An Exploration of the Potential of p-n Junction Devices for Transducer Applications

Project No.: A-971

Project Director: M. E. Sikorski

Sponsor: Dept. of the Navy, Office of Naval Research

Effective: September 1, 1966

Estimated to run until: August 31, 1967

Contracting Officer: Code 350, Contracting Officer (for admin. matters)

Director, Acoustics Programs
Naval Applications Group
Office of Naval Research
Washington, D. C. 20350

Attn: Mr. A. W. Price, GS 137-304 (for technical matters)

Amount: $29,613

Reports: Status Reports - Letter type, semiannually
Final Technical Report - upon completion

Contact Person: Department of the Navy
Office of Naval Research
Washington, D. C. 20350

Attn: Code 350, Contracting Officer (for admin. matters)

Solid State Branch

assigned to Physical Sciences Division

OPIES TO:

[ ] Project Director
[ ] Director
[ ] Associate Director
[ ] Assistant Director(s)
[ ] Division Chiefs
[ ] Branch Head
[ ] General Office Services
[ ] Rich Electronic Computer Center
[ ] Engineering Design Services
[ ] Technical Information Section
[ ] Photographic Laboratory
[ ] Shop
[ ] Security Officer
[ ] Accounting
[ ] Purchasing
[ ] Report Section
[ ] Library

400 (Rev 10-62)
PROJECT TERMINATION

Date: Feb. 18, 1969

PROJECT TITLE: An Exploration of the Potential of p-n Junction Devices for Transducer Applications

PROJECT NO.: A-971

PROJECT DIRECTOR: M. P. Sikorski

SPONSOR: Dept. of the Navy, Office of Naval Research

TERMINATION EFFECTIVE: 8-31-68

CHARGES SHOULD CLEAR ACCOUNTING BY: All acceptable charges have cleared

Project Director to transfer overrun to Division "E" Account.

COPIES TO:
Project Director
Director
Associate Director
Assistant Directors
Division Chief
Branch Head
Accounting
Engineering Design Services

Reports
300. A-971

General Office Services
Photographic Laboratory
Purchasing
Report Section
Library
Security
Rich Electronic Computer Center
"An Exploration of the Potential of p-n Junction Devices for Transducer Applications."
Georgia Tech Research Institute
1 September 1966-31 August 1967 ($28,618)
For the Period: 1 September 1966 through 31 October 1966

Background

This program is devoted to studies of the response of semiconductor p-n junction devices to mechanical stress and the evaluation of the potential of these effects to transducer applications. Preliminary work in this area indicates a very high sensitivity of p-n junction transducers, especially in transistor configuration, excellent frequency response and a high signal-to-noise ratio. In order to better understand the physical mechanisms involved in the transducer action, two stress systems will be used in the investigations, namely, uniaxial and inhomogeneous stresses. Studies of crystallographic orientation, doping level and of surface conduction, just to mention a few, need to be made.

In order to better organize the program, a program scheduling chart has been developed, a copy of which is attached.

Accomplishments

Stress Response of Germanium Transistors. Studies of germanium oxide passivated transistors subjected to inhomogeneous stresses have been initiated. Data similar to those already published for silicon
transistors will be obtained and evaluated in the light of existing theory.

Stress Effects on V-L-S Silicon Whiskers. Apparatus is being assembled for the investigation of stress responses of very small silicon whiskers which were grown by the Vapor-Liquid-Solid method. This approach to transducers, if successful, would offer advantages of extreme miniaturization and ruggedness.

Studies of Indenter Bonding Methods. Attempts are being made to develop a transducer capsule for convenient evaluation of stress responses of various transistor-indenter structures. In particular, a pressure transducer configuration is under study.

Papers Presented or in Preparation. A paper entitled "Semiconductor Microphone" was presented at the Audio Engineering Society Meeting on October 10, 1966. A preprint of the paper is attached. This work was done with the aid of institutional funds before the present Contract was granted and serves as background for the whisker transducer approach. Two additional papers of relevance to the present program are in preparation.

Fiscal Data

<table>
<thead>
<tr>
<th></th>
<th>Expenditures and Encumbrances</th>
<th>Contract Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Services</td>
<td>$2,760.89</td>
<td>$11,964.11</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>53.44</td>
<td>4,946.56</td>
</tr>
<tr>
<td>Travel</td>
<td></td>
<td>500.00</td>
</tr>
<tr>
<td>Overhead</td>
<td>1,573.71</td>
<td>6,819.29</td>
</tr>
<tr>
<td>Total</td>
<td>$4,388.04</td>
<td>$24,229.96</td>
</tr>
</tbody>
</table>

Respectfully submitted,

M. E. Sikorski
Principal Investigator

Enclosures: 2
Introduction

The purpose of the present work is to study the response of p-n junction devices to mechanical stress and to evaluate the potential of p-n junction sensors. Studies started in the first bimonthly period have been continued during the second interval. In addition, the following has been accomplished.

Modification of Data-Collecting Equipment

A modification of the equipment has been initiated to extend the current range of data recording from two to seven decades of current. With the incorporation of the changes it will be possible to display diode or transistor currents in the range from $10^{-9}$ to $10^{-2}$ amperes.

Procurement of Materials

Additional germanium oxide-passivated transistors have been procured from the Motorola Co. for stress effect studies. Information has been collected on the availability of silicon materials for crystallographic orientation and doping level studies.

Response of P-N Junctions to Vibrations at Ultrasonic Frequencies

Equipment is being collected for the study of stress response of transistors to vibrations at frequencies in the 10 megacycle range.
Travel

A visit was made by M. E. Sikorski to the Research Triangle Institute in Durham, N. C. The purpose of this visit was to arrange for the manufacture of special diode structures for crystallographic orientation and doping level studies as soon as the materials become available.

Fiscal Data

<table>
<thead>
<tr>
<th></th>
<th>Expenditures and Encumbrances</th>
<th>Constant Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Services</td>
<td>$1,617.52</td>
<td>$10,346.59</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>10.23</td>
<td>4,936.33</td>
</tr>
<tr>
<td>Travel</td>
<td>79.12</td>
<td>420.88</td>
</tr>
<tr>
<td>Overhead</td>
<td>921.99</td>
<td>5,897.30</td>
</tr>
<tr>
<td>Total</td>
<td>$2,628.86</td>
<td>$21,601.10</td>
</tr>
</tbody>
</table>

Respectfully submitted,

M. E. Sikorski
Principal Investigator

MES:srt
Introduction

The purpose of the present program is to investigate the p-n junction stress effects and to study their applicability to pressure transducers. The work in the third bimonthly period covered the following areas.

Modification of the Data-Collecting Equipment

Preliminary results have been obtained using the modified apparatus. Diode characteristics have been displayed over eight decades of current, namely, from $10^{-8}$ ampere to 1 ampere. The transition from the ideal to high injection current conduction mechanism has been readily observed. This is the region of current where the piezoresistance effect is of great importance in the behavior of stressed diodes and transistors. Work is proceeding on the extension of the lower current range by two more decades of current. This is of interest for the study of generation-recombination mechanisms which dominate the stress effects at low current values.

The test setup will be used to study the response of silicon and germanium transistors.
Response of P-N Junctions to Vibrations at Ultrasonic Frequencies

Two experiments have been made to test the stress response of transistors to longitudinal ultrasonic waves of 2.25 mc frequency. Thus far the results have been negative. However, the use of a mechanical transformer for the indenter support should yield positive results. The work in this area is continuing.

Studies of Indenter Bonding Methods of Transducer Structures

The usefulness of various adhesives for bonding indenters to transistor surfaces continues to be studied. A supporting structure has been constructed for extremely small (0.006 in. on a side) beam lead transistors. Photographic reduction in size of the part of about 120 diameters had to be made to accomplish the above. Now it will be possible to determine the stress sensitivity of such small transistors.

Paper for Publication

A paper intended for publication in the Journal of Applied Physics and entitled, "The Effect of Hydrostatic Pressure on p-n Junction Characteristics and the Pressure Variation of the Band Gap," has been reviewed. The paper is being authored by M. E. Sikorski of Georgia Tech and investigators at the Bell Telephone Laboratories. The object of the paper is to describe a very simple approach for the evaluation of pressure sensitivity of semiconductor materials.

The method consists in the determination of the pressure shifts of the current-voltage (I-V) characteristics of p-n junctions which are formed in the semiconductor material under study. In particular, the voltage shifts are evaluated at constant current for the portions of the I-V curves whose slopes remain constant with pressure. These voltage shifts correspond to changes in the energy gap of the semiconductor material with pressure. The same method will be used in the present work for the determination of the sensitivity of p-n junction to non-hydrostatic stresses.
Fiscal Data

<table>
<thead>
<tr>
<th></th>
<th>Expenditures and Encumbrances</th>
<th>Contract Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Services</td>
<td>$3,170.08</td>
<td>$7,176.51</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>121.36</td>
<td>4,814.97</td>
</tr>
<tr>
<td>Travel</td>
<td>20.88</td>
<td>420.88</td>
</tr>
<tr>
<td>Overhead</td>
<td>1,806.94</td>
<td>4,990.36</td>
</tr>
<tr>
<td>Total</td>
<td>$5,098.38</td>
<td>$16,502.72</td>
</tr>
</tbody>
</table>

Respectfully submitted,

M. E. Sikorski
Principal Investigator

MES:srt
Introduction

In the fourth bimonthly period the effort was expanded primarily in the following areas: (1) Design and construction of pre-aligned transducer elements, (2) Modification of the apparatus and (3) Evaluation of the stress response of germanium transistors.

Design and Construction of Pre-Aligned Transducer Element

In the design of miniature solid-state transducers it is desirable that the electrically active element be completely assembled and aligned before incorporating it into a complete transducer housing. This is because the location of the most stress-sensitive region of the transistor is difficult to determine during the final assembly procedure. Further, a complete active device can be applied more easily to a variety of transducer applications.

The following is a description of the effort to produce a miniature pressure transducer utilizing the stress-sensitive properties of transistors. The effort was divided into three distinct phases. First, was the research into a reliable technique for the preassembly of the active element. Second, was the design and construction of the active element.
Third, was the design and construction of the mechanical parts of the transducer.

Transistors utilizing a planar chip as an active element were found to be the most convenient for the first phase of the effort. The RCA 2N3053 was chosen because of its stress-sensitivity and accessibility of the sensitive areas.

The first step was to select a material and configuration for a stylus to concentrate the stress in the appropriate area. It was conjectured that a sphere was a good configuration from the standpoint of contact to a diaphragm or some other mechanical element. Glass spheres of appropriate diameter were readily available and these were utilized in the initial research.

Glass spheres of various diameters from 2 to 10 mils were cemented to the 2N3053 chip without regard to locating them on a sensitive area. Various cements were investigated as possible media for holding the spheres to the chip. The first type was those which dry on contact with the air, namely, "Duco," "Elmer's," and Eastman "910." Of these, only Eastman "910" remained workable in small quantities long enough to allow application, and was the only one which had good adherence to the chip. The second type of cement used was epoxy resin. This cement is mixed with a catalyst to produce a hard durable cement. The types used were Dupont Mending Epoxy, Boxer "E," and Techkit "E-63" and "A-12." All of these cements except the "A-12" are "50-50" type epoxies. It was characteristic of these cements that very small quantities would not cure reliably even if mixed in larger portions. When wet, all types adhered well to the glass and the silicon chip. However, various difficulties were encountered on drying. In particular, the A-12 cement, the most reliable in curing, seemed to attack the glass making it crumble on application of a load. When placed on the chip in large enough quantities to insure bonding, the epoxies crept over the smaller spheres making it impossible to
hold them with a vacuum tool. Larger spheres could not be used because of insufficient stress and difficulty of placement. Spheres were pre-
cemented with "910" and then epoxied for lateral support, but the surface tension of the epoxy would dislocate the attached sphere.

At this point the use of sapphire phonograph stylii was considered. With these stylii, a small contact radius of about 0.5 to 1.0 mil could be obtained and still have a large vertical dimension to prevent overrun of the cement. The work on the construction of a pressure transducer utilizing such a stylus will be described in the next bimonthly report.

L. H. Glassman

Modification of the Data-Collecting Apparatus

Apparatus has been modified to display both base- and collector-
current curves over the range from $10^{-8}$ ampere to 1 ampere. Results obtained on germanium transistors are described in the next section.

Stress Response of Germanium Transistors

Motorola 2N 961 transistors have been subjected to mechanical stresses using a 1 mil radius sapphire indenter. In similarity with the response of silicon transistors, the sensitivity increased as the point of stress application was moved toward the base-emitter boundary. An interesting and useful difference between the stress responses of silicon and germanium transistors is that while in the case of silicon a large prestress is needed to attain a sensitive mode of operation, for germanium a much lower prestress value appears to be sufficient. This is important from the practical point of view since smaller prestressing loads correspond to a greater potential ruggedness of p-n junction transducers.

Another interesting result was obtained in the course of this work, namely, that light from an incandescent bulb enhanced the sensitivity of Ge transistors to mechanical stress.
Further tests on germanium transistors are contemplated using 2N 705 and 2N 3323 Ge transistors.

**Paper Submitted for Publication**

Paper entitled "The Effect of Hydrostatic Pressure on p-n Junction Characteristics and the Pressure Variation of the Band Gap," co-authored by M. E. Sikorski has been submitted for publication in the Journal of Applied Physics. A copy of this paper will be attached to the proposal for renewal of the present contract.

**Fiscal Data**

<table>
<thead>
<tr>
<th></th>
<th>Expenditures and Encumbrances</th>
<th>Contract Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Services</td>
<td>$4,724.86</td>
<td>$4,043.65</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>311.24</td>
<td>2,062.58</td>
</tr>
<tr>
<td>Travel</td>
<td>420.88</td>
<td></td>
</tr>
<tr>
<td>Overhead</td>
<td>2,693.17</td>
<td>2,305.19</td>
</tr>
<tr>
<td>Total</td>
<td>$7,729.27</td>
<td>$8,832.30</td>
</tr>
</tbody>
</table>

Respectfully submitted,

M. E. Sikorski
Principal Investigator

MES:brj
NOTICE

This document is not to be used by anyone prior to 8-31-70 without permission of the Georgia Institute of Technology and the Office of Naval Research.

Mr. R. E. Faires
Code 468
Office of Naval Research
Washington, D. C. 20360

Subject: Fifth Bimonthly Report - Contract N00014-67-A-0159-0001,
NR 187-804
"An Exploration of the Potential of p-n Junction Devices for
Transducer Applications"
Georgia Tech Research Institute
1 September 1966 - 31 August 1967 ($28,618)
For the Period: 1 May 1967 through 30 June 1967

Introduction

In the fifth bimonthly period the effort was expanded primarily in
the following areas: (1) Design and construction of pre-aligned transducer
elements, (2) Evaluation of the stress response of silicon and germanium
transistors, and (3) Evaluation of the piezoresistance effect.

Design and Construction of Pre-Aligned Transducer Elements

The fabrication of a prototype p-n junction pressure transducer has been pursued based on experience gained and described in the Fourth Bi-
monthly Report.

Difficulties encountered with glass spheres indicated that a phono-
tograph type stylus might be more suitable for stressing the device. Both
sapphire and diamond tips are readily available and can be obtained in a
variety of standard sizes suitable for this application. Present work in-
dicates that a tip radius of the order of 0.001" is optimum; however, care
must be taken not to overstress the transistor chip. Larger radii require
too much force to develop the required stresses. However, it must be noted
that sensitivity also depends upon the design of the chip, the location of
the stress, and the configuration of the mechanical parts of the transducer.

The current prototype of the pressure transducer uses a 0.0007" tip
radius. Loads in excess of 20 grams cause irreversible changes in charac-
teristics. Therefore, during the assembly process, care is taken not to
exceed a force of 10 grams. The base for the transducer is a TO-18 tran-
istor header. The diameter of this header is about 0.170". The headers are prepared by smoothing the top surface with 3/0 dry emery paper. The through leads of the header are ground off flush with the top surface.

The active element of the transducer is a planar epitaxial chip supplied by the Raytheon Manufacturing Corporation and designated as type N500 for the NPN and P500 for the PNP. The NPN chip was chosen for the first device. Both NPN and PNP chips have the same surface configuration which has the lead contact areas far removed from the pressure sensitive region. The chip size is 35 x 35 mils and the exposed emitter-base junction area is about 1 mil wide.

Other chips are under investigation. Another Raytheon chip which is 17 x 17 mils and has the collector contact through the back will be mounted shortly. This chip has been tested for stress sensitivity in the 2N 3250 Raytheon transistor. Suitable configurations have also been found in the Union Carbide chips. Included in these are dual transistor chips which may be useful in controlling temperature effects in more advanced versions of p-n junction transducers.

The first version of the pressure transducer consisted of a brass cylinder reamed to fit over the TO-18 header and a one mil thick stainless steel diaphragm which was cemented over one end of the cylinder to contact the blunt end of the stylus. A photograph of this transducer was included in the proposal for the continuation of the present work.

A more recent version of the pressure transducer consists of a cylinder made of invar instead of brass. Invar was used to lower the expansion of the transducer body upon temperature changes. The diameter of the diaphragm is about 0.17". The diaphragm was protected from mechanical damage by use of a protective cap also made of invar. The pressure sensitivity of this transducer was about 0.1 volt/in. H2O. This sensitivity was obtained with a simple resistive circuit without any amplification of the electrical signal. More transducers of this type are under construction for further evaluation of pressure and temperature sensitivities. The performance data for these transducers will be given in the Final Report.
Evaluation of the Stress Response of Si and Ge Transistors

The evaluation of stress sensitivity of silicon and germanium transistors has continued using the apparatus for the display of base and collector current curves over large current ranges. The sensitivity is being estimated by the method described in the paper which was attached to the Proposal for the Continuation of the Present Contract.

The same method was used for a comprehensive review of data published in the literature on the sensitivity to mechanical stress of p-n junction devices. The results of this work will also be given in the Final Report.

Evaluation of the Piezoresistance Effect

Current-voltage characteristics of stressed p-n junctions are being evaluated in order to determine the importance of the piezoresistance effect on the stress sensitivity of devices. Additional experiments using uniaxial stress application are contemplated to further substantiate the differences in the response of npn and pnp transistors under similar stress conditions.

