675 | 650 | 625 | 600 | 582 |
   b. B&R Numbers
      |   |   |   |   |   |   |   |   |   |
      | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
   c. Planned
      |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
      | 12.0 | 7.7 | 9.6 | 10.8 | 13.4 | 14.5 | 16.4 | 14.9 | 9.7 | 10.4 | 15.7 | 14 | 25.7 | 14 | 25.7 |
   d. Actual
      |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
      | 4.8 | 2.9 | 1.7 | 1.7 | 2.0 | 2.9 | 4.9 | 6.0 | 6.0 | 13.9 | 16.3 | 13.4 | 14.4 | 14.6 | 14.6 |
   e. Variance
      |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
      | 5.5 | 5.5 | 8.2 | 8.2 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 | 17.9 |
   f. Total Estimated Costs for Contract
      | 757,661 |
   g. Total Contract Value
      | 757,661 |
   h. Unfilled Orders Outstanding
      | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
   i. Estimate for Subsequent Reporting Period
      | 757,661 |

10. Manpower Status (Direct Labor)
   a. Manpower Plan Date: 6-1-87
   b. Planned Manpower Prior FY's
      | 17,337 |
   c. Actual Manpower Prior FY's
      | 16,678 |
   d. Total Estimated Manpower for Contract
      | 22,278 |
   e. Total Contract Manpower
      | 22,278 |
   f. Planned Manpower
      | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 |
   g. Actual Manpower
      | 386 | 264 | 334 | 404 | 513 | 443 | 485 | 464 | 254 | 898 | 961 | 908 | 919 |
   h. Variance
      | 14 | 136 | 66 | 4 (4) | (113) | (43) | (85) | (64) | (85) | 45.2 | 498.961 | 908 | 919 |

11. Major Milestone Status:
   a. Task 7: Invest. CdS
   b. Task 8: CdS Film Charac.
   c. Task 9: Fabric. CdTe
   d. Task 10: Fab. CdZnTe
   e. Task 11: Charac. Cells
   f.
   g.
   h.
   i.

12. Remarks:

13. Signature of Contractor's Project Manager and Date
14. Signature of Government Technical Representative and Date
May 31, 1992

Mr. Rick Mitchell  
NREL  
1617 Cole Blvd  
Golden, Co 80401-3393

Re: CMSR: March 1-31, 1992  
XL-7-06031-1

Dear Mr. Mitchell:

Enclosed please find an original and 3 copies of the March and final CMSR report on the above referenced contract.

Rochelle Kraehe

rfk  
enc: as stated
August 20, 1987

Mr. Ken Zweibel
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the periods 6/1/87-6/30/87 and 7/1/87-7/31/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THIN FILM SOLAR CELLS

A. Rohatgi, C.J. Summers and A. Erbil

First Monthly Report for the Period
June 1 to June 30, 1987

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332
**Introduction**

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells (Figure 1) will be fabricated with glass/SnO₂CdS window with thin CdS layer to maximize transmission and current. Absorber films (Eg ~ 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p⁺-ZnTe interlayer by MBE between the metal grid and the absorber film by MBE.

**Technical Progress**

In the first month of this program we made attempts to grow CdMnTe films by MOCVD on single crystal GaAs (111) substrate, with and without CdTe buffer layer. Process conditions for the first 9 runs are listed in Figure 2. Growth temperature for CdMnTe films was in the range of 400-450°C, reactor pressure was 250 torr, Te partial pressure was fixed at 127 torr, Mn partial pressure was
FIGURE 1: Schematic and energy band diagram of a n⁺-p-p⁺ double heterojunction solar cell. In this program three different p-type absorber materials: CdZnTe, CdMnTe and HgZnTe; and two different p⁺-layers: CdZnTe and HgZnTe will be investigated.
### PRELIMINARY CdMnTe RUNS

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<th>Time (min)</th>
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<th>$P_{Cd}$ (mtoorr)</th>
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Substrate is 2" GaAs(111) wafer (LEC grown)

FIGURE 2: Growth conditions of preliminary CdMnTe runs on GaAs by MOCVD
3-4 torr, and Cd partial pressure was varied in the range of 4.6 - 18.5 torr to control the bandgap, composition, and surface morphology. CdMnTe films were obtained with thickness in the range of 0.5 to 5 ppm. Three films analyzed by photoluminescence showed bandgaps of 1.83 eV, 2.11 eV and 2.15 eV. The PL peaks were broad for the films grown on CdTe buffer layers, possibly indicating some diffusion of Mn into the buffer layer. X-ray double crystal diffraction provided evidence for the epitaxial growth of the films.

Figure 3 shows the FTIR measurements on the last film (A0425871) in Figure 1. The transmission data shows two distinct peaks, at 142 cm⁻¹ and 185 cm⁻¹, which correspond to CdTe and CdMnTe modes, respectively. The sharpness of the peak is indicative of high quality film. This is expected because this film is crystalline. Absence of any shoulder in the CdTe peak also suggests no clustures in the film. Transmission data was fed into a multi-oscillator computer program where resonance frequency and amplitude is a function of X or the magnese content. This gave a value of X = 0.29.

Figure 4 shows the FTIR data in the reflectance mode. Again we see two sharp peaks for CdTe and CdMnTe modes. The flat baseline in spectra is indicative of low free carrier concentration (< 10¹⁴ cm⁻³) on these films, which were not intentionally doped.

Figure 5 shows the remaining spectra of this film in which we only observe sharp LO or LO + TO modes which is indicative of good crystalline quality film with very low undesirable impurity/defect content.
FIGURE 3: FTIR measurement on CdMnTe/CdTe/GaAs grown by MOCVD

FIGURE 4: Reflectance measurement on CdMnTe/CdTe/GaAs structure
FIGURE 5: Raman spectra of CdMnTe grown by MOCVD

FIGURE 6: Photoluminescence spectra of CdMnTe film
FIGURE 7: Electromicroprobe data of CdMnTe film grown by MOCVD
Figure 6 shows the photoluminescence spectra for this film. The peak position gives a bandgap of 2.005 eV and 77°k. Using the relationship \( E_g = 1.58 + 1.51 \times \), we obtain manganese content of 0.28, which is consistent with the electron microprobe data, Figure 7, acquired at SERI. Figure 7 shows that the film has uniform Te content of 50% over the 1.5 cm long region investigated. However, Mn content increased from 24% to 28%, with a corresponding decrease in Cd content. This is probably due to the fact that incorporation coefficient of Cd is higher than Mn under these growth conditions, therefore, Cd content decreases as the gas flow traverses the wafer. We think uniformity can be improved further by adjusting the growth conditions.

We are now in the process of growing CdMnTe films on glass, glass/SnO\(_2\), and glass/SnO\(_2\)/Cds substrates to do material characterization and cell fabrication on polycrystalline films. We would like to acknowledge the help of Dr. Meyer of Amtek for providing the substrate and the window material for the initial runs.

**Acknowledgements**

The authors would like to thank K.T. Pollard, J. Welch, G. Augustine, S. Ringel and B.K. Wagner for growth and characterization of films, and Kay Meeks for typing the manuscript. We would also like to thank Prof. Pertkowich and Dr. Sudershan of Emory University for the help in FTIR and PL measurements.
August 20, 1987

Mr. Ken Zweibel
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO  80401-3393

SUBJECT:  Contract No. XL-7-06031-1 under DE-AC02-83CH10993
          Project Director:  A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the periods
6/1/87-6/30/87 and 7/1/87-7/31/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THIN FILM SOLAR CELLS

A. Rohatgi, C.J. Summers and A. Erbil

Second Monthly Report for the Period
July 1 to July 31, 1987

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332
**Introduction**

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO₂CdS window with thin CdS layer to maximize transmission and current. Absorber films (Eg \( \approx 1.75 \, \text{eV} \)) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p⁺-ZnTe interlayer by MBE between the metal grid and the absorber film by MBE.

**Technical Progress**

In the previous monthly report we discussed the MOCVD growth and characterization of CdMnTe film. In the second month of the program we have made attempts to grow CdZnTe and ZnTe films on single crystal GaAs (001) substrates in our Varian Gen-II MBE machine equipped with RHEED. Binary CdTe and ZnTe sources, which were 5N and 6N pure were used for depositing these films. The growth rate was \( \approx 0.4 - 0.6 \, \text{microns/hr.} \) and the growth
temperature was in the range of 300-420°C. To grow CdZnTe, both CdTe and ZnTe source shutters were open simultaneously. Because the sticking coefficient of CdTe decreases more rapidly than that of ZnTe with increasing growth temperature, CdZnTe layer can be made Zn rich by increasing the growth temperature. In order to continue the growth of ZnTe on CdZnTe, the CdTe shutter was closed and ZnTe growth proceeded. In some instances ZnTe films were grown directly on GaAs substrates.

Secondary ion mass spectroscopy (SIMS) was performed on MBE grown films to determine if the constituent elements of the substrate and the epitaxial layer interdiffused across the interface. SIMS depth profiles and line scans employed a 150 nA Ar + beam with scan widths from 0.36 to 2 mm. Figure 1 shows the SIMS profile of a ZnTe layer grown directly on (001) GaAs with no oxide. Oxide layer was removed, prior to ZnTe deposition, by heating the substrate to 580°C. The data shows a nearly uniform ZnTe layer on GaAs substrate, however there was appreciable diffusion of Ga into ZnTe layer and some diffusion of Zn and Te into GaAs.

Figure 2 shows SIMS data for a combination ZnTe film grown on top of the CdZnTe film, consistent with our proposed cell design. SIMS data verifies the growth of a thin CdZnTe under the ZnTe layers. None of these films were intentionally doped. SIMS profile again shows some interdiffusion of Ga into ZnTe layer but it is significantly less than what was seen in Figure 1, when no CdZnTe layer was present.
**FIGURE 1:** SIMS profile of ZnTe Film on GaAs
Depth Profile

FIGURE 2: SIMS profile of ZnTe/Cd Zn Te/Ga As structure grown by MBE
(001) ZnTe on GaAs
(no oxide)

**Depth Profile**

**FIGURE 3:** Photoluminescence spectra of ZnTe film on (001) GaAs at 10°K
Figure 3 shows a 10°k photoluminescence spectra of ZnTe layer on GaAs. Three peaks were observed, two very close to the bandgap energy (≈ 2.3 eV) and one deep level corresponding to λ = 0.5340 μm. The two sharp peaks may represent the defects or impurities which tend to make an intentionally doped ZnTe film p-type. Further analysis is being done to investigate the PL results.

We have successfully demonstrated the MBE growth of CdZnTe and ZnTe, singly and in combination, on GaAs (001) substrate. We are now in the process of growing these films (polycrystalline) on glass/SnO2 and glass/SnO2/CdS substrates to make solar cells. These substrates were provided by Amtek, courtesy of Dr. Meyer. Results on polycrystalline films will be reported in the near future.

Acknowledgements

The authors would like to thank B.K. Wagner and Gene Oakes for the growth and characterization of the films, and Kay Meeks for typing the manuscript.
September 18, 1987

Mr. Ken Zweibel
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the period 8/1/87-8/31/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C.J. Summers and A. Erbil

Third Monthly Report for the Period
August 1 to August 31, 1987

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332
Introduction

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO₂/CdS window with thin CdS layer to maximize transmission and current. Absorber films (Eg ~ 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p+-ZnTe interlayer by MBE between the metal grid and the absorber film by MBE.

Technical Progress

In this monthly we report the solar cell results from CdMnTe film grown on glass/SnO₂/CdS substrate. This film was grown at 420°C for 2 hours in our MOCVD reactor to produce a film thickness of about 2 microns. The total reactor pressure was 250 torr and the partial pressure of Cd, Mn and Te were 4.7, 288,
and 342 mtorr, respectively. These growth conditions on single crystal substrate gave a Mn content of 28% with a bandgap of ~1.9 eV.

Cell fabrication was done in 3 parts: a) without any anneal b) after 400°C/30 min anneal and c) 400°C/30 min anneal followed by electrodeposition of p⁺-ZnTe layer at 200°C. Solar cell results from each part are as follows:

**RUN A (glass/SnO₂/CdS/CdMnTe/Au)**

**Process Sequence**

. No annealing after the film growth
. Samples were etched in 0.02% bromine methanol for ≤ 10 secs.
. Methanol dip + N₂ dry
. 200Å° Au evaporation through 8mm² shadow mask

**AM 1 cell data**

<table>
<thead>
<tr>
<th>Voc</th>
<th>Jsc</th>
<th>FF</th>
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</thead>
<tbody>
<tr>
<td>200 mV</td>
<td>1 mA/Cm²</td>
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</tr>
</tbody>
</table>

**Source of Problem:**

diaky junction with very little indication of rectification - could be caused by pin holes or non-uniformity
RUN B (glass/SnO$_2$/CdS/CdMnTe/Au)

**Process Sequence:**
- 400°C/30 min anneal in breathing air
- Bromine methanol etch for ≤ 10 secs
- Methanol + blow dry N$_2$
- 200Å° Au evaporation

**Cell data:**
- $V_{oc} = 570$ mV
- $J_{sc} = 2.5$ mA/cm$^2$
- $FF = 0.3$
- $\eta = 0.47\%$

**Dark I-V/Spectral Response:**
Slightly improved rectification compared to the unannealed case but still poor long wavelength response. Junctions were still leaky.

RUN C (glass/SnO$_2$/CdS/CdMnTe/ZnTe/Au)

**Process Sequence**
- 400°C/30 min anneal in air
- Bromine methanol etch for ≤ 10 secs.
- Electrodeposition of p$^+$-ZnTe at 200°C
- Au evaporation

**Cell Data:**
- $J_{sc} = 6$ mA/Cm$^2$
- $V_{oc} = 400$ mV
- $FF = 0.35$
- $\eta = 0.85\%$
Observations:

- Jsc and FF went up after ZnTe deposition, Voc decreased but cell efficiency increased
- Cell became more leaky possibly due to copper diffusion through grain boundary or pin holes. Cu is used as p+ dopant in electrodeposited ZnTe films.

Summary and Future Work

We have successfully deposited CdMnTe film on glass/SnO2/CdS substrate with 28% Mn and 1.9 eV bandgap. After 400°C/30 min anneal cell efficiencies were 0.5% and with the p+ZnTe cap cells were about 0.85% efficient. Main source of problem was leaky junctions. We are tailoring our growth conditions to improve film quality and change the bandgap of the film. In the next report we will discuss our progress on solar cells made from MBE grown CdZnTe films.

Acknowledgements

The authors would like to thank Earl Meeks, Kim Pollard and Jim Welch for their help in the experimental work and Kay Meeks for typing the manuscript. They appreciate the tremendous help and guidance provided by Peter Myers and Ray Liu of Ametek in cell fabrication.
November 3, 1987

Mr. Ken Zweibel
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
        Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the
period 9/1/87-9/30/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

        Sincerely,

                  /s/
        Pam Majors
        Research Administrator

pm
Enclosures

cc: Ms. Debbie Larson
Introduction

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO$_2$CdS window with thin CdS layer to maximize transmission and current. Absorber films (E$_g$ >1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p+-ZnTe interlayer by MBE between the metal grid and the absorber film by MBE.

Technical Progress

In molecular beam epitaxy (MBE), the growth conditions interact in many ways. In particular the substrate temperature affects the surface energy and sticking coefficient of the growth components and thus influences the physical nature of the film, the growth rate, and the alloy composition. Is is difficult to isolate these interactions experimentally in a single variable.

Therefore, during this period of the program fifteen MBE growth runs were made with widely varying conditions in order to identify as quickly as possible the important parameters for the growth of good solar cell materials. Multiple substrates of glass, glass + SnO$_2$ and glass + SnO$_2$ + CdS were used in each run.
In all, forty-five layers were produced and a listing of all runs with growth conditions and some of the measured properties is given in Table 1. The interaction of substrate type, growth temperature, ZnTe/CdTe flux ratio, Sb doping, and laser assisted doping was investigated.

Undoped layers with constant ZnTe/CdTe flux ratio were grown with substrate temperatures between 100 and 300°C. Auger measurements on one sample grown at 250°C confirmed the predicted alloy ratio (Zn_{0.25}Cd_{0.75}Te) within experimental error. Auger measurements have not been made on layers grown at other temperatures and may not be necessary since the evaluations of the material thus far indicate the 250°C is the optimum growth temperature.

Surface photomicrographs of selected layers have been made and the band edge transmission cut-off (E_g) has been measured on layers from all runs using a Carey spectrometer. The spectrometer measurements indicate that the material improves with substrate temp and the sharpest transmission cut-offs were measured on layers grown at 250°C and 300°C as shown in Figures 1 and 2 respectively. The figures are very similar but the surface photomicrographs of the same layers, shown in Figure 3, are quite different. No deposition occurred at 300°C until growth was first started 250°C. The 300°C growth was possible using this procedure but will not be necessary in the future since the photomicrograph of the layer grown at 250°C shows a clearly superior surface. Future growth runs will be made at 250°C unless cell evaluations indicate otherwise.

Other undoped layers were grown using the same growth temperature but changing the ZnTe/CdTe flux ratio in order to vary the Zn alloy composition from 0.09 to 0.5. Spectrometer measurements on the layers with the highest ZnTe/CdTe show no observable band edge cut-off. Even layers grown at 100°C show some band edge transmission cut-off but as shown in Figure 4, no cut-off is observed if the ZnTe/CdTe flux ratio exceeds 1.0. The desired band gap energy of 1.75 eV
was measured on films grown with a ZnTe/CdTe flux ratio of 0.64, therefore
revealing a critical region of flux control.

Doped layers were also grown using Sb for the doping source. The same
Sb flux and substrate temperature were used for each of the doped runs but again
it was attempted to vary the Zn alloy ratio from 0.09 to 0.5. A defocused laser
beam impinging on the surface of one of the substrate pieces was used during
Sb doped runs in order to evaluate the effect of the laser on the incorporation
of Sb in the grown layer. Some enhancement in Sb doping of single crystal layers
has been observed using this technique.

Figures 5 and 6 show the band edge cut-off for doped and undoped films
grown under the same conditions. It is noted that the Sb doping appears to improve
the film quality but no explanation of the improvement is given at this time.

Summary and Future Work

We have successfully deposited CdZnTe films on glass/SnO₂/CdS substrate
with Zn alloy ratio from 0.09 to 0.5. Growth temperature was varied and an
optimum temperature of 250°C was established. In selected instances we have
started using Sb to dope the CdZn Te films. These films have been characterized
by transmission measurements to determine the bandgap. Auger measurements
were done on selected films to determine the composition. Cells are being
fabricated and the data will be reported in the next report.

Acknowledgements

The authors would like to thank Kim Pollard and Jim Welch for their help
in the experimental work and Kay Meeks for typing the manuscript. They appreciate
the tremendous help and guidance provided by Peter Myers and Ray Liui of Ametek
in cell fabrication.
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**TABLE 1:** Listing of layers grown with growth parameters
FIGURE 1: Band edge transmission for layer grown on glass at 250°C
FIGURE 2: Band edge transmission for layer grown on glass at 300°C
FIGURE 3: Layers grown on glass
FIGURE 4: Layer grown on glass Ts = 200 \( x = .5 \)
FIGURE 5: Layer grown on glass $T_{sub} = 200^\circ C$, $x = 0.09$
FIGURE 6: Layer grown on glass $T_{sub} = 200$
$x = .09$ with Sb doping

\( \lambda \text{nm} \)
February 10, 1988

Mr. Ken Zweibel
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Reports for the periods 10/1/87-10/31/87, 11/1/87-11/30/87, and 12/1/87-12/31/87. Also, enclosed are material samples and 2 charts corresponding with the samples.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THIN FILM SOLAR CELLS

A. Rohatgi, C.J. Summers, A. Erbil and E. Meeks

Fifth Monthly Report for the Period
October 1 to October 31, 1987

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332
GROWTH AND CHARACTERIZATION OF CdMnTe AND CdZnTe

POLYCRYSTALLINE THIN FILMS FOR SOLAR CELLS

Microelectronics Research Center
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and

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ABSTRACT

Thin films of Cd$_{1-x}$Zn$_x$Te and Cd$_{1-x}$Mn$_x$Te with x < 0.5 have been deposited by MBE and MOCVD techniques, respectively. Electrical and optical properties of these films have been studied in addition to the fabrication and characterization of glass/SnO$_2$/CdS/CdZnTe or CdMnTe/ZnTe/Au front wall solar cells. Polycrystalline Cd$_{1-x}$Mn$_x$Te films with x as high as 0.3 were successfully grown by the MOCVD technique. The Cd$_{0.95}$Mn$_{0.05}$Te film gave cell efficiencies in the range of 6.0-6.7%. Polycrystalline CdZnTe films with bandgap of ~1.65 eV were successfully grown by MBE. CdZnTe efficiency was only about 1% due to very high series resistance of the undoped films, although the spectral response of CdZnTe cell was much better than that of the 6.2% efficient CdMnTe cells. CdZnTe films are now being doped with antimony.
The 1.5 eV bandgap of CdTe film is nearly optimum for high efficiency solar cells. Single junction polycrystalline thin film heterojunction solar cells have been fabricated from CdTe film on glass/SnO₂/CdS substrates with AM1 cell efficiencies in excess of 10% [1-2]. Further optimization of film properties could increase conversion efficiency to about 15%. However, economic calculations suggest that 18-20% efficient cells, or greater than 15% efficient modules, will be required at a cost of less than $1/watt to provide electricity at a rate of less than 10¢/kWhr. Such high efficiency polycrystalline cells can only be realized by a tandem cell structure which has optimum bandgap of ~1.7 eV and 1.0 eV for the upper and lower cells, respectively. A greater than 10% efficient top cell with about 80% subgap transmission coupled with a 12-15% efficient bottom cell can produce a tandem cell efficiency in the range of 15-20%. CdTe does not have the optimum bandgap for the top cell, however, a solid solution of CdTe and ZnTe (Eg ~ 2.2 eV) or MnTe (Eg ~ 2.2 eV) can provide a bandgap of ~1.7 eV.

This paper describes the development of polycrystalline CdZnTe and CdMnTe alloys for the top cell. Zn and Mn content is varied to tailor the bandgap of these films. Electrical and optical properties of these films along with the preliminary solar cell results are summarized in this paper.
Thin Film Growth

CdMnTe films were grown by MOCVD on glass/SnO₂/CdS substrates in the temperature range of 400-450°C. Hydrogen was used as the carrier gas while di-methyl cadmium, di-isopropyl telluride, and tri-carbonyl manganese were used for the metallorganic sources for Cd, Te, and Mn, respectively. During typical film growth, reactor pressure was 250 torr, Te partial pressure was fixed at 136 mtorr, Mn partial pressure was 3.5 mtorr, but the Cd partial pressure was varied in the range of 4.6-18.5 mtorr to control the bandgap, composition, and surface morphology. No attempts were made to intentionally dope these films.

Polycrystalline thin films of CdZnTe were grown on glass/SnO₂/CdS substrates by molecular beam epitaxy (MBE) technique in a Varian Gen II machine. High purity, 5N or better, CdTe, and ZnTe sources were used for evaporation. In MBE, the substrate temperature affects the surface energy and sticking coefficient of growth components and this influences the physical nature of the film, growth rate, and alloy composition. Undoped CdZnTe films were grown with substrate temperature in the range of 100-300°C with constant ZnTe/CdTe flux ratio of 0.33. From previous experience on single crystal films, this flux was estimated to give Cd₁₋ₓZnₓTe films with \( x = 0.25 \). Auger measurements on one polycrystalline film grown at 250°C confirmed the \( x = 0.25 \) ratio. Some undoped layers were grown at 200°C with varying ZnTe/CdTe flux to vary Zn alloy ratio from 0.09 to 0.50.
Cell Fabrication

Front wall solar cells were fabricated with glass/SnO₂/CdS/CdZnTe or CdMnTe/ZnTe/Au structure. About 1500 Å thick CdS was deposited on SnO₂ coated glass in a pyrolytic reactor from an aerosol containing CdCl₂ and thiourea. Polycrystalline CdZnTe or CdMnTe absorber films were deposited on glass/SnO₂/CdS substrate by MBE or MOCVD technique. Thin films were annealed at 400°C for 30 minutes in N₂ followed by a mild etch of Br:methanol prior to the vacuum evaporation of ZnTe. Cu-doped p⁺-ZnTe interlayer facilitates the ohmic contact formation when Au contacts are evaporated through a shadow mask with 8 mm² openings.