Fiscal Data

<table>
<thead>
<tr>
<th></th>
<th>Expenditures and Encumbrances</th>
<th>Contract Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Services</td>
<td>$3,064.71</td>
<td>$ 978.94</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>191.32</td>
<td>1,901.16</td>
</tr>
<tr>
<td>Travel</td>
<td>420.88</td>
<td>420.88</td>
</tr>
<tr>
<td>Overhead</td>
<td>1,746.89</td>
<td>558.30</td>
</tr>
<tr>
<td>Total</td>
<td>$5,002.92</td>
<td>$3,859.28</td>
</tr>
</tbody>
</table>

Respectfully submitted,

M. E. Sikorski
Principal Investigator

MES/srt
Subject: Semi-Annual Status Report No. 1
"An Exploration of the Potential of p-n Junction Devices for Transducer Applications"
Georgia Tech Research Institute
1 September 1966-31 August 1967 ($28,618)
For the Period: 1 September 1966 to 1 March 1967

Introduction

The goal of the research program for this year is to evaluate the p-n junction transducer concept. Preliminary work in this area indicated a very high sensitivity of junction transistors to mechanical stress, i.e., a large current change for a given mechanical load, an excellent frequency response, essentially limited by the design of the diaphragm-indenter assembly, and a high signal-to-noise ratio. Optimization of transducer performance can be obtained by studies of the effects of crystallographic orientation, conductivity type of the semiconductor material, and of the impurity concentration.

The effort in the first six months of the program has been expanded towards ordering of materials, training of personnel and experimental and theoretical studies. The experimental and theoretical work is described in more detail in what follows.

Transducer Structures

Early transistor transducer (microphone) structures\(^1,2\) were quite bulky (Figure 1). The diameter of the diaphragm was about 1.5 inches and the height of the microphone about 2.5 inches. The transducer structure consisted of a sapphire needle which was mounted at the center of the
diaphragm and pressed against the surface of the transistor. The critical phase of the assembly was to accurately position the transistor under the needle near the emitter-base junction edge in order to arrive at a high sensitivity. The sensitivity is defined by $\frac{\Delta I}{\Delta \sigma}$, where $\Delta I$ is the change in the current upon application of a load $\Delta \sigma$. The requirements for a high sensitivity in standard commercially available devices have already been experimentally established and the results were published.3

In spite of the knowledge of the factors controlling the sensitivity, the assembly procedure was still very tedious, time consuming and thus impractical. Therefore, a search has been initiated for a simpler transducer assembly procedure.

The goal of this investigation is to be able to permanently attach an indenter to the transistor and thus obtain a sensing indenter-transistor capsule which then could be incorporated into a pressure transducer or microphone structure. To this end various adhesives are being tried and a search is being made for suitable transistor chips. Wires will be attached to the transistor chips using the equipment shown in Figure 2.

In the meantime, in order to be able to evaluate the response of small transducers, parts for two small pressure transducers have been manufactured. The diaphragms are 2 mm in diameter. Although the indenters (sapphire needles) are still attached to the diaphragms, the transistors are bonded to cylindrical supports which can be rotated for positioning purposes. These transducers have not been assembled as yet.

Data Collecting Equipment

Figure 3 is a photograph of a section of the laboratory where the sensitivity of transistors to mechanical stress is evaluated. The stressing jig is situated on the antivibration table. The transistor characteristics are displayed on the face of the oscilloscope or recorded graphically with the help of an X-Y recorder.

Two circuit configurations are presently in use for the study of electrical characteristics of devices. One allows the display of diode characteristics over eight decades of current and the other is used to plot base and collector currents of transistors over three decades of current. The first circuit mentioned is useful in evaluating the effects
of properties such as crystallographic orientation and doping level on
the stress sensitivity of a single p-n junction as well as for the deter-
mination of stress coefficients of energy gap by a method which will be
described in the next section. The second circuit allows a rapid eval-
uation of the stress sensitivity of a transistor as a whole. This
approach has been used previously. 3

Determination of Stress Coefficients of Energy Gap

The forward current in a p-n junction can be written as follows:

$$I_f = I'_o \exp \frac{q}{nkT} (V - \Delta E_g/q)$$

where $I'_o$ is the current for zero stress, $q$ the electronic charge, $kT$
Boltzmann energy, $V$ the applied voltage, $\Delta E_g = (dE_g/d\sigma) \sigma$, where $\sigma$ is the
applied stress and $n$ is a coefficient, in general, different from unity.
The value of $n$ lies between 1 and 2 depending on the current conduction
mechanism. For an ideal current (diffusion), $n = 1$ and for generation -
recombination currents $n = 2$.

It can be easily shown that as long as the value of $n$ is independent
of pressure for a fixed current, the change in the energy gap is compensated
by a corresponding change in $V$.

Taking logarithms of both sides of Eq. (1) and rearranging terms we
obtain

$$\ln \frac{I_f}{I'_o} = \frac{q}{nkT}(V - \Delta V_g)$$

(2)

where $\Delta V_g = \Delta E_g/q$. The above equation can also be written as follows

$$V = K + \frac{dV}{d\sigma} \sigma$$

(3)

where $K$ is a constant and $\sigma$ is the applied stress. Differentiating both
sides of the equation we get that

$$\frac{dV}{d\sigma} = \frac{dV_g}{d\sigma}$$

(4)

Thus, the applied bias voltage $V$ changes appropriately to compensate for
the stress induced changes in $V_g$ or $E_g$. Under these conditions, i.e.,
constant current and a value of $n$ independent of stress, the shift in the
applied bias voltage with stress is an exact measure of the change in the energy gap, irrespective of whether the junction is ideal \((n = 1)\) or not \((1 < n \leq 2)\).

In order to determine the stress coefficient of energy gap for different crystallographic orientations it is sufficient to display the current-voltage (I-V) characteristics of a p-n junction device at various values of mechanical stress and to evaluate the voltage shifts at constant current for the portions of I-V curves whose slopes do not change with stress. Slopes remain constant with stress for currents of about 1 milliampere or less. In general, for currents larger than 1 milliampere the slopes change with stress on account of series resistance effects.

The origin of series resistance effects can be easily seen from Eq. (5)

\[ I = I_0 \exp \frac{q}{nkT} (V - \Delta E_g/q - IR - \Delta R) \]  

(5)

where \( R \) is the diode series resistance and \( \Delta R \) is the change in the resistance with applied mechanical stress.

The approach of evaluating the voltage shifts with pressure has been taken in a recently completed work whose aim was to study the effect of hydrostatic pressure on p-n junction characteristics and experimentally determining the pressure variation of the band gap of Si and GaAs materials. The results of the above work will be published by A. Jayaraman of the Bell Telephone Laboratories and co-authored by M. E. Sikorski. This work was started when Mr. Sikorski was at the Bell Telephone Laboratories.

The same procedure will be followed in the present work for the determination of uniaxial stress coefficients of energy gap for Si and Ge. This will allow a comparison of transducer sensitivities for different crystallographic orientations.

**Miscellaneous Projects**

In addition to the study of indenter bonding methods, pressure transducer structures and the circuit work, efforts have been expanded in the area of response of p-n junctions to vibrations at ultrasonic frequencies. Also a jig has been built to study stress response of V-L-S silicon whiskers.
One application of small p-n junction transducers sensitive to ultrasound might be to detect noises emitted by metals under stress such as hulls of ships undergoing fatigue or stress-corrosion cracking. Similarly the V-I-S whiskers may offer potential for very sensitive and small sound sensors.

**Future Program**

The program for the next interval is to construct and test transistor pressure transducers, and to evaluate the effects of crystallographic orientation, doping level and environment on the sensitivity to mechanical stress of p-n junction devices.

**Publications and Presentations Since September 1, 1966**

**Papers Presented**


**Papers in Preparation**


**Personnel Employed on the Project**

- M. E. Sikorski Principal Investigator
- L. Glassman Research Physicist
- R. Newsom Electronics Technician
- C. K. Kuo Graduate student in Electrical Engineering
- J. U. Hiter, Jr. Undergraduate student in Physics
- J. S. Lund, Jr. Undergraduate student in Physics

Respectfully submitted,

M. E. Sikorski
Principal Investigator

MES/srt

---


Mr. Hugh M. Fitzpatrick  
Office of Naval Research, Code 468  
Room 4221, Main Navy Building  
Washington, D. C. 20360

Dear Mr. Fitzpatrick:

According to our telephone conversation of this morning I have requested a three-month no-cost extension of Contract N00014-67-A-0159-0001, NR 187-804. The papers will be processed through the Georgia Tech Research Institute.

I am enclosing a copy of a letter from Dr. M. M. Atalla about the Solid State Sensors Symposium. The letter contains the information about the Conference that you requested. Enclosed you will also find the abstract of our paper to be presented at the Sensors Symposium, and a manuscript of a paper on MOS transducers which we would like to publish in the Proceedings of IEEE.

Two additional papers which will describe completed work will follow as soon as practicable. The first paper will cover the studies of noise in transistors and the second will describe the results obtained on transistor transducers.

Dr. E. J. Scheibner, Chief of the Physical Sciences Division, has agreed to supervise the preparation of a brief proposal for the continuation of our work in the three areas that I described verbally, namely, (1) metal-oxide-semiconductor (MOS) devices, (2) noise studies, and (3) computer-aided optimization of transistor transducers.

I appreciate very much your comments and suggestions. It was a real pleasure to talk to you this morning and I will contact you again as soon as possible.

Best regards,

Very truly yours,

M. E. Sikorski  
Senior Research Physicist

Enclosures: 3
MAY 13, 1968

DEAR DR. SIKORSKI:

We are pleased to inform you that the paper "Mechanical Stress Phenomena in Field Effect and Bipolar Transistors and their Potential for Transducer Applications," authored by you and Messrs. Woodward and Kuo, has been accepted for presentation at the 1968 Solid State Sensors Symposium.

Sincerely,

M. M. ATALLA
Program Chairman

MMA:emr
Mechanical Stress Phenomena in Field Effect and Bipolar Transistors and Their Potential for Transducer Applications†

by

M. E. Sikorski, R. P. Woodward and C. K. Kuo

Physical Sciences Division
Engineering Experiment Station
Georgia Institute of Technology

ABSTRACT

This paper is devoted to the discussion of certain solid-state sensors which convert mechanical signal inputs into electrical outputs and which are compatible with integrated circuit technology. Mechanical stress affects the electrical characteristics of semiconductor devices, giving rise to a mechanical-electrical transduction mechanism. It is possible to utilize discrete semiconductor devices and process the signal externally or, alternatively, build both the transducer and processing circuit on a single integrated circuit chip. Historical background will be given on developments in the field of stress effects in solid-state active devices over the last ten years.

Inhomogeneous stress effects, namely, changes in collector or channel currents, in bipolar, junction field effect, and MOS transistors are detailed. Important factors which influence the sensitivity of bipolar transistors are indentor position, internal geometry, and conductivity type, i.e., pnp or npn. Each of these factors has been studied and sensitivity may be predicted approximately from them. MOS capacitance effects will also be described. The potential of these various effects for sensitive pressure, force, or displacement transducers is evaluated.

† This work was supported in part by the Office of Naval Research, Contract No. N00014-67-A-0159-0001, NR 187-804.
Internally generated noise has been measured for transistor stress transducers under a variety of operating modes. For each of the several transistors studied, noise spectra were obtained for both stress transducer operation and normal transistor operation. By this means the noise characteristics of transducer operation can be related to the normal (published) noise characteristics of the transistors. The empirical results suggest how the noise effects of transducer operation may be predicted if the noise spectrum of the specific transistor is known. These results appear to agree with present theory on noise in transistor operation. Design rules are given so that sensitivity, signal to noise ratio, and dynamic range may be optimized.
MOS Transducers with Digital Measurement Capability

Abstract—A new MOS type transducer is reported, which can be used to measure mechanical pressure or force, temperature and, light in digital form.

Recently the piezoresistance effect of semiconductor materials and the piezojunction effect of semiconductor p-n junctions have been utilized in transducers to measure force or mechanical pressure. Semiconductor devices such as resistors, diodes, bipolar transistors,\textsuperscript{1,2} unipolar transistors\textsuperscript{3} and thin film transistors\textsuperscript{4} have all been exploited as electro-mechanical transducers. This correspondence reports a unique solid-state transducer using the capacitance change in a metal-oxide-semiconductor (MOS) structure. The MOS capacitive transducer can be used to measure mechanical pressure, temperature, or light intensity, and it can easily be incorporated into electronic circuits to obtain measurements in digital form.

When operating at a sufficiently high frequency so that surface state charges and minority carriers cannot follow the signal variation, the MOS capacitance in the inversion region is equivalent to series connection of oxide capacitance and the semiconductor space-charge capacitance. The high-frequency semiconductor inversion capacitance, which is dependent on the energy-band gap, impurity concentration, relaxation time of minority carriers, and the signal frequency, is sensitive to mechanical pressure, temperatures and light. The pressure effect on the high-frequency inversion capacitance can be related to changes in the energy-

\* This work was supported in part by the Office of Naval Research, Contract No. N00014-67-A-0159-0001, NR 187-804.
band gap. It has been shown, for example, the energy-band gap is decreased when the silicon is under mechanical stress.\(^5\) This decrease has the effect of increasing the high-frequency inversion capacitance.\(^6\) The increase of temperature in the semiconductor has an effect similar to a decrease of the energy-band gap. The high-frequency inversion capacitance will therefore increase with the increase of temperature.\(^7\) When the MOS is illuminated, the semiconductor surface is under thermal non-equilibrium because of carrier excitation. However, the semiconductor inversion capacitance under non-equilibrium steady-state conditions can be treated similarly to the condition of thermal equilibrium.\(^8\) The high-frequency inversion capacitance will increase with increasing illumination. One factor that will affect the inversion capacitance under all conditions of pressure, temperature, and illumination is that the inversion capacitance will increase whenever the increase of carrier generation rate is sufficient to cause a transition from high-frequency type to low-frequency type.

In experimental work, commercially available 2N4351-N channel type and 2N4352-P channel type MOS FETs are used to provide the MOS structures. Since both of these MOS FETs are for enhancement-mode operation, gate metals overlap portions of diffused sources and drains; this creates useful MOS structures between gate and source and between gate and drain. The MOS structure between gate and channel is not used because of its less favorable C-V characteristics. When using the MOS as pressure or force transducer, the force is applied by a sapphire indenter of 0.001-inch radius on the gate metal where it overlaps either the source or the drain depending on which one of the MOS structures is used. Figure 1(a) shows a typical N type MOS C-V characteristic with and without mechanical pressure. The curves are plotted on a X-Y recorder by an automatic C-V plotter.
operating at 1 MHz. Figure 1(b) gives the measured capacitances as a function of force.

In order to accomplish the digital measurement capability, the MOS capacitive transducer is built into an astable multivibrator to control the oscillating frequency. Figure 2 shows the circuit of the astable multivibrator with a MOS frequency-controlling element. The circuit is designed to satisfy these criteria: (1) the oscillating frequency is sufficiently high so that minority carriers and surface state charges cannot follow the signal variation; (2) the MOS is operating in inversion region at any point of an oscillating cycle; (3) percentage change of the oscillating frequency is as close as practical to that of the MOS capacitance change. No special effort has been made thus far to obtain good frequency and temperature stabilities. Figure 3(a) and 3(b) show respectively the digitally measured frequencies as function of mechanical pressure and illumination. In the illumination experiment, light intensity is measured by the voltage applied across a focused microscope light source. The noise equivalent of the transducer varies from ±10 Hz without pressure or light to ±200 Hz with pressure or light on the MOS.

The output capacitance of a bipolar transistor is also known to be sensitive to mechanical stress. In comparison, the MOS has the advantages that it is a two-terminal passive device, it does not consume power, and it does not require dc bias. The dc voltage bias can be avoided by introducing positive surface state charges into P-type MOS and negative surface state charges into N-type MOS, thus shifting the MOS C-V characteristic curves from their theoretical forms, so as to have inversion regions around zero dc bias voltage. The ready availability of MOS structure
in integrated circuits make it easy to incorporate MOS capacitive transducers therein.

C. K. Kuo
M. E. Sikorski
E. J. Scheibner
Physical Sciences Division
Georgia Institute of Technology
Atlanta, Georgia 30332
Manuscript received


Figure 1. (a). Pressure Effect on MOS C-V Characteristic (N Type). (b). MOS Capacitance as Function of Pressure.
Figure 2. MOS Transducer With Digital Output.
Figure 3. (a). Frequency as Function of Pressure.
(b). Frequency as Function of Light.
FINAL REPORT

PROJECT A-971

AN EXPLORATION OF THE POTENTIAL OF P-N JUNCTION DEVICES FOR TRANSDUCER APPLICATIONS

By M. E. Sikorski, R. P. Woodward, L. H. Glassman and C. K. Kuo

Prepared for

Office of Naval Research
Department of the Navy
Washington, D.C.

Contract No. N00014-67-A0159-0001
NR 187-804

1 September 1966 to 31 August 1968

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
AN EXPLORATION OF THE POTENTIAL OF P-N JUNCTION
DEVICES FOR TRANSDUCER APPLICATIONS

By

M. E. Sikorski, R. P. Woodward, L. H. Glassman and C. K. Kuo

Contract No. N00014-67-A0159-0001
NR 187-804
1 September 1966 to 31 August 1968

Prepared for
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
WASHINGTON, D.C.

Reproduction in whole or in part is permitted
for any purpose of the United States Government
FOREWORD

This report was prepared by the Georgia Institute of Technology, Physical Sciences Division of the Engineering Experiment Station under Office of Naval Research Contract No. N00014-67-A-0159-0001, NR187-804, "An Exploration of the Potential of p-n Junction Devices for Transducer Applications." The work was administered by the Acoustics Programs, Robert E. Faires, Technical Monitor.

We wish to express our appreciation to Mr. Hugh M. Fitzpatrick of the Office of Naval Research, Acoustics Programs, for his continued interest and helpful suggestions concerning the program. Special credits are also due Mr. R. A. Newsom of Georgia Tech for his invaluable contributions in all phases of the experimental work, and to H. P. Lee for the analysis of some of the experimental data and testing of pressure transducers.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II.</td>
<td>GENERAL CONSIDERATIONS CONCERNING STRESS EFFECTS IN P-N JUNCTION DEVICES</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2.1 The Need for High Stress Levels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2 Effect of Crystallographic Orientation</td>
<td></td>
</tr>
<tr>
<td>III.</td>
<td>RESPONSE OF TRANSISTORS TO STRESS</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>3.1 Experimental Apparatus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.2 Curve Plotter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.3 NPN Transistors Stressed Near the Emitter-Base Junction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.4 FPN Transistors Stressed Near the Emitter-Base Junction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5 FPN Transistors Stressed Away from the Emitter Edge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.6 FPN Germanium Transistors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.7 Junction and Insulated-Gate or MOS Field-Effect Transistors</td>
<td></td>
</tr>
<tr>
<td>IV.</td>
<td>CONSTRUCTION AND TESTING OF TRANSISTOR TRANSDUCERS</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>4.1 Early Transistor Transducers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2 Design and Construction of Pre-Aligned Transducer Elements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.3 Testing of Pressure Transducers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.4 Some Applications of Transistor Transducers</td>
<td></td>
</tr>
<tr>
<td>V.</td>
<td>NOISE STUDIES</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>5.1 Noise in Stressed Transistors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.2 Conclusions and Results</td>
<td></td>
</tr>
<tr>
<td>VI.</td>
<td>TEMPERATURE EFFECTS</td>
<td>69</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>VII. DISCUSSION</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>VIII. CONCLUSIONS</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>IX. RECOMMENDATIONS</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>APPENDIX D</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>APPENDIX E</td>
<td>122</td>
<td></td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Experimental Apparatus ........................................... 9</td>
</tr>
<tr>
<td>3.2</td>
<td>Circuit Schematic of the Diode and Transistor Curve Plotter .................. 10</td>
</tr>
<tr>
<td>3.3</td>
<td>Photographs of the Surface Features of Four Types of Transistors ............. 12</td>
</tr>
<tr>
<td>3.4</td>
<td>I-V Characteristics of Motorola 2N834 [111] NPN Silicon Transistor Under Various Conditions of Stress ........................................ 14</td>
</tr>
<tr>
<td>3.5</td>
<td>Plots of Collector Current Versus Load (in Grams) on the Indenter Obtained from Data of Fig. 3.4 for Three Values of Base Current .................. 15</td>
</tr>
<tr>
<td>3.6</td>
<td>Sensitivity in Volts/Gram as a Function of Base Resistance .................... 16</td>
</tr>
<tr>
<td>3.7</td>
<td>I-V Characteristics of a Special Motorola Transistor Diffused into a [100] Oriented Silicon Wafer Under Various Stress Conditions .................. 18</td>
</tr>
<tr>
<td>3.8</td>
<td>Plots of Collector Current Versus Load on the Indenter Obtained from Data of Fig. 3.7 for Three Values of Base Current .................. 19</td>
</tr>
<tr>
<td>3.9</td>
<td>I-V Characteristics of a Motorola 2N837 [111] PNP Silicon Transistor Under Various Conditions of Stress ........................................ 21</td>
</tr>
<tr>
<td>3.10</td>
<td>Plots of Collector Current Versus Load on the Indenter Obtained from Data of Fig. 3.9 for Three Values of Base Current .................. 22</td>
</tr>
<tr>
<td>3.11</td>
<td>I-V Characteristics of a Motorola 2N2905 [111] PNP Silicon Transistor Under Various Stress Conditions ........................................ 23</td>
</tr>
<tr>
<td>3.12</td>
<td>Plots of Collector Current Versus Load for the Transistor of Fig. 3.11 .......... 24</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>3.14</td>
<td>Plots of Collector Current Versus Load for the Transistor of Fig. 3.13</td>
</tr>
<tr>
<td>3.15</td>
<td>I-V Characteristics of a Motorola 2N961 [111] PNP Germanium Transistor Under Various Conditions of Stress</td>
</tr>
<tr>
<td>3.16</td>
<td>I-V Characteristics for a Germanium Transistor of Fig. 3.15 Except That Stress was Applied Near the Junction</td>
</tr>
<tr>
<td>3.17</td>
<td>Comparison of Basic Lead Terminology of Vacuum Tubes, Bipolar Transistors and Field-Effect Devices</td>
</tr>
<tr>
<td>3.18</td>
<td>A Photograph of a Motorola 2N4320A Junction Field Effect Transistor</td>
</tr>
<tr>
<td>3.19</td>
<td>A Photograph of a Motorola 2N4352 MOS Transistor</td>
</tr>
<tr>
<td>4.1</td>
<td>An Early Transistor Microphone</td>
</tr>
<tr>
<td>4.2</td>
<td>Experimental Arrangement for Testing the Stress Sensitivity of Transistor Chips</td>
</tr>
<tr>
<td>4.3</td>
<td>Cross-sectional View of a Transistor Pressure Transducer</td>
</tr>
<tr>
<td>4.4</td>
<td>A Photograph of an Assembled Pressure Transducer and Its Component Parts</td>
</tr>
<tr>
<td>4.5</td>
<td>Transducer Sensitivity Test Setup</td>
</tr>
<tr>
<td>4.6</td>
<td>Circuit for Biasing Transistors and Measuring Pressure Sensitivity of Transducers</td>
</tr>
<tr>
<td>4.7</td>
<td>Electrical Circuit of a Portable Pressure Transducer Tester</td>
</tr>
<tr>
<td>4.8</td>
<td>Photograph of a Transducer Tester</td>
</tr>
<tr>
<td>4.9</td>
<td>Pressure Dependence of the Collector to Emitter Voltage ($V_{CE}$) of a Transistor Pressure Transducer</td>
</tr>
<tr>
<td>4.10</td>
<td>A Photograph of a Public Address System Using Semiconductor Microphones</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>4.11</td>
<td>Schematic of a Battery-Operated Power Supply for the Microphones of Fig. 4.10</td>
</tr>
<tr>
<td>5.1</td>
<td>Minority Carrier Density Ratio of the Stressed State to the Unstressed State</td>
</tr>
<tr>
<td>5.2</td>
<td>Base and Collector Current Curves for a 2N3798 PNP Transistor</td>
</tr>
<tr>
<td>5.3</td>
<td>Base and Collector Current Curves for a 2N3798 Transistor Stressed Away from the Emitter-Base Junction</td>
</tr>
<tr>
<td>5.4</td>
<td>Base and Collector Current Curves for a 2N3798 Transistor Stressed Near the Emitter-Base Junction</td>
</tr>
<tr>
<td>5.5</td>
<td>Noise Spectra for a Well-Behaved 2N929 NPN Transistor</td>
</tr>
<tr>
<td>5.6</td>
<td>Noise Spectra for a 2N4351 MOS and a 2N4220A Field Effect Transistor</td>
</tr>
<tr>
<td>A-1</td>
<td>I-V Characteristics of a Uniaxially Stressed Silicon Mesa Diode for Two Stress Conditions: T = 0 and T = 1.73 x 10^{10} dynes/cm^{2}</td>
</tr>
<tr>
<td>C-1</td>
<td>Stress Induced Base Currents in a PNP Transistor</td>
</tr>
<tr>
<td>C-2</td>
<td>Stress Induced Energy Level Changes Near the Surface of Bulk Semiconductor Material</td>
</tr>
<tr>
<td>D-1</td>
<td>Biasing Circuits for Transistors Used in the Noise Tests</td>
</tr>
<tr>
<td>D-2</td>
<td>Noise (v_{n}) and Signal (v_{s}) Components Across the Load Resistor</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pressures Under the Indenter</td>
<td>5</td>
</tr>
<tr>
<td>2. Pressure Dependence of Energy Gap</td>
<td>7</td>
</tr>
<tr>
<td>3. Performance of Selected Bipolar and Field-Effect Transistors</td>
<td>65</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

A number of papers have been published in which the effects of mechanical stress on pn junction devices have been described. These papers can be classified according to whether they give essentially qualitative description of the stress effects,\textsuperscript{1-15} theory of the phenomena observed,\textsuperscript{16-37} or applications of the effects to transducers.\textsuperscript{38-53}

In the course of the various investigations, pn junction structures have been stressed hydrostatically, uniaxially and also by means of spherically ended indenters of small radii. In the last case a highly inhomogeneous stress pattern is obtained which makes the theoretical treatment quite involved. However, the results can be explained qualitatively by assuming a uniaxial stress applied over a small portion of the pn junction.\textsuperscript{20}

In all cases studied, namely, ordinary diodes, tunnel diodes and transistors which were stressed mechanically, a shift in the current-voltage (I-V) characteristic of the devices was observed, thus giving rise to a transducer action in that mechanical energy was converted into an electrical signal. The magnitude of the stress effects depends on the semiconductor material used, the crystallographic orientation of the single crystal from which the device is made, and on the geometry of the device and the stress applicator.

Various applications of the observed stress effects have been suggested such as hydrostatic pressure transducers\textsuperscript{41-43} microphones,\textsuperscript{37,40,44,47,50} phonograph pickups and accelerometers.\textsuperscript{46,49,54} Tunnel diodes appear to be especially well suited for miniature hydrostatic pressure sensors and have recently been used in an underwater application.\textsuperscript{55} The sensitivity to pressure of such devices and their temperature stability might be improved.
by a different choice of material and optimization of the doping level. 47

Preliminary work in using transistors as sensing elements indicated a very high sensitivity of junction transistors to mechanical stress, i.e., a large current change for a given mechanical load, an excellent frequency response, essentially limited by the design of the diaphragm-indenter assembly, a high signal-to-noise ratio, and a potential for miniaturization on account of very small sizes of transistor chips. For example, an early experimental transistor microphone has yielded a higher sensitivity than the carbon microphone. 40,47 The frequency response was found to extend from zero Hz to frequencies in the MHz range. 36,49

The purpose of the present study was to explore the potential of pn junction devices for transducer applications by evaluating the response to stress of a variety of unmounted semiconductor devices, as well as those in a pressure transducer configuration. In addition to bipolar transistors (npn and pnp), junction field effect (JFET) and metal-oxide-semiconductor (MOS) transistors were used in this work. An emphasis was placed on obtaining the type of information that would be useful in assessing the applicability of pn junction devices for particular applications such as, for example, underwater sound detectors. In addition to stress sensitivity, quantities such as equivalent noise input, linear and dynamic ranges were obtained for representative devices.

Section II deals with general considerations concerning stress effects. An amplified discussion is given in Appendices A and C. In Section III experimental results are presented for selected devices to illustrate the various types of behavior that have been observed on transistors. Section IV deals with the construction of pressure transducers and presents selected experimental data. Noise studies are discussed in Section V and
Appendix D, and temperature effects in Section VI. Appendix B contains a reprint of a recently published paper on the use of MOS transistors as transducers with digital measurement capability. Appendix E contains an Abstract of a paper presented at the 1968 Solid State Sensors Symposium in Minneapolis, Minnesota. Discussion, Conclusions and Recommendations are given in Sections VII, VIII and IX, respectively.
II. GENERAL CONSIDERATIONS CONCERNING STRESS EFFECTS
IN PN JUNCTION DEVICES

2.1 The Need for High Stress Levels

As will become apparent later in this report (See, for example, Appendices A and C), high levels of mechanical stress, of the order of $10^9$ to $10^{10}$ dynes/cm$^2$, are required to obtain high sensitivity of transducer action. The fact that stresses of this order are easily obtained when the force is applied to a diode or a transistor by means of a small spherical indenter is apparent from the following considerations. The radius of the area of contact on the basis of Hertz's analysis can be expressed by

$$a = \sqrt[3]{\frac{3\pi}{4} \frac{W R}{E_1 \left( \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right)}}$$

where $v_1$ and $E_1$ are the Poisson's ratio and Young's modulus for the sapphire spherical indenter of radius $R$, and $v_2$ and $E_2$ are analogous quantities for silicon, while $W$ is the applied load in grams. Poisson's ratio can be taken as $v_1 = v_2 = v = 0.3$ and the elastic moduli are $E_1 = 1.87 \times 10^{12}$ dynes/cm$^2$ for silicon and $E_2 = 3.45 \times 10^{12}$ dynes/cm$^2$ for sapphire. Hence, the radius $a$ (in centimeters) is given by

$$a = 0.83 \times 10^{-4} \sqrt[3]{\frac{W R}{4}}$$

For a sapphire indenter of radius $R = 25$ microns (1 mil-inch), the radii "a" for loads of 2, 25 and 60 grams are 1.42, 3.3 and 4.41 microns,
respectively. The pressure exerted on the transistor surface under the indenter is given by the expression

\[ p = \frac{3W}{2\pi a} \sqrt{1 - \frac{r^2}{a^2}} \]

It is easily seen that the pressure at the center of the circle of contact \( p_0 \) is \( 1 - \frac{1}{2} \) times the average pressure and is equal to zero at the edge of the circle of contact. The calculated maximum \( (p_0) \) and average pressures \( (p) \) under the indenter for loads of 2, 25 and 60 grams are given in Table 1.

<table>
<thead>
<tr>
<th>Force (Grams)</th>
<th>Maximum Pressure ( (p_0) ) (dynes/cm(^2))</th>
<th>Average Pressure ( (p) ) (dynes/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( 4.74 \times 10^{10} )</td>
<td>( 3.16 \times 10^{10} )</td>
</tr>
<tr>
<td>25</td>
<td>( 1.10 \times 10^{11} )</td>
<td>( 7.34 \times 10^{10} )</td>
</tr>
<tr>
<td>60</td>
<td>( 1.47 \times 10^{11} )</td>
<td>( 9.80 \times 10^{10} )</td>
</tr>
</tbody>
</table>

Considering that the above values of pressure, or stress, are rather high, the load on the indenter should be kept at a minimum. Completely reversible behavior has been observed up to loads of 20 grams in earlier work. In the results that will be presented later in this report, reversible behavior of stressed transistors has been observed also. In the construction
of transducer structures the load has also been kept to a minimum value, usually, less than 5 grams.

2.2 Effect of Crystallographic Orientation

At present, various investigators agree on the fundamental physical mechanism responsible for the stress effects, namely, the change in the energy gap of the semiconductor material with applied stress. Briefly, the energy gap of a semiconductor represents the minimum energy that has to be supplied to a crystal to make it conduct electricity. This energy might be provided by irradiating the crystal with light of suitable wavelength or by heating it. Similarly, mechanical stress can alter the electrical properties of such semiconducting crystals as silicon or germanium by making them more or less conducting. The magnitude of the effect for a given applied stress depends, among other things, on the semiconductor material and the crystallographic direction in which stress is applied. Therefore, it is important to know the appropriate stress coefficients of energy gap of a semiconductor in order to characterize its usefulness as a potential transducer material. The symbol which will be used for the pressure coefficient of energy gap is $\frac{\partial E_g}{\partial T}$, where $E_g$ is the energy gap and $T$ is the applied stress.

Table 2 which has been adapted from Reference 32 lists energy gap coefficients for the most important orientations which are used in the production of silicon and germanium transistors.
Table 2

Pressure Dependence of Energy Gap

<table>
<thead>
<tr>
<th>Material</th>
<th>Crystallographic Direction</th>
<th>$\frac{\partial E_g}{\partial T}$ (eV dyne$^{-1}$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>$\langle 111 \rangle$</td>
<td>$-5 \times 10^{-12}$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$\langle 100 \rangle$</td>
<td>$-8 \times 10^{-12}$</td>
</tr>
<tr>
<td>Germanium</td>
<td>$\langle 111 \rangle$</td>
<td>$-9 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

The coefficients for $\langle 110 \rangle$ oriented silicon and for the remaining two orientations for germanium are smaller than those listed above.

The sensitivity of transistors to stress increases as the absolute value of the energy gap coefficient increases. In addition, the greater the absolute value of the coefficient, the lower is the prestress necessary to achieve the regime of high sensitivity. On this basis it would appear that germanium transistors should offer the best choice for transducer applications. However, germanium devices are more temperature sensitive than their silicon counterparts; therefore, the particular application and/or the ability to compensate for temperature effects has to be considered before a choice can be made. The coefficient for $\langle 100 \rangle$ oriented silicon has a value that is close to that of $\langle 111 \rangle$ germanium. Therefore, it would appear that $\langle 100 \rangle$ oriented silicon devices present a good alternative choice.
III. RESPONSE OF TRANSISTORS TO STRESS

3.1 Experimental Apparatus

Figure 3.1 shows the experimental apparatus for stressing transistors. The stressing jig is situated on the antivibration table. It consists of a needle holder, which is mounted on one X-Y-Z micromanipulator so that the needle can be accurately positioned on the transistor wafer, and a dynamometer which is attached to a second X-Y-Z micromanipulator. First, the needle is placed on the transistor surface in a desired region and then a force, whose value is read on the scale of the dynamometer, is applied to the needle. This approach makes the positioning of the needle independent of the application of force, thus eliminating the danger of scratching the surface of the transistor with the hard tip of the sapphire needle.

The transistor current-voltage (I-V) characteristics can be displayed on the face of the oscilloscope, or recorded graphically with the help of an X-Y recorder.

3.2 Curve Plotter

To study pressure effects on semiconductor devices, a versatile and easy to operate I-V curve plotter has been built. The plotter draws the I-V characteristic curves of diodes and npn or pnp transistors on an X-Y recorder. All currents are plotted on a logarithmic scale.

The schematic of the circuit of the plotter is shown in Fig. 3.32. The currents to be measured are converted into logarithmic scale by reference diodes which, in the current range of \(2 \times 10^{-9}\) amp. to \(2 \times 10^{-1}\) amp., have the "ideal" diode characteristics that the current through the diode is proportional to the exponential of the voltage across the junc-
Figure 3.1. Experimental Apparatus.
Figure 3.2. Circuit Schematic of the Diode and Transistor Curve Plotter.
tion. The reference diode used was obtained by connecting five base-emitter junctions of Motorola 2N2222 transistors in parallel. The purpose of parallel connections is to improve the "ideal" diode characteristics at high current ranges. Collectors and bases are connected together to minimize storage charges.