Thin Film and Cell Characterization

Attempts were made to determine carrier concentration profile and optical property of the films by depth resolved C-V and surface photovoltage (SPV) measurements. Both these measurements are done automatically in an electrochemical etching profiler in which an electrolyte is used to perform precise step-by-step etching coupled with I-V, C-V, G-V, and SPV measurements after each step [3,4]. A Schottky barrier, formed between the electrolyte and the semiconductor, facilitates both C-V and SPV measurements. SPV measurements were performed in the wavelength range of 0.40 to 0.95 microns. The optics of the SPV set-up have a characteristic response in this wavelength range which results in two bumps in the SPV spectrum at ~560 and ~720 nm that are not related to sample quality and should be ignored in the analysis (Figure 1). The choice of electrolyte is dictated by the properties of the semiconductor. We have found that for these thin films, a solution of 0.2 M
NaOH + 0.1 M EDTA is an adequate electrolyte for Schottky barrier formation and electrochemical etching.

Some films were grown on glass substrates for transmission measurements using Cary spectrometer in order to determine the optical bandgap. In selected instances, Auger measurements were performed to determine and confirm the film composition.

Solar cells were characterized by lighted and dark I-V measurements and spectral response measurements in the wavelength range of 0.35 to 1.1 microns. Cell efficiencies were determined under 100 mW/cm² AM 1 illumination.

RESULTS AND DISCUSSION

CdMnTe Films and Solar Cells

Table 1 shows the MOCVD conditions used to grow a CdTe and several CdMnTe films with different Mn content. Film thickness was in the range of 0.5 to 2 microns. Figure 1 shows that the Mn content can be increased by reduced Cd partial pressure or increased growth temperature, since the cut-off edge of the SPV spectra moves toward shorter wavelength. Figure 2 shows the SPV response of the three films grown on glass/SnO₂/CdS substrates, prior to any heat treatment. CdTe film has the best response in the long wavelength range and a sharp cut-off at 840 nm which corresponds to a bandgap of ~1.48 eV. The second film (A093087-1) shows an SPV cut-off at 810 nm or an optical bandgap of $E_{g} = \frac{1.24}{0.810} = 1.53$ eV. The third film (A080787-1) showed SPV cut-off at 740 nm that translates into a bandgap of ~1.68 eV. Using the empirical equation [5] $x = \frac{E_{g}}{1.462}$ for the Mn content, valid for $x < 0.3$, we
obtain $x = 0.05$ for the film A093087-1 and $x = 0.18$ for the film A080787-1. $E_{co}$ is the energy position of the edge for maximum absorption which is assumed to be equal to the cut-off edge at half maximum of the SPV spectrum. Figure 2 indicates that the film quality or the SPV response of $x = 0.18$ film is actually better than $x = 0.05$ film, however, the adhesion of $x = 0.18$ film was poor since it lifted off and became very thin during the 400°C anneal. Therefore, in spite of the near optimum bandgap, we were unable to fabricate cells on Cd$_{0.82}$Mn$_{0.18}$Te film. Further work is in progress to improve the adhesion or lower the annealing temperature so the cells can be fabricated on high Mn content films.

Figure 3 shows a comparison of the SPV response of Cd$_{0.95}$Mn$_{0.05}$Te film before and after 0.5 micron removal via electrochemical etching. SPV response of this as-grown film is actually better near the CdS/CdMnTe junction compared to near-surface region. If the film quality was uniform, SPV response would have decreased as we approached the CdS/CdMnTe junction because a competition develops for the carriers generated between the electrolyte/semiconductor Schottky barrier and the CdS/CdMnTe heterojunction. Figure 3 also indicates that Mn content is fairly uniform as a function of depth since the SPV cut-off edge remains essentially unchanged. In addition to providing information about optical band gap and Mn content, the depth resolved SPV could be used as a quick and powerful tool for studying the uniformity of the films and even process induced effects, without having to fabricate solar cells.

Figure 4 shows a doping profile in Cd$_{0.95}$Mn$_{0.05}$Te film obtained by the depth resolved C-V measurements in the electrochemical etching
Profiler. The data gives a film thickness of ~0.6 microns and carrier concentration in excess of $10^{17}$ cm$^{-3}$ which appears much higher than expected. We are in the process of finding an explanation for any excess charge that may be sensed by C-V measurement on this structure which includes a Schottky barrier on top and a heterojunction underneath.

Solar cells fabricated on low Mn content ($x = 0.05$) film gave cell efficiencies in the range of 6.0–6.7%, with $V_{OC} = 680$ mV, $J_{SC} = 20.6$ mA/cm$^2$, and $FF = 0.442$ to 0.500, Figure 5. Dark I-V measurement, Figure 6, suggests that low fill factor is due to excess junction leakage current. Attempts are being made to perform DLTS measurements to investigate traps in the depletion region of the device and to explain the excess leakage current.

Figure 7 shows the spectral response of a 6.2% efficient Cd$_{0.95}$Mn$_{0.05}$Te cell when illuminated from the front (CdS) and back (ZnTe) side. The data confirms that CdS/CdMnTe is indeed the collecting heterojunction since the front spectral response is much higher. Notice also that the spectral response cut-off edge (~810 nm) of the finished cell corresponds very well with the SPV cut-off edge of the as-grown film. This indicates that Mn content remains unchanged during the cell fabrication.

CdZnTe Solar Cells

Due to the high resistance of the MBE grown undoped CdZnTe films, we have so far been unable to make depth resolved C-V and SPV measurements. Therefore, we have performed the transmission measurements on the films grown on glass slides to determine the optical band-
gap. Figure 8 shows that material quality improves with substrate 
temperature and sharpest cut-offs are measured on layers grown above 
250°C. Above 300°C, it becomes somewhat difficult to grow these poly-
films and, in addition, film begins to show more defects in the photo-
micrographs. Thus 250°C seems to be an optimum growth temperature for 
these polycrystalline films. A film grown at 250°C with ZnTe/CdTe flux 
ratio of 0.64 gave an optical bandgap of 1.63 eV (760 nm cut-off). Solar 
cell efficiency was only about 1% with $V_{OC} = 600$ mV, $J_{SC} = 4$ mA/cm$^2$, and 
$FF = 0.28$. This low efficiency was primarily due to the high series 
resistance, Figure 9, of the undoped films. In fact, the spectral 
response, Figure 10, of CdZnTe cell was better than the spectral 
response of 6.2% CdMnTe cell. We are now in the process of doping these 
films with antimony during the MBE growth and the cell data on these 
films will be reported in the near future.

CONCLUSIONS

CdMnTe and CdZnTe polycrystalline films were successfully grown by 
MOCVD and MBE techniques, respectively, onto glass/SnO$_2$/CdS substrates. 
Mn and Zn content was varied to obtain bandgap in the range of 1.60-
1.75 eV. A depth resolved SPV technique was successfully applied on 
CdMnTe films to determine the optical bandgap, Mn content, uniformity 
and optical property of the film. Cell efficiencies in the range of 
6.0-6.7% were achieved on Cd$_{0.95}$Mn$_{0.05}$Te film using glass/SnO$_2$/
CdS/CdMnTe/ZnTe/Au front wall solar cell structure so far. Solar cells 
could not be made on higher Mn content film due to poor adhesion. Solar 
cells were fabricated on wide bandgap (~1.65 eV) CdZnTe film, but cell
efficiencies were only about 1% due to high resistance, however, the spectral response was quite good. Thus, the preliminary work indicates that both $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ and $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ are promising material for optimum bandgap top cell. Further work is needed in the area controlled doping, ohmic contact formation, and property optimization before these cells can become a commercial reality.

ACKNOWLEDGEMENT

This work was supported by the Solar Research Institute under SERI/DOE subcontract No. XL-7-06031-1.

REFERENCES


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GROWTH CONDITIONS FOR MOCVD CdMnTe FILMS

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**FIGURE CAPTIONS**

**Figure 1:** Surface photovoltage spectra for MOCVD CdMnTe films grown at (a) 400°C with Cd partial pressure of 5.6 mtorr, 9.2 mtorr, and 18.5 mtorr, and (b) 450°C with Cd partial pressure of 4.6 mtorr.

**Figure 2:** Surface photovoltage spectra for CdMnTe films grown at (a) 420°C with P\textsubscript{Cd} = 4.6 mtorr, (b) 420°C with P\textsubscript{Cd} = 9.3 mtorr, and (c) 400°C with P\textsubscript{Cd} = 19.9 mtorr and P\textsubscript{Mn} = 0.

**Figure 3:** Surface photovoltage spectra of a Cd\textsubscript{0.95}Mn\textsubscript{0.05}Te film before and after 0.5 micron etching.

**Figure 4:** Doping profile of a Cd\textsubscript{0.95}Mn\textsubscript{0.05}Te film obtained by depth resolved C-V measurements.

**Figure 5:** Lighted I-V data of a 6.2% efficient polycrystalline CdMnTe cell.

**Figure 6:** Forward and reverse dark I-V data for a 6.2% efficient CdMnTe cell.

**Figure 7:** Spectral response of a 6.2% efficient polycrystalline CdMnTe cell.

**Figure 8:** Transmission data for MBE CdZnTe films grown at different temperatures with constant ZnTe/CdTe flux ratio of 0.33.

**Figure 9:** Dark I-V data for polycrystalline CdZnTe solar cell.

**Figure 10:** Spectral response of a polycrystalline CdZnTe solar cell.
The diagram shows the spectral response in millivolts as a function of wavelength (nM) for different temperatures and cadmium pressures. The wavelengths are indicated as:

- **400°C, 9.2 mtorr Cd**
- **400°C, 4.6 mtorr Cd**
- **420°C, 4.6 mtorr Cd**
- **400°C, 18.5 mtorr Cd**
Eff = 6.2%
Jsc = 20.6 mA/cm²
Voc = 680 mV
FF = 0.442
Area = 0.08 cm²
\( Zn_x \text{Cd}_{1-x} \text{Te} \)

\( x = 0.25 \pm 0.03 \)

TRANSMISSION

\( \lambda \text{ (nm)} \)

720 750 800 850 900 950 1000
Jsc = 4 mA/cm²
Voc = 600 mV
FF = 0.280

Forward Bias

Reverse Bias

LOG (J)

-10

VOLTS

0 0.2 0.4 0.6 0.8 1
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C.J. Summers and A. Erbil

Sixth Monthly Report for the Period
November 1 to November 30, 1987

Solar Energy Research Institute
Contract No. XL-7-0631-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332
Introduction

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO2CdS window with thin CdS layer to maximize transmission and current. Absorber films (Eg ~1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p+ZnTe interlayer by MBE between the metal grid and the absorber film by MBE.

Technical Progress

Characterization of CdMnTe Alloy Thin Films by Infrared Spectroscopy

Infrared spectroscopy is one of the non-destructive characterization techniques for semiconductors. The phonon modes carry information about the quality of films. We have used this technique to characterize CdMnTe thin films of different Mn concentration and thicknesses, grown on GaAs, glass and heavily doped CdS films. Infrared reflectance measurements on these samples were made from 10-220 cm⁻¹, using a modified Grubb-Parsons interferometer with a Golay cell as a modified detector. All the spectra were taken with a resolution 2 cm⁻¹.

It is known that CdMnTe alloy has a two phonon mode behavior; CdTe-like and MnTe-like modes. In CdMnTe the CdTe-like phonon frequency (140 cm⁻¹) and MnTe-like phonon frequency (180 cm⁻¹) do not vary with Mn concentration, but
the strengths of modes vary with Mn concentration. The phonon parameters are well known for all Mn concentrations in bulk CdMnTe.

Figure 1 shows the reflectance spectrum of one of the CdMnTe film grown on GaAs substrate. The phonon modes at 140 and 180 cm⁻¹ correspond to CdTe-like and MnTe-like modes respectively. In order to get Mn concentration in these films, we used a theoretical model. According to this model the dielectric function has three terms: lattice, free carrier and interband terms which is given as

\[ \varepsilon(\omega) = \varepsilon_{\text{lattice}} + \varepsilon_{\text{free carrier}} + \varepsilon_{\text{interband}} \]

We considered only the lattice term since the reflectivity seems to have no contribution from other terms. Then the dielectric function can be represented by a Lorentzian oscillator for each phonon of the form.

\[ \varepsilon(\omega) = \varepsilon_{\infty} + \sum_{j} \frac{S_j \omega_j^2 \Gamma_j}{\omega_j^2 - \omega^2 - j\omega\Gamma_j} \]

Where the \( \omega \), \( S \), \( \Gamma \) and \( \varepsilon_{\infty} \) correspond to frequency, strength, damping constant and high frequency dielectric constant respectively. Using the known phonon parameters and standard expressions for reflectivity which include thickness of the films, we fitted the reflectivity data. The theoretical fit is also shown in Figure 1 as a dashed line. From the analysis we find both Mn concentration and thickness of CdMnTe films. Table 1 gives our analysed values for several samples.

In some of the films, the reflectivity spectrum at 300K shows weak phonon modes, but on cooling the phonon modes sharpen, which allows the determination of the Mn concentration. The appearance of weak phonon modes at room temperature indicates a presence of defects in the films. At present the nature of defects are not known. We plan to pursue this problem in the future.

We also measured the reflectance of CdMnTe films grown on various substrates under the same conditions. Figures 2 (a), (b) and (c) show the reflectance of CdMnTe films on GaAs, glass, and heavily doped CdS films respectively. It
is clear from the figures that the shape of reflectance is different, which suggests that the quality may be different. Further, there are no phonon peaks in Figure 2c, probably due to high free carrier concentration in CdS films.

In the future we plan to study films annealed at different temperatures and also at low temperatures. These studies may give information about the behavior of defects in the films.

\[ \varepsilon = \varepsilon_{\infty} + \sum_{j=1}^{N} \frac{S_j \omega_j^2}{\omega_j^2 - \omega^2 - i \omega \Gamma_j} \]

**Acknowledgements**

We would like to thank R. Sudharsanan and S. Perkowitz for the FTIR measurements and analysis.
FIGURE 1: Room temperature measured (solid line) and theoretical fit (dashed line) reflectivity of single crystal CdMnTe (AO 50487l).
FIGURE 2(a) Room temperature far-infrared reflectance of Cd Mn Te grown on GaAs substrates under the same conditions.
FIGURE 2(b) Room temperature far-infrared reflectance of Cd Mn Te grown on n-CdS film under the same conditions.
FIGURE 2(c) Room temperature far-infrared reflectance of Cd Mn Te grown on glass under the same conditions.
Table 1

FTIR Results on CdMnTe Films Grown on Single Crystal GaAs Substrate

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Thickness of CdMnTe</th>
<th>Thickness of Buffer Layer</th>
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<tr>
<td>A0504871</td>
<td>204.</td>
<td>2.23 mm.</td>
</tr>
<tr>
<td>A0622871</td>
<td>less than 5%</td>
<td>3.2 mm.</td>
</tr>
<tr>
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<td>20%</td>
<td>-</td>
</tr>
<tr>
<td>A0623871</td>
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<td>-</td>
</tr>
<tr>
<td>A0925871</td>
<td>~15%</td>
<td>-</td>
</tr>
<tr>
<td>A0917871</td>
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</tr>
<tr>
<td>A0918872</td>
<td>less than 5%</td>
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HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C.J. Summers, A. Erbil and J. Welch

Seventh Monthly Report for the Period
December 1 to December 31, 1987

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332
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Technical Progress

In this monthly report we show another application of surface photovoltage technique, which uses the electrochemical Schottky barrier contact, in establishing the optimum annealing conditions for the MOCVD grown films for solar cells. Electrochemical SPV is a rapid and nondestructive technique that can be used to assess the quality and bandgap of the thin films. It is especially useful for solar cell development because back ohmic contact can be easily made by scratching a small area to expose n+ CdS. Schottky barrier contact on the front surface is made by the electrochemical used. The measurement takes only ten minutes or less without destroying the film. This gives an opportunity to find out about the film quality or optimum annealing conditions for the films, prior to fabricating the solar cell. In this report we have made an attempt to prove this point by annealing the MOCVD grown film in forming gas at various temperatures,
documenting the change in SPV response, and correlating it with cell efficiency.

Recently we had some problem with our Mn source in MOCVD, therefore, the films used in these experiments have very little Mn (< 5%). Four samples (A to D) from the MOCVD run # A120187-1 were used for this experiment. Samples A, D, and C were annealed at 200, 300, and 400°C, respectively, in the forming gas for 30 minutes. Sample B was not annealed. Figures 1, 2 and 3 show a comparison of SPV response before and after the annealing for each sample. It is interesting to note that 200 and 300°C anneal reduced the SPV response but 400°C anneal enhanced the SPV response. This suggests that 400°C anneal is the best for improving the quality of this film. Maximum SPV response increased by a factor of 2, from 10 mV to 20 mV; after 400°C while 200°C anneal reduced the maximum response signal by a factor of 2, from 10 mV to 5 mV.

In order to see the correlation between the SPV response and cell efficiency, solar cells were fabricated by evaporating Au on the films. Table 1 shows that indeed 400°C anneal gave the best cell efficiency.

An attempt was made to revive the SPV response of 200°C annealed sample by reannealing it at 300 and 400°C. Figure 4 shows that the SPV response gradually improves and the material quality becomes respectable again after the 400°C anneal. This is supported by the improved cell efficiency in Table 1.

This SPV technique can be used as an effective non-destructive tool to monitor film quality and optimize annealing condition, prior to cell fabrication. We plan to perform DLTS measurements on these cells in an attempt to correlate the SPV response to the defect states in the depletion region of the CdS/CdMnTe junction. We are in the process of replacing the Mn source and a valve in our MOCVD machine which prevented us from growing films with higher Mn content in the last month. We have recently grown a few CdZnTe films by MBE with Sb doping. These results will be reported in the next monthly report.

Acknowledgements

The authors would like to thank Jim Welch, Steve Ringle and R. Liu for all the experimental work.
FIGURE 1: SPV response of Film A, before and after 200°C anneal in forming gas.
FIGURE 2: SPV response of Film B, before and after 300°C anneal in forming gas.
FIGURE 3: SPV response of Film C, before and after 400°C anneal in forming gas.
FIGURE 4: SPV response of Film A before and after 200, 300, and 400°C anneal in forming gas.
Table 1
Performance of CdMnTe Solar Cells
Annealed at Different Temperatures

<table>
<thead>
<tr>
<th>Film ID</th>
<th>Annealing Temperature</th>
<th>Voc (mV)</th>
<th>Jsc (ma/cm²)</th>
<th>FF</th>
<th>%</th>
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<tbody>
<tr>
<td>B</td>
<td>Unannealed</td>
<td>393</td>
<td>2.99</td>
<td>0.438</td>
<td>0.52</td>
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<tr>
<td>D</td>
<td>300°C</td>
<td>456</td>
<td>4.02</td>
<td>0.382</td>
<td>0.70</td>
</tr>
<tr>
<td>C</td>
<td>400°C</td>
<td>488</td>
<td>7.96</td>
<td>0.353</td>
<td>1.37</td>
</tr>
<tr>
<td>A</td>
<td>200-400°C</td>
<td>421</td>
<td>9.82</td>
<td>0.326</td>
<td>1.35</td>
</tr>
</tbody>
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HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil and J. Welch

Eighth Monthly Report for the Period
January 1 to January 31, 1988

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This report describes the test CdMnTe and CdZnTe solar cells made so far at Georgia Tech.
WIDE BANDGAP THIN FILM SOLAR CELLS FROM CdTe ALLOYS

A. Rohatgi, S. A. Ringel, and E. Meeks
School of Electrical Engineering
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P. V. Meyers and C. H. Liu
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Harleysville, Pennsylvania 19438

EXTENDED ABSTRACT

The 1.5 eV bandgap to CdTe films is nearly optimum for high efficiency solar cells. Single junction polycrystalline thin film heterojunction solar cells have been fabricated from CdTe films on glass/SnO₂/CdS substrates with AM1 cell efficiencies in excess of 10% [1, 2]. Further optimization of film properties could increase conversion efficiencies to about 15%. However, economic calculations suggest that 18-20% efficient cells, or greater than 15% modules, will be required at a cost of less than $1/watt to provide electricity at a rate of less than 10¢/kWhr. Such high efficiency polycrystalline cells can only be realized by a tandem cell structure which has optimum bandgap of ~1.7 eV and 1.0 eV for the upper and lower cells, respectively. A greater than 10% efficient top cell with about 80% subgap transmission coupled with a 12-15% efficient bottom cell can produce a tandem cell efficiency in the range of 15-20%. CdTe does not have the optimum bandgap for the top cell, however, an alloy of CdTe and ZnTe (E_g ~2.2 eV) or MnTe (E_g ~2.2 eV) can provide a bandgap of ~1.7 eV.

CdMnTe films were grown by MOCVD on glass/SnO₂/CdS substrates in the temperature range of 400-450°C. Hydrogen was used as the carrier gas while di-methyl cadmium, di-isopropyl telluride, and tri-carbonyl manganese were used for the metallorganic sources for Cd, Te, and Mn, respectively. No attempts were made to intentionally dope these films.

Polycrystalline thin films of CdZnTe were grown on glass/SnO₂/CdS substrates by molecular beam epitaxy (MBE) in a Varian Gen II machine. Elemental sources of Cd, Zn, and Te were used as evaporant sources for CdZnTe. Both undoped films and films doped with Sb were grown. Films were grown with substrate temperatures in the range of 250-300°C to thicknesses on the order of 1.1 um. The target composition to reach a bandgap of ~1.70 eV was Cdₐ₀.₇₅Znₐ₀.ₒ₅Teₐ.

Front wall solar cells were fabricated with glass/SnO₂/CdS/CdZnTe or CdMnTe/ZnTe/Au structures. This was done in collaboration with Ametek. About 150 nm thick CdS was deposited on SnO₂ coated glass in a pyrolytic reactor from an
aerosol containing CdCl₂ and thiourea. Polycrystalline CdZnTe or CdMnTe absorber films were deposited on glass SnO₂/CdS substrates by MBE or MOCVD techniques. Thin films were annealed at 400°C for 30 minutes in N₂ followed by a mild etch of Br:methanol prior to the vacuum evaporation of ZnTe. The Cu-doped p⁺-ZnTe interlayer facilitates the ohmic contact formation when Au contacts are evaporated through a shadow mask with 8 mm² openings.

Figure 1 shows that the Mn content can be increased by reduced Cd partial pressure or increased growth temperature, since the cut-off edge of the SPV spectra moves toward shorter wavelength. CdMnTe films were grown with Mn content ranging from 5-28% and the corresponding bandgaps were in the range of 1.55-1.75 eV, as indicated in Figure 1. SPV measurements were performed as a function of depth via electrochemical etching to check the uniformity and doping profiles in the film. Optimum annealing conditions were investigated by a combination of heat treatment and SPV measurements. The SPV response of the film seems to improve after a 400°C anneal.

Solar cells fabricated on low Mn content (x ≈ 0.05) gave cell efficiencies in the range of 6.0-6.7% with \( V_{OC} = 689 \text{ mV} \), \( J_{SC} = 20.6 \text{ mA/cm}^2 \), and \( FF = 0.443 \) to 0.500 (Figure 2). Dark I-V measurements suggest that low fill factor is due to excess junction leakage current. Attempts are being made to perform DLTS measurements to investigate traps in the depletion region of the device and to explain the excess leakage current. Cells are being fabricated on high Mn content films.

Figure 3 shows the spectral response of a 6.2% efficient Cd₀.₉₅Mn₀.₀₅Te cell when illuminated from the front (CdS) and the back (ZnTe). The data confirms that CdS/CdMnTe is the collecting heterojunction since the front response is much higher.

To determine the optical bandgap of undoped CdZnTe films, transmission measurements were performed on films grown on glass slides since SPV and depth-resolved C-V measurements were not possible due to the high resistance of the undoped film. Solar cell efficiencies for undoped films were about 1% with \( V_{OC} = 600 \text{ mV} \), \( J_{SC} = 4 \text{ mA/cm}^2 \), and \( FF = 0.28 \). This low efficiency was primarily due to the high series resistance of the undoped film. In fact, the spectral response, Figure 4, of the CdZnTe cell was better than the spectral response of the 6.2% CdMnTe Cell. We have recently doped these films with Sb during the MBE growth to reduce the series resistance. First runs gave cell efficiencies of about 3.5% with \( V_{OC} = 541 \text{ mV} \), \( J_{SC} = 15 \text{ mA/cm}^2 \), and \( FF = 0.41 \) (Figure 5). This 1 um film was Sb doped with a bandgap of ~1.7 eV (Figure 6). Pin-holes were responsible for low \( V_{OC} \).
and FF. Thicker films are being grown to circumvent this problem. In addition, extensive optical and electrical characterization is presently underway using FTIR, PL, DLTS, and SPV to determine film properties and attempts are being made to push the cell efficiencies of these widegap cells to ~10%. Update results will be presented.

REFERENCES


Fig. 1: Surface photovoltage spectra for MOCVD CdMnTe films grown at (a) 400°C with Cd partial pressure of 5.6 mtorr, 9.2 mtorr, and 18.5 mtorr, and (b) 450°C with Cd partial pressure of 4.6 mtorr.

Fig. 2: Lighted I-V data of a 6.2% efficient polycrystalline CdMnTe cell.

Fig. 3: Spectral response of a 6.2% efficient polycrystalline CdMnTe cell.
Voc = 0.541 V  
Jsc = 15.0 mA/cm²  
FF = 0.41  
Eff = 3.29%  

**Fig. 4:** Spectral response of a polycrystalline CdZnTe solar cell

**Fig. 5:** Lighted I-V data of a 3.3% efficient polycrystalline CdZnTe cell

**Fig. 6:** Surface photovoltage spectra for MBE CdZnTe films for various Zn content showing bandgap control from (a) 1.5 eV (CdTe) to (b) 1.6 eV and (c) 1.7 eV (Cd.75Zn.25Te)
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil

Ninth Monthly Report for the Period
February 1 to February 29, 1988

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TECHNICAL PROGRESS

During the past month, both undoped and doped layers of CdZnTe have been grown by MBE (molecular beam epitaxy) on substrates of glass, and glass + SnO₂ + CdS. The proper growth parameters for a reasonable growth rate and Zn incorporation (for bandgap control) had to be re-established since the MBE source material was changed from the compound material used previously (ZnTe, CdTe) to elemental evaporants (Cd, Tn, Te) to increase film purity. Table 1 shows the growth parameters used here. To insure high quality material, a substrate temperature of 300°C is necessary as shown in a previous report. However, the
evaporants did not stick well initially at this temperature so the substrate temperature was started at 250°C before being increased to 300°C. In later runs, as seen in Table 1, high quality films were obtained at 275°C with the advantage that the temperature could be held constant throughout the run, eliminating any possible variation in composition due to this variable. Both undoped and doped layers were grown using Sb as the dopant source. The Sb flux was increased in a stepwise fashion for each run. Selected substrates were irradiated with a defocused laser beam since this has been shown to enhance dopant incorporation in single crystal films. Table 1 shows a summary of the growth conditions used for the successful runs made as described above.

To check the compositional control, the band edge transmission cut-off ($E_g$) was measured on films from all runs using a Cary spectrometer in transmission mode and by open circuit surface photovoltage (SPV) techniques. The bandgaps calculated from the cut-off wavelengths are listed in Table 1 as determined from SPV. Both measurements yielded comparable values however, the SPV data is preferred since the cut-off edge is much sharper probably because the only region of the sample being probed is the CdZnTe film itself while for the transmission measurement the entire device including the glass substrate, SnO$_2$, and CdS as well as the film interfaces contributes to the transmission. An example of the SPV data is shown in Figure 1 for a film with a bandgap of ~1.70 eV. The cut-off wavelength is taken at the midpoint of the absorption edge. The bandgap was maintained between ~1.65-1.70 eV for all Sb fluxes indicating that the Sb has no effect on the ratio of the incorporation of Cd or Zn into the growing film. Film thicknesses were measured using an Alpha-step profilometer by scratching part of the film away to reveal the CdS coated substrate. From this, growth rates were found to be slow, roughly 1/3 rm per hour at 275°C.

Solar Cells were fabricated using the R87-50, R88-1, R88-2, and R88-3 with laser films by Ametek. All cells exhibited large series resistance and high leakage current. The highest efficiency obtained thus far has been 3.3% on R88-1 with $V_{oc} = 0.541$ V, and $J_{sc} = 15.0$
mA/cm$^2$ with FF = 0.4062. Other films had lower efficiencies with a large drop in $V_{oc}$ but not as much in $J_{sc}$, indicating that shunting resistance is a large problem. In addition, many of the films tended to evaporate during the cell fabrication leaving a high pin-hole density causing shorts or high leakage currents for working cells. Sample R88-2 had an efficiency of 2%, however the laser-assisted sample showed only an efficiency of 1.8%. The reasons for this will be investigated in the future.

To alleviate the above problems, we will grow another series of CdZnTe films a target thickness of ~2 μm or greater to eliminate the pin-hole formation. ZnTe layers will be grown on top of the CdZnTe by MBE for in-house ohmic contact formation. C-V measurements will be made to continue the dopant studies and DLTS and will be used to investigate deep level effects that may be important to the cell performance. In addition, x-ray diffraction and FTIR will be used to study some of the structural variations in the films, especially the importance of grain boundaries and their effects on dopant incorporation.

ACKNOWLEDGEMENTS

The authors would like to thank S. A. Ringel and Raj for their help in conducting the experimental work. They appreciate the tremendous help and guidance provided by P. Meyers and R. Liu of Ametek in cell fabrication.
<table>
<thead>
<tr>
<th>ID</th>
<th>Target Composition</th>
<th>T$_{SUB}$ (°C)</th>
<th>Dep. Time (hrs.)</th>
<th>Beam Flux (x 10$^{-7}$ torr) (Zn/Cd, Sb)</th>
<th>Film Thickness (µm)</th>
<th>$E_G$ (SPV) (eV)</th>
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<tr>
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<td>CdTe</td>
<td>250</td>
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<td>0, .022</td>
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<td>?, 0.028</td>
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<td>0.367, 0.005</td>
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</tbody>
</table>
FIGURE 1. SPV plot of CdZnTe Film indicating a bandgap of ~1.7 eV as measured from the midpoint of the absorption edge.
April 22, 1988

Mr. Ken Zweibel
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
         Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the period 3/1/88-3/31/88 on
the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Research Administrator

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, and A. Erbil

Tenth Monthly Report for the Period
March 1 to March 31, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO\textsubscript{2}/CdS window with thin CdS layer to maximize transmission and current. Absorber films (E\textsubscript{g} 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p\textsuperscript{+} ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

This monthly report contains the summary of photoluminescence, Raman, and Infrared measurements of CdMnTe films. Single crystal CdMnTe films were grown on GaAs substrate with and without CdTe buffer layer. Polycrystalline CdMnTe films were grown on glass and glass/SnO\textsubscript{2}/CdS substrates. The substrate temperature was varied from 360°C to 450°C. Photoluminescence, Raman and Infrared measurements were made, to characterize these films. Photoluminescence and Raman spectra, excited by Ar\textsuperscript{+} 488 nm laser line, were measured with a triple monochromator using a cooled optical multichannel analyzer. All measurements were
done at 80K. Infrared measurements were made using a Grubb-Parson's cube interferometer over the region 10 to 220 cm\(^{-1}\) at 300K. All spectra were measured with a resolution of 2 cm\(^{-1}\).

Figure 1 shows the infrared spectra of CdMnTe single crystal films without a CdTe buffer layer for different substrate temperatures. All spectra show two peaks: 140 cm\(^{-1}\) corresponds to CdTe-like mode and 185 cm\(^{-1}\) corresponds to MnTe-like mode. It is clear from the spectra for substrate temperatures less than 400°C the CdTe-like peak is well pronounced but MnTe-like peak appear very weak. This indicates that the Mn concentration is less than 10%. At 420°C substrate temperature the MnTe-like peak is clearly seen, indicating higher Mn concentration (20%). At 450°C substrate temperature, even though the MnTe-like mode is stronger, but the CdTe-like mode is weakened. This indicates poor film quality, perhaps more defects. These results suggest that the optimum substrate temperature for good quality single crystal CdMnTe films is 420°C. Also at 420°C it is possible to grow higher Mn concentration films. In addition, infrared measurements can be used to estimate the Mn concentration and film thickness (as explained in report #6). Figure 2 shows the infrared spectra of two CdMnTe single crystal films with and without CdTe buffer layer, grown at substrate temperature of 420°C. Both spectra show strong phonon modes, indicating good quality, and higher Mn concentration. These results show that it is possible to grow good quality single crystal films of CdMnTe with and without CdTe buffer layer.

Figure 3 shows Raman spectra of different batch of CdMnTe films grown at different substrate temperatures. In Raman spectra, it is known that appearance of sharp phonon peaks and higher order phonon peaks indicate good quality films. The Raman spectra show several sharp phonon peaks; the peaks at 167 and 205 cm\(^{-1}\) correspond to CdTe-like and MnTe-like first order longitudinal optic phonon modes. The peaks above 250 cm\(^{-1}\) correspond to higher order phonon modes. Below 400°C the Raman spectra show sharp phonon peaks and higher order phonon peaks. This shows the quality of films is good but the Mn concentration is less
than 10% (Mn concentration was estimated from photoluminescence measurements). This result agrees well with the Infrared results. At 420°C substrate temperature, the Raman spectra indicates good quality film. The disappearance of higher order phonon modes at 450°C indicates poor quality. Consistent with IR findings, PL measurements also showed increased incorporation of Mn at growth temperature greater than 400°C.

In conclusion, the infrared and Raman results show that the optimum substrate temperature for growing good quality single crystal CdMnTe films is 420°C. Also at 420°C substrate temperature it is possible to grow higher Mn concentration (> 10%) films.

Our preliminary results on polycrystalline films indicate that we can successfully grow higher Mn content films, but, as expected, the quality seems to be inferior to single crystal films. Figure 4 shows the Raman spectra of CdMnTe films grown on different substrates. We will perform Raman, PL, and FTIR measurements on poly and single crystalline films at 5K in order to identify the impurities.

Two talks were given based on these results in a recent American Physical society March meeting at New Orleans.

ACKNOWLEDGEMENTS

We would like to thank R. Sudharsanan, Z. Feng, and S. Perkowitz of Emory University for the FTIR, Raman, and PL measurements.
FIGURE 1. Infrared spectra of single crystal CdMnTe films grown at different substrate temperatures.
FIGURE 2. Infrared spectra of single crystal CdMnTe films with and without CdTe buffer layer.
MOCVD Cd$_{1-x}$Mn$_x$Te/GaAs

**FIGURE 3.** Raman spectra of single crystal CdMnTe films grown at different substrate temperatures.
FIGURE 4. Comparison of Raman spectra of polycrystalline and single crystal CdMnTe films.
June 2, 1988

Mr. Ken Zweibel  
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1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi  

Dear Mr. Zweibel:

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Sincerely yours,

Pam Majors  
Research Administrator  

pm  
Enclosures  

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, and R. Sudharsanan

Eleventh Monthly Report for the Period
April 1 to April 30, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/Sn02/CdS window with thin CdS layer to maximize transmission and current. Absorber films (Eg = 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown, MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p+ ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

In this monthly report, we present the results of material characterization and solar cell results on polycrystalline CdMnTe films. Several polycrystalline CdMnTe films were grown on CdS/Sn02/glass substrates under different conditions. X-ray, infrared and photoluminescence (PL) measurements were performed to characterize these films. Solar cell measurements were made in collaboration with AMETEK on some of the polycrystalline films.

Analysis of single crystal CdMnTe (Report #10) indicated that the optimum substrate temperature for growing high quality films is 420°C. In order to optimize the substrate temperature for growing good quality polycrystalline films, we varied the substrate temperature from 380°C to 450°C. In addition, we varied the growth-time and partial pressures of Cd, Mn, and Te to optimize the growth conditions. The above parameters control thickness and quality of films. The bandgap of the films was determined from X-ray, PL, and surface photovoltage (SPV) measurements. Infrared technique was used to estimate the thickness of films. PL measurements give information about the quality of films. All of the above techniques, were also applied to characterize the polycrystalline CdMnTe films and the results are summarized below.
X-ray measurements were done on some of the films using Phillips X-ray diffractometer to estimate the Mn concentration. Figure 1 shows the X-ray diffraction of one of the polycrystalline samples. The peaks at 23.709, 39.394 and 46.528 correspond to CdMnTe films. The other peaks arise from CdS/SnO$_2$/glass substrate. The lattice constant of the film is calculated using the equation $a = \frac{d\sqrt{h^2 + k^2 + l^2}}{2}$, where "a" is the lattice constant, h, k, l are the indices. The Mn concentration is estimated from the equation $a = 6.487 - 0.149X$, where X is Mn concentration. The appearance of sharp peaks indicate the film has a single phase of CdMnTe.

Nondestructive infrared measurements were performed on poly films to estimate the thickness. IR measurements were made within the wave number range of 450-4000 cm$^{-1}$ using Digilab FTS-40 rapid scan interferometer with a resolution of 2 cm$^{-1}$ at room temperature. The thin films thickness was determined by

$$t = \frac{f}{2} n \gamma$$

where n is the index of refraction, $\gamma$ is the wavenumber at which f-th maximum lies. For thick films ($t > 1.5 \mu m$) with many fringes, the thickness can be estimated by

$$t = \frac{f}{2} \Delta \gamma n$$

where $f$ is the number of extrema in the wavenumber interval ($\Delta \gamma$) with average index of refraction n. Figure 2 and 3 show the IR spectra of a thick and a thin film. In calculating the thickness, we assumed that the refractive index of CdMnTe is the same as that of CdTe, since the variation in the high frequency dielectric constant ($\epsilon_\infty = n^2$) is small. We estimated the film thicknesses of sampler A1112871 and A0217881 as 2.8 and 1.12 mm, respectively. The estimated thickness agrees well with the $\alpha$-step measurements.

PL measurements were used to identify impurities and investigate film quality. PL measurements were done at 80 K with excited by Ar$^+$ 488 nm laser line and a cooled photomultiplier as detector. Figure 4 shows the spectrum of a (A1113871) polycrystalline film. The peak at 2.014 eV gives the bandgap at 80 K of the material, from which we have estimated the Mn concentration using the equation

$$E_g = 1.58 + 1.51 X eV$$
where \( X \) is the Mn concentration. Generally, the full width at half maximum (FWHM) is indicative of film quality (lower the value, better the quality). The FWHM for this film is 155 mev. Surprisingly this value is same as that of good quality of single crystal CdMnTe film (159 mev, report #2). Figure 5 shows the spectrum of another polycrystalline (A0122881) film grown at same substrate temperature as that of previous film (420°C). The bandgap is very close to that of sample (A1113871), indicating same Mn concentration. But the spectrum quality is poorer than A1113871 sample spectrum. These results suggest that the substrate temperature has a big influence on Mn incorporation, consistent with the single crystal findings. The other factors, like partial pressures of Cd, Mn, and Te and growth-time are important in determining the quality of films. Further measurements like PL over a broader range (up to 900 nm) or at very low temperature (4 K) are necessary to understand the growth conditions and the quality.

Solar cell measurements were done at AMETEK. Previous measurements indicated that some of the films evaporated during 400°C annealing. In order to avoid this problem, films were annealed at 350°C and 375°C. A thin layer of ZnTe was deposited on some of the films. Ni and Au films were evaporated for contacts. Because of very thin films, pin holes, and annealing induced film evaporation, only one sample (A0217881) out of many gave cells with efficiency of 0.3%. Table 1 gives the solar cell parameters.

In summary, polycrystalline CdMnTe films were grown successfully under different conditions. X-ray, infrared, PL and SPV measurements were successfully performed to characterize the poly films. The above measurements show that we have grown good quality polycrystalline CdMnTe films; the optimum substrate temperature for growing higher Mn films is 420°C; the partial pressures of Cd, Mn and Te and growth-time control the quality of films. Several samples were used to fabricate solar cell but only one gave 0.3% efficiency. The low efficiency may be due to pin holes or process-induced degradation. In order to understand the quality of films after processing, further measurements like X-ray, Auger, PL and SPV are planned.

**ACKNOWLEDGEMENTS**

We would like to thank Z. C. Feng, R. Liu and Steve Ringle for all the help in the experimental work.
Figure 1. X-ray diffractogram of CdMnTe polycrystalline films. The peaks marked 1, 2, 3 are CdMnTe film and other peaks are due to CdS/SnO$_2$/glass substrate.
Figure 2. IR reflection spectrum of thick sample (A112871)
Figure 3. IR spectrum of thin sample A0217881
Figure 4. PL spectrum of polycrystalline sample A113871
Figure 5. PL spectrum of polycrystalline sample A0122881
<table>
<thead>
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<th>Sample</th>
<th>$V_{oc}$</th>
<th>$J_{sc}$</th>
<th>FF</th>
<th>%</th>
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</thead>
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<td>1.96</td>
<td>0.285</td>
<td>.13%</td>
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HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, and R. Sudharsanan

Twelveth Monthly Report for the Period
May 1 to May 31, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO\textsubscript{2}/CdS window with thin CdS layer to maximize transmission and current. Absorber films (E\textsubscript{g} = 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p\textsuperscript{+} ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

In this monthly report, we present the results of characterization of CdZnTe polycrystalline films by X-ray diffraction (XRD), Infrared (IR), and Auger measurements. The purpose of these measurements is to identify the different phases of CdZnTe, the surface composition, contaminants on the surface and thickness of as grown films.

X-ray diffraction measurements were done using Phillips X-ray diffractometer. IR measurements were done using Digilab FTS-40 in the region 400-4500 cm\textsuperscript{-1} resolution. In-situ Auger spectra were collected using Varian MBE/GEN II and Ex-situ Auger measurements were done using Perkin Elemer PHI 600.

Our earlier solar cell measurements on polycrystalline CdZnTe samples showed an efficiency of 3%. The low efficiency may be due to pin-holes in the samples. One way of resolving this pin-hole problem is to grow thicker (2 microns) CdZnTe films as opposed to less than 1 \( \mu \text{m} \) in the 3% cell. Hence, another batch of samples were grown by MBE technique on CdS/SnO\textsubscript{2}/glass substrates. The growth conditions were similar to previous growth conditions except for the thickness of the films. Immediately following the growth, in-situ Auger measurements were performed, in order to find out the surface composition and also the
presence of Sb in the films. Figure 1-3 show in-situ Auger spectra of CdZnTe, CdZnTe:Sb, and ZnTe:Sb/CdZnTe samples. The spectra show the presence of Cd, Te, Zn, and Sb. From the intensity of peaks we have estimated the composition of CdZnTe films. The composition was found to be Cd$_{0.8}$Zn$_{0.2}$Te. The composition from Auger measurements is not generally very accurate, but the measurements at least show that the surface has no contaminants.

Figure 4 shows the Auger spectrum on one of the samples (E88-5) measured after exposing the sample to laboratory atmosphere for several weeks. The spectrum clearly shows many contaminants such as S, Cl, C, and O on the surface.

XRD measurements were performed to estimate the composition, and to identify the other phases of CdZnTe. Figure 5 shows the X-ray diffractogram of one of the polycrystalline (CdZnTe:Sb/CdS/SnO$_2$/glass) samples. The peaks at 23.7900, 39.5000, and 46.7100 correspond to CdZnTe, and all other peaks are due to CdS/SnO$_2$/glass substrate. The procedure for calculating lattice constant was reported earlier (refer to Report #11). In order to determine the lattice constant more accurately, we used an extrapolation technique (Nelson-Riley technique). Fig. 6 shows the extrapolation plot for CdZnTe sample (R87-46). Knowing the lattice constant the Zn concentration was estimated from lattice constant versus Zn concentration plot. The estimated Zn concentration value agrees well with the surface photovoltage (SPV) measurement. Also the XRD indicate that the film has a single phase of CdZnTe because otherwise, there will be additional lines corresponding to other phases.

Figure 7 shows the infrared spectrum of one of the CdZnTe samples (E88-1). Infrared measurements were done to estimate the thickness of films. As described earlier in report #11, the thickness of the sample was calculated from the fringe spacing. The estimated thickness was 2.3 microns.

In summary, polycrystalline CdZnTe, CdZnTe doped with Sb were grown by MBE. In-situ Auger measurements confirmed the formation of CdZnTe film and also the presence of Sb in the films. In-situ Auger measurements indicated a clean surface without any contaminants. Ex-situ Auger measurements showed that films surfaces were contaminated with C, Cl, S, O after exposing them to laboratory atmosphere for a couple of weeks. The film composition was estimated from X-ray measurements, which agreed with SPV measurements. XRD measurements revealed that the films are indeed single phase.

We plan to fabricate solar cells on these films, and to study the annealing effects, optimum annealing conditions and etching effects on these films using Auger, IR, and SPV techniques.
ACKNOWLEDGEMENTS

We would like to thank Steve Ringel and E. Meeks for all the help in the experimental work.
Figure 1. In-situ Auger spectrum of CdZnTe:Sb/CdS/SnO$_2$/glass
Figure 2. In-situ Auger spectrum of CdZnTe:Sb/CdS/SnO₂/glass
Figure 3. In-situ Auger spectrum of ZnTe:Sh/CdZnTe/CdS/SnO₂/glass.
Figure 4. Ex-situ Auger spectrum of CdZnTe:Sb/CdS/SnO$_2$/glass sample after exposing to laboratory atmosphere for a couple of weeks.
Figure 5. X-ray diffractogram of polycrystalline CdZnTe sample. Peaks marked 1, 2, 3, correspond to CdZnTe and all other peaks arise from substrate.
Figure 6. Extrapolation versus lattice constant plot of CdZnTe. The extrapolated lattice constant value is 6.419 Å.
Figure 7. Infrared spectrum of CdZnTe polycrystalline sample E85-1.
Mr. Ken Zweibel  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-ACO2-83CH10993  
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the period 6/1/88-6/31/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors  
Research Administrator

pm  
Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Robatgi, C. J. Summers, A. Erbil, and R. Sudharsanan

Thirteenth Monthly Report for the Period
June 1 to June 30, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe or MnTe alloys by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiencies of 15-20% provided the bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cell will be fabricated with a glass/SnO2/CdS window using a thin CdS layer to maximize transmission and current. Absorber films (Eg - 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contacts will be formed by growing a p+ ZnTe inter-layer between the metal grid and absorber film.

TECHNICAL PROGRESS

In this monthly report, we present the results of material characterization of MBE grown polycrystalline CdZnTe and CdTe films that have undergone various annealing procedures similar to those successfully used in the fabrication of CdTe solar cells elsewhere. Auger Electron Spectroscopy (AES), Surface Photovoltage (SPV), and infrared (IR) measurements were performed to characterize these films.

Post deposition annealing in the presence of oxygen has been shown by a number of groups to (i) cause a change in conductivity to p-type in as-grown CdTe and (ii) improve the quality of the CdTe/CdS heterojunction used in these solar cell structures. This effect has been well documented for CdTe grown in a variety of methods such as electrodeposition, close space vapor transport, etc., but annealing has not been attempted for MBE films, particularly ternary compounds such as CdZnTe. Since repeated attempts to dope CdZnTe with Sb have not been successful so far we are making attempts to optimize an annealing procedure for our films.

Anneals were performed in the range of 375-450°C for 30 min. The lower bound of 375°C was chosen since films which were earlier annealed at 325-375°C gave poor cells. Since oxygen was shown to be a necessary component in the CdTe process, the annealing was...
performed in laboratory (cleanroom) air. One anneal was done in an Ar ambient to confirm the necessity of oxygen. Figures 1-3 shows Auger depth profiles of MBE as-grown CdTe - 2.7 um thick (E88-7), CdZnTe - 2.9 um thick (E88-8), and CdZnTe:Sb - 1 um thick (R88-1) films indicating excellent compositional uniformity and interface clarity in each case. The thicknesses of these films were found by IR measurements as described in earlier reports. The atomic concentration values are in error here since correct sensitivity factors for CdTe and CdZnTe are presently not available. The CdZnTe film in Figure 3 (R88-1) has been reported earlier and gave a cell efficiency of 3.3%.

Figure 4 shows SPV spectra taken at the surfaces of E88-7 (CdTe), E88-8 (CdZnTe), and a different CdZnTe:Sb film (E88-9) which has the same composition and target Sb concentration as R88-1 but whose thickness is close to the other films so that the SPV data is less ambiguous. The SPV cutoff wavelengths indicate the proper bandgaps for CdTe (1.5 eV) and CdZnTe (1.7 eV) while the absorption edges are sharp, particularly for CdTe indicating little sub-bandgap absorption suggesting high material quality. The relative heights and shapes of these spectra are most likely a result of either changing material quality, i.e. carrier lifetime, or Fermi level position which would change the amount of band bending present at the electrolyte/semiconductor interface. We hope to resolve this question in the future.