The measurement of the voltage across a diode is accomplished with the help of a Hewlett-Packard Model 425A Micro-Ammeter (M) in series with a $1 \times 10^{10}$ ohm resistor. The error created from the current drawn by this voltmeter is negligible when measuring a diode current of $10^{-9}$ amp. or larger. The selection of either pnp or npn transistor is achieved by an eight-pole switch which can reverse the connections of power supplies and reference diodes in the circuits simultaneously. A motorized sweep driver is connected to the shaft of the potentiometer $R_1$ to control the base current. The voltage across the base-emitter junction and the current of either base or collector of a transistor are recorded directly on an X-Y recorder. If the device to be tested is a diode, it is connected across the terminals of base and emitter.

3.3 NPN Transistors Stressed Near the Emitter-Base Junction

Figure 3.3 contains photographs of the surfaces of four different types of transistors. Picture (a) shows surface features of a 2N834 silicon npn transistor whose stress behavior will be discussed in this section. The stress behavior of the other transistors will be taken up in following sections.

The innermost rectangle in picture (a), which contains one of the electrical leads, establishes the boundary of the emitter region. The sapphire indenter of 25 micron radius was placed at a distance of about 10 microns from the edge of the emitter. The collector and base current
Figure 3.3. Photographs of the Surface Features of Four Types of Transistors. (a) 2N334 Silicon [111] NPN Transistor; (b) Special Motorola [100] Oriented Silicon PNP Transistor; (c) 2N2905 Silicon [111] PNP Transistor; (d) 2N3250 Silicon [111] PNP Transistor. Magnification 175X.
curves that were plotted with the apparatus described in previous sections are shown in Fig. 3.4. These results are similar to those shown in an earlier publication. However, the range of currents covered in the present work is much greater.

A measure of stress sensitivity for this particular transistor can be obtained by plotting the values of the collector current at different loads on the indenter for fixed values of base current. Such results for three fixed base currents are shown in Fig. 3.5. It will be observed that the sensitivity, or the slope of the current versus load line, increases with base current. There is usually an optimum value of base current, however, for which the sensitivity reaches a maximum. Further increases in base current result in a decreased sensitivity. This is because the mechanical stress is applied only to a small area of the emitter region which causes the stress-induced current curves to come together at higher current values, as can be seen from Fig. 3.4. The sensitivity for \( I_B = 0.32 \) mA is approximately 2mA/gram.

Figure 3.6 illustrates the effect of base resistance \( R_B \) on the sensitivity of a 2N834 silicon transistor. The data were obtained for a base current of 200 microamperes in the following fashion. A preload of 5 grams was put on the needle to render the transistor sensitive. After fixing the value of base resistance, a load of two grams was added to the indenter. The voltage across the output resistor was then measured after adjustment of the base current to the original value. Sensitivity for a given \( R_B \) was obtained by dividing the voltage change by the change in the loading force. It is apparent from Fig. 3.6 that the sensitivity increases with increasing base resistance. However, a plateau is reached at a resistance of about 10 kohms. These results are in agreement with data reported by other
Figure 3.4. I-V Characteristics of Motorola 2N834 [111] NPN Silicon Transistor under Various Conditions of Stress. Indenter Radius 25 Microns.
Figure 3.5. Plots of Collector Current Versus Load (in Grams) on the Indenter Obtained from Data of Fig. 3.4 for Three Values of Base Current. Sensitivity for $I_B = 0.32$ MA is 2 MA/GRAM. Approximate Linear Range is 7 Grams.
Figure 3.6. Sensitivity in Volts/Gram as a Function of Base Resistance. Prestressing Load was 5 Grams, and the Incremental Load was 2 Grams. Transistor was 2N834 NPN Silicon.
investigators and are typical of npn transistors. For pnp transistors stressed away from the edge of the emitter it is advantageous to have a low value of base resistance, hence, to operate in the constant voltage, rather than constant current mode. Characteristic curves of pnp transistors will be shown in Section 3.5.

3.4 PNP Transistors Stressed Near the Emitter-Base Junction

The results of Fig. 3.7 are characteristic of a special Motorola transistor which was formed in a [100] oriented silicon wafer. According to Table 1, optimum sensitivity can be realized with this orientation in silicon material. In addition to a change in the orientation of the silicon wafer, an indenter with a radius of 10 microns was used in this case. A reduction in the radius of the indenter is also expected to result in an increase in the stress sensitivity of a transistor. In fact, the results of Fig. 3.8 support these expectations; the sensitivity for a constant current operation at $I_B = 0.32$ mA is approximately equal to $15 \text{ mA/gram}$. If we consider an output resistor of 10,000 ohms, a change of one gram force on the indenter would result in a voltage change of 150 volts.

$$\Delta V = \Delta IR = 15 \times 10^{-3} \text{amperes} \times 10^4 \text{ohms} = 150 \text{ volts}$$

Similarly, since one gram-force is approximately equal to 1000 dynes, a change in the force of one dyne on the indenter would result in a signal of 150 millivolts.

As is shown in Fig. 3.8, the price that one has to pay for such a high sensitivity is a reduced linear range of operation. The linear range in the present case is only about one gram.
Figure 3.7. I-V Characteristics of a Special Motorola Transistor Diffused into a [100] Oriented Silicon Wafer under Various Stress Conditions. Indenter Radius 10 Microns.
Figure 3.8. Plots of Collector Current Versus Load on the Indenter Obtained from Data of Fig. 3.7 for Three Values of Base Current. Sensitivity for $I_B = 0.32$ MA is $15$ MA/GRAM. Approximate Linear Range is One Gram.
In order to increase the linear range, a wedge-type indenter has been used in a separate experiment. The results are shown in Figs. 3.9 and 3.10. In this case a linear range of 10 grams was obtained. The sensitivity for $I_B = 0.32$ mA was 1 mA/gram. The wedge was positioned with its edge parallel to the emitter-base boundary and about 10 microns from it.

The results on another pnp transistor are shown in Figs. 3.11 and 3.12. In this case a spherical indenter of 25 micron radius was also positioned near the edge of the emitter. The corresponding values of sensitivity and linear range are 2.5 mA/gram and 5 grams, respectively.

In all cases where the indenter was placed in the vicinity of the emitter edge (a distance of less than 10 microns) a decrease in the collector current was observed with application of force to the indenter. In the following section, results are shown for a pnp transistor which was stressed away from the emitter boundary. In this case the collector current was observed to increase with an increase in the force on the indenter.

### 3.5 PNP Transistors Stressed Away from the Emitter Edge

The curves of Figures 3.13 and 3.14 are typical of pnp transistors which are stressed away from the emitter edge. A transition in the type of stress response with position of the indenter is easily observed providing the transistor is large enough with respect to the indenter.

The maximum sensitivity is observed when the indenter is positioned very close to, or right over the emitter-base boundary. The amount of decrease of collector current (for a given fixed base current) falls off as the indenter is moved away from the emitter edge. At some point the stress sensitivity disappears altogether. We are assuming a fixed load on the
Figure 3.9. I-V Characteristics of a Motorola 2N2837 [111] PNP Silicon Transistor under Various Conditions of Stress. A Wedge-Type Indenter was Used.
Figure 3.10 Plots of Collector Current Versus Load on the Indenter Obtained from Data of Fig. 3.9 for Three Values of Base Current. Sensitivity for $I_B = 0.32$ MA is $1$ MA/GRAM. Linear Range is 10 Grams.
Figure 3.11. I-V Characteristics of a Motorola 2N2905 [111] NPN Silicon Transistor under Various Stress Conditions. Spherical Indenter of 25 Micron Radius was Used.
Figure 3.12. Plots of Collector Current Versus Load for the Transistor of Fig. 3.11. Sensitivity 2.5 MA/GRAM. Linear Range 5 Grams.
Figure 3.13. I-V Characteristics of a Motorola 2N3250 [111] PNP Silicon Transistor under Various Stress Conditions. Spherical Indenter of 25 Micron Radius was Used. Note that Little Change is Observed in the Base Current Curves and Instead the Collector Current Curves Undergo a Shift. The Indenter was Placed Away from the Emitter Edge.
Figure 3.14. Plots of Collector Current Versus Load for the Transistor of Fig. 3.13. Sensitivity 1 MA/GRAM. Observe that the Collector Current Increases with Stress.
indenter. At a distance greater than approximately 10 microns from the emitter edge, the collector current is observed to increase, instead of decreasing, for the same load on the indenter.

This subject matter is discussed in more detail in Section V, since what is important from the point of view of transducer applications is not only the sensitivity but also the signal-to-noise ratio. The electrical noise is very high when transistors are stressed very close to, or right on the junction; therefore, this mode of operation is not recommended.

3.6 PNP Germanium Transistors

Figures 3.15 and 3.16 show collector and base current curves for a germanium transistor stressed by means of a 25 micron radius sapphire indenter. The difference in the behavior of the transistor characteristics under stress between the two figures is due to a different position of the indenter on the surface of the transistor. Sensitivity to stress is much greater when the stress is applied near the base-emitter junction just as in the case of silicon transistors.

Because of the large absolute value of the pressure coefficient of energy gap in germanium, large decreases in collector current were observed for relatively small prestressing loads, namely, two to three grams. However, germanium transistors were not as extensively studied as silicon transistors on account of their greater temperature sensitivity, as was mentioned in Section 2.2.

3.7 Junction and Insulated-Gate or Metal-Oxide-Semiconductor (MOS) Field Effect Transistors

The field effect transistors (FET) either junction or insulated-gate, differ radically from the conventional (bipolar) npn and pnp transistors studied thus far. While in bipolar transistors both positive and negative
Figure 3.15. I-V Characteristics of a Motorola 2N961 [111] PNP Germanium Transistor under Various Conditions of Stress. Indenter Radius 25 Microns. Stress Applied Away from the Junction.
Figure 3.16. I-V Characteristics for a Germanium Transistor of Fig. 3.15, Except that Stress was Applied Near the Junction.
free carriers take part in the conduction process, in field effect (unipolar) transistors the current is carried only by the free majority carriers in the conduction channel. A good description of field effect devices is given, for example, in Reference 60.

Figure 3.17 compares the basic lead terminology of an FET, a conventional bipolar transistor and the vacuum-tube triode.

Mechanical stress was applied by means of a 25 micron radius indenter to Motorola junction field effect 2N4220A transistors in the region of the source. A photograph of this type transistor is shown in Fig. 3.18. The results of this investigation are reported in Table 3.

The response to stress of insulated-gate (MOS) field effect transistors has also been studied using the same stressing apparatus. Large shifts in the I-V characteristics of Motorola 2N4351 and 2N4352 transistors have been observed when the indenter was placed over the gate metallization in the vicinity of the source and drain regions. The results of these investigations are given in Table 3 and also in Appendix C, which constituted a recent publication in the September 1968 issue of the Proceedings of IEEE. A photograph of an MOS transistor of the type used in our studies is shown in Fig. 3.19.
Figure 3.17. Comparison of Basic Lead Terminology of Vacuum Tubes, Bipolar Transistors and Field Effect Devices.
Figure 3.18. A Photograph of a Motorola 2N4220A Junction Field-Effect Transistor. Magnification 400X.
Figure 3.19. A Photograph of a Motorola 2N4352 MOS Transistor. Magnification 400X.
4.1 Early Transistor Transducers

Early transistor transducer (microphone) structures\textsuperscript{40,47} were quite bulky as shown in Fig. 4.1. The diameter of the diaphragm was about 1.5 inches and the height of the microphone about 2.5 inches. The transducer structure consisted of a 1 mil-radius sapphire needle which was mounted at the center of the diaphragm and pressed against the surface of the transistor. The critical phase of the assembly was to accurately position the transistor under the needle near the emitter-base junction in order to arrive at a high sensitivity.\textsuperscript{50} The above construction procedure was found to be very tedious, time consuming and thus impractical. The goal of the present program was to devise a simpler transducer assembly procedure.

4.2 Design and Construction of Pre-Aligned Transducer Elements

It was thought desirable to construct a transistor sensing capsule which could be incorporated into a pressure sensor or other transducer applications such as microphones or hydrophones.

The considerations for the design of the transistor transducers were based on an attainable sensitivity of about 100 millivolts per inch of water into a load of 10 kohms or 100 microamperes per inch of water. We decided to construct a pressure transducer about the size of a standard TO-46, or TO-18 transistor header. The TO-18 header has a diameter of .167 in. Using a diaphragm of this size yields a surface area of .022 in.\textsuperscript{2} In terms of total force on the diaphragm this would be about .36 grams per inch of water. However, if the diaphragm does not bend very much, then, because the edges are fixed and bear part of the total force, the force actually applied to the centered stylus is only 1/3 of the total force on
Figure 4.1. An Early Transistor Microphone.
the diaphragm. Thus, for a depth of one inch of water, a force of 120 dyne is applied to the stylus.

Numerous manufacturers are currently marketing silicon planar transistor chips for the transistor and integrated circuit industry. The problem of choosing a suitable chip for stress applications was to obtain drawings or samples of the chips. The chip should have an accessible emitter region that is not interfered with by the lead contact areas. The chips used by us for the current transducers were made by the Raytheon Corp. located in Mountainview, Calif. and designated as processes N500C and P500C for the npn and pnp chips, respectively. These chips were supplied untested but the batch contained very few faulty samples, most of which were found to be pnp chips. The chip size is 35 x 35 x 6 mils but most of the surface area is occupied by three large contact tabs. This configuration made wire bonding quite convenient and the emitter region was thus free from obstruction. The collector could be contacted from the back of the chip as well.

Stress sensitivity of the chips was determined by probing with the stylus that would be used in the finished transducer. In this way the ultimate sensitivity of the finished unit could be estimated. A plot of collector current versus force was made on an X-Y recorder for each chip as is shown in Fig. 4.2. A sensitivity of at least 1 mA/gm was found necessary for a resultant sensitivity of the transducer to be 120 microamperes per inch of water. The most reliable spot for the placement of the stylus was determined to be one in whose vicinity the sensitivity was nearly constant. In general, transistor chips tended to have rather large regions where this condition existed. The sensitivity depended only on the amount of preload required for the operation in the linear portion of the Collector
Figure 4.2. Experimental Arrangement for Testing the Stress Sensitivity of Transistor Chips.
Current \((I_c)\) vs. Force, or the sensitivity, curve.

The construction of the transducer is shown in a cross-sectional view in Fig. 4.3. An assembled transducer and its component parts are shown in Fig. 4.4. The diaphragms were made of 302 stainless steel shim stock .001 and .002 inches thick. They were prepared by cutting with surgical shears and also by punching with a hardened punch and die. The latter technique was used exclusively on the .002 inch thick diaphragms. Cases were made of both stainless steel and "Invar," a 36% Ni, 64% Fe alloy noted for extremely low thermal expansion.

The assembly procedure was to construct the case and diaphragm as one integral unit and the header, chip and stylus as another, and then join the two units together to form a finished transducer. In this fashion it was possible to make the necessary alignment of the stylus before the final assembly. Proper preload was attained in the final phase of joining the header and case-diaphragm assemblies.

The fabrication of the transducers was straightforward. A header and case were matched for easy fit. The header was then ground flat on top and the chip was cemented thereon. Eastman 910 cement held the chips quite securely, however, one was then compelled to connect the collector to the body of the header. If we chose to connect the emitter to the body of the header, it was necessary to lay down an insulating layer of epoxy before attaching the chip. The chips were then attached to the insulating layer with more epoxy since the solvent in the 910 cement tended to attack the epoxy layer. The chips were wired electrically with .002 in. diameter aluminum wire. Bonding was done using an ultrasonic bonder. The chip was then evaluated with the aid of a Tektronix Transistor Curve Tracer and probed to determine a good location for the stylus.
Figure 4.3. Cross-sectional View of a Transistor Pressure Transducer.
Figure 4.4. A Photograph of an Assembled Pressure Transducer and Its Component Parts.
The problem of attachment of the stylus required considerable effort. Most cements caused a damping effect on the transmission of stylus pressure to the chip. A silicone potting compound was finally used to both support the stylus and insulate the chip and the wiring. After the stylus was mounted, the header, chip and stylus could be stored for future use or assembled right away into a pressure transducer.

The main parts of the transducer were sealed together with epoxy cement. Epoxy was also applied to the sides of the header and to the blunt end of the stylus immediately before final assembly. With the help of a micromanipulator the two subassemblies were held in the required position for proper preload until the epoxy cured. This operation was controlled by keeping the pen of the curve tracer on the linear portion of the sensitivity curve.

4.3 Testing of Pressure Transducers

The completed transducers were tested by first applying air and then water pressure in a J-tube arrangement as shown in Fig. 4.5. Circuits used for electrical biasing of transducers and for the measurement of pressure sensitivity are given in Figs. 4.6 and 4.7. Figure 4.8 shows a photograph of a portable transducer tester whose electrical circuit was given in Fig. 4.7.

In Fig. 4.9 results are shown for a pressure transducer whose sensitivity was 200 millivolts per inch of water. The pressure range over which the measurements were taken was five inches of water. The curves shown in the figure were obtained for three different biasing conditions. The base current was changed over a factor of four. Two different output resistors were used, namely, 1 and 2 kohms to obtain the data shown. The above results were completely reversible.
Figure 4.5. Transducer Sensitivity Test Setup.
Figure 4.6. Circuit for Biasing Transistors and Measuring Pressure Sensitivity of Transducers.
Figure 4.7. Electrical Circuit of a Portable Pressure Transducer Tester.
Figure 4.8. Photograph of a Transducer Tester.
Figure 4.9. Pressure Dependence of the Collector to Emitter Voltage ($V_{CE}$) of a Transistor Pressure Transducer. The Sensitivity of this Unit was 200 MV/IN. Water.
The sensitivities that were observed for a number of transducers ranged from about 100 to 350 microamperes per inch of water.