Figure 5 shows the effect of annealing at the indicated temperatures for 30 min in air in the E88-8 CdZnTe film. Note the increasing response with temperature from no anneal to 425°C with the bandgap and hence film composition remaining constant. In addition, the relatively poor cutoff edge of the unannealed sample is straightened considerably indicating fewer sub-bandgap defects present. The variations in the SPV responses were not found to be a result of thickness differences between the samples after the anneals since IR measurements taken immediately after the anneals indicate the thickness did not change. All of these observations strongly suggest that the SPV response magnitude is proportional to the bulk material quality. In contrast, the 450°C anneal response is drastically altered, with the response magnitude significantly reduced, the bandgap shifting toward that of CdTe, and a broadening in the edge itself. IR measurements show that the thickness of this film decreased to 2.5 um indicating the evaporation of the film. Thus, Figure 5 indicates that the optimal annealing temperature for maximum SPV response and band edge abruptness is 425°C. SPV measurements were also made on a sample annealed in Ar but the response had little or no change from the as-grown film. It should be noted that the SPV response is measured from the back of the device and probably tells little about the CdS/CdZnTe heterojunction itself. We are presently devising a way to measure the SPV from the front of the cell.
Auger measurements were done on some of the annealed samples to determine if changes in uniformity occurred. Figure 6 shows the Auger depth profile of the E88-7 CdTe sample after 30 min 400°C air anneal. A large concentration of oxygen is present near the surface as well as a depletion of Te. The CdS/CdTe interface is slightly less sharp than the as-grown sample due to some Te diffusion but the compositional uniformity within the film is still quite good. In comparison to an electrodeposited 9% efficient CdTe solar cell grown by Ametek, Figure 7, the interface quality and compositional uniformity are similar, except that the Ametek film has a ZnTe cap layer that is present for the first 5 min of sputtering and the significantly smaller amount of oxygen in the Auger profile near the surface. The large amount of oxygen at the surface of our film was removed by a 5 min chemical etch in dilute buffered NaOH as indicated by further Auger profiling.

Figure 8 shows the Auger depth profile of the 3.3% efficient CdZnTe sample (R88-1) after the Ametek fabrication process. Note that the Zn segregates toward the ZnTe cap layer and that it follows the oxygen line. This has been seen in other CdZnTe films as well. We plan on continuing our Auger profiling on the other films annealed at different temperatures to clarify this effect.

In summary, MBE grown polycrystalline CdZnTe and CdTe films were annealed under various conditions and characterized by IR, SPV, and Auger profiling experiments. Compositional uniformity, interface quality, and purity were excellent in as grown films. SPV response was a maximum in CdZnTe film at annealing temperature of 425°C in an oxygen containing ambient. At higher annealing temperatures the bandgap changed, approaching that of CdTe. Anneals in inert atmospheres showed no increase in SPV response. Auger profiling after heat treatment showed that a high surface concentration of oxygen was present in CdTe and CdZnTe but could be removed by a dilute NaOH etch. In addition, there appears to be a relation between the oxygen and Zn profiles. In future work, we will investigate this observation using XPS and more AES. We will continue using AES to profile the effects of heat treatment on our films. We also will fabricate devices on these annealed films and test them as well as some other films. Preliminary testing has shown that the E88-7 CdTe film discussed above gave a cell efficiency of 9.3%, Jsc = 24.8 mA/Cm². Voc = 0.688 V and FF = .542, our best cell to date. Electrical measurements such as I-V and C-V and possibly DLTS will be performed. We are also designing a special sample holder so that we may perform EBIC on selected samples to determine the quality of heterojunction formation after annealing.
ACKNOWLEDGEMENTS

We would like to thank Steven A. Ringel and Dr. Brent Carter for all the help in the experimental work.
Figure 1. Auger depth profile of MBE grown polycrystalline CdTe on CdS/SnO$_2$/glass substrate. CdTe film thickness is ~2.7 μm.
Figure 2. Auger depth profile of MBE grown polycrystalline CdZnTe on CdS/δSnO$_2$/glass substrate. CdZnTe film thickness is ~2.9 μm.
Figure 3. Auger depth profile of MBE grown polycrystalline CdZnTe:Sb on CdS/SnO₂/glass substrate. CdZnTe:Sb film thickness is ~1 μm.
Figure 4. SPV spectra of (a) CdTe, (b) CdZnTe, and (c) CdZnTe:Sb, all of approximately the same thickness.
Figure 5. SPV spectra of E88-8 CdZnTe film annealed for 30 min. in air at indicated temperatures.
Figure 6. Auger depth profile of E88-7 CdTe film (Fisoi 1) after 30 min. 400°C air anneal.
Figure 7. Auger depth profile of a 9% CdTe Ametek cell for comparison with our work.
Figure 8. Auger depth profile of 3.3% CdZnTe (R88-7) cell after Ametek processing.
Mr. Ken Zweibel  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-ACO2-83CH10993  
Project Director: A. Rohatgi  

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Enclosures  

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HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE 
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, and R. Sudharsanan

Fourteenth Monthly Report for the Period
July 1 to July 31, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA  30332
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells are being fabricated with glass/SnO₂/CdS window with thin CdS layer to maximize transmission and current. Absorber films (E_g = 1.75 eV) are being grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact are being formed by growing a p⁺ ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

In this monthly report, we present Auger electron spectroscopy (AES) results of polycrystalline CdMnTe films grown on CdS/SnO₂/glass substrates. Auger depth profile measurements were done to investigate the film composition, uniformity, and the interface quality between CdMnTe and CdS films. AES analyses were performed on CdTe and CdMnTe polycrystalline films grown by MOCVD. AES was done on a Physical Electronics Model 600 Scanning Auger Multiprobe. All AES data were taken using a 3 KeV electron beam with a current of 1.0 μA. Auger depth profiles were taken by alternatively collecting data and sputtering with a rastered beam of 2 KeV Ar⁺ ions.

Figures 1 and 2 show the Auger depth profile of CdTe and CdMnTe films on CdS/SnO₂/glass substrates. The Cd and Te concentrations are uniform and flat in CdTe film, suggesting homogeneous composition of CdTe whereas in the case of CdMnTe film, the Cd, Te, and Mn concentrations are not uniform suggesting compositional inhomogeneity. These Auger depth profiles correlate well with the sharp and broad absorption edges observed in the CdTe and CdMnTe spectra, respectively.

We find that the CdMnTe/CdS interface is broad and has Mn accumulation in the CdS region. The broad interface may be due to interdiffusion of CdTe and CdS films which may
occur due to the combination of high growth temperature (380°C) and slow growth rate of CdTe film by MOCVD.

In addition to performing depth profiles, specimens were fractured in atmosphere and immediately placed in the AES spectrometer for point analysis on the film fractured cross sections. This was done to avoid possible artifacts due to sputtering and to confirm the depth profile results of an apparent Mn accumulation near the interface of MOCVD grown CdMnTe. The compositions of the fractured film across sections at several points lying on apparent straight lines normal to the specimen surfaces were analyzed. A 10 KeV electron beam of about 5 nA was used for these analyses in which the beam was approximately normal to the fracture surface. These measurements clearly indicated the presence of Mn at the interface and eliminated the possibility of sputtering artifact in depth profile analysis. Also, the depth profile analysis showed that the chemistry of Mn at the interface and in the film is different. This is presently being investigated.

Auger depth profile analysis on single crystal CdMnTe grown on GaAs (111) simultaneously, showed no Mn accumulation at the interface (Figure 3), suggesting that interdiffusion of CdS and CdMnTe films is the result of excess Mn at the interface. Further measurements are necessary to understand the mechanism of interdiffusion which may involve Cd from CdS.

In summary, AES measurements on polycrystalline CdMnTe film showed non-uniform composition resulting Mn pile up at the CdMnTe/CdS interface and depletion of Cd from CdS. Also, for the growth conditions investigated, MOCVD grown CdTe/CdS interface is broader than MBE grown CdTe/CdS. Further, AES and SPV measurements will be performed on CdMnTe and CdTe polycrystalline films after processing.

ACKNOWLEDGEMENTS

We would like to thank Dr. Brent Carter and Steven A. Ringel for all the help in the experimental work.
Figure 1. Auger depth profile of MOCVD grown polycrystalline CdTe/CdS film.
Figure 2. Auger depth profile of MOCVD grown polycrystalline CdMnTe/CdS film.
Figure 3. Auger depth profile of MOCVD grown single crystal CdMnTe/GaAs film.
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SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Status Report for the period 8/1/88-8/31/88 on the above referenced contract.

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Sincerely yours,

Pam Majors  
Research Administrator

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cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, and R. Sudharsanan

Fifteenth Monthly Report for the Period
August 1 to August 31, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
ABSTRACT

Ternary films of CdZnTe and CdMnTe were grown by molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), respectively, on glass/SnO\(_2\)/CdS substrates with target bandgap of 1.7 to 1.8 eV for solar cell applications. X-ray diffraction, surface photovoltage spectroscopy, and Auger electron spectroscopy measurements were performed to estimate bandgap, compositional uniformity, and interface quality of the films. Front-wall CdTe cell (glass/SnO\(_2\)/CdS/CdTe/ZnTe/Metal) efficiencies were ~9%, while CdZnTe and CdMnTe efficiencies were ~3.6% and 6%, respectively. n-i-p cell efficiencies were consistently higher than n-p cells. Optimum cell processing temperature for CdZnTe films was found to be less than 400°C. Higher processing temperatures caused a shift in bandgap coupled with film quality degradation.

EXPERIMENTAL PROCEDURE

Film Growth

CdZnTe and CdTe films were grown by molecular beam epitaxy (MBE) using a Varian Gen II MBE system. Elemental sources were used for all constituents having a purity of at least 5N. The films were grown on glass/SnO\(_2\)/CdS substrates. The substrates were baked out at 250°C for 3-4 hours before film growth. The substrate temperature was kept at 275°C for 30 minutes to commence film growth and increased to 300°C for the remainder of the run. Growth rates were typically ~1 um/hr for both CdTe and CdZnTe. Film purity was monitored using in-situ Auger measurements which detected the presence of Cd, Te, and Zn only, indicating high purity of the as-grown MBE films.

CdTe and CdMnTe films were grown by metalorganic chemical vapor deposition (MOCVD) on glass/SnO\(_2\)/CdS substrates. CdMnTe films were grown using dimethylcadmium, diethyltellurium, and tricarbonylmethylcyclopentadienyl manganese as source materials for Cd, Te, and Mn, respectively. The CdMnTe films were grown at substrate temperature 420°C, while CdTe films were grown at substrate temperature in the range of 300° to 400°C with diallyltellurium as a source for Te.

Film Characterization

X-ray diffraction (XRD) measurements were performed on these films to determine both the film composition and the possible formation of mixed phases. The lattice constant was found by extrapolation method [4]. Surface photovoltage (SPV) measurements were performed using an electrochemical etching profiler which has an advantage over techniques, such as optical absorption in that measurements can be made in a depth-resolved fashion so that compositional uniformity and material quality can be determined by tracking variations in the absorption edge and the magnitude of the SPV response, respectively [5]. The SPV measurements were made using an electrolytic solution consisting of 0.2 M NaOH+0.1 M EDTA (ethylenediaminetetraacetic acid) which forms a Schottky barrier contact on these films. To study the compositional uniformity in more detail, Auger
electron spectroscopy (AES) was performed on CdTe and CdZnTe films using a Physical Electronics Model 600 Scanning Auger Multiprobe. The angle between the sample normal and the electron beam was 45°.

**Cell Fabrication**

Front-wall solar cells were fabricated with a glass/SnO₂/CdS/CdZnTe or CdMnTe/ZnTe/Ni structure. In selected instances, MBE and MOCVD CdTe solar cells were made with identical structures. The films were annealed at 400°C for 30 minutes in breathing air followed by a mild etch of Bromine methanol before the vacuum evaporation of a Cu-pro external p⁺-ZnTe interlayer which facilitates the ohmic contact to subsequently evaporated 8 mm² Ni dots.

**RESULTS AND DISCUSSIONS**

Bandgap, compositional uniformity, and interface quality were determined by a combination of XRD, SPV, and AES techniques. Figure 1 shows XRD of MBE-grown polycrystalline CdTe and CdZnTe films grown on CdS/SnO₂/glass substrates, which gave 7.5% and 3.6% efficiencies. The lattice constant "a" of the CdZnTe film determined by an extrapolation method [4] was used to estimate the Zn content (x) in CdZnTe as-grown films according to a(x)=6.481-0.301X Å. The estimated atomic concentration (x) of Zn in CdZnTe film was 0.40. The bandgap of this film was found to be ~1.7 eV from the relationship between x and bandgap (Eₕ) derived from optical absorption measurements [6].

Same procedure was used to determine bandgap of CdMnTe films from X-ray measurements [7]. X-ray plots in Fig. 1 clearly indicate that there are no other mixed phases present in the CdZnTe film since only peaks corresponding to cubic CdZnTe are observed.

Figure 2 shows the SPV spectra of the same MBE-grown CdTe and CdZnTe films along with MOCVD-grown CdTe and CdMnTe polycrystalline films. The bandgaps found from the midpoint of the absorption edge were 1.45 eV (MBE-CdTe), 1.7 eV (CdZnTe), 1.45 eV (MOCVD-CdTe), and 1.7 eV (CdMnTe), in good agreement with X-ray measurements. Notice that the cutoff edges of MBE-grown CdTe films are much sharper than the CdMnTe bandedge. The broad shape of the CdMnTe SPV spectrum suggests nonuniformity distributed Mn within the film.

In order to get a more direct indication of depth resolved composition as well as interface quality, AES measurements were performed on these films. Figure 3 shows the Auger depth profile analysis of MBE-grown CdTe and MOCVD-grown CdMnTe polycrystalline films which gave 7.5% and 11% efficiencies, respectively. The Cd and Te lines in CdTe films grown by MBE and MOCVD, and the Cd, Te, and Zn lines in MBE-CdZnTe were flat indicating uniform composition. In addition, the film interface with CdS was found to be sharp (Fig. 3). However, in the case of CdMnTe film, the Cd, Te, and Mn lines were not flat, confirming compositional
nonuniformity as suggested by the SPV results. Furthermore, the CdMnTe and CdS interface was broad and showed Mn accumulation due to interdiffusion, probably resulting from relatively high temperature (420°C) used in the growth of the CdMnTe film.

**CELL CHARACTERIZATION AND ANALYSIS**

Both n-p and n-i-p CdTe and CdZnTe solar cells were fabricated. For n-i-p cells, a p-ZnTe film was deposited on top of the absorber layer prior to back contact metallization. Figure 4 shows the spectral response of n-p and n-i-p CdTe and CdZnTe solar cells. The n-i-p spectral response was higher over most of the spectral range in both cases. This is consistent with higher values of $J_{sc}$, $V_{oc}$, fill factor, and efficiency of n-i-p cells. Table 1 gives the solar cell parameters of CdTe, CdZnTe, and CdMnTe solar cells.

The cell data and spectral response measurements indicate that we were successful in making 7.5-9.3% polycrystalline CdTe solar cells by MBE and MOCVD techniques with $V_{oc}$ as high as 740 mV and $J_{sc}$ approaching 17.4 mA/cm$^2$. Fill factor was somewhat low because of high series resistance.

Table 1. Solar Cell Parameters of Our Best CdTe, CdZnTe, and CdMnTe n-i-p Cells. The Zn Concentration is 40% in CdZnTe and Mn Concentration is 10% in CdMnTe Films.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Efficiency</th>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>Fill Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE-CdTe</td>
<td>7.1</td>
<td>740</td>
<td>17.1</td>
<td>55.7</td>
</tr>
<tr>
<td>MBE-CdTe</td>
<td>7.6</td>
<td>666</td>
<td>17.5</td>
<td>65.3</td>
</tr>
<tr>
<td>MOCVD-CdTe</td>
<td>9.3</td>
<td>713</td>
<td>22.6</td>
<td>57.7</td>
</tr>
<tr>
<td>MBE-CdZnTe</td>
<td>3.6</td>
<td>511</td>
<td>14.4</td>
<td>48.4</td>
</tr>
<tr>
<td>MOCVD-CdMnTe</td>
<td>6.0</td>
<td>680</td>
<td>20.6</td>
<td>44.2</td>
</tr>
</tbody>
</table>
We were successful in tailoring the bandgap of as-grown CdZnTe and CdMnTe to the target value of 1.7–1.8 eV. However, as discussed later, the cell processing resulted in bandgap reduction of CdZnTe films, whereas no appreciable bandgap reduction was observed in CdMnTe film. CdZnTe cell efficiencies were around 3.6% with V of 511 mV and J of 14.4 mA/cm² which, to the best of our knowledge, is the highest efficiency of CdZnTe/CdS solar cell to-date but not high enough to produce 18–20% efficient polycrystalline tandem cells. CdMnTe efficiencies with low Mn content (<1%) and Ep = 1.53 eV were around 6%. Detailed information about 6% CdMnTe has been published elsewhere (8). So far, attempts to fabricate CdMnTe cells with higher Mn content (>1%) have resulted in cell efficiencies of less than 2%. Work is in progress to optimize the film growth and processing temperature to achieve high efficiency cells.

Attempts are being made to understand the material properties, its control, and response to heat treatment in order to fabricate higher efficiency cells.

The spectral response, Fig. 4, of the CdZnTe films indicate that Ep was reduced from 1.7 eV prior to processing to 1.55 eV after processing. In order to understand the decrease in bandgap, transmission measurements were performed on these films before and after processing. Figure 5 shows the transmission data for these films. The spectra of the as-grown films indicate that CdZnTe films have higher subbandgap transmission (lower subbandgap absorption) than CdTe. This difference is not necessarily due to defects but most likely is related to difference in absorption coefficient or bandgap. After annealing at 410 °C for 30 minutes (optimum condition for CdTe), CdZnTe films showed a decrease in bandgap, Fig. 5b, which is consistent with the spectral response measurements taken on these cells. One of the CdZnTe films was annealed intentionally for a longer time (50 minutes) and the transmission of this film showed not only a decrease in bandgap but also a significant increase in subbandgap absorption which is indicative of process induced defects that may be related to loss of Zn from its substitutional sites in the film as suggested by reduced bandgap. Auger depth profile analysis on this film after processing indicated a nonuniform distribution of Te throughout the film with some Zn segregation to the ZnTe/CdZnTe interface within the bulk film. However, Zn line leveled off close to the value found before processing. This possibly indicates that Zn has left its lattice sites in CdZnTe and may be forming other defect complexes which can result in the observed increase in subbandgap absorption. This hypothesis was supported by the very low cell efficiency (0.6%) observed for this particular film. The above results suggest that processing time and temperature used for CdZnTe solar cells were not optimum.

In an attempt to optimize cell processing temperature, SPV measurements were performed on CdZnTe films annealed at different temperatures. Figure 6 shows the SPV spectra of CdZnTe film annealed in air for 30 minutes in the temperature range 360° to 410°. The SPV response increases...
without any change in the bandgap or Zn content up to an annealing temperature of 385°C. This indicates that annealing improves the film quality. However, SPV response of the film annealed at 410°C decreased drastically. This quality degradation was associated with a shift in the absorption edge towards low bandgap, identical to what was observed in the transmission measurements in Fig. 5. These results suggest that the optimum annealing condition for MBE-grown CdZnTe film is 385°C. The 3.7% CdZnTe solar cell went through the 410°C/30 min. anneal, which may be the reason for low efficiency. Cells are now being fabricated with optimum annealing condition with the goal of achieving CdZnTe efficiencies approaching 10%.

CONCLUSIONS

Both MBE and MOCVD growth techniques have been used to fabricate CdTe based solar cells. Without any material growth and design optimization, CdTe front-wall cells (glass/SnO₂/Cds/CdTe/ZnTe/Metal) with efficiencies in the range 7-9% were fabricated. Thickness optimization is being done to improve the CdTe cell efficiencies beyond 10%. MBE CdZnTe and MOCVD CdMnTe films with bandgap around 1.7-1.8 eV have been deposited on glass/SnO₂/CdS substrates. Unlike the CdTe cells, the optimum process/annealing temperature for ternary cells was found to be lower than 400°C. MBE films showed uniform composition and sharp interfaces but MOCVD CdMnTe films grown at 420°C showed broad interface and compositional nonuniformity. Best n-i-p CdZnTe cell efficiencies were ~3.6% and CdMnTe (<10% Mn) cell efficiencies were ~6%. Although these are some of the highest efficiencies reported to-date on CdTe based alloys, further improvements are necessary to make respectable absorber films for the top cell in the tandem cell design.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. E. Meeks, K. T. Pollard, and Dr. C. J. Summers for their help in film growth, and Dr. S. Stock and Dr. B. Carter for their help in X-ray and Auger measurements. Also we would like to thank K. Zweibel of SERI for his help in cell measurements. This work was supported by the Solar Energy Research Institute under Contract No. XL-7-06031-1.

REFERENCES

November 7, 1988

Mr. Ken Zweibel  
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SUBJECT:  Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
          Project Director:  A. Rohatgi

Dear Mr. Zweibel:

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Sincerely yours,

Pam Majors  
Research Administrator

pm
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cc:  Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE-BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, and R. Sudharsanan

Sixteenth Monthly Report for the Period
September 1 to September 30, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program front wall solar cells will be fabricated with glass/SnO\textsubscript{2}/CdS window with thin CdS layer to maximize transmission and current. Absorber films ($E_g = 1.75$ eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p$^+$ ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

In this monthly report we present photoluminescence (PL), Raman, and Auger electron spectroscopic (AES) studies on CdMnTe films grown on GaAs, CdTe/GaAs, and CdS/SnO\textsubscript{2}/glass substrates.

It is known that interface states affect the performance of polycrystalline heterojunction solar cells. Auger measurements on CdMnTe films showed accumulation of Mn at the CdMnTe and CdS interface. In order to understand the quality of CdMnTe films on different substrates Raman scattering, photoluminescence and Auger depth profile measurements were carried out.

Raman scattering and Photoluminescence measurements were done using 514 nm Ar$^+$ laser excitation at 2K and 80K. CdMnTe samples were deposited by MOCVD on CdTe/GaAs (111), GaAs (111), and CdS/SnO\textsubscript{2}/glass substrates. X-ray measurements were performed to identify the composition and crystallinity of films grown on different substrates. The films grown on CdTe/GaAs (111) and GaAs (111) were single crystals with 111 orientation. The films grown on CdS/SnO\textsubscript{2}/glass were polycrystalline nature with no preferred orientation. All the CdMnTe films were grown at a substrate temperature of 420°C and under similar conditions.
Figure 1 shows Raman spectra of films grown on different substrates. Raman spectra of films grown on GaAs and CdTe/GaAs show sharp peaks and many higher order peaks. In general, appearance of higher order peaks in Raman spectra reflect good quality of films. Many researchers have observed higher order peaks in Raman spectra in CdMnTe/CdTe super-lattices and quantum well structures. In the case of films grown on CdS/SnO₂/glass and glass the Raman spectra show a few sharp peaks and no higher order peaks. It is possible that the appearance of higher order peaks depends on the crystallinity of films. Hence, Raman spectra indicate that quality of CdMnTe polycrystalline films is inferior to single crystal films.

Photoluminescence measurements were carried out to understand the quality of polycrystalline and single crystal films from the point of view of defects. Figure 2 shows PL spectra of CdMnTe single and polycrystalline films. In the case of CdMnTe film grown on CdTe/GaAs substrate, the PL spectra (Fig. 2a) show peaks at 2.036, 1.598, 1.490, and 1.44 eV. The peak at 2.036 eV corresponds to CdMnTe bandgap and the other peaks correspond to CdTe/GaAs substrate as shown in the bottom of the figure, (the substrate PL was measured separately to identify the peaks in CdMnTe PL spectrum). The PL spectrum of CdMnTe film grown on GaAs substrate (Fig. 2b) shows peaks correspond to CdMnTe (2.005 eV) and GaAs substrate (1.490, 1.457 eV). But the substrate peaks appear on a broad band which is not observed in the CdMnTe film with a CdTe buffer layer (Fig. 2a). The appearance of broad band may be due to defects occurring due to large lattice mismatch (14.5%) between CdMnTe and GaAs substrate. This suggests that thin CdTe buffer layer improves the quality of CdMnTe film. The polycrystalline CdMnTe film PL spectrum (Fig. 2c) has peaks at 2.004 and 1.62 eV. The peak at 2.004 eV corresponds to CdMnTe bandgap. The peak at 1.62 eV is not observed in single crystal film and also in the CdS/SnO₂/glass substrate (Fig. 2c). This suggests that the peak may correspond to defects due to polycrystalline nature of films. It is also possible that this peak may occur due to interface states in polycrystalline films. This later argument was further supported by Auger measurements on these films (Fig. 3). Auger measurements showed accumulation of Mn at the CdMnTe/CdS interface and not in the CdMnTe/GaAs interface.

In order to confirm the interface states in CdMnTe/CdS polycrystalline films further measurements like PL on CdMnTe films with different Mn concentrations and on oxygen annealed samples will be pursued. This work was presented in the 35th AVS meeting held in Atlanta during October 3-7, 1988.
ACKNOWLEDGEMENTS

We would like to thank Dr. Z. C. Feng and Prof. S. Perkowitz of Emory University for their help in PL measurements. Also, we thank Dr. Brent Carter for Auger depth profile analysis.
Figure 1. Raman scattering spectra of CdMnTe films on different substrates.
Figure 2. PL spectra of single and polycrystalline CdMnTe films on (a) CdTe/GaAs, (b) GaAs, and (c) CdS/SnO$_2$/glass substrates.
Figure 3. Auger depth profile analysis of (a) single crystal CdMnTe, (b) polycrystalline CdMnTe, and (c) polycrystalline CdTe films.
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SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
Project Director: A. Rohatgi

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Pam Majors
Research Administrator

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cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Seventeenth Monthly Report for the Period
October 1 to October 31, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INVESTIGATION OF COMPOSITIONAL UNIFORMITY AND INTERFACE QUALITY
IN POLYCRYSTALLINE Cd(Zn,Mn)Te/Cds HETEROJUNCTIONS

S. A. Ringel,(a) R. Sudharsanan,(a) A. Rohatgi,(a) and W. B. Carter(b)
Microelectronics Research Center
Georgia Institute of Technology
Atlanta, Georgia 30332 USA

Polycrystalline films of Cd_{1-x}Zn_xTe and Cd_{1-x}Mn_xTe were grown by MBE and MOCVD, respectively, on CdS/SnO_2/glass substrates for solar cell applications. The compositional uniformity and interface quality of these films were investigated by surface photovoltage spectroscopy, Auger electron spectroscopy, and X-ray diffraction measurements. The results indicated adequate compositional control (0 < x < 0.3) and abrupt interfaces for MBE Cd_{1-x}Zn_xTe films grown at 300° C. However, MOCVD Cd_{1-x}Mn_xTe films grown at 420° C showed nonuniform bulk composition coupled with a diffuse Cd_{1-x}Mn_xTe/Cds interface. In addition, Mn accumulation was observed near the interfacial region of the polycrystalline films, but single crystal films grown simultaneously on GaAs substrates showed no such pile-up suggesting enhanced Mn diffusion due to Cds substrate.

(a) School of Electrical Engineering.
(b) School of Materials Engineering.
In recent years, CdTe has become a strong candidate for photovoltaic applications due to its desirable bandgap (1.5 eV), high absorption coefficient, and ease of deposition. To date, solar conversion efficiencies of ~15% have been obtained from crystalline CdTe solar cells\(^1\) and >10% for polycrystalline CdTe based thin film cells.\(^2-4\) The practically achievable efficiency for polycrystalline CdTe solar cells is predicted to be ~15%. To improve thin film cell efficiencies beyond 15%, a tandem or cascade cell design should be used in which two cells of different bandgap semiconductors are grown on top of each other (1.7 eV on 1.1 eV).\(^5\) Semiconducting alloys, such as Cd\(_{1-x}\)Zn\(_x\)Te and Cd\(_{1-x}\)Mn\(_x\)Te, are good candidates for the top cell since the proper bandgap can be obtained by tailoring the film composition. Although these films have been grown on various substrates, the film uniformity and interface quality, which are essential for high cell efficiencies, have not been thoroughly investigated. In this letter, we report the growth of Cd\(_{1-x}\)Zn\(_x\)Te and Cd\(_{1-x}\)Mn\(_x\)Te polycrystalline films grown by molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), respectively, on CdS/SnO\(_2\)/glass substrates. Films were characterized by X-ray diffraction (XRD), electrochemical surface photovoltage (SPV), and Auger electron spectroscopy (AES) to determine proper growth conditions, compositional uniformity, and interface quality.

Cd\(_{1-x}\)Zn\(_x\)Te and CdTe films were grown by MBE using a Varian Gen II MBE system. Elemental sources were used for all constituents having a purity of at least 5N. The films were grown on CdS/SnO\(_2\)/glass and glass substrates. The fluorine doped SnO\(_2\) serves as an antireflection coating and a transparent contact to the undoped CdS (~1500 \(\AA\)) for the solar cell structure. The substrates were baked out at 250\(^\circ\)C for 3–4 hours before film growth.
substrate temperature was kept at 275°C for 30 minutes to commence film growth and increased to 300°C for the remainder of the run. Growth rates were typically ~1 um/hr for both CdTe and Cd$_{1-x}$Zn$_x$Te. Film purity was monitored using in-situ Auger measurements which detected the presence of Cd, Te, and Zn only, indicating high purity of the as-grown MBE films.

To determine the proper growth conditions for optimal composition (~1.7 eV bandgap), films were grown with various Cd/Zn beam flux ratios. XRD measurements were performed on these films to determine the film composition. The lattice constant, "a", was found by extrapolation method. These values are given in Table 1. From the lattice constants, the atomic concentration of zinc (x) in Cd$_{1-x}$Zn$_x$Te film was found using $a(x) = 6.481 - 0.381x$ Å which, in turn, gave the bandgaps of the films using optical absorption data. The Cd, Zn, and Te beam flux values and the corresponding bandgaps are given in Table 1.

SPV measurements were performed on the CdTe and Cd$_{1-x}$Zn$_x$Te films using an electrochemical profiling system. Electrochemical SPV has an advantage over techniques such as optical absorption in that measurements can be made in a depth-resolved fashion, so that compositional uniformity and material quality can be determined, by tracking variations in the absorption edge (bandgap) and the magnitude of the SPV response, respectively. The SPV measurements were made using an electrolytic solution consisting of 0.2 M NaOH + 0.1 M EDTA (ethylenediaminetetraacetic acid) which forms a Schottky barrier contact with the films.

Figure 1 shows SPV spectra of CdTe and Cd$_{1-x}$Zn$_x$Te films grown on the CdS/SnO$_2$/glass substrates. Bandgaps determined from the cutoff wavelengths of these spectra are listed in Table 1 along with two other films of different
composition for comparison with the XRD data. In addition, the sharpness of the absorption edge reflects uniform film composition and good material quality for both CdTe and Cd$_{1-x}$Zn$_x$Te films. The fact that bandgaps are dictated by the amount of Zn flux in the MBE growth indicates that the Zn is properly substituting for the Cd in the crystal structure. In addition, XRD measurements showed no signs of mixed ZnTe or CdTe phases, confirming the presence of only one CdTe phase (zincblende) in the films.

To study the compositional uniformity in more detail, AES analyses were performed on CdTe and Cd$_{1-x}$Zn$_x$Te films. AES was done on a Physical Electronics Model 600 Scanning Auger Multiprobe. The angle between the sample normal and the electron beam was 45°. All AES data were taken using a 3 KeV electron beam with a current of 1.0 μA. The sputtering rate for depth profiling was found to be 290 Å/min by sputtering a CdTe film of known thickness.

Figure 2 shows the Auger depth profile for the same CdTe and Cd$_{1-x}$Zn$_x$Te samples used in Figure 1. Both films show compositional uniformity, as suggested by the sharp SPV cutoffs in Figure 1. The CdTe/CdS and Cd$_{1-x}$Zn$_x$Te/CdS interfaces are abrupt indicating no interdiffusion between the various films. The high concentration of oxygen in the Auger profile beneath the CdS layer is due to the SnO$_2$ contact layer. Thus, in addition to controlling the bandgap, we were able to grow sharp interfaces.

Cd$_{1-x}$Mn$_x$Te polycrystalline films were grown by MOCVD on CdS/SnO$_2$/glass substrates using a commercial system (Cambridge Instruments MR102). The source materials for Cd, Te, and Mn were dimethylcadmium (DMCd), diethyltellurium (DETe), and tricarbonyl methylcyclopentadienylic manganese (TCPMn), respectively. The source temperatures were kept at 0° C for Cd and
20° C for both Te and Mn. The reactor pressure was varied from 250 torr to 50 torr, and the partial pressures of the Cd, Te, and Mn were typically 4.6, 126, and 4.3 mtorr, respectively. Infrared measurements on single crystal Cd$_{1-x}$Mn$_x$Te films suggested an optimum substrate temperature of about 420° C for growing good quality single crystal Cd$_{1-x}$Mn$_x$Te films with Mn concentration greater than 10%. The substrate temperature of Cd$_{1-x}$Mn$_x$Te and CdTe polycrystalline films were maintained at 420 and 400° C. Under these conditions, the deposition rate of Cd$_{1-x}$Mn$_x$Te films were 0.5 um/hr and for CdTe films were 1.5 um/hr.

The lattice constant of the film was calculated as described above, and was found to be 6.470 Å. The Mn concentration (x) was calculated using the relation $a = 6.487 - 0.149x$ Å.  

The SPV spectra of CdTe and Cd$_{1-x}$Mn$_x$Te polycrystalline films grown on CdS/SnO$_2$/glass substrates are shown in Figure 1. The CdTe spectrum exhibited a sharp cutoff edge at 840 nm corresponding to a bandgap of 1.48 eV, whereas the Cd$_{1-x}$Mn$_x$Te has a broad absorption edge around 720 nm (at half width) corresponding to a bandgap of 1.72 eV. From the bandgap of the Cd$_{1-x}$Mn$_x$Te film, the Mn concentration was estimated using the relation $E_g = 1.50 + 1.34x$ eV at room temperature. The calculated Mn value of 16% agrees reasonably well with the X-ray measurement value of 11%.

The absorption edge of the SPV spectrum for the MOCVD-grown CdTe film is as sharp as that of MBE-grown CdTe and Cd$_{1-x}$Zn$_x$Te polycrystalline films, suggesting good quality. However, the broad absorption edge for the Cd$_{1-x}$Mn$_x$Te film suggests a possible compositional inhomogeneity in bulk film. Auger depth profile measurements on these films confirmed the bulk inhomogeneity (Figure 3), and revealed the presence of a diffused Cd$_{1-x}$Mn$_x$Te/
CdS interface where Mn accumulation is evident. This suggests a possible interaction of Mn with Cd in CdS, since this was not observed for the MBE-grown Cd$_{1-x}$Zn$_x$Te/CdS interface. Auger cross-sectional measurements across the interface showed high Mn concentration at the interface, indicating the observed Mn accumulation is not the result of sputtering artifact during the depth profile analysis. In contrast, Auger depth profile analysis on single crystal Cd$_{1-x}$Mn$_x$Te-grown simultaneously on GaAs (111), showed no accumulation of Mn near the Cd$_{1-x}$Mn$_x$Te/CdS interface suggesting that interdiffusion of CdS and Cd$_{1-x}$Mn$_x$Te films may be responsible for the Mn accumulation at the interface. Further measurements are necessary to understand the mechanism of interdiffusion which may involve Cd from CdS. Similarly, the interface region between MOCVD CdTe/CdS was found to be broader as compared to MBE-grown CdTe/CdS. However, for this case the interdiffusion is probably due to the combination of high growth temperature (380°C) and slow growth rate of CdTe film by MOCVD.

In summary, SPV, XRD, and Auger measurements were performed to characterize Cd$_{1-x}$Zn$_x$Te, Cd$_{1-x}$Mn$_x$Te polycrystalline films for composition and their interface quality with CdS for solar cell applications. SPV results agree well with the X-ray diffraction for bandgap determination and also with Auger depth profile analysis for compositional uniformity. Polycrystalline Cd$_{1-x}$Zn$_x$Te films grown on CdS/SnO$_2$/glass by MBE had uniform composition and sharp interfaces, whereas polycrystalline Cd$_{1-x}$Mn$_x$Te films grown by MOCVD had nonuniform composition and showed Mn accumulation at the Cd$_{1-x}$Mn$_x$Te/CdS interface. In addition, for the growth conditions investigated, MBE-grown CdS/CdTe interface is sharper than the MOCVD-grown CdS/CdTe interface. These results are important in terms of solar cell performance, since nonuniform composition and interfacial disorder can affect the solar cell efficiency.
Acknowledgements. The authors would like to thank Dr. S. Stock for his help in X-ray diffraction measurements, and C. J. Summers, K. T. Pollard, and A. Erbil for their assistance in film growth. This work was supported by the Solar Energy Research Institute under SERI/DOE Subcontract XL-7-06031-1.
REFERENCES

FIGURE CAPTIONS

Figure 1. SPV spectra of MBE-grown (a) CdTe, (b) Cd\(_{1-x}\)Zn\(_x\)Te, and MOCVD-grown (c) CdTe, (d) Cd\(_{1-x}\)Mn\(_x\)Te films grown on CdS/SnO\(_2\)/glass substrates. The peaks at ~560 and ~710 nm are due to the SPV system response.

Figure 2. Auger depth profiles of MBE-grown (a) CdTe and (b) Cd\(_{1-x}\)Zn\(_x\)Te.

Figure 3. Auger depth profiles of MOCVD-grown (a) CdTe and (b) Cd\(_{1-x}\)Mn\(_x\)Te.
TABLE 1. Lattice constant, composition, and bandgap of CdZnTe films grown under different conditions as measured by XRD and optical absorption. The bandgap determined by SPV is listed for comparison.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Incident Beam Flux (BEP x10^-7 Torr)</th>
<th>Composition of CdZnTe Films</th>
<th></th>
</tr>
</thead>
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<tr>
<td></td>
<td>Cd</td>
<td>Zn</td>
<td>Te</td>
</tr>
<tr>
<td>E88-7</td>
<td>10.0</td>
<td>0.0</td>
<td>16.0</td>
</tr>
<tr>
<td>R87-44</td>
<td>4.6</td>
<td>0.63</td>
<td>6.8</td>
</tr>
<tr>
<td>R88-1</td>
<td>6.0</td>
<td>2.2</td>
<td>11.0</td>
</tr>
<tr>
<td>E88-8</td>
<td>6.0</td>
<td>3.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>
January 9, 1989

Mr. Ken Zweibel  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Progress Report for the period 11/1/88-11/30/88 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors  
Research Administrator

pm  
Enclosures  

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Eighteenth Monthly Report for the Period
November 1 to November 30, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve the basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO₂/CdS window with thin CdS layer to maximize transmission and current. Absorber films (E₉ = 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown MOCVD. Transparent ohmic contact will be formed by growing a p⁺ ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

In this monthly report, we present the device measurements of MOCVD-grown CdTe/CdS/SnO₂/glass structures. MOCVD-grown CdMnTe films gave poor efficiency because of several problems like non-homogenity of bulk CdMnTe films, accumulation of Mn at the interface, and interdiffusion of CdS and CdTe at the interface. The above problems may be due to growth of CdMnTe films at high temperatures like 420°C. Also, annealing CdMnTe films in oxygen atmosphere at 400°C reduces the bandgap of the films. In order to understand whether the growth conditions affect the cell efficiency and the maximum possible cell efficiency obtainable from MOCVD-grown CdTe solar cells, we have grown CdTe solar cells by MOCVD and MBE techniques.

Polycrystalline CdTe films were grown on CdS/SnO₂/glass substrates and glass substrates by MOCVD. Dimethacadmium, diallyltellurium were used as sources for Cadmium and tellurium and were kept at 0°C and 20°C respectively. Diallyltellurium source has an advantage that it has low cracking temperature so that CdTe films can be grown at lower substrate temperature (260 to 350°C). We have grown CdTe polycrystalline films on CdS/SnO₂/glass substrates by varying the substrate temperature and time of growth. Also, prior to deposition of CdTe the substrates were heated to 450°C in hydrogen atmosphere for 30 minutes. The above process
is known to give very clean CdS surface. Table 1 gives the growth parameters of CdTe polycrystalline films.

The thickness of the CdTe films were found from infrared reflection measurements. The procedure to obtain thickness from infrared measurements have been described in previous report (#11). Surface photovoltage measurements were performed to verify the bandgap of CdTe films. Auger depth profile analysis confirmed uniform bulk composition.

Front wall solar cells were fabricated by AMETEK Applied Materials Laboratory. The films were annealed at 400°C for 30 minutes in breathing air followed by a mild etch of Bromine methanol before the vacuum evaporation of ZnTe. A copper doped p⁺ ZnTe interlayer facilitates the back ohmic contacts. Ni contacts were made as back contacts. The finished solar cell structure is Ni/p⁺ - ZnTe/CdTe/CdS/SnO₂/glass.

One of the CdTe solar cells gave a cell efficiency of 9.7% with \( V_{OC} = 730 \text{ mV} \), \( J_{SC} = 22.16 \text{ mA/cm}^2 \), and fill factor 59.8% and figure 1 shows the lighted I-V plot. The \( V_{OC} \) and fill factor values are typical of those obtained in most polycrystalline CdTe solar cells grown by other methods but our \( J_{SC} \) is comparable to \( J_{SC} \) values obtained in some of the highest efficiency CdTe cells grown by other methods. We have not yet optimized the cell parameters to get high efficiency in our CdTe solar cells. The high value of \( J_{SC} \) is further confirmed by the quantum efficiency plot of the above cell which is shown in figure 2. The external quantum efficiency is above 0.9 in the range of 400 to 800 nm. Figure 3 shows the dark I-V characteristics of the cell.

In conclusion, we have demonstrated that the MOCVD-grown CdTe solar cells can give efficiency of 9.7% with the quantum efficiency better than the polycrystalline CdTe solar cells grown by other methods. This suggests that p-i-n structure is better for CdTe polycrystalline solar cell. Further analysis is in progress to support this point.

We also made attempts to grow CdMnTe polycrystalline films using the new diallyltellurium source instead of theold isoprophyl tellurium. We were not successful in growing CdMnTe films due to higher cracking temperature of Mn source which is around 450°C.

ACKNOWLEDGEMENTS

We would like to thank K. T. Pollard and S. Ringel for their help in growth and analysis. Drs. P. V. Meyers, V. Ramanathan, and C. H. Liu of AMETEK Applied Materials Laboratory for their help in solar cell fabrication and measurements. We appreciate the help of Mr. Ken Zweibel of SERI for confirming our solar cell measurements.
Table 1. Growth Parameters of MOCVD-CdTe Samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate Temperature</th>
<th>Growth Time Hrs.</th>
<th>Thickness µm</th>
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<tbody>
<tr>
<td>A0817881</td>
<td>300°C</td>
<td>2</td>
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</tr>
<tr>
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<td>300°C</td>
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<td>1.2</td>
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<td>A0819882</td>
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<td>-</td>
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<td>1.2</td>
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<td>300°C</td>
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<td>1.20</td>
</tr>
<tr>
<td>*A1018882</td>
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</tr>
<tr>
<td>*A1019881</td>
<td>300°C</td>
<td>1 1/2</td>
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</tr>
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<td>*A1020882</td>
<td>300°C</td>
<td>2</td>
<td>2.16</td>
</tr>
</tbody>
</table>

*The substrates were annealed at 450°C for 30 min. in hydrogen atmosphere before CdTe deposition.
Table 2. Solar Cell Parameters of MOCVD-CdTe Cells.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$V_{oc}$ mV</th>
<th>$J_{sc}$ mA/cm$^2$</th>
<th>FF</th>
<th>Efficiency</th>
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<td>613</td>
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<tr>
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<td>587</td>
<td>22.4</td>
<td>58.2</td>
<td>7.68</td>
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</table>
ZnTe/CdTe/CdS/SnO2, global, 1000W/m²

Sample: GIT–1

Nov. 4, 1988 3:26 pm

Temperature = 25.0°C

Area = 0.0790 cm²

\[ \text{Figure 1. Illuminated I-V data of 9-7-1-efficient polycrystalline CdTe cell.} \]
ZnTe/CdTe/CdS/SnO2/glass

Sample: GIT-1

Nov. 4, 1988 3:39 pm

Temperature = 25.0°C

Area used = 0.0790 cm²

Light bias = 0.50 mA

Zero voltage bias

Figure 2. Spectral Response of CdTe Cell.
ZnTe/CdTe/CdS/SnO2

Sample: GIT-1  
Temperature = 25.0°C  
Nov. 4, 1988 3:28 pm  
Area = 0.0790 cm²

Figure 3. Dark I-V data for a polycrystalline CdTe solar cell.

\[ R_{\text{shunt}} = 1.87E+03 \text{ Kohms} \]
\[ R_{\text{series}} = 338 \text{ ohms} \]
Equivalent \( R_s \) = 135 ohms
Mr. Ken Zweibel  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO  80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi  

Dear Mr. Zweibel:  

Enclosed please find copies of the Technical Progress Report for the period 12/1/88-12/31/88 on the above referenced contract.  

If you have any questions, please feel free to contact me.  

Sincerely yours,  

Pam Majors  
Research Administrator  

Enclosures  

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Nineteenth Monthly Report for the Period
December 1 to December 31, 1988

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve the basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wise bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell designs can be optimized. Greater than 10% efficient top cell with about 8% subgap transmission can produce cascade cell efficiencies of 15-20% provided the bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO₂/Cds window with thin CdS to maximize transmission and current. Absorber films ($E_g = 1.75$ eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contacts will be formed by growing a P-type ZnTe interlayer by MBE between the metal grid and absorber film.

TECHNICAL PROCESS

In this monthly report, we present the results of extensive MBE growth of CdZnTe of various compositions, and we report our first attempts to dope these films using Arsenic and a p-type source both with and without the use of an Argon laser for photoassisted dopant incorporation.
A total of 45 MBE growth runs were made resulting in approximately 300 samples necessary for a number of experiments. Table 1 lists the major variables covered in these runs. Film thickness were varied from 1.2 um to 2.7 um and the bandgaps were varied from 1.45 (CdTe) to 1.80 eV to generate a matrix for experimental work and device fabrication. Arsenic was used as a p-type dopant in these films since were unsuccessful in our attempts to dope with Sb as reported previously. Arsenic has been reported to be a more reliable dopant in CdTe by other growth techniques and recently has been shown to be effective in doping single crystal CdTe films grown by a photo-assisted MBE technique where an Argon laser was used to enhance, as incorporation in CdTe. We have grown first CdTe doped with an without the assistance of an Argon laser as well as undoped films on CdS and on uncoated glass to investigate doping in polycrystalline films. We have similarly grown CdZnTe using the same variables. The As partial pressure used in all runs was 3-tx10^{-9} torr (~ 0.1% of the total metal ion pressure) and the laser intensity at the substrate surface was 35 mW/cm^2. It was found that the growth rate decreased by ~ a factor of two when the As source was used as compared to unintentionally doped runs for all compound compositions. The presence of Arsenic did not, however, affect the optimum beam pressures (Cadmium versus Zinc) necessary to obtain the targeted compositions as shown by the absorption cutoffs from the SPV (surface photovoltage) measurements in Figure 1. The interpretation of overall shapes of these curves is not absolutely clear at this time, but we feel that the presence of two SPV signs
in the spectra of the thinner films is due to carrier collection by both the front electrolyte/semiconductor Schottky barrier and the buried heterojunction which will develop independent photovoltages of opposite polarities. More will be investigated on this later.