4.4 Some Applications of Transistor Transducers

Figure 4.10 is a photograph of a public address system which can be operated with either of the two semiconductor microphones shown; the one on the left is a piezoresistive microphone of an earlier vintage, and the one on the right is a transistor microphone which was constructed recently. The sensing element of the transistor microphone is a commercial pressure transducer (PITRAN) which was purchased from Stow Laboratories.* The sensitivity of the Pitran pressure transducer as given on the manufacturer's calibration chart was 6.6 volts/gram when operated at $I_B = 60$ microamperes, $I_C = 0.8\ mA$ and $V_{CB} = 2$ volts. Since 1 gram of force is equivalent to 14 inches of water for this transducer and $R_L = 10,000$ ohms, the current sensitivity is 47 microamperes per inch of water. For comparison purposes, the sensitivity of the transducer of Fig. 4.9 was 200 millivolts per inch of water. Since $R_L$ was only 2,000 ohms for similar bias conditions, the equivalent current sensitivity is 100 microamperes per inch of water, hence somewhat greater than that for the Pitran transducer used.

In the construction of the above transistor microphone, the bottom of a carbon transmitter-type diaphragm of 10 cm$^2$ effective area was attached by means of epoxy to the center region of the diaphragm of the Pitran.

The sound quality of the system is quite good. The transistor microphone requires about 20 db less amplification than the piezoresistive microphone for the same output power. However, the transistor microphone appeared to have a greater self-noise than the piezoresistive microphone.

* Stow Laboratories Inc., Stow, Mass.
Figure 4.10. A Photograph of a Public Address System Using Semiconductor Microphones. The Microphone on the Right is a Transistor Transducer, the One on the Left a Piezoresistive Transducer.
The circuit diagram of the power supply is given in Fig. 4.11.

Numerical data on signal and noise of selected stressed transistors are given in Section V, Table 3. To minimize noise, low noise amplifier transistors should be used.

A similar approach could be taken in the construction of a hydrophone. Toward this goal we have built a pressure sensor with a hole in the side of the case for pressure equalization purposes. This transducer could be operated under water because of the internal lead insulation as is shown in Fig. 4.3.
Figure 4.11. Schematic of a Battery-Operated Power Supply for the Microphones of Fig. 4.10.
V. NOISE STUDIES

5.1 Noise in Stressed Transistors

Noise in mechanically stressed transistors may arise both from the governing physical phenomena and from anomalies connected with actual damage of the device. Preliminary measurements indicate that the major portion of the noise arises from the physical phenomena of stress induced currents, rather than from damage. A related question is the reversibility of the stress effect induced noise. Here the experimental evidence is good that both the dc characteristics and the noise characteristics are reversible. There is also good correlation, qualitatively at least, between the behavior of the stress induced noise and physical model for the stress effect. Quantitative correlation has been hindered by difficulties in separating electron and hole currents crossing the emitter-base junction and measurement of the true potential barrier at the junction. These problems have been recently solved and quantitative verification will hopefully follow.

The importance of an adequate model for the stress phenomena should be obvious if any attempt is to be made to predict noise behavior for various operating modes. A detailed model has been worked out for bipolar junction transistors using the theory of stressed pn junctions developed by Wortman, Hauser and Burger.\textsuperscript{20,22} It is similar to the model presented by Edwards.\textsuperscript{19} This model states that the principal effect of mechanical stress is to change the energy gap of the semiconductor. The effect of compressive stress in silicon is to lower the bandgap. This decrease of $E_g$ means that, in a non-degenerate semiconductor, the minority carrier concentration is increased. The product of electron and hole concentrations may be written as
\[ pn = n_i^2 \exp\left(-\frac{E_g}{kT}\right) \]

where \( n_i \) is a constant determined by the material and temperature. All of the donors (acceptors) are assumed ionized at normal operating temperatures. Decreasing the energy gap has the primary influence of increasing the hole (electron) concentration in the non-degenerate semiconductor. Of course holes and electrons are created in equal numbers, but the great percentage increase occurs for the minority carriers.

When stress is applied to bipolar transistors, both npn and pnp, the interesting effects occur for stress in the pn junction. Stress was applied in an inhomogeneous fashion by a sapphire stylus pressed against the emitter. Planar diffused silicon transistors were used for the most part. The same theory holds for silicon and germanium mesa transistors.

Only the qualitative aspects of the theory will be presented here. A more detailed explanation and representative calculations are given in Appendix C. It is encouraging that all of the details of stress-current curves can be explained with this model, particularly with respect to variations of these curves as the stylus position is changed.

Wortman introduces the function \( \gamma(e) \) which expresses the ratio of minority carrier density under stress to the unstressed state. This is an exponential function and is pictured in Figure 5.1. There is essentially no increase until a stress level of \( 10^9 \) dynes/cm\(^2\) is reached. Consider a pnp transistor with stress at the base edge of the emitter-base junction. If the fraction of the junction area not stressed is \( A \), and the fraction stressed is \( B \), then the hole current crossing the junction from emitter to base is
MINORITY CARRIER RATIO

STRESS (DYNES/CM\(^2\))

10^5
10^4
10^3
10^2
10^1
1

10^7 10^8 10^9 10^{10} 10^{11} 10^{12}

AFTER WORTMAN, HAUSER AND BURGER
J. APPL. PHYS. 35, 2122 (1968)

Figure 5.1. Minority Carrier Density Ratio of the Stressed State to the Unstressed State.
\[ I_{pe} = I_{po} (A + By) \exp(qV/kT) \]  

\[ (1) \]

\( I_{po} \) is a constant dependent on the material and doping level. \( q/kT \) evaluated at room temperature is \((26 \text{ millivolts})^{-1}\). \( V \) is approximately the applied bias voltage, as long as the resistive drops inside the transistor structure are small. Exactly, it is the difference between the quasi-Fermi levels for holes and electrons, evaluated at the center of the junction.

The stress is to be evaluated at the edge of the space charge region of the junction. Application of stress thus causes an increase in emitter hole current.

An analogous equation can be written for electrons diffusing from the base to the emitter across the barrier. \( I_{no} \) would normally be very small compared to \( I_{po} \) since the base is more lightly doped than the emitter (p+n junction).

Successful interpretation of this theory requires that the unstressed concentration of carriers be explicitly evaluated in the region where the stress exists. Use of average values of concentrations will not yield correct results when inhomogeneous stress is applied. It is also important to realize that the entire emitter is not being stressed, only a particular fraction, but the entire emitter current must be measured at the terminal. We are measuring at the terminal \( I_e \), where

\[ I_e = I_{pe} + I_{ne} \]  

\[ (2) \]

If the model treats \( I_{pe} \) and \( I_{ne} \) separately, as it does for inhomogeneous stress, then all three terminal currents must be measured in order to ob-
tain the electron and hole portions of each.

Figure 5.2 shows a typical plot of collector and base current as a function of emitter-base voltage for a 2N3798 pnp silicon planar transistor. The slope of the curve has a simple form when the logarithmic vertical scale is used. Taking the logarithm and then differentiating with respect to V in Equation 1 gives

\[ \text{slope} \propto \frac{q}{kT}. \]  

(3)

The current should increase a decade each

\[(26 \times 10^{-3}) \log_{10} 10 = 60 \text{ millivolts} .\]

This slope indicates that the "ideal" currents of elementary transistor theory are dominant. Sah, Noyce and Shockley\textsuperscript{62} described the process of carrier generation-recombination in the barrier region of a pn junction. The argument of the exponential function is \( qV/2kT \) in this case, so the slope will only be one half that of the "ideal" currents. This gives a method of separating generation-recombination currents from other currents in the junction. Note however that surface and volume recombination currents will display the usual \( qV/kT \) dependence since they are proportional to minority carrier concentration. Current-voltage characteristics which are linear (resistive) will appear as a logarithmic curve on the plot. The resistance value may be determined from the curvature. Some rounding of the curves at high current levels is from resistive effects.

The quantity \( h_{FE} \) is the vertical distance between the base and collector current curves. The doubling of \( h_{FE} \) at higher currents is in agree-
Figure 5.2. Base and Collector Current Curves for a 2N3798 PNP Transistor.
went with Webster. Cutoff current agrees with published characteristics. High current injection (base conductivity modulation) causes the reduction of $h_{FE}$ at high collector currents.

Figure 5.3 shows the results of stressing the transistor in the center of the emitter with a sapphire stylus. Collector current increases greatly (often by 10-100) while base current shows only slight increases. The current distribution in a planar transistor and the stress distribution explain this. Stress is concentrated in the junction region under the emitter (as opposed to the "side" of the emitter). This region is characterized by very high base resistivity, because of the diffusion process of manufacture, low volume recombination, and low injected hole densities under normal operation. Lateral current flow through the high resistance base tends to cut off this portion of the emitter. Stress on the emitter side of the junction multiplies the electron current from the base, as in Equation 1. $I_{no}$ is so small for this region that the contribution to total base current can be neglected. Stress on the base side multiplies the hole current from the emitter. $I_{po}$ for this region is a respectably large number. $I_{pe}$ for this region under ordinary operation was small because of the potential drop through the base, not because of the doping level in the emitter. Thus appreciable hole current flows with the lowered potential barrier. The slight increase in base current could be either from bulk recombination or $I_{ne}$. Obviously this stress effect is dependent on a thin emitter, a criterion not satisfied by all transistors.

Figure 5.4 shows the same results for a stylus located about 10 microns from the junction as it rises to the surface. Both collector and base currents increase with stress. Slope of the base current curve for low or moderate stresses is $q/kT$ but falls off towards $q/2kT$ at higher stress lev-
Figure 5.3. Base and Collector Current Curves for a 2N3798 Transistor Stressed Away from the Emitter-Base Junction.
Figure 5.4. Base and Collector Current Curves for a 2N3798 Transistor Stressed Near the Emitter-Base Junction.
els (when the surface of the junction becomes stressed). Surface recombi-
nation should be increased because of the large number of centers located in the stressed region. Stress increases the hole current into this sur-
face recombination region and the centers "gobble up" the new holes. In-
creased electron current from the base is also likely because the doping level in the base is much higher at the surface. Collector current shows some increase because, as before, there is increased hole injection from the sides and bottom of the emitter. The base current curves tend together at higher current levels, probably because of the base resistance. The rounding of collector current is an indication of high level injection. High level injection occurs when the concentration of minority carriers exceeds the concentration of majority carriers (electrons) in the base. The argument of the exponential is replaced by qV/2kT and the contribu-
tion of this portion of the emitter becomes less significant as base bias voltage is increased. High level injection occurs for this device as a whole for 10 mA of collector current, as witnessed by a reduction of pub-
lished β for higher currents.

Similar effects take place when the stylus is placed directly over the junction. Base current shows a tremendous increase and has a q/2kT slope at high stress levels, indicating the importance of recombination in the junction and high level injection. Collector current, on the other hand, will remain constant or actually decrease up to 30%. High current densities result in lowered emitter efficiency and the increased base cur-
rent tends to reduce the forward bias in the stressed region. Thus this portion of the junction actually contributes less to the collector current in the stressed state than it did in the unstressed state.
Noise spectral densities were measured with bandpass amplifiers and, separately, with a Tektronix type 315 spectrum analyzer. Details of the measurement system are given in Appendix D. Acoustic noise and effects of light on the photosensitive transistor had to be eliminated. Generally speaking, with proper care it was possible to have the stressed noise level be within a factor of ten of the unstressed level. Not all transistors behaved this well, as might be expected.

Care must also be taken in comparing noise levels in the stressed and unstressed state. Background noise of the transistor is very dependent on current levels, and these current levels change with the application of stress. Application of stress close to the junction with high base resistance would decrease the collector current. If a comparison were made between, say, 1 mA no load noise and 0.1 mA collector current stressed noise, the loaded transistor would sometimes be quieter at high frequencies (10 kHz) but noisier at low frequencies. This would result from a reduction of collector current shot noise at high frequencies, where it is dominant, and an increase in 1/f noise (related to base current) at low frequencies. However, if the comparison were made between the same stressed operating point and a new operating point for the unstressed transistor, namely, 0.1 mA collector current, the unstressed transistor would be quieter.

Figure 5.5 gives the spectra for a well-behaved bipolar transistor and Fig. 5.6 gives the spectra for a junction field effect and a MOS transistor. The general shape of the noise spectrum was always similar in both the stressed and unstressed modes. This suggests that the same mechanisms giving rise to noise in ordinary operation also give rise to noise in stressed operation. This would be indicated by the model, which states that the effect of stress is just to change the relative distribution of currents
Figure 5.5. Noise Spectra for a Well-Behaved 2N929 NPN Transistor.
Figure 5.6. Noise Spectra for a 2N4351 MOS and a 2N4220A Field Effect Transistor.
within the transistor. The differences in noise spectra, for a given collector current, result from the differences between shot noise and $1/f$ noise. In addition to the different spectra shapes, shot noise power is proportional to average current and $1/f$ noise power is proportional to mean square current. When comparison is to be made between the low frequency portions of different spectra, a better starting point would be equal base currents rather than equal collector currents. There is a strong connection between recombination currents and $1/f$ noise, although the question is not yet settled.

The importance of a good model can be reemphasized. Comparison of operating locations, quiescent current levels and biasing impedances all require a knowledge of the different currents flowing within the transistor. Some contribute to collector current (hole current from the emitter of a pnp device), some contribute to the base current (electron diffusion current into the emitter and recombination currents), and all of the mentioned contribute to emitter current. Since each has a unique spectral density function it is necessary to know each if the maximum signal-to-noise ratio is to be achieved with a given transistor structure.

Although exact quantitative correspondence has yet to be achieved between the model and experimental noise spectra (the same could be said for ordinary transistor operation!), the qualitative correlation is good. Experimental results suggest that the transistor pressure transducer is capable of giving good noise performance. Dynamic ranges and equivalent input noise force are given for selected transistors in Table 3.

5.2 Results and Conclusions

1. Noise effects are reversible. The noise level returns to that of the unstressed level as the load is removed.
<table>
<thead>
<tr>
<th>Transistor Type</th>
<th>$I_c/I_d$</th>
<th>Stress Sensitivity (mA/gram)</th>
<th>Linear Range (G)</th>
<th>Equivalent Noise</th>
<th>Input (Grams) 10-100 Hz</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NPN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2N929</td>
<td>1 mA</td>
<td>0.5</td>
<td>2</td>
<td>$0.85 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>44 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42 dB</td>
</tr>
<tr>
<td><strong>PNP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2N3250</td>
<td>0.1 mA</td>
<td>1.2</td>
<td>2</td>
<td>$0.25 \times 10^{-4}$</td>
<td>$0.40 \times 10^{-4}$</td>
<td>49 dB</td>
</tr>
<tr>
<td>2N3798</td>
<td>0.1 mA</td>
<td>0.7 (up)</td>
<td>4</td>
<td>$0.30 \times 10^{-4}$</td>
<td>$0.45 \times 10^{-4}$</td>
<td>51 dB</td>
</tr>
<tr>
<td></td>
<td>1 mA</td>
<td>0.1 (down)</td>
<td>9</td>
<td>$4 \times 10^{-4}$</td>
<td>$6 \times 10^{-4}$</td>
<td>43 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>41 dB</td>
</tr>
<tr>
<td><strong>MOSFET</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2N4351</td>
<td>2 mA</td>
<td>0.06</td>
<td>50</td>
<td>$14 \times 10^{-4}$</td>
<td>$20 \times 10^{-4}$</td>
<td>45 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44 dB</td>
</tr>
<tr>
<td><strong>JFET</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2N4220A</td>
<td>5 mA</td>
<td>0.4</td>
<td>10</td>
<td>$0.75 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>51 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>49 dB</td>
</tr>
</tbody>
</table>
2. The spectra for the stressed and unstressed transistor are the same in shape but differ in level. Transistors yielding basically similar results included

<table>
<thead>
<tr>
<th>NPN</th>
<th>PNP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2N834</td>
<td>2N3248</td>
</tr>
<tr>
<td>2N929</td>
<td>2N3250</td>
</tr>
<tr>
<td>2N2222</td>
<td>2N3798</td>
</tr>
<tr>
<td>2N3020</td>
<td>2N3799</td>
</tr>
<tr>
<td>2N3947</td>
<td>MM2503</td>
</tr>
</tbody>
</table>

N-channel JFET: 2N4220A

N-channel MOS: 2N4351

Included are general purpose, low noise audio amplifier, RF amplifier, and switching transistors.

3. Quieter transistors will be quieter. Transistors not designed for low noise work would typically have noise spectra 10 times higher than the low noise units. These noisier units would typically be noisier unstressed than the low noise units would be stressed. Thus it is important to choose transistors which are quiet in the unstressed state.

4. A rule of thumb for an upper bound to noise in the stressed mode would be to multiply the unstressed noise level by 10. The noise power will always be greater for a given current level when the transistor is stressed than unstressed (collector current in stressed transistor equal to collector current in an unstressed transistor); but, the noise power of a stressed transistor may be greater than or less than the no load case, depending on how the currents change as a result of stress.

5. For a given transistor and stylus position, the quiescent current levels seem to have little effect on the signal-to-noise ratio. This is in agreement with earlier work by Rindner. Sensitivity is often proportional to the quiescent current level; doubling quiescent currents will
about double stress sensitivity. RMS noise voltage is proportional to quiescent current for 1/f noise, so signal voltage and noise voltage would increase equally with quiescent current.

6. For a given transistor, stylus position and quiescent current level, the optimum base impedance is that impedance which gives a maximum sensitivity. For the case of transistors whose collector current levels are increasing with stress (away from junction, base current approximately constant), this impedance is zero, a voltage source. For the case of transistors stressed near the junction so that the base current increases and collector current decreases, the stress sensitivity increases with base impedance. However little increase occurs for base impedances higher than 10 kilohms, and since noise does increase for higher impedances, the optimum base resistance is about 10 kilohms. The sensitivity-base impedance curve should be obtained in any particular case.