Auger depth profiling was performed on sample nos. SAR8, and SAR16 to (i) check the compositional uniformity and (ii) to investigate the possibility of chemical changes in the CdZnTe due to the different compositions in the films. Figure 2 shows the Auger depth profiles for each of these films indicating uniformity as expected from the SPV measurements. Note that the Cd/Zn peak to peak ratio for SAR16 is reduced as compared to the other film as would be expected from the higher bandgap measured by SPV. To investigate the chemical nature of the Cd, Zn, and Te peaks, detailed Auger scans were taken at the film surface, within the film itself, and at the film/CdS interface. Figure 3a-c shows the Auger lineshapes of Cd, Zn, and Te at the CdZnTe film surface (3a), the bulk of the film (3b), and at the CdZnTe/CdS interface (3c). Similarly, Figure 4a-c shows the Auger lineshapes of Cd, Zn, and Te for SAR16, which has ~10% absolute more Zn than SAR8. In all cases, there is a drastic change in lineshape for all elements at the film surface as compared to the bulk film and interface. This may be attributed to surface containments or surface oxides since these films were exposed to laboratory air for some time before insertion into the Auger system. For SAR8 (Figure 3), there is a shift in energy of the Auger peaks by ~ 2 eV to lower energies as the film was sputtered from the bulk to the interface for Cd, Zn,
and Te, suggesting a possible sputtering artifact (this will be investigated). However, for SAR16 (Figure 4), sputtering artifacts are not evident. As the film is sputtered from the bulk to the CdZnTe/CdS interface, the Te peak does not change or shift while the Zn and Te peaks both shift up by ~1 eV. At present, the reason for this apparent chemical change in the CdZnTe film is not clear and we are planning to undertake XPS measurements to clarify this observation.

Future work will involve fabricating both CdTe and CdZnTe p-i-n and p-n solar cells using different processing procedures. The transport properties of the CdTe or CdZnTe/CdS heterojunctions will be investigated using temperature dependent I-V measurements and models. In addition, the effects of processing on the film properties will be studies using Auger spectroscopy and XPS, and SPV, as discussed above.

ACKNOWLEDGEMENTS

We would like to thank Dr. B. Carter for help with the Auger measurements and D. Rajavel for help with the MBE growth.
Table 1: Tabulation of Major Variables Used in the MBE Growth of CdTe and CdZnTe Films

<table>
<thead>
<tr>
<th>ID</th>
<th>Material</th>
<th>Bandgap(eV)</th>
<th>Thickness(um)</th>
</tr>
</thead>
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<td>1.2 - 2.7</td>
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<tr>
<td>SAR15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAR16-</td>
<td>CdZnTe</td>
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<td>1.3 - 2.5</td>
</tr>
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<td>SAR18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>CdZnTe</td>
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<td>SAR43-</td>
<td>CdZnTe:As, laser</td>
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<td>1.3 - 2.5</td>
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</table>
Figure 1: Surface photovoltage measurement taken on (a) undoped CdZnTe with $E_g=1.70\text{eV}$, (b) CdZnTe with $E_g=1.80\text{eV}$, and (c) CdZnTe: As with $E_g=1.70\text{eV}$. 
Figure 2: Auger depth profiles of CdZnTe for (a) SAR8, Eg=1.70 eV, and (b) SAR16, Eg=1.80 eV.
Figure 3: Auger peak lineshapes of Cd, Zn, and Te is SAR8 at (a) film surface, (b) within bulk of film, and (c) at CdZnTe/CdS interface.
Figure 4: Auger peak lineshapes of Cd, Zn, and Te in SAR16 at (a) film surface, (b) within bulk of film, and (c) O, Zn, Te (CdO).
February 28, 1989

Mr. Ken Zweibel  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Progress Report for the period 1/1/89-1/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors  
Research Administrator

pm  
Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Twentieth Monthly Report for the Period
January 1 to January 31, 1989

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INTRODUCTION

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 eV) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 80% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 eV bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO₂/CdS window with thin CdS layer to maximize transmission and current. Absorber films (E_g = 1.75 eV) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p-ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

TECHNICAL PROGRESS

In this monthly report we present photoluminescence (PL) results of polycrystalline and single crystalline films of CdTe, CdMnTe and CdZnTe films. Polycrystalline films were grown on CdS/SnO₂/glass substrates and single crystal films were grown on GaAs substrates. PL measurements were performed, excited by Ar⁺ 514.5 nm laser line. All measurements were done typically with laser power of 40 mW and at 2K.

PL measurements were performed to determine the quality of films and the effect of processing. Figure 1 shows the PL spectrum of MOCVD as-grown CdTe films on CdS/SnO₂/glass substrates. The spectrum has a weak point at 1.59 eV and a strong and broad peak at 1.46 eV. The 1.59 eV peak corresponds to the free excitonic transition of CdTe. From literature, we could assign the 1.46 eV peak to Cd vacancy related peak. Figure 2 shows the PL spectrum of MOCVD as-grown CdMnTe polycrystalline film grown on CdS/SnO₂/glass substrates. The spectrum has two strong peaks at 1.99 eV and at 1.45 eV and weak peaks at 2.14 and 1.81 eV. Since the CdMnTe film is very thin (0.7 um) it is possible that light can probe the CdS/SnO₂/glass substrate. Hence, at this point it is difficult to assign the free exciton peak. From surface photovoltage and X-ray measurements on this sample we estimated the Mn composition as 16%. Based on the above Mn value we can assign
tentatively the 1.99 eV peak to free exciton of CdMnTe. Then, we can assign the weak peak at 1.81 eV to a shallow level and the peak at 1.45 eV to a deep level.

Figure 3 shows PL spectrum of MBE as-grown single crystal CdZnTe film grown on GaAs substrate. The spectrum has three peaks at 1.88, 1.80, and at 1.50 eV. The peak at 1.88 eV is the strongest and corresponds to free exciton peak of CdZnTe. The peaks at 1.80 and 1.50 eV correspond to shallow and deep levels in the film. At this point, we are not able to assign these levels to any particular impurity. Figure 4 shows the PL spectrum of a polycrystalline CdZnTe film grown on CdS/SnO2/glass substrates. There are many differences in PL spectra of poly and single crystal CdZnTe films. The PL intensity of polycrystalline film is smaller than single crystal PL intensity and it is difficult to observe a clear free exciton peak in polycrystalline films. Another interesting feature is that polycrystalline PL spectrum does not have a peak at 1.50 eV, which is observed in MOCVD-grown CdTe and CdMnTe and MBE-grown CdTe single and polycrystalline films.

Figure 5 shows PL spectrum of Ni/ZnTe/CdZnTe/CdS/SnO2/glass structure after processing. The spectrum has a broad peak and shifted towards low energy side from the unannealed film. The decrease in bandgap is consistent with the optical absorption measurements. Also, PL intensity of processed film increased compared to unannealed film which suggests that the quality of the film is improved. Further measurements are necessary to confirm this result. Figure 6 shows the PL spectrum of CdMnTe solar cell after processing. Besides, the decrease in bandgap of CdMnTe film, the PL intensity is decreased. Also, the ratio of intensity of peaks changed from unannealed films. The PL peak at 1.96 eV is weaker than the peak of 1.80 eV.

PL measurements on MOCVD-grown CdTe solar cell and on as-grown MBE CdTe films are planned to understand the effect of oxygen annealing on the film quality.

We would like to thank Dr. Z. C. Feng of Emory University and Dr. W. J. Choyke of University of Pittsburgh for their help in PL measurements.
Figure 1. PL spectrum of MOCVD-grown CdTe/CdS/SnO$_2$/glass at 2 K.

Figure 2. PL spectrum of MOCVD-grown CdMnTe/CdS/SnO$_2$/glass at 2 K.
Figure 3. PL spectrum of MBE-grown single crystal CdZnTe/GaAs.

Figure 4. PL spectrum of MBE-grown polycrystalline CdZnTe/CdS/SnO$_2$/glass.
Figure 5. PL spectrum of p-i-n CdZnTe solar cell after processing.

Figure 6. PL spectrum of p-i-n CdMnTe solar cell after processing.
Mr. Ken Zweibel  
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SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Progress Report for the period 2/1/89-2/28/89 on the above referenced contract.

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Research Administrator

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HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Twenty First Monthly Report for the Period
February 1 to February 28, 1989

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
Introduction

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 ev) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 80% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 ev bandgap) efficiency is around 12-15%.

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Technical Progress

In this monthly report we present growth of CdMnTe films by MOCVD and device measurements on CdMnTe cells. Previously, we had grown CdMnTe films by MOCVD using TCPMn as a source for Mn. CdMnTe polycrystalline films grown on CdS/SnO₂/glass substrates using the above source were non-
homogeneous in composition and the interface with CdS showed Mn accumulation. Also, it was difficult to get 2μm thick films because of very slow growth rate (.5μm/hr). In order to improve the quality of CdMnTe films another Mn source Bis (isopropylcyclopentadieny1) Manganese was used. Growth conditions, including the Mn source temperature (between 80 and 100°C), the reactor pressure in the range of 50 to 250 torr, and the substrate temperature (420°C to 450°C) were varied. It is known that in the temperature range of 80 to 100°C a combination of high Mn vapor pressure and low reactor pressure (50torr) may give more Mn for CdMnTe deposition. Several preliminary runs were made to optimize the growth conditions to get 1.7 ev bandgap CdMnTe film with thicknesses in the range of 1.5 to 2.5μm. We found that good quality CdMnTe films can be grown with Mn source temperature of 100°C, reactor pressure of 50 torr, and the substrate temperature in the range of 420 to 440°C. Figure 1 shows the SPV spectrum of one of the CdMnTe films grown on CdS/SnO2/glass substrates. The spectrum reveals a sharp bandedge at 720 nm (midpoint of the straightline portion) corresponding to 1.74 ev bandgap. This also suggests that the CdMnTe film has uniform composition. Auger depth profile measurement on this film (figure 2) confirmed the compositional uniformity. CdMnTe film grown earlier with TCPMn source (report # 17) showed a broad absorption edge in the SPV spectrum. The thickness of this film was estimated to be 2.4 um from Infrared measurement. Mn accumulation at
the CdMnTe/CdS interface is less but not negligible compared
to the films grown previously (Report # 17), may be due to
growth temperature (420 to 450°C).

Ni/ZnTe/CdMnTe/CdS/SnO2/glass p-i-n cells were
fabricated by AMETEK company using their standard CdTe
annealing process along with p-i-n cells without annealing
CdMnTe/CdS/SnO2/glass structures in air. Table 1 shows solar
cell parameter values for both kinds of CdMnTe cells. The
cells fabricated on unannealed films gave very low current
as shown in Table 1. Cells fabricated on annealed films
showed better performance but transmission measurements
revealed a reduction in the bandgap. The highest efficiency
obtained on annealed cells was 3.3%. These results suggest
that oxygen annealing is necessary for higher currents (also
low series resistance) but the annealing condition has to be
optimized to avoid bandgap reduction. Figure 3 shows
spectral response curves for cells fabricated on films
before and after annealing. Cells fabricated on unannealed
films show a peak around 450 nm (the light enters through
glass) suggesting that only those carriers that are
generated near CdS/CdMnTe interface are collected probably
because of low diffusion length in CdMnTe film. After
annealing, the spectrum has a relatively uniform and higher
response in the range 500-800 nm suggesting that it now
behaves more like a p-i-n cell (field assisted collection)
but interface recombination may still be the reason for low
current. In order to improve the ternary cells extensive
processing and measurements are being done and the results will be reported.

Acknowledgement: We would like to thank Dr. P. V. Meyers, Dr. C. H. Liu, and Dr. V. Ramanathan of AMETEK for cell fabrication and measurements. Also, we would like to thank K. A. Pollard for his help in MOCVD growth.
### TABLE 1. Solar Cell Parameters of CdMnTe Cells

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<tr>
<th>Sample ID</th>
<th>Bandgap</th>
<th>$V_{oc}$ mV</th>
<th>$J_{sc}$ mA/cm²</th>
<th>FF</th>
<th>$R_s$ ohm</th>
<th>Efficiency &amp;</th>
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After Annealing in Air

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<th>$V_{oc}$ mV</th>
<th>$J_{sc}$ mA/cm²</th>
<th>FF</th>
<th>$R_s$ ohm</th>
<th>Efficiency &amp;</th>
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</tr>
</tbody>
</table>

Other cells have no measurable voltage.
Figure 1. Surface photovoltage spectrum of CdMnTe/CdS/SnO$_2$/glass.
Figure 2. Auger depth profile measurement on CdMnTe/CdS/SnO$_2$/glass.
Figure 3. Spectral response curves of unannealed and annealed CdMnTe cells. In both spectra peak value is normalized to 1.
Mr. Ken Zweibel  
Solar Energy Research Institute  
1617 Cole Blvd.  
Golden, CO 80401-3393  

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi  

Dear Mr. Zweibel:  

Enclosed please find copies of the Technical Progress Report for the period 3/1/89-3/31/89 on the above referenced contract.  

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Sincerely yours,  

Pam Majors  
Research Administrator  

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Twenty-Second Monthly Report for the Period
March 1 to March 31, 1989

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
ABSTRACT

A new in-situ technique has been developed to measure the growth surface temperature of a substrate, and to calibrate the temperature of substrate holders. The technique has been demonstrated to be accurate to < 5°C and is applicable for calibrating substrate temperatures between 160 and 190°C. In this temperature range, the condensation of an incident Te₂ flux occurred on CdTe surfaces when the pressure of the incident Te₂ dimers exceeded its calculated equilibrium vapor pressure at the temperature of the substrate. The onset of condensation was determined by a change in the reflection high-energy electron diffraction pattern of the substrate.
INTRODUCTION

It is important to know the temperature of the substrate accurately during the growth of compound semiconductors by molecular beam epitaxy (MBE). This is particularly true for the MBE growth and doping of CdTe and HgCdTe alloys. The growth rate and composition of Hg$_{1-x}$Cd$_x$Te alloys have been shown to be very sensitive to small changes in the substrate temperature$^1$. Likewise the doping of these alloys and studies of CdTe nucleation kinetics have shown a strong dependence of dopant incorporation and electrical activity on the growth surface temperature$^{2,3}$. Thus clearly, the temperature of the substrate must be precisely measured and controlled during the growth of these materials. This is difficult, both because of the low temperature range used for the growth and doping of HgCdTe and CdTe and because temperature reading based on the thermocouple in contact with the substrate is not accurate enough to ensure reproducibility; particularly when several substrate holders are utilized. Temperature calibration by means of the melting point of elements is not very accurate, because the exact melting point is difficult to observe and also not very practical during growth.

In this paper we report a new convenient in-situ technique to accurately measure the actual temperature of the growth surface of the substrate. The technique has the advantage that it is very sensitive over the temperature range used for the growth of CdTe and HgCdTe and also directly measures the growth surface temperature. This unique capability cannot be duplicated by any other technique and is a consequence of a pronounced change that is observed in the reflection high-energy electron diffraction (RHEED) pattern of the epilayer when a source element sublimated from an effusion-cell condenses on the substrate. In these experiments the onset of the condensation of Te$_2$ on CdTe surfaces was used both to determine the temperature of the epilayer and to
calibrate molybdenum substrate holders.

EXPERIMENTAL PROCEDURE

Experiments were performed in a Varian GEN II MBE system equipped with RHEED and dedicated to grow II-VI materials growth. The onset of the condensation of tellurium on a (001) CdTe epilayer was detected by observing the transition of the normally streaked RHEED pattern exhibited during the growth of CdTe (Fig. 1a) to a spotty pattern due to Te precipitates (Fig. 1b-1d). Condensation of tellurium is expected to occur when the pressure of the incident Te flux exceeds the equilibrium vapor pressure of Te over CdTe. The tellurium condensation technique was used to measure the correction to be applied to the thermocouple reading and to determine the absolute temperature on the surface of the substrate. Three Mo blocks were calibrated for temperature corrections by this in-situ technique. Doped (001) GaAs substrates were used to grow (001) and (111) CdTe films. The GaAs substrates were degreased, etched in a solution of H$_2$SO$_4$, H$_2$O and H$_2$O$_2$ (5:1:1) and mounted at the center of a Mo substrate holder. Small pieces of indium and bismuth metals in the shape of a cone, were soldered onto two different pieces of GaAs. These samples were mounted on the same Mo substrate holder. The substrate was heated slowly in the growth chamber of the MBE system to 130°C, as read by the thermocouple in contact with the back side the Mo substrate holder. The temperature was maintained at 130°C for about 15 minutes to allow the substrate and the Mo holder to attain thermal equilibrium. Subsequently, the substrate was further heated in steps of about 3°C every 5 minutes. The magnified shadow of the indium sample cast by the RHEED electron beam was observed on the phosphor screen. Drooping due to gravity and a change in the shape of the indium sample was taken as an indication that the temperature of the substrate was 157°C, the melting point of indium. In a similar manner, the temperature of the substrate was measured with the thermocouple at the melting
point of bismuth (271°C). The difference between the actual melting point and the corresponding temperature of the substrate as measured by the thermocouple was calculated for each of the two metals. As the change in shape of the specimens upon melting is not very obvious and hence difficult to determine accurately, the error in these measurements is estimated to be ± 5°C.

The thermocouple reading when the substrate was heated to almost completely desorb the oxide on GaAs in order to initiate (001) CdTe growth was also compared with that found in the literature. For this part of the experiment, the substrates were first heated slowly up to 550°C (as indicated by the thermocouple) and allowed to stabilize at that temperature. Beyond 550°C, the substrate was heated in steps of approximately 5°C every 3 minutes until the RHEED pattern indicated that enough oxide on the GaAs substrate had desorbed in order to grow (001) CdTe. The substrate was then cooled to 300°C under a CdTe flux to grow a (001) CdTe layer. It was found that the exact temperature at which the oxide desorbed from the GaAs substrate was dependent on the rate at which the substrate was heated. When the substrate was heated quickly, there was insufficient time for the substrate and the rest of the Mo holder to approach equilibrium. Hence, the accuracy of the temperature calibration by this method is about ± 5°C. In this manner, the offset between the thermocouple measurements and the absolute temperature was established at 157, 271 and 582°C which correspond to the melting points of indium and bismuth and the desorption temperature of the oxide on GaAs.

To study tellurium condensation on CdTe surfaces, a 1 µm thick CdTe layer was grown at 300°C using a binary CdTe source. A separate effusion-cell containing elemental Te was used to deposit tellurium to observe condensation. The approximate temperature at which a certain flux of Te₂, from the tellurium effusion-cell, condensed on the CdTe surface was first determined. This rough measurement was then used as a starting point to precisely
determine the condensation temperature for the same Te$_2$ flux. The approximate condensation temperature was measured by the following procedure. CdTe growth was terminated by closing the shutter of the CdTe effusion-cell and the substrate heater turned off. The shutter of the tellurium effusion-cell was then opened so that a Te$_2$ flux was incident on the substrate as it cooled rapidly. The RHEED pattern and the thermocouple reading were monitored as the substrate cooled. Prior to condensation the pattern was streaked and exhibited a Te-stabilized two fold reconstruction along the (110) azimuth (Fig. 1a). At the onset of the condensation of tellurium on the CdTe surface, a single bright spot was observed to be superimposed on the central streak (Fig. 1b). As condensation proceeded, more spots appeared superimposed on the bulk streaks, some closer to the shadow edge. The pattern became spottier as condensation proceeded further (Fig. 1c and 1d). For short durations of condensation, it was observed that the streaks due to the bulk and the reconstructed surface were not destroyed. The beam equivalent pressure (BEP) of the incident Te$_2$ flux was then measured by a nude ion-gauge that could be rotated to the position of the substrate.

In order to reuse the CdTe layer, the substrate temperature was heated up to 300°C and maintained at that temperature for three to five minutes to desorb the tellurium that had condensed on the substrate. When the original streaked RHEED pattern was restored, CdTe growth was once again started and 0.1 µm of CdTe was grown to preserve the initial crystalline quality of the film. In determining the condensation temperature by the above method, exact equilibrium between the film and the Mo holder was precluded. In order to determine the condensation temperature precisely, the substrate was cooled from the growth temperature (300°C) and stabilized at a temperature 25°C above the approximate condensation temperature determined previously. The shutter of the Te effusion-cell was then opened and the substrate was slowly cooled in steps
of about 3°C every 3 min until the onset of condensation was detected. In this manner, by cooling the substrate slowly, the substrate and the Mo holder approach equilibrium. Immediately after the determination of the Te₂ condensation temperature, the pressure of the incident Te₂ flux was measured once again with the nude ion-gauge.

RESULTS AND DISCUSSION

The reaction between excess tellurium condensed on a CdTe surface and the incident Te₂ dimer flux is expressed as

\[ \text{Te}_2 (g) \rightarrow 2\text{Te} (s) \quad [1] \]

The direction of this reaction is determined by the surface lifetime \( \tau_s \) of a Te atom on the surface of the layer and the magnitude of the incident flux. The lifetime \( \tau_s \) of a Te atom on the surface of CdTe is related to the absolute temperature \( T_s \) of the substrate by the following Arrhenius relationship

\[ \frac{1}{\tau_s} = A \exp\left(-\frac{E_a}{kT_s}\right) \quad [2] \]

Where \( A \) is a constant, \( E_a \) is the activation energy for the desorption of Te₂ and \( k \) is the Boltzmann constant. If \( \tau_s \) is less than the average time of arrival of the incident Te₂ molecules \( t_{av} \) on the substrate, there is no net accumulation of Te on the surface. However, when \( \tau_s \) is just greater than \( t_{av} \), condensation commences and Te precipitates start forming on the substrate. Thus, at a temperature \( T_s \) when \( \tau_s = t_{av} \), the equilibrium vapor pressure of Te₂ over the excess Te on the substrate balances the flux of the incident molecules. The temperature at which this occurs depends directly on the incident Te₂ flux and is determined in this experiment from measurements of the Te₂ flux.

The vapor pressures of gallium and arsenic over GaAs has been
experimentally measured by previous workers\textsuperscript{5,6}. It has also been reported that the activation energy for the desorption of excess Ga on GaAs is similar to the activation energy for the sublimation of Ga from metallic Ga\textsuperscript{7}. Previous work done at Georgia Tech indicates that the activation energy for the desorption of tellurium from (001) CdTe is very close to the enthalpy of sublimation for diatomic Te from solid tellurium\textsuperscript{8}. This indicates that the vapor pressure for excess tellurium over a CdTe surface is equal to the vapor pressure of solid tellurium. The equilibrium vapor pressure $P_\text{v}$ of Te$_2$ over solid Te can be calculated at an absolute surface temperature, $T_s$, using the relationship\textsuperscript{9}

\[
\log P(\text{torr}) = -9175/T_s - 2.711 \log T_s + 19.68 \quad [3]
\]

The thermocouple temperature ($T_{\text{meas}}$) which is measured at the onset of condensation, is plotted versus the theoretical equilibrium condensation temperature ($T_s$) of Te$_2$ determined in this manner in Fig. 2. The melting point of indium provides an absolute temperature datum and is in good agreement with the tellurium condensation data. The $T_{\text{meas}}$ versus $T_s$ plot is not linear, and deviates from the equilibrium theory at temperatures above 190°C. The reason for the departure of the Te$_2$ condensation temperature from the equilibrium theory at higher temperatures is not completely understood. The assumption that the vapor pressure of Te$_2$ over a CdTe epilayer is equal to the equilibrium vapor pressure of Te$_2$ over solid Te requires further investigation. The evaporation of the excess tellurium on a CdTe surface, in the growth chamber of an MBE system, approaches Langmuir (free) evaporation. Thus, in order to establish a certain pressure of Te$_2$, the substrate has to be heated higher than that predicted by using Eqn. 3. Also, the undercooling required to nucleate the precipitate has been neglected in this analysis. However, the inclusion of undercooling would further increase the deviation of the data from
the equilibrium theory. We define $T_{\text{actual}}$ as the substrate temperature as determined by the melting points of indium and bismuth and the desorption temperature of the oxide on GaAs. Fig. 3 shows a plot of $T_{\text{meas}}$ versus $T_{\text{actual}}$ for three different Mo holders. The condensation temperature for Te$_2$ pertaining to a beam equivalent pressure of 2.2X10$^{-7}$ torr is also shown in the same plot. Note that excellent agreement was found between all of the different temperature measuring techniques. Additionally, the condensation temperature for the Te$_2$ flux of beam equivalent pressure of 2.2X10$^{-7}$ is in excellent agreement for all holders measured, as shown in Fig. 3. For substrate holder A8, $T_s$ was found to be lower than $T_{\text{meas}}$ by about 73°C as indicated by the condensation temperature of Te$_2$. This large a discrepancy could be due to the different emissivity and thermal conductivity of that particular substrate holder. Similar data were also observed for substrate holder A7 for which $T_s$ was measured to be lower than $T_{\text{meas}}$ by an average of 14°C, and for substrate holder AA for which $T_s$ was measured to be an average of less than 1°C lower than $T_{\text{meas}}$. It is also possible for $T_s$ to be greater than $T_{\text{meas}}$, if the thermocouple is not in proper contact with the Mo substrate holder. However, this situation was not encountered in this experiment.