7. Maximum signal-to-noise ratios occur when the transistor is stressed not directly on the junction. Signal-to-noise ratio will often be degraded by a factor of 10 when the transistor is stressed directly on the junction. Although the stress sensitivity will be much higher, the noise level is even higher. This is due to the relatively large recombination currents now flowing around the periphery of the emitter and in the emitter-base junction. Tests on a 2N3798 showed that for a 0.3 mA/G sensitivity, the transistor stressed on the junction was 10 times noisier than the transistor stressed away from or even close to the junction. Equal sensitivities were obtained by adjusting the quiescent current level. Because of the increased noise and problems of possible indenter movement, stylus locations on the emitter-base junction should be avoided.
8. The stressed noise level is most likely to approach that of the unstressed transistor when the stylus is placed away from the junction, in the middle of the emitter. The effect of stress is now to increase the hole current from the emitter of a pnp. The base current is left relatively unchanged. Since this increased current flows from the bottom of the emitter where there are few recombination centers, the only noise component should be ordinary shot noise, associated with carriers crossing the potential barriers. Early experimental data indicates this is true, with little increase in $1/f$ noise as when the stylus is located on the junction. Of course it is necessary to have a thin emitter or no stress sensitivity is observed, in which case the noise level is unimportant.
VI. TEMPERATURE EFFECTS

Transistor transducers just as plain transistors are sensitive to temperature changes. This is because the energy gap of the semiconductor material depends on temperature.\textsuperscript{70} Compensation for temperature effects is therefore needed for most applications. It has been suggested previously\textsuperscript{71} that the encapsulation of the transducer be designed so as to reduce the pressure on the stylus as the temperature is increased. This approach is being used in the Stow transducers, one of which was tried in the transistor microphone configuration described in Section 4.4. A typical zero shift ($\Delta V_{CE}$) for a more temperature stable transducer of this type was quoted to be $\pm 50 \text{ mV/}^\circ C$ and the change in sensitivity as a function of temperature as $-0.2 \text{ percent/}^\circ C$.

An alternate method of temperature compensation might be to use two transistor chips on one header, or a chip containing two transistors (a matched pair) in a differential amplifier configuration. This approach would lead to automatic cancellation of temperature effects in the normal operation of transistors (such as emitter-base voltages, collector leakage currents, and current gain). However, since the stress sensitivity is both temperature and base current dependent, biasing diodes could be used to compensate for temperature changes. The sensitivity decreases with decreasing temperature\textsuperscript{4,9} and it increases with increasing base bias current, see Figs. 3.5, 3.8, etc. Therefore, by having the diodes increase the quiescent current levels when the temperature decreased, the decrease of the sensitivity could be avoided. An example of such diode compensation is given on page 35 and following of Reference 72, although the purpose there is to hold the operating point constant. In summary, by using a pair of transis-
tors, not only can normal changes in transistor operation with varying temperature be cancelled, but changes in the stress sensitivity can be compensated for also.
VII. DISCUSSION

The crucial question to answer is whether a new device concept, such as the pn junction transducer, can advance the present state of technology. The purpose of this project was to generate enough data and in such a form that comparisons could easily be made between the characteristics of present day devices and those of the new transducers. We have concentrated in our research on transistors, rather than diodes, because of the built-in amplification inherent in these devices, thereby reducing the problems of amplification of signals which are so typical of piezoelectric transducers. Furthermore, transistor transducers are characterized by a linear voltage response to forces on the indenter, the range of which can be controlled. Stable transistor sensing elements can be made providing safe loads are not exceeded by the indenter on the transistor, the diaphragm is firmly attached to the case, and the indenting structure, whatever it may be, a needle, knife edge, etc. are properly aligned so that slippage over the transistor surface cannot occur. Of course, the design of the transducer making use of such a sensor has to be carefully considered, so that excessive loads are not applied to the sensor.

The simplest circuit that can be used with transistor transducers is one which allows Class A amplifier operation (see Fig. 4.6, for example). Of the three possible configurations - common emitter, common base, common collector - the common emitter configuration offers the greatest power gain and is thus the best choice for routine applications. An example of an exception would be if the transducer had to drive a long coaxial line, in which case the common collector's low output impedance might be
of advantage.

The next step would be to use a differential amplifier with emitter coupling. Many of these are available in integrated circuit form and should be applicable for transistor transducer applications. The idea of using two transistors, either on separate chips, or a matched pair on a single chip, has been briefly mentioned in Section VI. The advantages of the differential pair are several. By using a bridge circuit, the output can indicate unbalances only; thus, the output meter can read zero with only the bias force applied. The advantages of allowing for compensation of temperature effects have already been discussed in VI. A further advantage of the differential pair is that small changes in supply voltages do not affect the performance, hence, battery power supply could be reliably used.

A further advancement in circuitry would be the use of a modulation and AC amplification scheme. This approach would offer optimum noise rejection. If the total collector current of a differential pair of transistors were modulated, the output signal would contain an AC component and thus AC amplification could be used. It would be possible to build a phase-locked system and achieve the theoretically optimum amplification with respect to $S/N$ ratio. About four individual integrated circuit cans would be needed, so the circuit would not actually be too complex. This approach would be especially advantageous in the following two cases. First, if an operational transducer were needed, this scheme would allow operation at the quietest frequency of the transducer and also an easy implementation of the best noise filtering methods. Secondly, the operation frequency could be made variable and then noise at each frequency could be easily measured. Thus the system would be a good noise measuring device.
Most of the experimental work was done on bipolar transistors. Various modes of stressing npn and pnp transistors have been explored and the results presented and explained. In order to allow comparisons with performance of conventional devices, we have obtained data on sensitivity, linear and dynamic ranges and calculated equivalent noise inputs to facilitate the determination of signal-to-noise ratios.

Presently, an illustrative example will be given of the calculation of the signal-to-noise ratio for the transducer of Section 4.2 using Table 3. Let us assume that a pressure of one inch of water is exerted on a transducer using a pnp 2N3798 transistor. Let the frequency range be from 10 to 1000 Hz. The sensitivity for the \( I_{c} \) mode (indenter placed away from emitter edge) from Table 3 is 0.7 mA/gram. For a pressure of 1 inch of water, the force on the indenter is 0.12 grams. Since the equivalent noise input (ENI) from Table 3 is \( 0.45 \times 10^{-4} \) grams, we have

\[
S/N = \frac{0.12 \text{ grams}}{0.45 \times 10^{-4} \text{ grams}} = 2.67 \times 10^3
\]

or

\[
S/N = 68.5 \text{ dB}
\]

Similarly, \( S/N \) for a 1 dyne/cm\(^2\) pressure is equal to approximately 10 dB.

If a microphone diaphragm of 10 cm\(^2\) effective area were attached to the transducer capsule, the signal-to-noise ratio for such a device for a 1 dyne/cm\(^2\) sound pressure would be equal to 47 dB.

It is interesting to note also that \( S/N \) would be equal to unity if one wished to detect a force of 0.05 dyne.
The results obtained with field effect transistors are quite encouraging. The MOS field effect transistor was characterized by a large linear range of 50 grams, although the sensitivity observed was relatively low (0.06 mA/gm). However, if stress is applied through an etched window in the gate metallization, sensitivity should be improved considerably. Another interesting development in connection with the work on MOSFET devices was the new type of transducer with digital measurement capability which can be used not only to measure mechanical pressure or force, but also temperature and light intensity.

The junction field effect transistor according to Fig. 5.6 had lower noise power than the MOS device for frequencies below 10 kHz, but the opposite was true for higher frequencies. In general, the noise power for the field effect transistors appeared to be less than for the bipolar transistors. Therefore, these devices may have a potential for larger S/N ratios than can be obtained with bipolar transistors.

On the basis of the work performed the following conclusions can be formulated.
VIII. CONCLUSIONS

1. Experimental results on transistors indicate that effects of mechanical stress and of stress-induced noise are reversible, providing excessive loads are not applied. Therefore, reliable transistor transducers can be, and have been made in the course of this work.

2. The stress effects can be explained most consistently by the bandgap model.

3. The stress-induced noise in transistors can be explained, at least qualitatively, on the basis of the current transistor noise theory.

4. The optimum crystallographic orientation is [100] for silicon and [111] for germanium transistors.

5. The sensitivity values obtained on bipolar transistors ranged from a fraction of a mA/gram to 15 mA/gram.

6. The linear range for bipolar transistors varied from one to ten grams and was even greater for field effect devices (up to 50 grams).

7. The dynamic range for various transistors under a variety of operating conditions was found to vary from 41 to 49 db.

8. Optimum base impedance is a function of mode of operation; large impedance should be used for npn transistors and low impedance for pnp transistors when stressed in the middle of the emitter (away from the emitter edge). This represents the optimum operating mode.

9. Signal-to-noise ratio is independent of quiescent current levels.

10. Signal-to-noise ratio is poor for "on junction" operation.

11. The effect of mechanical stress on the noise spectra of transistors is to raise the level of the noise power, but the shape of the spectra remains the same.
12. Low noise transistors have lower noise when stressed.

13. The upper bound for stressed-induced noise power is ten times the noise of unstressed devices.

14. MOS field effect transistors can operate as digital transducers for the measurement of pressure, light intensity, or temperature.
IX. RECOMMENDATIONS

Since a quantity of data have become available on various performance parameters of pn junction transducers, and theoretical work has led to the explanation of the main features of stress phenomena, it is felt that the time is ripe for the application of the transistor transducer concept in concrete problem areas. Use of integrated circuits can be made to compensate for temperature effects within limits dictated by a specific application and similarly, optimization of transducer designs can be made with the help of a computer. The size, geometry and positioning of the indenter could be introduced to relate applied force to electrical change. The basic forms of such relationships for sphere and wedge radii have already been detailed in mechanical theory; more specialized designs should be capable of easy extension. The model would be constructed only in those areas where current theory and/or data already exist. Similarly, the bandgap theory can be used to establish the relationships between mechanical force and electrical changes. The model so devised can then be programmed for computer usage.

In the area of basic studies, a more thorough investigation should be conducted of the MOS field effect structures similar to the one used in the construction of the capacitive digital transducer. In particular, MOS configurations should be constructed under well controlled conditions. The effects of putting in impurities, which affect surface conditions, should be thoroughly studied. The impurity effects should then be correlated with the electrical noise characteristics so as to attain the best $S/N$ ratio for a transducer application. Finally, a correlation should be established between the surface conditions, the applied voltage and the
amount of prestress necessary as well as the degree of linearity attainable upon application of stress to the MOS structure.

Other projects of interest would be to conduct a quantitative study of noise phenomena in bipolar transistors, and to measure high stress piezoresistance coefficients, which are not known at present, and which affect the performance of pn junction devices subjected to mechanical stress.
REFERENCES


57. See Reference 47, p. 310.

58. S. Fuchs, Phys. Z. 14, 1282-1285 (1913).


62. C. Sah, R. Noyce and W. Shockley, "Carrier Generation and Recombина-

63. W. Webster, "On the Variation of Junction-Transistor Current Ampli-


The purpose of this Section is to evaluate a probable value of the coefficient of energy gap for (111) direction in silicon using experimental data for a uniaxially stressed diode and a measured (reported) value of the piezoresistance coefficient.

According to the Shockley theory, current in a p-n junction is given by

\[ I = qA \left[ \frac{D_p n_p}{L_p} + \frac{D_n n_p}{L_n} \right] \left( \exp \frac{qV}{kT} - 1 \right) \]  

where \( q \) is the electronic charge; \( A \) is the area of the junction; \( n_p \) and \( n_n \) are the minority carrier densities; \( D_p \) and \( D_n \) are the diffusion constants for holes and electrons, respectively; \( L_p \) and \( L_n \) are the respective diffusion lengths; \( V \) is the voltage applied to the junction; and \( kT \) is the Boltzmann energy.

Since the diode in our study was heavily doped on the p-side, \( n_p \), or the electron concentration in the p-type material, is negligible compared with \( n_n \), and the current consists mainly of the minority hole flow from the n region. Hence, the first term in the bracket can be neglected.

The diffusion constant \( D_p \) is defined by

* All references for Appendix A are given at the end of this Section.
\[ D_p = \mu_p \frac{kT}{q} \]  
\[ I = \frac{AkT}{L_p} \mu_p p_n (\exp \frac{qV}{kT} - 1) \]

where \( \mu_p \) is the mobility of the holes. Thus Eq. (1) can be rewritten as follows:

neglecting for the moment the effect of the series resistance of the diode which is of importance at higher current levels. When the applied voltage \( V \) is positive and greater than 0.1 volt, the forward current \( I_F \) can be expressed by

\[ I_F = \frac{AkT}{L_p} \mu_p p_n \exp \frac{qV}{kT} \]

The densities of holes and electrons are related by

\[ n_p n_n = n_i^2 = N_c N_v \exp(-E_G/kT) \]

where \( n_n \) is the density of the majority carriers or electrons in the n-type material; \( p_n \) is the density of the minority carriers, or holes, in the n-type material; \( n_i \) is the intrinsic carrier density; and \( N_c \) and \( N_v \) are the effective densities of quantum states in the conduction and valence bands, respectively. Clearly, the density of the minority carriers \( p_n \) can change with the temperature and with the energy gap. The quantity \( n_n \), which can
be considered in our case to be equal to the number of donors \( N_D \) in the n-type material, is a constant.

If we make the substitution \( p_n = \frac{N_i^2}{N_D} \), then

\[
I_F = q\mu p \exp(-E_g/kT)\exp(qV/kT)
\]  

(6)

where \( C \) is a constant equal to \( AkT/L_n N_D \).

When a mechanical stress is applied to the diode, both the hole mobility \( \mu_p \) and the energy gap \( E_g \) will change. Let us consider separately the changes in these quantities.

Since the resistivity of the p-region is given by

\[
\rho = \frac{1}{q\mu_p N_A}
\]  

(7)

where \( N_A \) is the number of acceptors per cubic centimeter, a reciprocal relationship exists between the mobility \( \mu \) and the resistivity \( \rho \). By definition, \( \partial \rho / \rho = \pi_p T \), where \( \pi_p \) is the piezoresistance coefficient and \( T \) is the applied stress. Hence \( \partial \mu_p / \mu_p = -\pi_p T \). The ratio of hole mobility under stress \( \mu_p \) to the hole mobility at zero stress \( \mu_{p0} \) is given by

\[
\frac{\mu}{\mu_0} = 1 + \pi_p T .
\]  

(8)

By Eq. (5), the ratio of minority carrier density under stress \( p_n \) to the carrier density at zero stress \( p_{n0} \) will be
\[
\frac{p_n}{p_n^0} = \exp\left(-\frac{\Delta E_G}{kT}\right)
\]  (9)

The above expression is called \(\gamma(\varepsilon)\) by Wortman et al. (Ref. A-3). The quantity \(\Delta E_G\) in Eq. (9) can be written as

\[
\Delta E_G = \frac{\partial E_G}{\partial T} \Delta T,
\]  (10)

where \(\frac{\partial E_G}{\partial T}\) is the stress coefficient of energy gap and \(\Delta T\), or simply \(T\), is the stress increment.

From the above expressions, the forward current of the p-n junction subjected to a mechanical stress will be

\[
I_F = (1 + \pi_T T)I_0 \exp\left(\frac{q}{nkT} (V - \frac{1}{q} \frac{\partial E_G}{\partial T} T)\right)
\]  (11)

The quantity \(I_0\) is the reverse current under zero stress and \(n\) is a constant, different, in general, from unity.

For a stress of magnitude \(1 \times 10^{10}\) dynes/cm\(^2\) and with the piezoresistance coefficient \(\pi_T = 30 \times 10^{-12}\) cm\(^2\)/dyne,\(^*\) the quantity \((1 + \pi_T T)\) in Eq. (11) is equal to 1.3.

\* According to Ref. 2, \(\pi_T\) for p-type silicon in \langle111\rangle direction is \(93.6 \times 10^{-12}\) cm\(^2\)/dyne. The gage factor, or the product \(Y_{\langle111\rangle}(\pi_T)\langle111\rangle\) is 175. Mason et al.\(^4\) have shown that for highly doped p-type silicon the gage factor is only 60 or one third of the value quoted in Ref. 2. Hence, \(\pi_T\) in our case is taken to be approximately equal to \(30 \times 10^{-12}\) cm\(^2\)/dyne.
For small stresses, $T < 5 \times 10^8$ dynes/cm$^2$, an approximation $e^x = 1 + x$ can be made. For higher stresses the current increases exponentially with increasing stress.

Figure A-1 shows current-voltage characteristics of an uniaxially stressed silicon mesa diode for two stress conditions as indicated in the figure. We will now evaluate the relative effects of the changes in the energy gap with those affecting the series resistance of the diode as a result of the piezoresistance effect. Since the curves cross at high current levels the piezoresistance effect is expected to exert a prominent influence on the shifts of the I-V characteristics with stress.

The diode used in this experiment was made from an n-type antimony-doped silicon wafer of resistivity ranging from $\rho = 0.12$ to $\rho = 0.16$ ohm-cm. The breakdown voltage of the diode was about 50 volts. The axis of the diode lay in a (111) crystallographic direction. The highly doped p-type region was produced by the diffusion of boron atoms.

Expression (11) can now be rewritten including the terms associated with diode resistance.

$$I_T = I_0 \exp \left( \frac{q}{nkT} \left( V - \frac{1}{q} \frac{\partial E_g}{\partial T} T - IR + I \frac{\partial R}{\partial T} T \right) \right)$$

where $R$ is the diode resistance at zero stress and $\partial R/\partial T$ is the rate of change of resistance with stress. In similarity with the previous expression relating resistivity and piezoresistance coefficient, we can write

$$\frac{\Delta R}{R} = \nu_T T$$

(13)
Figure A-1. I-V Characteristics of a Uniaxially Stressed Silicon Mesa Diode for Two Stress Conditions: $T = 0$ and $T = 1.73 \times 10^{10}$ dynes/cm$^2$. Only the Forward Characteristics is Under Study.
where $\eta_\ell$ is the piezoresistance coefficient in the (111) direction. Hence

$$\frac{\partial R}{\partial T} = R\eta_\ell$$

(14)

For very small forward currents, the terms multiplied by $I$, and hence those involving resistance, can be neglected. For the diode of Fig. A-1 the resistive effects seem to appear for currents larger than $10^{-3}$ amperes. Since the current is plotted on a semilogarithmic scale, the slope of the curve represents $q/nkT$. The value of the term $\frac{q}{kt} \approx 38.6$ at room temperature. The curves of $\ln I$ vs. $V$ for zero stress and $1.73 \times 10^{10}$ dyne/cm$^2$ stress intersect at a current of 33 ma. Thus, at the intersection the sum of the two terms $(-\frac{1}{q} \frac{\partial E_g}{\partial T} T + I \frac{\partial R}{\partial T} \Delta T)$ is equal to zero. By equating the two terms, we have $I \frac{\partial R}{\partial T} = \frac{1}{q} \frac{\partial E_g}{\partial T}$. The quantity $\frac{\partial E_g}{\partial T}$, is the pressure dependence of energy gap, $I$ is equal to 33 ma, and $q$ is the charge of an electron, and $\partial R/\partial T$ is given by Eq. (14).

(1) Determination of $n$

From Fig. A-1 we have

$$\frac{\ln I - \ln I_o}{\Delta V} = \frac{q}{nkT} = \frac{1}{n} 38.6 ,$$

and

$$\frac{\ln 10^{-4} - \ln 10^{-7}}{0.557 - 0.214} = \frac{38.6}{n} .$$

Hence
\[ n = \frac{(38.6)(0.343)}{3 \ln 10} = 1.92 \]

(2) Determination of \( I_o \):

From Fig. A-1:

\[ I_o = 1.5 \times 10^{-9} \text{ amp.} \]

(3) Determination of \( R \):

At \( I = 33 \text{ ma} \)

\[
\frac{I}{I_o} = e^{\frac{q}{nkT} (V - IR)}
\]

Taking logarithms and substituting numbers we have,

\[
\ln \frac{33 \times 10^{-3}}{1.5 \times 10^{-9}} = \frac{38.6}{1.92} (V - 33 \times 10^{-3} R)
\]

\[
\ln 22 \times 10^6 = 20.1 (V - 33 \times 10^{-3} R)
\]

Since \( V = 1.3 \text{ volts when I = 33 ma} \),

\[ R = 13.9 \text{ ohm} \]

(4) Determination of \( \frac{\partial E_G}{\partial T} \):

Since
\[ \frac{\partial R}{\partial T} = \frac{1}{I} \frac{\partial E_G}{\partial T} = R \pi_t \]

\[ \frac{\partial E_G}{\partial T} = IR \pi_t \]

For \( I = 33 \times 10^{-3} \) ampere, \( R = 13.9 \) ohm and \( \pi_t = -7.6 \times 10^{-12} \text{cm}^2/\text{dyne} \)

\[ \frac{\partial E_G}{\partial T} = -3.5 \times 10^{-12} \text{V cm}^2/\text{dyne} \]

However, since \( n = 1.92 \), this indicates a strong contribution of the generation recombination currents, and the term

\[ -\frac{1}{q} \frac{\partial E_G}{\partial T} T \text{ in Eq. (12)} \]

should be multiplied by a factor \( 1/2 \).

Therefore, \( \frac{\partial E_G}{\partial T} = -7 \times 10^{-12} \text{V cm}^2/\text{dyne} \) for (111) direction is silicon.

The above value is comparable to \(-5 \times 10^{-12} \text{V cm}^2/\text{dyne}\) from Table 2 of the main text. It is possible that the piezoresistance coefficient \( \pi_t \) decreases with stress, in which case the two values for the pressure coefficient of energy gap would be even closer. High stress values for the piezoresistance coefficients do not appear to be available in the literature for \( n \) silicon in (111) direction.
REFERENCES


APPENDIX B

MOS TRANSUCERS WITH DIGITAL MEASUREMENT CAPABILITY
Published in Proc. IEEE 56, No. 9, 1599 (September, 1968).
MOS Transducers with Digital Measurement Capability

Abstract—A new MOS type of transducer is reported which can be used to measure mechanical pressure or force, temperature, and light in digital form.

Recently the piezoresistance effect of semiconductor materials and the piezoelectric effect of semiconductor $p-n$ junctions have been utilized in transducers to measure force or mechanical pressure. Semiconductor devices such as resistors, diodes, bipolar transistors [1], [2], unipolar transistors [3], and thin film transistors [4] have all been exploited as electro-mechanical transducers. This letter reports on the development of a unique solid-state transducer using the capacitance change in a metal-oxide-semiconductor (MOS) structure. The MOS capacitive transducer can be used to measure mechanical pressure, temperature, or light intensity, and it can easily be incorporated into electronic circuits to obtain measurements in digital form.

When operating at a sufficiently high frequency so that surface state charges and minority carriers cannot follow the signal variation, the MOS capacitance in the inversion region is equivalent to series connection of the oxide capacitance and the semiconductor space-charge capacitance. The high-frequency semiconductor inversion capacitance, which is dependent on the energy-band gap, impurity concentration, relaxation time of minority carriers, and the signal frequency, is sensitive to mechanical pressure, temperatures, and light. The pressure effect on the high-frequency inversion capacitance can be related to changes in the energy-band gap. It has been shown, for example, that the energy-band gap is decreased when the silicon is under mechanical stress [5]. This decrease has the effect of increasing the high-frequency inversion capacitance [6]. The increase of temperature in the semiconductor has an effect similar to a decrease of the energy-band gap. The high-frequency inversion capacitance will therefore increase with the increase of temperature [7]. When the MOS is illuminated, the semiconductor surface is under the condition of thermal nonequilibrium because of carrier excitation. However, the semiconductor inversion capacitance under nonequilibrium steady-state conditions can be treated similarly to the condition of thermal equilibrium [8]. The high-frequency inversion capacitance will increase with increasing illumination. One factor that will affect the inversion capacitance under all conditions of pressure, temperature, and illumination is that the inversion capacitance will increase whenever the increase of carrier generation rate is sufficient to cause a transition from high-frequency type to low-frequency type.

In experimental work, commercially available 2N4351-N channel-type and 2N4332-P channel-type MOS FET's are used to provide the MOS structures. Since both of these MOS FET's are for enhancement-mode operation, gate metals overlap portions of diffused sources and drains; this creates useful MOS structures between gate and source and between gate and drain. The MOS structure between gate and channel is not used because of its less favorable $C-V$ characteristics. When using the MOS as pressure or force transducer, the force is applied by a sapphire indenter of 0.001-inch radius on the gate metal where it overlaps either the source or the drain depending on which one of the MOS structures is used. Fig. 1(a) shows a typical $n$-type MOS C-V characteristic with and without mechanical pressure. The curves are plotted on an $x-y$ recorder by an automatic C-V plotter operating at 1 MHz. Fig. 1(b) gives the measured capacitances as a function of force.

In order to accomplish the digital measurement capability, the MOS capacitive transducer is built into an astable multivibrator to control the oscillating frequency. Fig. 2 shows the circuit of the astable multivibrator with an MOS frequency-controlling element. The circuit is designed to satisfy these criteria: 1) the oscillating frequency is sufficiently high so that minority carriers and surface state charges cannot follow the signal variation; 2) the MOS is operating in inversion region at any point of an oscillating cycle; 3) percentage change of the oscillating frequency is as close as practical to that of the MOS capacitance change. No special effort has been made thus far to obtain good frequency and temperature stabilities. Fig. 3(a) and (b) shows the digitally measured frequencies as a function of mechanical pressure and illumination, respectively. In the illumination experiment, light intensity is measured by the voltage applied across a focused microscope light source. The noise equivalent of the transducer varies from ±10 Hz without pressure or light to ±200 Hz with pressure or light on the MOS.

The output capacitance of a bipolar transistor is also known to be sensitive to mechanical stress [9]. In comparison, the MOS has the advantages of being a two-terminal passive device, of not consuming power, and of not requiring dc bias. The dc voltage bias can be avoided by introducing positive surface state charges into $n$-type MOS and negative surface state charges into $p$-type MOS, thus shifting the MOS $C-V$ characteristic curves from their theoretical forms, so as to have inversion regions around zero dc bias voltage. The ready availability of the MOS structure in integrated circuits makes it easy to incorporate MOS capacitive transducers therein.

 Manuscript received June 12, 1968. This work was supported in part by the Office of Naval Research under Contract N00014-67-A-0159-0001, NR 187-804.
Fig. 2. MOS transducer with digital output.

Fig. 3. Frequency as a function of (a) pressure and (b) light.

C. K. Kuo
M. E. Skowronski
E. J. Scheinbein
Physical Sciences Div.
Georgia Inst. Tech.
Atlanta, Ga. 30332

REFERENCES


‘Presently with Texas Instruments Inc., Dallas, Tex. 75222"
APPENDIX C

THEORETICAL CONSIDERATIONS OF THE STRESS EFFECT AND NOISE

This appendix is a catalog of phenomena thought to be important in describing mechanically stressed p-n junction transistors and the noise that arises from current flow in these transistors. An attempt is also made to describe the various theories proposed to explain the stress phenomena.

A. Requirements for a Stress Effect Model:

Any model for the stress effect must explain in a consistent way certain characteristics of the effect.

1. The model must explain whether device currents should increase or decrease with stress. The model should explain whether the change in currents should be linear with stress or exponential with stress. Inhomogeneous stress applied with a stylus affects only a fraction of the junction area in commercial transistors and diodes. Thus effects which decrease current in this area will only slightly affect terminal currents while effects which increase current flow through the stressed area can greatly affect terminal currents. The required prestress and high stress levels favor a model exponential in stress. The exponential behavior of currents with stress is shown in Figure C-1. These curves were obtained from a 2N3798 operated with the stylus near the emitter-base junction. Once the prestress of 4 grams is obtained, each increment of stress results in an equal increment of distance on the logarithmic vertical current scale. Thus the current is exponential in stress. Note: the "linear range" of a stressed transistor is obtained in one of the following two ways, in an analogous fashion to the way "linear" operation of ordinary transistors is obtained. If the
Figure C-1. Stress Induced Base Currents in a PNP Transistor.
source impedance to the base is small, only small variations in emitter-base voltage are allowed. The expression for collector current as a function of emitter-base voltage, similar to Equation (1) of Section 5.1, can be expanded in a Taylor series in \( V \) about the unstressed operating point. If the unstressed operating point was \( I_0 \) and the change in voltage is \( \Delta V \),

\[
I(V) = I_0 + \frac{(qAV/kT)I_0}{2} + \ldots
\]

Current appears linear in \( \Delta V \) for limited ranges of \( qAV/kT \). The second linearizing factor is the biasing circuit impedance. This factor is dominant when the base circuit source impedance is higher than \( h_{12} \).

2. The model should explain the slopes of stress-current curves as a function of applied emitter-base voltage. Diffusion and recombination currents originating in different portions of the transistor are characterized by different voltage dependencies. All are of the form \( \exp(qV/mkT) \) but may vary from 1 to 4. (See Figures 7 and 8, Reference 1; Reference 2 considers four different locations for the origination of currents and the ranges of the parameter \( m \) for each). As noted before, resistive voltage-current relationships would appear as logarithmic curves on the stress-current plot.

3. The model should account for transistor operation at the proposed current densities. Simple one-dimensional, low-level injection theory\(^3\) does not account for variations in transistor operation as a function of emitter current. High current densities give rise to a variety of effects which can dominate the low-level injection theory. The theory should also

\* All references for Appendix C are given at the end of this Section.
account for current distribution in the unstressed transistor. (See Reference 4 for the distribution of recombination currents around the emitter periphery; Section 4-4 of Reference 5 discusses current crowding in the base region of a diffused transistor. Chapter 7 of Reference 5 discusses typical impurity profiles for diffused transistors; from these sheet resistance and crowding effects can be computed).

4. The model should explain the variations in the stress-current plots as the stylus location is varied. The transistor is characterized by increased collector current and slightly increased base current when the emitter is stressed far from the emitter-base junction. The increase in collector current can be a factor of 20 or more (Figure 17, Reference 6). As the stylus is brought closer to the emitter-base junction, collector current remains increased but base current begins to increase also. As the stylus is placed on the junction the collector current will remain unchanged, or decrease from the no load value, and the base current may increase by a factor of 50 or more.

B. Possible Theoretical Explanations for Stress Effects:

There are two main schools of thought as to the phenomena causing the stress effect. These are the bandgap model (7,8,9) and the reversible dislocations model (10). The possibility of changes in mobility and lifetime causing the stress effect has also been mentioned (Section IV-B, Reference 11). The bandgap model offers the most consistent explanation of the experimental results.

1. The primary effect of stress in the bandgap model is to change the bandgap by varying both the valence and conduction band levels. For nondegenerate material this forces a change in the Fermi level. When stress is
applied to the edge of the space charge region of a p-n junction this band-gap change is equivalent to changing the applied bias voltage. The relationship between changes in valence band level, conduction band level, and Fermi level may be computed with the aid of Section B, Reference 7 and Table III of Reference 7. The Fermi level shifts so that the density of majority carriers remains essentially constant. The major changes occur in the minority carrier density. The coefficient for change in energy gap is about

\[ -10^{-11} \text{ cm}^2/\text{dyne electron volts} \]

Thus a uniaxial stress of $10^{10}$ dynes/cm$^2$ results in a bandgap change of -0.100 volts. If this change occurred at the edge of a forward biased p-n junction, the change in diffusion current through the stressed area would be

\[ \exp(100/26) = 47 \]

at room temperature. If the change occurred at the edge of a reverse biased p-n junction the effect would be increased leakage or drift current, since minority carriers are swept across a reverse biased junction by the electric field.

The effect of uniaxial stress on bulk material is illustrated in Figure C-2 for p material. In the (111) direction the conduction band drops more than the valence band rises. If we assume a stress of

\[ 10^{10} \text{ dynes/cm}^2 \]
the conduction band drops 0.060 volts and the valence band rises 0.048
volts. The Fermi level will rise so that Equation 7 of Reference 7 is sat-
ished. Interpretation of the new Fermi level requires care since there
are several energy minima in the conduction band and these shift different-
ly with stress.

Figure C-2 is interesting in that it suggests the formation of quasi-
electric fields as suggested by Kroemer. Electrons would tend to fall to-
wars the surface of the crystal because of the bending of the conduction
band. Holes would similarly feel a "quasi-electric" acceleration towards
the surface. This would be an interesting effect in a forward biased p-n
junction because of the great concentration of recombination centers at the
surface of the crystal. Thus stress applied directly to the p-n junction
can increase the surface recombination velocity. This would account for
the great increases in base current seen when the stylus is placed directly
over the emitter-base junction. This increase in surface recombination ve-
locity would account for increased 1/f noise when the junction is stressed
directly.

Although the change in conduction, valence, and Fermi energy levels
can be applied directly to p-n junction behavior, it is simpler to use the
equations for the unstressed state (Sections 12.4 and 12.5 of Reference 13)
with the appropriate increases in minority carrier density. The increased
minority carrier concentration gives rise to increased leakage current in a
reverse biased junction and increased diffusion current in the forward bi-
ased junction.

The energy gap model satisfies the four criteria listed in Section A.
The bandgap model predicts increasing minority density with compressive
stress. Stress on the base side of the emitter-base junction increases the
Figure C-2. Stress Induced Energy Level Changes Near the Surface of Bulk Semiconductor Material.
minority carrier current from the emitter. This will directly increase collector current. Stress on the emitter side increases injection from the base into the emitter. This lowers the injection efficiency of the emitter but does not affect collector current directly.

Collector current will be affected if the increased carrier injection from the base appreciably increases base current. Two conditions are necessary for this to happen though. First, the injected current from the base must be appreciable in the unstressed state for the stressed region, and secondly, the base current must not be dominated by recombination currents flowing elsewhere in the transistor. The injected current level from the base is directly proportional to the minority carrier density on the emitter side of the junction. This density is very low in a p^+ n junction. Normally base current is dominated by recombination currents which are linearly related to injected current density from the emitter.

Returning to criterion 1 of Part A, bandgap changes are linear in stress. Transistor currents are exponential in voltage so currents will be exponential with stress. This is in agreement with Figure C-1 where the stress induced currents are exponential in stress and the stress induced changes in Fermi levels (biasing voltages) are linear in stress.

Criterion 2 states that the model should explain the slopes of the stress-current curves. The stress induced currents have, for the most part, the same slopes as the unstressed current curves. This means that collector current has a q/kT dependence since it depends only on the injected current density from the emitter. Stress does not affect this slope except when high level injection occurs. The slope then has a q/2kT dependence (Equation 4-17, Reference 5). Collector current will show a
decreasing slope when the local level of minority carrier injection from the emitter exceeds greatly the normal concentration of majority carriers in the base. This occurs when high stresses are applied and when the stylus is placed near the emitter-base junction. Base current will show the normal $q/mkT$ dependence, $1 \leq m \leq 2$, except when the stylus is placed near or on the emitter-base junction and recombination in the space charge region is increased. Thus the bandgap model predicts straight lines on a stress-current plot, with slopes appropriate for transistor action at the induced current densities.

The bandgap model explicitly accounts for transistor operation at the injected current densities. In fact, the bandgap model states that the primary effect of stress is to alter the current densities and changes in characteristics should be in accord with the new, higher, densities. The main deviation from this rule is the increased recombination at the surface, and in the space charge region, when the emitter-base junction is stressed directly (and therefore the base transport factor is reduced).

The bandgap model successfully explains the variations in stress response as the stylus position is varied. These are now summarized.

**Away from junction:** Emitter injection is increased due to stress in the base region. Base injection into the emitter is increased but is still negligible because of low minority carrier concentration in the emitter. Increased base current does result from volume recombination in the base. This increased recombination current is linear in injected carrier density from the emitter. It is likely to be dominated though by the surface recombination currents around the periphery of the emitter. High level injection will not occur until high stress levels and high forward bias voltages are reached.
Close to the junction: Emitter injection is again increased by stress in the base region. Stress in the emitter region causes an increase in injected carriers from the base. Base current increases result from increased base injection and increased volume recombination (from the increased emitter injected current). Base current increases are relatively larger than the increases in collector current. At high stress levels the strain field includes the emitter-base junction as it intersects the surface. Increased space charge recombination then takes place and the base current curves roll off to a $q/2kT$ slope.