The data in Figs. 2 and 3 were measurements made for (001) CdTe. Similar studies to determine the condensation temperature for Te$_2$ on (111) CdTe were found to be within 3°C of the corresponding temperature for (001) CdTe. Thus, the technique is shown to be applicable to both orientations of CdTe. For condensation temperatures below 150°C, corresponding to a beam equivalent pressure of 1 X 10$^{-8}$ torr, the onset of condensation is difficult to observe and therefore the measurement is prone to error. Thus the lower limit of applicability of this technique is estimated to be around 150°C for the substrate cooling rate used in this experiment. Cooling the substrate at a slower rate can extend the lower limit of applicability of this technique and is currently
being studied. As the condensation of tellurium and its subsequent evaporation by heating can degrade the crystalline quality of the epilayer, occasional calibration of a substrate holder with a test substrate piece is adequate. Damage to the epilayer can be minimized if the incident flux is terminated as soon as the first signs of condensation of Te₂ is noticed.

Fig. 1a-1d illustrate the sequence of condensation of Te₂ on (001) CdTe. At the onset of condensation, the surface of the epilayer developed asperities and the RHEED electron beam was transmitted through the tellurium precipitates and displayed diffraction spots. Fig. 1b shows the appearance of a bright spot on the central streak, which is the first sign of the onset of condensation (all the substrate temperature measurements were made at this initial stage of commencement condensation of Te₂ on CdTe). This spot could be seen for all azimuthal orientations of the substrate. This indicates that first atomic layers of the condensate nucleate parallel to the CdTe epilayer. The existence of a specific crystallographic relationship between the condensate and the (001) CdTe epilayer is more obvious as condensation proceeds further. Fig. 1c shows the RHEED spot pattern that exhibits a square lattice indicative of the existence of four-fold periodicity. Some spots also appear on the reconstruction derived streaks, indicating twinning. Patterns similar to that shown in Fig. 1c can be seen at four different azimuthal orientations, two of which correspond to the orientations exhibiting a Te-stabilized 2x1 surface reconstruction pattern of (001) CdTe.

CONCLUSION

It has been demonstrated that the condensation of Te₂, on either (001) or (111) CdTe surfaces, as detected by a change in the RHEED pattern, provides an accurate (< 5°C) and convenient method of establishing the actual surface temperature on the substrate. This unique technique has been demonstrated to be
applicable for substrate surface temperatures between 160 and 190°C and can provide an absolute sensitivity of 3°C for the cooling rates used in these experiments. It should be noted that because the surface temperature is directly measured, the technique is inherently superior to current methods. It was found that the deviation of the actual growth surface temperature from the thermocouple temperature can be as large as 70°C indicating that substrate holders have to be carefully calibrated to ensure reproducibility. This technique is particularly useful when the thermocouple is not in direct contact with the substrate holder. Finally we note that further advantages of this technique are envisioned for other materials and growth techniques such as chemical beam epitaxy (CBE). CBE offers a more stable, quicker and better setting accuracy of the Te flux from run to run. Substrate temperature calibration in a CBE system utilizing a tellurium gas source can be accomplished by ramping the incident flux instead of lowering the substrate temperature.

ACKNOWLEDGEMENTS

The authors would like to thank B. Wagner for the useful discussions and F. Mueller for his assistance with the condensation experiments. This project was sponsored by SERI under contract No. XL-7-06031-1.
REFERENCES


FIGURE CAPTIONS

1a. RHEED pattern of a Te-stabilized 2X1 surface reconstruction on the (001) surface observed along the [110] azimuth.

1b. The first indication of the condensation of the incident Te$_2$ flux (BEP = 2.2X10$^{-7}$ torr) is the appearance of a bright spot superimposed on the central streak. For substrate holder AA, the thermocouple temperature was 192°C.

1c. RHEED pattern observed 5 s after the pattern shown in 1b. Diffraction spots due to tellurium precipitates can be seen superimposed on the streaks due to the bulk and exhibit a square lattice. Spots can also be seen superimposed on the reconstruction derived streaks.

1d. RHEED pattern observed 2 min after the onset of condensation, with a Te$_2$ flux incident on the substrate continuously. The thermocouple temperature was 192°C.

2. The thermocouple temperature plotted vs. the Te$_2$ condensation temperature (calculated from the equilibrium theory using Eqn. 3). The dashed lines represent quadratic fits to the experimental data. The solid lines follow from the equilibrium theory and have a slope equal to one. The In melting point data are represented by the symbol .

3. The thermocouple temperature plotted vs. the actual substrate temperature determined by the melting point of In and Bi and the desorption temperature of the oxide on GaAs. Also shown are the Te$_2$ (flux of BEP = 2.2X10$^{-7}$ torr) condensation data.
Fig. 2
The graph shows the relationship between the actual substrate temperature and the thermocouple temperature for different substrate holders. The oxide desorption temperature for GaAs is indicated. The graph includes data points for Te₂-flux, Bi, and In. The legend indicates the substrate holders AA, A8, and A7 with corresponding symbols. The graph is labeled as Fig. 3.
May 30, 1989

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SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Progress Report for the period 4/1/89-4/30/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors  
Research Administrator

pm  
Enclosures

cc: Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Twenty-Third Monthly Report for the Period
April 1 to April 31, 1989

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
INVESTIGATION OF POLYCRYSTALLINE CdZnTe, CdMnTe, AND CdTe FILMS FOR PHOTOVOLTAIC APPLICATIONS

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SUMMARY

Polycrystalline thin films of CdZnTe and CdMnTe have been grown by MBE and MOCVD, respectively, on CdS/SnO₂/glass substrates, with bandgaps of 1.65-1.75 eV for the top cell of a two cell tandem design. P-i-n cells were fabricated and tested using Ni/p⁺-ZnTe as a back contact to the ternary films. CdTe cells were also fabricated using both growth techniques which resulted in 9-10% efficiency and provided a baseline for ternary cell development. It was found that standard CdTe processing (400 C air annealing) reduces the ternary bandgaps from ~ 1.7 to ~ 1.55 eV, resulting in significantly reduced subgap transmission with cell efficiencies of 3-4%. Optimum air annealing conditions were determined to retain the 1.7 eV bandgap, however, the cell performance was still limited by both poor CdZnTe/CdS interface quality and high series resistance. The junction interface was found to improve by annealing in the presence of hydrogen which resulted in V₆₅ values from 0.500 V to as high as 0.65 V, but the cell performance became increasingly limited by series resistance. The effects of cell processing on the properties of the CdZnTe/CdS interface, the bulk CdZnTe film, and the back contact region have been investigated to provide guidelines for achieving high efficiency in widegap ternary cells.
1. INTRODUCTION

CdTe is a promising material for high efficiency thin film solar cells due to its near optimum 1.45 eV bandgap, ease of deposition, and strong optical absorption. Polycrystalline thin film heterojunction solar cells have been fabricated using CdTe films on CdS/SnO2/glass substrates with efficiencies of 10-11% [1-3] with a potential of exceeding 15 %. [4] It is well known that cell performance can be increased significantly by fabricating a tandem cell structure with a wide bandgap cell (E_g = 1.65-1.75 eV) on top of a low bandgap cell (E_g = 1.0 eV). A greater than 10% efficient top cell with \sim 80% subgap transmission coupled with a 12-15% bottom cell can produce a combined cell efficiency of 15-20%. [5] Polycrystalline CuInSe2 cells are well suited for the bottom cell because of its 1 eV bandgap with efficiencies approaching 15 %. [6] However, the top cell material has not yet been established. CdZnTe and CdMnTe are two of the promising materials for the top cell application because their bandgaps can be tailored between 1.45-2.26 eV (CdTe-ZnTe) and 1.45-2.85 eV (CdTe-MnTe), respectively, by controlling the film composition.

This paper presents the progress of polycrystalline CdZnTe and CdMnTe solar cells. CdZnTe and CdMnTe films were grown by MBE and MOCVD, respectively, on CdS/SnO2/glass substrates for solar cell applications. Polycrystalline CdTe cells with efficiencies of 9-10% were fabricated first by both techniques to establish a high efficiency baseline process for II-VI solar cells. The Zn and Mn content was varied to tailor the bandgap to \sim 1.7 eV. Electrical and optical properties of the ternary films were measured before and after annealing in different ambients. Ternary solar cells were fabricated and analyzed. Ternary cell performance was lower than the CdTe cells. Therefore, a combination of measurements were performed to investigate the bulk and interfacial properties of the ternary films in the ZnTe/Cd(Zn,Mn)Te/CdS/SnO2/glass cell structure to provide guidelines for achieving high efficiency CdZnTe and CdMnTe solar cells.

2. EXPERIMENTAL PROCEDURE

2.1 Film Growth

CdZnTe and CdTe films were grown by molecular beam epitaxy (MBE) using a Varian Gen II MBE system. Elemental sources of 5N purity or better were used for all constituents. The films were grown on CdS/SnO2/glass substrates that were baked in vacuum at 250 C for 1-2 hours before commencing film growth.
Films were grown in an excess of Te and at a substrate temperature of 275 C for the first 30 min to achieve uniform nucleation which was then increased to 325 C for the remainder of the run. Growth rates were typically \( \sim 1 \text{ um/hr} \), regardless of film composition. Film purity was monitored using in-situ Auger measurements.

CdTe and CdMnTe films were grown by metalorganic chemical vapor deposition (MOCVD) on CdS/SnO_{2}/glass substrates using dimethylcadmium, diethyltellurium and diallyltellurium, and BIS (isopropylcyclopentadienyl) manganese as source materials for Cd, Te, and Mn, respectively. The CdMnTe films were grown at a substrate temperatures of 420 C while CdTe films were grown in the range of 300 C to 400 C.

2.2 Cell Fabrication

Front wall solar cells were fabricated with a glass/SnO_{2}/CdS/CdTe or Cd(Zn,Mn)Te/ZnTe/Ni structure. The \( \sim 0.15 \text{ um n-type CdS} \) layer was deposited on SnO_{2} coated glass in a pyrolytic reactor from an aerosol containing CdCl_{2} and thiourea. Polycrystalline CdTe, CdZnTe, or CdMnTe films were grown on the CdS. No attempts were made to intentionally dope the films. The structure was subsequently annealed under various conditions as described later. The anneal was followed by a mild surface etch of Br:CH_{3}OH to remove any oxides prior to p-type ZnTe (Cu-doped) evaporation to complete the p-i-n structure. Finally Ni was evaporated to form ohmic contacts on the ZnTe film.

2.3 Material and Device Characterization

Surface photovoltaic and depth-resolved Auger measurements were performed to confirm the bandgaps and compositional uniformity, respectively. X-ray photoelectron spectroscopy (XPS) measurements were performed to investigate the chemical nature of the CdZnTe film surfaces after various heat treatments and surface etching to shed some light on the subsequently formed CdZnTe/ZnTe interface behavior. Selected photoluminescence measurements were performed to investigate defect states of the film. Dark I-V-T measurements were performed in the temperature range of 80 K to 400 K and the data was analyzed using a multivariable regression analysis to determine the pertinent device parameters such as leakage current, diode factor, series and shunt resistances. Spectral response measurements were made using an Optronics Laboratory phase sensitive detection system in which the samples were illuminated through the glass substrate. Lighted I-
3. RESULTS AND DISCUSSION

3.1 CdTe Solar Cells

CdTe films were grown by both MOCVD and MBE on CdS/SnO$_2$/glass substrates. P-i-n solar cells were fabricated by depositing p$^+$/ZnTe capped by Ni to establish a baseline process for the ternary cell development. No attempts were made to intentionally dope the CdTe films. Figure 1 shows the lighted I-V data for our best CdTe cell, grown by MOCVD. The 9.7% efficiency achieved is the highest reported efficiency for MOCVD-grown CdTe. Compared to the best reported CdTe thin film cell to date (11%), fabricated by electrodeposition [7] our cell has a higher $J_{sc}$ (22.16 mA/cm$^2$) and a lower $V_{oc}$ (0.730 V), Table 1. Spectral response and I-V measurements were performed to understand this difference and to obtain guidelines for improving the CdTe cell performance further.

The spectral response shown in Figure 2 indicates that a true p-i-n heterojunction (rather than a buried homojunction) was formed for this 2.6 um thick CdTe film since the response is not only flat for all the wavelengths ranging from the CdS cutoff (0.5 um) to the CdTe cutoff (0.83 um), but the cutoffs are sharp also. Note that the external quantum efficiency values are over 90% throughout the usable spectrum which is better than the quantum efficiency of the highest efficiency (11%) CdTe cell, Figure 2. [7] This explains the higher $J_{sc}$ value for the MOCVD cell and suggests that under short circuit conditions, the MOCVD cell has a lower interface recombination velocity. The p-i-n behavior in our cells is supported by C-V measurements which showed that the CdTe is fully depleted at zero bias. Since the bulk CdTe is fully depleted, the interface must play an important role in limiting the cell performance. In order to evaluate the interface quality, bias-dependent spectral response measurements were performed which showed about a 10% uniform increase in the quantum efficiency at 1 volt reverse bias, Figure 2. It has been shown that this type of behavior can be attributed to changes in interface recombination through a field-dependent collection function term which modifies the light-generated current. [4] The 10% increase in quantum efficiency under reverse bias indicates that $J_{sc}$ can be improved significantly to > 24 mA/cm$^2$ in our cells by lowering the interface recombination velocity. Furthermore, similar measurements on the highest efficiency 11% CdTe cell [7] (Figure 2) showed less than a
5% increase in quantum efficiency under 1 volt reverse bias. It is apparent that the interface state behavior can be different for the MOCVD and electrodeposited CdTe cells. This can result in a different field dependence of carrier collection because of different rate of increase in the interface recombination velocity as the bias condition changes from short circuit to open circuit. I-V and bias dependent spectral response data indicate that compared to electrodeposited cells, MOCVD cells have a lower interface recombination velocity at short circuit but higher interface recombination velocity as the voltage approaches \( V_{oc} \). This explains why the MOCVD cell has a superior \( J_{sc} \) but lower \( V_{oc} \) and fill factor.

Dark I-V measurements were performed to reveal and understand the loss mechanisms in more detail in these cells. Figure 3a shows the I-V behavior of a ~10% cell over a temperature range of 170-310 K. A multivariable regression analysis was used to fit the I-V curves to an equivalent circuit response consisting of two diodes with a shunt and series resistance so that the current density can be described as a function of the applied voltage by

\[
J = J_1 + J_2 = J_{01}\exp(B_1(V-JR_s) - 1) + J_{02}\exp(B_2(V-JR_s) - 1) + (V-JR_s)/R_{sh}
\]

where

\[
B_{1,2} = q/(n_{i,2}kT)
\]

At 310 K, the I-V behavior was dominated by one diode \( (J_2) \) with a \( J_{02} \) value of \( 1.5 \times 10^8 \) A/cm\(^2\), a diode factor \( n \) of 1.75, a series resistance (dark) of 5.28 ohm-cm\(^2\), and a 18 kohm-cm\(^2\) shunt resistance, Figure 3b. We also found that as the temperature is lowered from 310 K to 250 K, \( J_{02} \) decreases and the diode factor remains close to 1.75, suggesting a space-charge recombination controlled transport mechanism. At temperatures below 250 K, this transport becomes less important and other mechanisms (like tunneling, in addition to increased series resistance) become important, Figure 3. These changes are being analyzed further to shed more light on the characteristics and importance of the interface states. CdTe/CdS cells were also fabricated using MBE-grown CdTe films with efficiencies as high as 9%.

3.2 CdZnTe and CdMnTe Solar Cells

The bandgaps of polycrystalline CdZnTe films grown by MBE and CdMnTe films grown by MOCVD
on CdS/SnO₂/glass substrates were successfully tailored to any desired value. However, most emphasis was placed on 1.7 eV bandgap films for tandem cell applications. Based on the success of our CdTe films, ZnTe/CdZnTe/CdS and ZnTe/CdMnTe/CdS p-i-n cells were fabricated using the CdTe cell process. A summary of selected results are shown in Table 1. A post-deposition anneal was found to be necessary to obtain measurable cell data. However, the 410 C annealing procedure used for CdTe cells resulted in a significant decrease in the bandgap, from 1.7 eV to 1.55 eV, with cell efficiencies of 3-4%, Table 1. [8] Annealing in air was performed for various combinations of temperatures and times to determine optimum conditions and to retain the bandgap. A 30 min. anneal at 350 C gave the highest efficiency while maintaining the bandgap for CdZnTe, Table 1. Obviously, a significant decrease in cell performance is observed for the CdZnTe-based devices compared to the CdTe-based cells.

Various measurements were performed to understand the loss mechanisms in ternary cells. C-V measurements made on the CdZnTe cells showed a doping density of ~ 5x10¹⁵ cm⁻³ (p-type) which is about an order of magnitude greater than the measured doping in the MBE-grown CdTe films. This could result in incomplete depletion of the CdZnTe film. This was confirmed by spectral response measurements, Figure 4, which showed a strong wavelength dependence with reduced carrier collection at longer wavelengths. This suggests that, unlike the CdTe cells, these cells are behaving like p-n instead of p-i-n devices and hence are suffering from recombination in the undepleted bulk. Attempts are being made to reduce the film thickness to 1.0-1.5 um to achieve p-i-n-like behavior. However, the undepleted bulk does not explain the very large decrease in the absolute spectral response (Figure 4) compared to CdTe. This drop in response can only be due to a combination of CdZnTe/CdS interface and back contact region (Ni/ZnTe on CdZnTe) effects.

The most glaring difference between the two types of cells is in the values of series resistance and J sc. Average R s values (under illumination) were 2-3 ohm-cm² for the air annealed CdZnTe cells compared to 0.5-0.8 ohm-cm² for CdTe cells. In order to understand the source of high R s, CdZnTe films were grown intentionally with different bandgaps but the same thickness. Figure 5 shows room temperature dark I-V data taken on three CdZnTe p-i-n cells with different bandgaps (compositions). As seen in the inset of the figure, the dark series resistance increased by a factor of ~4 compared to the CdTe regardless of the CdZnTe composition. The undepleted bulk resistance (~0.01 ohm-cm²) cannot account for the observed high R s value (2-3 ohm-cm²), therefore, the back contact region (Ni/ZnTe on CdZnTe) and the CdZnTe/CdS interface were investigated to find the cause of R s.
Dark I-V and photoluminescence (PL) measurements were performed to analyze the bulk and interface defect states. Figure 5 shows that the value of $J_0$ steadily increased with increasing Zn concentration suggesting that the interface quality declines for higher Zn concentrations. This is consistent with previous reports on crystalline CdS/CdZnTe junctions in which this kind of degradation was attributed to an increase in interface states resulting from increased distortion of the CdZnTe lattice. [9] This poor interface quality can also explain the low $V_{oc}$ observed in these air annealed films. Furthermore, preliminary photoluminescence measurements show broader luminescence peaks for CdZnTe and CdMnTe compared to CdTe which indicates a more defective bulk for the ternary films compared to CdTe. In order to modify the interface without changing the bandgap, an attempt was made to grow a very thin (~0.1 um) CdTe interlayer between the CdS and CdZnTe. This structure gave a higher $J_{sc}$ but $V_{oc}$ and $R_s$ did not change appreciably suggesting that the high $R_s$, which is limiting the cell performance, is not due to the CdZnTe/CdS interface.

Since the CdZnTe devices showed poor performance using the air annealing process, various annealing ambients, including forming gas (10% hydrogen + 90% nitrogen) and argon were investigated to see if the performance could be improved by lowering $J_0$ by passivating bulk and interfacial defects and reducing $R_s$ by avoiding surface oxide formation. Films were subjected to anneals using combinations of temperatures (100-400 C) and times (10 - 50 min) prior to ZnTe and Ni depositions. Surface photovoltage measurements showed that the bandgaps were not affected by these annealing conditions. No measurable cell data was obtained for either unannealed or argon annealed CdZnTe cells. In contrast, forming gas annealed films showed the highest $V_{oc}$ values (0.646 V) reported for any CdZnTe/CdS junction. In addition, the $J_{sc}$ values were as high or higher than those for the air annealed cells. However, the series resistance of the forming gas annealed cells was 3-5 times higher than the air annealed CdZnTe cells and about one order of magnitude higher than the CdTe cells. This is also reflected in the extremely low values of fill factor for the forming gas annealed cells (Table 1). Figure 4 shows that the forming gas anneal increases the quantum efficiency almost uniformly over the entire spectrum absorbed in the CdZnTe film as well as on either side of the CdZnTe/CdS junction. This combined with the high $V_{oc}$ indicates that the forming gas anneal improves the interface quality, however the increase in quantum efficiency does not fully depict the huge improvement in $V_{oc}$ because the higher $R_s$ in the forming gas annealed cell lowers the overall spectral response. This also confirms that the high $R_s$ in the CdZnTe cells is not due to the CdS/CdZnTe interface quality which leaves only the back contact region (Ni/ZnTe on CdZnTe) as the primary suspect.
In order to investigate if the series resistance is mainly due to the back contact region, the annealed CdZnTe films were analyzed by optical transmission and x-ray photoelectron spectroscopy (XPS). Figure 6 shows the subgap transmission of CdZnTe films on CdS/SnO$_2$/glass substrates after air, forming gas, and argon anneals for 20 min at 350°C. The as-grown film transmission is also shown for comparison. Air annealing results in about 20% decrease in absolute transmission while the forming gas and argon anneals cause no degradation in transmission. In addition, the transmission of the air annealed CdZnTe/CdS structure decreases even further (~35% decrease in absolute transmission for 30 min at 350°C) with increased time and temperature while the forming gas and argon anneals showed no such tendency. XPS measurements indicate that the surface of the air annealed CdZnTe is rich in Zn content (Table 2) which is mostly oxidized. A 10 sec. etch in .02% Br:CH$_3$OH removes all of the oxides (and forms a Te-rich surface (Te/(Cd + Zn) = 1.56). However, the CdZnTe surface is not quite as rich in Te as a Br:CH$_3$OH etched p-CdTe surface where the Te/Cd ratio is typically 2-3. [10,11]

Forming gas annealed CdZnTe films, which had the highest $R_s$, showed an even lower Te/(Cd + Zn) ratio of 1.33. This suggests that the Te rich surface, which makes the surface more p-type, may be important in lowering $R_s$ by increasing the transport of carriers across the CdZnTe/ZnTe interface and improving the current in the external circuit. Attempts are being made to investigate various etching techniques to make the CdZnTe surface more Te-rich and to improve the CdZnTe/ZnTe interface. This combined with a forming gas anneal to reduce interface states, and thinning the CdZnTe film to obtain true p-i-n devices is expected to give a significant improvement in the cell performance.

CONCLUSIONS

Front wall polycrystalline thin film solar cells with Ni/ZnTe/CdTe/CdS/SnO$_2$/glass structures were fabricated with efficiencies in the range of 9-10%. CdTe films were grown by MBE and MOCVD techniques. Spectral response and dark I-V analyses showed that these cells behave like p-i-n diodes and their response is limited in part by high interface recombination velocity.

CdZnTe and CdMnTe films of 1.7 eV bandgap were grown by MBE and MOCVD, respectively, for tandem cell applications. The standard CdTe process was not optimum for ternary films and resulted in a decrease in the bandgap. A 350°C, 30 min anneal in air was found to improve the efficiency of CdZnTe cells while still maintaining the bandgap. However, the air annealed CdZnTe cells showed both high series resistance...
and high $J_0$ values compared to the CdTe cells resulting in low cell performance. It was found that annealing the CdZnTe films in forming gas increased the $V_{oc}$ to $\sim 0.65$ V, the highest reported value for CdZnTe/CdS junctions, as compared to $\sim 0.4$ V for air annealed CdZnTe by improving the interface quality. However, the series resistance increased by an additional factor of $\sim 3$ which resulted in low cell performance in spite of the high $V_{oc}$ on the CdZnTe cells. Spectral response measurements suggest that the CdZnTe cells do not behave as a true p-i-n diode but instead as a p-n cell, probably due to a higher doping level. The series resistance contribution due to the undepleted CdZnTe region was not found to be a major factor in the observed high series resistance of the cell. Thus, the back contact region and the CdZnTe/CdS interface states together may be responsible for limiting the cell performance. Hence, a combination of forming gas anneal and proper surface etching prior to contact formation is being investigated to achieve low $R_s$, high fill factor, and better cell performance. In addition, novel structures are also being studied which involve a thin (.1 um) interlayer of CdTe between the CdZnTe and CdS to increase the quality of the CdZnTe/CdS interface. Preliminary results have shown higher $J_{sc}$ values for this structure than for the conventional CdZnTe device, without any significant change in the observed cutoff of the CdZnTe.