On the junction: Base current is greatly increased, both from injection and recombination. Quasi-electric fields accelerate injected minority carriers up towards the surface, thus increasing surface recombination velocity and reducing base transport factor. Less collector current may flow in the stressed case than in the unstressed case. A reduction in transport factor is indicated by a constant percentage decrease in collector current over all emitter-base voltages. Sometimes collector current will show no variation with stress, indicating that increased injection is cancelling the effects of transport reduction.

2. The reversible dislocation theory is explained in (10,11) and the references cited therein. The effect of stress in this model is to introduce reversible dislocations and thereby introduce traps in the energy gap. The effect of such traps is to increase generation-recombination currents (1,8,13,14,15). Traps act as "stepping stones" for electrons wishing to go from the valence band to the conduction band (generation) or from the conduction band back down to the valence band (recombination). Introduction of traps into a reverse biased p-n junction increases leakage current by acting as a source of electron-hole pairs in the depletion region.
Carriers generated here are swept away by the electric field and flow in the external circuit. Traps located in a forward biased p-n junction act as recombination centers for injected minority carriers. Such traps in the emitter-base junction of a transistor result in increased base current, a $q/2kT$ dependence with voltage, and reduced collector current. Dislocation density and recombination current are approximately linear in stress (Appendix A of Reference 15).

The main difficulty with this theory is that it is linear in stress, and therefore would tend to be dominated by an exponential dependence on stress at high stress levels, and it does not explain the increases in collector current when the stylus is away from the junction. It would seem most reasonable in the case of reverse biased junctions, but even here the bandgap model (2) is adequate. Dislocation effects are probably most important in forward biased junction theory when the stylus is directly on the junction. Introduction of dislocations here would decrease the base transport factor; whether this effect or the quasi-electric fields are more important has not been established.

3. A third effect of stress is to change the mobility of carriers in the stressed region (Section IV-B of Reference 11). Drift currents are linear in mobility and diffusion currents are proportional to the square root of mobility. The coefficient of change in both silicon and germanium is about

$$ \pm 10^{-10} \text{ cm}^2/\text{dyne} .$$

A stress level of $10^{10} \text{ dynes/cm}^2$ would therefore either halve or double
mobility, depending on the appropriate sign. This change may be compared with the factor of 50 change in current density from stress induced band-gap changes at this stress level. The difference would be even greater at higher stress levels.

Base resistivity plays an important role in determining current distributions in a transistor. Stress induced changes in base resistance may be significant in the stressed region but it must be remembered that the remaining series resistance to the base contact is not altered. Although transverse voltage drops in the base tend to limit emitter injection in the region under the emitter, another, perhaps even more important, limitation is the low minority carrier density in the base region under the emitter, as compared to the base region near the surface. In other words, the electrostatic barrier is higher under the emitter than on the emitter sides near the surface. Even drastic lowering of base resistivity by increasing mobility in a selected, stressed, region may not greatly decrease the total resistance from junction to base contact. Base resistance does not seem to be important until base current reaches the 100 microampere level, at which time collector current is typically 10 mA. Decreased base resistance because of increased mobility would then be an important factor. Base resistance is important when the stressed and unstressed base current curves tend together at higher currents.

The effect on diffusion currents by changes in mobility would be important at all current levels, rather than just at high current levels as with drift currents. As an example, consider a pnp transistor. Consider the common (111) transistor and let the stress level be

\[ 2 \times 10^{10} \text{ dynes/cm}^2 \]
Base resistance in the stressed area is dependent on electron mobility (electrons are majority carriers in n material). The mobility change in n material with this orientation is

\[-7.6 \times 10^{-12} \text{ cm}^2/\text{dyne}\]

so we would expect a small increase in base resistance in the stressed region. Making the usual assumption that the mobility of holes is the same in n material as in p, we would use the coefficient for holes

\[93.6 \times 10^{-12} \text{ cm}^2/\text{dyne}\]

This stress level would increase the mobility by a factor of about three, and thus increase diffusion current in the base of a pnp transistor by about 3. This change is not important compared to bandgap changes.

C. Noise Processes:

Noise effects in transistor operation can be grouped in three categories: thermal noise, shot noise, and 1/f noise.

1. Thermal noise arises from the random motion of charge carriers as they drift in an electric field. The spectral density of such noise is constant to very high frequencies (> $10^9$ Hz). Thermal noise can be represented by a voltage source with spectral density

\[S_e = 2 kT R \]

R is the real part of the impedance of the device and
at 25°C. Thermal noise is not important in junction transistor operation because of the dominance of shot noise and 1/f noise.

2. Shot noise includes both generation-recombination noise in the p-n junction and the noise from random diffusion of carriers across the junction. The general expression for shot noise at low frequencies is

\[ S_i = q I_{AVG} \]

where \( I_{AVG} \) is the mean current flow. Deviations from this are given in Reference 16 for generation-recombination in the depletion region of the junction. These deviations are not great, however. The spectral density is flat out to the characteristic time constant of the process, in this case the minority carrier lifetime, after which rolls off in a \( 1/f^2 \) fashion. Lifetimes are typically of the order of \( 10^{-6} \) seconds in transistor work, so shot noise will be important to \( \sim 10^6 \) Hz. One important fact is that high level injection tends to increase the spectral density more rapidly than the above expression.

3. 1/f noise is different from shot noise in that it has a spectral density

\[ S_e \propto 1/f \]

and is proportional to mean square current flow. That is
The origins of l/f noise are not as well understood as shot noise. l/f noise is important because it dominates other noise sources below $\sim 10^3$ Hz. There is a definite connection between surface states\textsuperscript{18} and l/f noise (19, 20, 21). l/f noise is present both in field effect structures and bipolar transistors. It is dependent on majority carrier density, interface state density, and density of fixed oxide charges. l/f noise is minimized by careful surface treatment and by limiting the surface recombination velocity.

The origin of l/f noise is the trapping process in which a carrier is trapped and then later released. This can be contrasted to generation-recombination (shot noise) currents where hole-electron pairs are either created or destroyed. The fundamental event in l/f noise is thus similar to shot noise in that it involves the trapping process, but the distribution of time constants is different. Shot noise is characterized by a single time constant, the lifetime of carriers, but l/f noise is characterized by a $1/T$ distribution of lifetimes.

$$S_{\text{SHOT}} \propto I_{\text{AVG}}^2 \text{ and } S_{l/f} \propto I_{\text{AVG}}^2.$$
REFERENCES


REFERENCES (Concluded)


APPENDIX D

MEASUREMENT TECHNIQUES

Absolute measurement of noise in semiconductor devices requires some care. Fortunately the transistor is an amplifying device so that noise power from internal mechanisms is amplified and dominates the thermal noise of the load resistor. It was thus possible to have background noise from the measurement system be down by 10 dB or more over the entire spectrum. The problem of noise induced in the transistor, and then amplified by it, was considerably more troublesome. Noise sources from the environment include electromagnetic pickup, acoustic noise coupled through the stylus, and noise from light sources. For example, many transistors are photosensitive and respond to such light sources as overhead fluorescent lamps. This light source contains strong 120 Hz and harmonic components out to about 2000 Hz. Shielding of all electrical leads is a necessity. Otherwise, the spectrum from 560 kHz to 1.5 MHz will show all the local AM radio stations. Electrical noise was found to be a problem at all frequencies above 60 Hz. Acoustic noise is one of the biggest problems and is important to at least 1000 Hz.

The bipolar transistors were operated in a common emitter configuration, the most likely configuration for applications because of the high power gain and moderate output impedance. The field effect transistors were operated in a source follower configuration. The basic circuits are shown in Figure D-1. The field effect transistors were biased into the pinch-off region by the 6 volt source. Since the source resistor was only 100 ohms and the $I_{DSS}$ was 2 to 5 mA, the reverse bias was small. The

113
Figure D-1. Biasing Circuits for Transistors Used in the Noise Tests. Upper is for Bipolar (NPN and PNP) Transistors, Middle is for N-Channel Junction Field-Effect Transistors, and the Bottom is for N-Channel Enhancement Mode MOS Transistors.
bipolar transistors were tested with collector currents from 10 microamps to 10 milliamps.

The use of the source follower circuit for the field-effect transistors yields the same signal-to-noise ratio as a common source circuit since the signal-to-noise ratio is established in the gate circuit. Similarly, the value of the collector load resistor and the collector-to-emitter voltage for the bipolar transistors has no effect on the signal-to-noise ratio.

The noise voltage, $e_{\text{noise}}$ of Figure D-1, was measured with one of two basic schemes. The first used a Millivac VS-64A low noise preamplifier and a Krohn-Hite 3100 bandpass filter. The output of the filter was observed on an oscilloscope or measured with a Hewlett-Packard 400 AC voltmeter. The second method used a Tektronix 315 spectrum analyzer. This plug-in for the 560 series oscilloscope covers the frequency range from 10 Hz to 1 MHz. Both the voltmeter and the spectrum analyzer are average reading meters calibrated in RMS units. A correction factor, dependent on the amplitude probability density function of the noise, must be applied to determine the true RMS reading. Alternatively, a true RMS meter (e.g., a thermocouple type) could have been used.

The amplitude distribution function is assumed to be gaussian. Visual examination with the oscilloscope indicated that this assumption was reasonable. Both the voltmeter and the spectrum analyzer used average value detectors with scales calibrated in RMS units for sine wave inputs. The correction factor for noise signals with gaussian probability density functions is easily computed.\footnote{All references for Appendix D are given at the end of this Section.}
The gaussian amplitude density function is

\[ f(x) = \frac{1}{\sigma(2\pi)^{\frac{1}{4}}} \exp\left(-\frac{x^2}{2\sigma^2}\right). \]

A true RMS meter would read the square root of the expectation of \( x^2 \). That is,

\[ \left[ E(x^2) \right]^{\frac{1}{2}} = \left[ \int_{-\infty}^{\infty} x^2 f(x) \, dx \right]^{\frac{1}{2}} = \sigma. \]

The integral is evaluated in Reference 1. Now for the same process an averaging meter would read

\[ M = E(|x|) = \int_{-\infty}^{\infty} |x| f(x) \, dx = (2/\pi)^{\frac{1}{2}} \sigma = 0.79786 \sigma. \]

The approximation \( \sigma = 1.25 \sigma \) was used in all computations.

The spectral density \( S \) can be computed if the noise bandwidth of the filter is known. Noise bandwidth can be computed two ways. If the filter has a sharp cutoff characteristic, as the Krohn-Hite does, the 3 dB bandwidth can be used. If the response function \( H(j\omega) \) is known, where \( H \) is the ratio of output voltage to input voltage at radian frequency \( \omega \), the noise bandwidth is

\[ B_w = \int_{-\infty}^{\infty} |H(j\omega)|^2 \, d\omega. \]
\( H(j\omega) \) must be measured by conventional techniques for the bandpass filter, but a simpler method is available with the spectrum analyzer. Since the analyzer is a swept filter, a sinusoidal signal of fixed frequency may be applied to the input and the analyzer will trace out its own \( H(j\omega) \) as it sweeps through the signal frequency. This is true for analyzers which have a fixed bandwidth but varying center frequency. It is not precisely true for analyzers of the "constant percentage bandwidth" type (e.g., some General Radio units normally used in acoustic and audio work).

The output of the averaging detector is, in itself, a random process. The desired quantity, the RMS value \( \sigma \), is the mean of this process (within the detector correction factor 1.25). To estimate this mean requires a "video" filter. The time constant of an analog meter provides such a filtering. The output of the spectrum analyzer was filtered with a Donner 3500 analog computer. The questions of filter time constant, sweep speed, and system resolution must be carefully considered. An excellent discussion of this problem is given in Chapter 7 of Reference 2.

The spectral density \( S_e \) of the voltage across the 100 ohm load resistor is \( \sigma^2/2\pi \), with units of volts\(^2\)/Hz. The power spectral density \( S_n \) is then \( S_e/R_L \), or in this case \( S_e/100 \). \( S_n \) has units watts/Hz. If it is desired to square the output voltage from the analyzer with an analog computer multiplier, the question of multiplier dynamic range must be considered. Reference 2 also discusses this problem.

The spectral density function is useful because it allows computation of signal-to-noise ratio and equivalent noise input for any desired system bandwidth or linear transfer function. One nice property of the gaussian amplitude density function is that the output of a linear filter is gaussian if the input is gaussian. Thus we need consider only the fre-
quency spectra (and not also the amplitude density function) when linear filtering is used. The general relationship between input spectra $S_1$, linear transfer function $H(\omega)$, and output spectra $S_2$ is

$$S_2(\omega) = |H(\omega)|^2 S_1(\omega).$$

Given a voltage or current spectral density $S$, the corresponding RMS quantity is

$$\sigma = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) d\omega.$$  

Equivalently,

$$\sigma = \int_{-\infty}^{\infty} S(\omega) d\omega.$$  

Equivalent noise input is computed from knowledge of the spectral density $S_e$ across the load resistance and the stress sensitivity of the transistor. The corresponding RMS voltage is obtained for the desired bandwidth. The stylus load required to give a signal voltage equal to the RMS noise voltage is the equivalent input noise load. A signal load required to give a peak voltage equal to the RMS noise voltage was used in the preparation of Table 3 of the main text. Thus a square wave signal was assumed. This definition is somewhat arbitrary, and is clarified in Figure D-2.

As an example, if the RMS noise voltage were 10 microvolts RMS,
Figure D-2. Noise ($v_n(t)$) and Signal ($v_s(t)$) Components Across the Load Resistor. The Total Waveform is the Sum $v = v_n + v_s$. $\sigma$ is the RMS Value of the Noise Signal and is Also the Peak Value of the Signal Waveform.
the sensitivity were 2 mA/gram, and the load resistor were 100 ohms, the equivalent noise input load would be

\[
E.N.I. = \frac{10 \times 10^{-6} \text{ volts}}{2 \times 10^{-3} \text{ amps/gram} \times 100 \text{ ohms}} = 0.5 \times 10^{-4} \text{ grams peak}
\]

The dynamic range was computed by dividing the total linear range by the peak-to-peak equivalent noise input. In this example, if the linear range was 3 grams, the dynamic range would be

\[
D.R. = \frac{3 \text{ grams}}{2 \times 0.5 \times 10^{-4} \text{ grams}} = 3 \times 10^4
\]

since the peak-to-peak equivalent noise input is $10^{-4}$ grams. The corresponding figure expressed in decibels is

\[
10 \log_{10} D.R. = 44.77 \text{ db}
\]
REFERENCES


MECHANICAL STRESS PHENOMENA IN FIELD EFFECT AND BIPOLAR TRANSISTORS AND THEIR POTENTIAL FOR TRANSDUCER APPLICATIONS
Mechanical Stress Phenomena in Field Effect and Bipolar Transistors
and Their Potential for Transducer Applications *

by

M. E. Sikorski, R. P. Woodward and C. K. Kuo

Physical Sciences Division
Engineering Experiment Station
Georgia Institute of Technology

ABSTRACT

This paper is devoted to the discussion of certain solid-state sen-
sors which convert mechanical signal inputs into electrical outputs and
which are compatible with integrated circuit technology. Mechanical stress
affects the electrical characteristics of semiconductor devices, giving
rise to a mechanical-electrical transduction mechanism. It is possible to
utilize discrete semiconductor devices and process the signal externally
or, alternatively, build both the transducer and processing circuit on a
single integrated circuit chip. Historical background will be given on
developments in the field of stress effects in solid-state active devices
over the last ten years.

Inhomogeneous stress effects, namely, changes in collector or chan-
nel currents, in bipolar, junction field effect, and MOS transistors are
detailed. Important factors which influence the sensitivity of bipolar
transistors are indentor position, internal geometry, and conductivity
type, i.e., pnp or npn. Each of these factors has been studied and sensi-
tivity may be predicted approximately from them. MOS capacitance effects
will also be described. The potential of these various effects for sensi-
tive pressure, force, or displacement transducers is evaluated.

* This work was supported in part by the Office of Naval Research,
Internally generated noise has been measured for transistor stress transducers under a variety of operating modes. For each of the several transistors studied, noise spectra were obtained for both stress transducer operation and normal transistor operation. By this means the noise characteristics of transducer operation can be related to the normal (published) noise characteristics of the transistors. The empirical results suggest how the noise effects of transducer operation may be predicted if the noise spectrum of the specific transistor is known. These results appear to agree with present theory on noise in transistor operation. Design rules are given so that sensitivity, signal to noise ratio, and dynamic range may be optimized.
An Exploration of the Potential of PN Junction Devices for Transducer Applications

The purpose of the project was to explore the potential of pn junction devices for transducer applications. In particular, the aim was to generate information that could be used to assess whether this new transducer concept can advance the present state of transducer technology. We have used transistors as sensing elements because of the built-in amplification and a linear relationship that exists between bias voltage $V_{CE}$ and pressure. The linear range can be controlled. For transducer action, the stress is applied to the transistor by means of a sharp sapphire indenter. Transistor transducers are characterized by very high sensitivity, excellent frequency response, from dc into the MHz range, and small size.

The optimum crystallographic orientation is [100] for silicon and [111] for germanium transistors. The sensitivity ranged from a few tenths of a mA/gram to 15 mA/gram; the linear range varied from 1 to 10 grams for bipolar transistors, and was found to be as high as 50 grams for a MOSFET. The dynamic range varied from 41 to 49 dB for various transistors. Equivalent noise inputs (in grams) have been calculated to allow determination of S/N ratios.
14. KEY WORDS

Transducers  
PN Junctions  
Semiconductor Sensors  
Stress Effects  
New Transducer Concepts

**INSTRUCTIONS**

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether “Restricted Data” is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

   1. “Qualified requesters may obtain copies of this report from DDC.”
   2. “Foreign announcement and dissemination of this report by DDC is not authorized.”
   3. “U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ______.”
   4. “U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ______.”
   5. “All distribution of this report is controlled. Qualified DDC users shall request through ______.”

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

   It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

   There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.
Abstract (Cont.)

A new MOSFET transducer concept has been demonstrated which allows digital measurement capability of quantities such as pressure, temperature and light.

Noise studies have revealed, among other things, that low noise transistors are best for transducer applications.

Stable transistor transducer elements can be made providing the diaphragm is firmly attached to the case so that the position of the indenter on the transistor surface is fixed.

Transistor transducer capsules should be tried in underwater instrumentation.