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REFERENCES


LIST OF FIGURES

Figure 1  Measured lighted I-V characteristic of 9.7% MOCVD-grown CdTe p-i-n cell having a \( J \) of 22.16 mA/cm\(^2\), a \( V_{oc} \) of 0.730 V, and a fill factor of 0.59.

Figure 2  Spectral response of the 9.7% MOCVD-grown CdTe cell for two external bias conditions: (a) no externally applied bias, and (b) 1 volt externally applied reverse bias. The spectral response (no applied bias) of an 11% CdTe cell [7] is shown for comparison.

Figure 3 (a) Forward bias dark I-V characteristics measured for the temperature range of 310 K (curve 1) to 170 K (curve 8) in steps of 20 K, as indicated in the figure. (b) An example (310 K) of the theoretical fit to the actual I-V data used to determine the transport parameters.

Figure 4  Spectral response of air annealed ZnTe/CdZnTe/CdS and forming gas annealed ZnTe/CdZnTe/CdS p-i-n cells for same CdZnTe thickness.

Figure 5  Forward bias dark I-V characteristics for (a) CdTe, (b) CdZnTe \( (E_g = 1.7 \text{ eV}) \), and (c) CdZnTe \( (E_g = 1.8 \text{ eV}) \) cell structures.

Figure 6  Visible-near IR transmission of CdZnTe films that have undergone (a) no anneal, (b) argon anneal, (c) forming gas anneal, and (d) air anneal, all for 20 minutes at 350 C.
External Quantum Efficiency

Wavelength (nm)

(a)

(b)

(c)
\( J_0 = 1.5 \times 10^{-8} \text{ A/cm}^2 \)
\( n = 1.75 \)
\( R_s = 5.28 \text{ ohm-cm}^2 \)
\( R_{sh} = 18 \text{ Kohm-cm}^2 \)
Forming gas annealed

Air annealed

External Quantum Efficiency vs. Wavelength (nm)
The image shows a graph with the x-axis labeled as "voltage (volts)" and the y-axis labeled as "log of current." The graph includes three curves labeled [a], [b], and [c].

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Mr. Ken Zweibel  
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1617 Cole Blvd.  
Golden, CO  80401-3393  

SUBJECT:  Contract No. XL-7-06031-1 under DE-AC02-83CH10993  
Project Director:  A. Rohatgi  

Dear Mr. Zweibel:  

Enclosed please find copies of the Technical Progress Report for the period 5/1/89-5/31/89 on the above referenced contract.  

If you have any questions, please feel free to contact me.  

Sincerely yours,  

Pam Majors  
Research Administrator  

cc:  Ms. Debbie Larson
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

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Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
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ATLANTA, GA 30332
Introduction

The overall goal of this program is to improve basic understanding of CdTe and ZnTe alloys, by growing and characterizing these films along with cell fabrication. The major objective is to develop wide bandgap (1.6 - 1.8 ev) material for the top cell, along with compatible window material and transparent ohmic contact, so that cascade cell design can be optimized. Greater than 10% efficient top cell with about 80% subgap transmission can produce cascade cell efficiency of 15-20% provided bottom cell (1 ev bandgap) efficiency is around 12-15%.

In this program, front wall solar cells will be fabricated with glass/SnO\textsubscript{2}/CdS window with thin CdS layer to maximize transmission and current. Absorber films (E\textsubscript{g} =1.75 ev) will be grown by MBE and MOCVD techniques, which provide excellent control for tailoring the film composition and properties. CdZnTe will be grown by MBE and CdMnTe will be grown by MOCVD. Transparent ohmic contact will be formed by growing a p-ZnTe interlayer by MBE between the metal grid and absorber film by MBE.

Technical Progress

In this monthly report we present the results of X-ray photoelectron spectroscopy (XPS) measurements on Br:MeOH and K\textsubscript{2}Cr\textsubscript{2}O\textsubscript{7} etched surfaces of MBE-grown CdZnTe films. The objective of these measurements is to understand the effects of these chemical treatments in obtaining low contact resistance to CdZnTe films. It is known from literature for
p-type CdTe polycrystalline films, the surface should be Te-rich to get low contact resistance. Many researchers have used both Br:MeOH and K₂Cr₂O₇ chemical treatments to get Te-rich surface. It has been shown recently that on Br:MeOH etched polycrystalline CdTe films gives a Te-rich surface (≈50Å), but the contact resistance still remains high. On the other hand K₂Cr₂O₇ etch not only gives a Te-rich surface (>100Å) but also gives a low contact resistance. So far no such studies have been carried out on polycrystalline CdZnTe films. We have recently reported that our CdZnTe solar cells suffer from very high series resistance compared to CdTe solar cells. Further analysis has suggested that contact resistance may be part of the reason for high series resistance.

We used 1% Br:MeOH solution for 10 secs and saturated K₂Cr₂O₇ in H₂O for 10 secs to etch as-grown, air and forming gas annealed CdZnTe films. XPS measurements were performed immediately after the chemical etch. Figures 1 and 2 show XPS spectra of as-grown CdZnTe films after Br:MeOH and K₂Cr₂O₇ etch. Br:MeOH etch gives a surface with Cd, Zn and Te with Te/Cd+Zn ratio of 1.3, whereas K₂Cr₂O₇ etch leaves only Te on the surface without Cd and Zn. Depth profile analysis indicated that K₂Cr₂O₇ etch gives a thicker Te-rich surface than Br:MeOH etch. These results indicate that K₂Cr₂O₇ etch gives a more desirable Te-rich surface than Br:MeOH etch.
Figures 3 and 4 show XPS spectra of $K_2Cr_2O_7$ etched CdZnTe films for air and forming gas annealed films respectively. In both cases, the surface is Te-rich with no detectable Cd or Zn on the surface. Table 1 shows the relative concentrations of Cd, Zn, and Te in Br:MeOH etched CdZnTe films annealed in different ambient. In all the cases, the surface still has some Cd and Zn in contrast to $K_2Cr_2O_7$ etch.

Measurements like I-V are being performed in order to find out whether $K_2Cr_2O_7$ etch improves the contact and the contact resistance.

Acknowledgements

We would like to thank Dr. Mike Owens for his help in doing XPS measurements.
<table>
<thead>
<tr>
<th>Description:</th>
<th>SAR14 CdZnTe No Anneal Br/MeOH Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>No sputter</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1.** XPS spectrum of Br/MeOH etched as-grown CdZnTe film.
Figure 2. XPS spectrum of Potassium dichromate etched as-grown CdZnTe film.
**Figure 3.** XPS spectrum of potassium dichromate etched air-annealed CdZnTe film.
Figure 4. XPS spectrum of potassium dichromate etched forming gas-annealed CdZnTe film.
Relative concentrations of Cd, Zn, and Te in CdZnTe films processed as indicated

<table>
<thead>
<tr>
<th>Element</th>
<th>As-grown</th>
<th>Air anneal</th>
<th>Br:MeOH etch</th>
<th>Forming anneal</th>
<th>Br:MeOH etch</th>
<th>Argon anneal</th>
<th>Br:MeOH etch</th>
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</thead>
<tbody>
<tr>
<td>Cd</td>
<td>.56</td>
<td>.29</td>
<td>.66</td>
<td>.50</td>
<td>.67</td>
<td>.43</td>
<td>.67</td>
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<tr>
<td>Zn</td>
<td>.44</td>
<td>.71</td>
<td>.34</td>
<td>.50</td>
<td>.33</td>
<td>.57</td>
<td>.33</td>
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<tr>
<td>Te</td>
<td>1.1</td>
<td>.57</td>
<td>1.56</td>
<td>1.0</td>
<td>1.33</td>
<td>.86</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Mr. Ken Zweibel  
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XL-7-06031-1 under DE-AC02-83CH10993
Project Director: A. Rohatgi

Dear Mr. Zweibel:

Enclosed please find copies of the Technical Progress Reports for the period 6/1/89-6/30/89, 7/1/89-7/31/89, and 8/1/89-8/31/89 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Research Administrator

cc: Ms. Nancy Gardner
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE 
BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Twenty-Fifth Monthly Report for the Period
June 1 to June 30, 1989

Solar Energy Research Institute
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GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
EFFECTS OF PRE-HEAT TREATMENT OF CdS ON MOCVD CdTe/CdS SOLAR CELL PERFORMANCE

R. Sudharsanan and A. Rohatgi
School of Electrical Engineering
Georgia Institute of Technology, Atlanta, Georgia 30332

EXTENDED ABSTRACT

Polycrystalline CdTe solar cells are one of the leading candidates for terrestrial solar cell applications. Theoretical calculations predict an efficiency of 27% [1], while the practically achievable efficiency is -22% [2]. Recently, an efficiency of 12.3% has been achieved on CdTe films grown by spray pyrolysis technique [3]. In order to obtain the practically achievable limit, many design modifications have been suggested, like replacing the CdS window by a higher bandgap material, and the transparent conducting SnO$_2$ layer by ZnO to improve $J_{SC}$. In addition, a fundamental understanding of carrier loss and transport mechanisms at the CdTe/CdS heterojunction is necessary to improve $V_{OC}$ and fill factor values to the theoretical limit. Every growth technique for fabricating CdTe/CdS solar cells uses a either chemical or thermal treatment to clean the CdS surface prior to deposition of CdTe films. Also, it has been shown [4] that cleaning of CdS films prior to deposition of CdTe modifies the defects and transport mechanism of the heterojunction which dictates $V_{OC}$, and fill factor values. But the surface modifications of CdS and the nature of defects formed due to pre-heating are not understood. In this paper a systematic study of pre-heat treatment of CdS prior to deposition of CdTe by MOCVD, and their effects on device performance are discussed. The objective is to improve the understanding of the effects of pre-cleaning used in different growth techniques to fabricate CdTe/CdS solar cells.

CdS films were deposited on commercially available SnO$_2$/glass substrates by spray pyrolysis at a substrate temperature of 450 C. Prior to CdTe deposition, CdS/SnO$_2$/glass substrates were annealed inside MOCVD reactor in hydrogen atmosphere in the temperature range 300 to 450 C. CdTe films were deposited on these substrates under same conditions in the temperature range 300 to 400 C. Front wall n-i-p solar cells were fabricated with glass/SnO$_2$/CdS/-CdTe/ZnTe/Ni structures. Dark and lighted I-V measurements under AM1.5 sunlight were performed to monitor the device performance.

Dark I-V measurements (figure 1) show that CdTe/CdS diode behavior improves with increasing annealing temperature of CdS/SnO$_2$/glass substrates. A multivariable regression analysis was performed to fit the measured dark I-V data to a single exponential diode given by
\[ I = I_o \left[ \exp \left( \frac{q}{AKT} (V - IR_s) \right) - 1 \right] + \frac{V - IR_s}{R_{sh}} \]

where \( A \), the diode ideality factor, \( R_s \), the series resistance, and \( R_{sh} \), the shunt resistance of the diode. Devices made on substrates without any heat treatment showed high series resistance (1600 ohms-cm\(^2\)) in dark and a diode ideality factor of 2.1. Annealing decreased the series resistance (56 ohms-cm\(^2\) at 450 c) and the diode ideality factor to 1.5. These results suggest a modification of CdS surface on heat treatment which may possibly change the transport mechanism at the CdTe/CdS heterojunction. These results are consistent with Chu et. al., who showed a change in transport mechanism after in-situ cleaning of CdS in close-spaced sublimation technique.

The improvement of CdTe/CdS interface upon heat treatment is further reflected in light I-V measurements (figure 2). The open circuit voltage and fill factor values increased with heat treatment and thus increasing the efficiency of CdTe/CdS device from 5.8% to 8% (Table 1). In these experiments, the CdTe film thickness (1.5 um) and growth conditions were not optimized and hence only 8% efficiency was observed. However, the above results clearly suggest a direct correlation between pre-heat treatments and cell performance.

Using the guidelines of the above study for best pre-heat treatment and optimized CdTe thickness of 2.5 um, we were able to fabricate 9.7% efficient cell (figure 3). This is the highest efficiency obtained on MOCVD-grown CdTe/CdS cell to date. The \( V_{oc} \) (.730V) and fill factor (.6) values of MOCVD-grown CdTe/CdS cells are lower than the best (11-12%) CdTe/CdS cells grown by other techniques like electro-deposition. Bias dependent spectral reponse measurements (figure 4) show wavelength independent decrease in spectral response with increasing forward bias voltage. The above results suggest high recombination of carriers at CdTe/CdS interface which is voltage dependent. Optimization of pre-heat treatments and CdTe growth conditions, CdS surface modifications after each treatment and their effects on device performance will be presented in this paper.

REFERENCES

Figure 1. Dark I-V data of CdTe/CdS solar cells fabricated on CdS/SnO$_2$/glass substrates annealed at different temperatures.

Figure 2. Lighted I-V data of CdTe/CdS solar cells fabricated on CdS/SnO$_2$/glass substrates annealed at different temperatures.
Table 1. Light I-V data on CdTe/CdS cells prepared on CdS/SnO$_2$/glass substrates annealed at different temperatures.

<table>
<thead>
<tr>
<th>Substrate Temperature</th>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>Fill factor</th>
<th>Efficiency (%)</th>
</tr>
</thead>
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<tr>
<td>No heat</td>
<td>600</td>
<td>20.9</td>
<td>47</td>
<td>5.9</td>
</tr>
<tr>
<td>300</td>
<td>620</td>
<td>20.2</td>
<td>53</td>
<td>6.6</td>
</tr>
<tr>
<td>350</td>
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<td>7.0</td>
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<tr>
<td>450</td>
<td>680</td>
<td>20.5</td>
<td>56</td>
<td>7.9</td>
</tr>
<tr>
<td>*450</td>
<td>730</td>
<td>22.47</td>
<td>60</td>
<td>9.7</td>
</tr>
</tbody>
</table>

* CdTe film thickness was 2.5 um and 1.5 um in other cases.
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sudharsanan, and S. Ringel

Twenty-Sixth Monthly Report for the Period
July 1 to July 31, 1989

Solar Energy Research Institute
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GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
Technical Progress

In this monthly report we present the status and future directions for CdTe solar cells. The motivation for developing a wide bandgap photovoltaic material stems from the fact that the optimum two cell tandem design consists of 1.7 eV bandgap cell on top of a 1 eV bandgap cell. A high efficiency wide bandgap cell on top of a 15% efficient low bandgap cell can give tandem cell efficiency of the order of 20%. Considerable progress has been made on the bottom cell, particularly CuInSe2 which has given a small area cell efficiency > 14%. But the 1.7 eV material for the top cell has not yet been studied.

CdTe is a promising polycrystalline material which has given a small area cell efficiency >12%, but it’s bandgap is only 1.45 ev. So we either need to raise the CdTe efficiency >15% or to develop 1.7 eV bandgap cell to take greater advantage of the bottom cell in order to get up to 20% tandem cells. We are trying to do both by depositing CdTe films by MBE and MOCVD and increasing the CdTe bandgap to 1.7 eV by growing CdMnTe and CdZnTe films.

MOCVD CdTe films were grown by usign dimethylcadmium as the source for Cd and diallyltellurium and diisopropyl tellurium as sources for Te. Growth temperatures were in the range of 300 to 400 C, resulting in a growth rate of 1.5 um/hr. n-i-p CdTe solar cells were fabricated by depositing the CdTe films by MBE and MOCVD on glass/SnO2/CdS substrates. After film deposition they were subjected to
chemical treatments in CdCl$_2$ solution followed by 400° C anneal in air for 30 minutes. Back contact was formed by a quick Br:MeOH etch followed by Cu-doped p-ZnTe deposition which was capped by Ni metal.

Figure 1 shows a 9.7 % efficient MOCVD-grown CdTe cell verified by SERI. Also, we have recently obtained efficiency in excess of 10% in MBE-grown CdTe cells (figure 2). Figure 3 shows that MOCVD cells have a strong bias dependent spectral response. However, the response is fairly uniform and flat supporting the n-i-p behavior. Bias dependent spectral response indicates defects at the CdS/CdTe interface in n-i-p cells, which tend to make the interface recombination velocity sensitive to electrical field.

Figure 4 shows what needs to be done to raise the efficiency of MOCVD-grown CdTe cells to >15%. First of all we need to clean the defects which make the collection factor sensitive to the bias. In an ideal case collection factor should be one for all voltages. Calculations based on interface charging model suggest that we can improve the efficiency >13% if we could make collection function term one for all voltages.

Another major loss is associated with absorption in the CdS/SnO$_2$/glass substrates. The transmission through with and without CdS indicate that the photons that are absorbed or lost in the CdS amount to ~ 4 mA of current. If we can have a wider window material then efficiency can easily exceed 15%.
In order to improve CdTe cell efficiency to >15% our future directions are 1. optimization of in-situ pre-heat treatment of the CdS/SnO\textsubscript{2}/glass substrates prior to CdTe deposition, 2. replacing CdS layer by a wider bandgap CdZnS layer to reduce absorption losses, and 3. texturing the substrates to improve the overall collection because oblique penetration of photons generate carriers closer to the junction region.
Figure 1. Lighted I-v Data of 9.7% MOCVD CdTe Cell.

ZnTe/CdTe/CdS/SnO2, global, 1000W/m²

Sample: GIT-1  
Temperature = 25.0°C  
Jan. 10, 1989 11:18 am  
Area = 0.0790 cm²

\[ V_{oc} = 0.7266 \text{ volts} \quad I_{sc} = 1.775 \text{ mA} \]
\[ J_{sc} = 22.47 \text{ mA/cm}^2 \]
Fill factor = 59.66 %  
Efficiency = 9.7 %  
\[ I_{max} = 1.410 \text{ mA} \quad V_{max} = 0.5457 \text{ V} \]

* Best MOCVD CdTe Efficiency 10.2%
Voc = 0.7676 V
Jsc = 23.313 mA/cm²
Area = 0.08 cm²
Rse = 8.07 ohm·cm²
Rsh = 655.2 ohm·cm²
FF = 0.568
Efficiency = 10.17 %

Figure 2. Lighted I-V Data of 10.17% MBE-Grown CdTe Cell
BEST MBE CdTe PIN CELL
TO DATE (8-11-89):

\[ \text{EFF} = 10.5 \% \]

\[ \text{Voc} = 765 \text{ mV} \]

\[ \text{Jsc} = 22.6 \text{ mA/cm}^2 \]

\[ \text{FF} = 0.612 \]

\[ \text{Rs} = 0.68 \text{ ohm-cm}^2 \]

\[ \text{CdTe Thickness} = 1.65 \text{ um} \]
ZnTe/CdTe/CdS/SnO2 vs. bias

Sample: GIT-1  
Temperature = 25.0°C
Jan. 11, 1989 10:56 am  
Area used = 0.0790 cm²

Light bias = 0.85 mA

Figure 3. Bias-Dependent Spectral Response of 9.7% MOCVD CdTe Cell.
FIGURE 4.

LOSSES & POTENTIAL OF MOCVD CdTe CELL

<table>
<thead>
<tr>
<th>FACTORS</th>
<th>OBSERVED</th>
<th>POTENTIAL A</th>
<th>POTENTIAL A+B</th>
</tr>
</thead>
<tbody>
<tr>
<td>CURRENT</td>
<td>22.47 mA/cm²</td>
<td>&gt;24 mA/cm²</td>
<td>28.0 mA/cm²</td>
</tr>
<tr>
<td>VOLTAGE</td>
<td>.726 V</td>
<td>.781 V</td>
<td>.81 V</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>.59</td>
<td>.72</td>
<td>.80</td>
</tr>
<tr>
<td>Efficiency</td>
<td>9.7%</td>
<td>13.5%</td>
<td>18%</td>
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</table>
HIGH EFFICIENCY CADMIUM AND ZINC TELLURIDE BASED THIN FILM SOLAR CELLS

A. Rohatgi, C. J. Summers, A. Erbil, R. Sadharsanan, and S. Ringel

Twenty-Seventh Monthly Report for the Period August 1 to August 31, 1989

Solar Energy Research Institute
Contract No. XL-7-06031-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GA 30332
Technical Progress

This monthly report deals with the status and future directions of CdZnTe solar cells. Table 1 shows the status of CdZnTe solar cells fabricated in other laboratories. The highest efficiency reported for CdZnTe solar cells so far by other laboratories is 3.7%.

Figure 1 shows the development of CdZnTe solar cell in our laboratories. We were successful in growing 1.7 ev bandgap polycrystalline CdZnTe films, shown by the cut-off of surface photovoltage response. However, when we fabricated the cells according to the same process as used for CdTe, three undesirable problems happened; first the bandgap shifted from 1.7 to 1.55 ev as seen in the spectral response where the cut-off is 820 nm instead of 720 nm, secondly, resistance of ternary cells was a factor of 3 to 4 higher than the CdTe cells, and lastly the absolute spectral response was lower and it was not flat indicating that there are more defects in CdZnTe bulk and heterointerface and thus appears as a diffusion limited p-n junction. Inspite of all these problems, efficiency of 4.4% was obtained. This is the highest efficiency for CdZnTe solar cell with 1.55 ev.

In order to solve these problems several experiments were performed. The reason for bandgap reduction was the CdCl$_2$ treatment and not the heat treatment. Without CdCl$_2$ treatment, we were able to preserve the bandgap at 1.7 ev however, cell efficiency decreased from 4.4% to 1.1% . This suggests chemical treatment is necessary to passivate
defects and grain boundaries in ternary II-VI materials. This is further supported by the spectral response that without CdCl₂ treatment not only the spectral response is much lower but also looks more diffusion-limited process in the cell. CdTe cells without chemical treatment gave efficiencies lower than 5%. Hence, a new chemical treatment is necessary for ternary cells.

Recently, we were successful in preserving the bandgap of 1.7 ev by using a combination of CdCl₂+ZnCl₂ treatment. This may be due to the excess Zn present in the solution which prevents the Zn replacement by Cd thus preserving the bandgap even after chemical treatment. Figure 2 shows transmission data of CdZnTe before and after different chemical treatments. The new chemical treatment might help in solving the bandgap and defect passivation problems.

Figure 3 shows Auger depth profiles of MBE-grown CdTe and CdZnTe after Br:MeOH and potassium dichromate etches. Br:MeOH etch gives a Te-rich surface on CdTe but gives Te-rich surface to a lesser extent in CdZnTe films. This may be part of the reason for high Rₛ in CdZnTe cells. Chromate etch not only gives a high Te-rich surface on CdZnTe films but also gives a thicker Te-rich layer. Chromate etch on CdZnTe films may help in lowering the Rₛ. At present we are fabricating CdZnTe cells with chromate etch to improve the cell efficiency.

The future work will involve; 1. optimization of chemical treatment on CdZnTe along with chromate etch to
improve efficiency 2. growing of very thin interlayers to improve CdZnTe/CdS interface.
**TABLE 1.**
Comparison of CdZnTe cell parameters

<table>
<thead>
<tr>
<th>Group</th>
<th>Bandgap</th>
<th>( J_{sc} ) (mA/cm(^2))</th>
<th>( V_{oc} ) (volts)</th>
<th>FF</th>
<th>Efficiency</th>
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</thead>
<tbody>
<tr>
<td>ISET</td>
<td>1.55</td>
<td>15</td>
<td>.55</td>
<td>.45</td>
<td>3.7</td>
</tr>
<tr>
<td>Southern Methodist University</td>
<td>1.55</td>
<td>8</td>
<td>.58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stanford*</td>
<td>1.70</td>
<td>8.7</td>
<td>.58</td>
<td>.53</td>
<td>1.9</td>
</tr>
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</table>

* Single Crystal
FIGURE 2. CdZnTe Fabricated by CdTe PIN Process

<table>
<thead>
<tr>
<th>Voc</th>
<th>Jsc</th>
<th>Rs</th>
<th>EFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>18.45</td>
<td>0.432</td>
<td>&gt; 2</td>
</tr>
</tbody>
</table>

External Q.E. (A.U.)

800 nm

V (mV)

J (mA/cm²)

wavelength (um)
FIGURE 3.

CdZnTe Transmission on CdS Substrates

1. as-grown
2. air annealed
3. CdCl₂ + air
4. CdCl₂ + ZnCl₂ + air
Auger Depth Profiles of MBE CdTe and CdZnTe for Two Surface Etches

Br:CH₃OH

Sputter Time (min)

chromate