FY06 ACCOMPLISHMENTS

Nanoelectronics Manufacture, Inspection, and Repair using Thermal Dip Pen Nanolithography

William P. King
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FY06 was the second year of this grant, and thus was the first year for the results to be publicized. This second year produced three major scientific accomplishments and a number of other accomplishments.

Scientific Accomplishment 1: We have demonstrated the use of a nanoscale heated probe tip to find and measure a nanoscale gap in an electronic circuit, and then deposit conductive metal across the gap. The same tip was used to image the device and write onto the substrate. This demonstration of direct-write circuit repair is not possible with conventional probe-based deposition techniques and is a significant advance for nanoprobe-based manufacturing. Because the technique uses the same tip for writing and metrology, it can be scaled to a large array of parallel tips. These results were described in a paper published in Applied Physics Letters.

Scientific Accomplishment 2: We have demonstrated single-molecule precision during deposition of molecular electronics materials. A major challenge in the manufacture of molecular electronics devices is precise and local control of the materials that form the active devices. The thickness, width, and overall amount of deposited material can be controlled through the tip temperature or the tip power. These results were described in a paper published in Journal of the American Chemical Society. This breakthrough was widely disseminated in the weekly nanotechnology news of the ACS.

Scientific Accomplishment 3: We have demonstrated quantitative understanding of probe sensitivity during nanometrology. It has been known for nearly 20 years that a heated nanoprobe can be used to sensitively measure the topography of nanodevices. Recently, we have demonstrated how a heated probe tip can be used to make quantitative measurements of nanodevices. This work is currently being submitted for publication.

Other Accomplishments Acknowledging ONR Support:
• One patent licensed to Nanoink, Inc. This patent is owned jointly by Georgia Tech and NRL.
• This work was cited in the 2006 Defense Nanotechnology Report.
• Project PI William King was named “Young Manufacturing Engineer” by the Society of Manufacturing Engineers
• Project PI William King was named to the TR35 - “one of the most innovative people in the world under the age of 35” by “Technology Review” Magazine
• Project PI William King was awarded the PECASE from the Department of Energy for his related work on Nano-Manufacturing
• Project PI William King was invited to attend the US-Japan Exchange Program on Nanotechnology and Nano-Manufacturing
Nanoelectronics Manufacture, Inspection, and Repair using Thermal Dip Pen nanolithography
William King, Georgia Institute of Technology

Thermal Nanowriting Technique

Project Objective
- Develop arrays of nanoscale probe tips capable of manufacture, inspection, and repair of next-generation nanoelectronics devices and systems.
- Develop techniques for rapid, low-cost prototyping of nanoelectronics devices.

Navy / DoD Relevance
The DoD requires high-performance electronics systems having nanoscale components. Commercial manufacturing volume / cost and capabilities do not accommodate DoD / Navy needs.

Scientific/Technical Approaches
- Nanoscale probe tips with integrated sensing elements allow for inspection / mapping of nanoscale architectures.
- Nanoscale probe tips with integrated heating elements can be used as miniature soldering irons.

These devices and systems are used in communications, cryptography, targeting, and RADAR.
Nanoelectronics Manufacture, Inspection, and Repair using Thermal Dip Pen Nanolithography
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Nanoscale Circuit Repair

Electrodes Indium / Indium Oxide

Scientific Accomplishments
• Demonstrated Nanoscale Repair of a Broken Device Interconnect
• Demonstrated Single-Molecule Control during Fabrication of Molecular Electronics
• Demonstrated quantitative understanding of topographical sensitivity during inspection of Nanodevices
• 1 Patent licensed, 1 Patent pending

Other Accomplishments
• 8 journal papers
• 30 conference papers
• 1 book chapters
• 15 invited talks
• DOE PEASE Award for King for related work
• King named to TR35 – most innovative people in the world under the age of 35
• This research cited in the 2006 Defense Nanotechnology Report

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Collaboration with Surface Nanoscience Section (6177) at Naval Research Laboratory
Nanoscale Deposition of Electronic Materials using Thermal Dip Pen Nanolithography

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20.0 um
Background: Dip Pen Nanolithography

- Significant efforts at more than 60 labs in the world (and 1 startup company).
- Semiconductor, dielectric, and metal surfaces.
- Covalently bound molecules, SAMs, DNA and proteins, etc.
- Best resolution: 5-15 nm

- Critical Problems and Opportunities:

Ink is deposited when tip contacts surface, causing problems for contamination and registration.
Not vacuum compatible.

Thermal Dip Pen Nanolithography

- Tip-substrate contact is smallest controlled heating source ever produced – and has applications in nanomanufacturing.
Heated AFM Cantilevers

- Developed at Stanford and IBM, now made and used at Georgia Tech.
- Our cantilevers are well-suited to interface with commercial AFM systems.

Cantilever Features

- Temperature: 25 °C – 900 °C
- Time: as fast as 1 μsec / 1 MHz

Resonant Frequency: 30-70 kHz
Spring Constant: 0.02-1 N/m
Q: ~50-100
Cantilever Temperature Precision Calibration

Infrared Microscopy

Image of cantilever with scale 200 μm.

Graph showing Cantilever Electrical Resistance (kΩ) vs. Tip Temperature (°C).

Legend: Graph data points and trend line.
Thermal DPN Results

Octadecylphoshonic acid (OPA) on Mica

- binds to engineering metals, many metal oxides, mica
- melting temperature: ~99°
- self-assembles

height image of OPA deposition

Each scan 300 seconds

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Thermal DPN Molecular Control of Deposition

- Control PDDT thickness vs. writing speed
- Polymer is hot: *self-assembles during deposition*

**Histogram: 2.7 nm per layer**

- Apparent structure agrees with SAM film XRD characterization
  - Prosa, Macromolecules '92

*Direct-write “molecular” layer epitaxy!*
Controlling Molecular Thickness

Writing speed

0.1 → 20 μm/s
Linewidth (fwhm)
300 → 170 nm
Monolayers
26 → 1 MLs
Measuring Ink Transport

![Graph showing line width vs. scan speed.](image)
Investigating Transport Mechanisms

OPA on Mica

113 °C

130 °C

147 °C

8s 16s 32s 64s

--- 1 μm

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Electronic Device Integration

Position tDPN tip in imaging mode

Deposit PDDT in writing mode

Tapping-mode image after writing

Heating “OFF”

Heating “ON”

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Deposited Material Characterization

![Image of deposited material and AES spectra]

- AES Spectra
  - Energy (eV)
  - N(E) (a.u.)
  - Si, Au, C, O

- Depositions:
  - SiO_x Substrate
  - Gold Contact Pad

1 μm scale
Deposited Material Characterization

- Measure I-V’s for PDDT nanostructure with multi-probe

- "Semi-Permanent"
  - Lasted few hours
  - No current effects

![Image of PDDT nanostructure with multi-probe](image)

![Graph showing I-V characteristics](graph)
Nanosoldering: Indium Metal Deposition

- Deposited at 150-200° C
- 65 – 150 nm widths
Nanosoldering: Indium Metal Deposition

Electrodes

Indium / Indium Oxide

600nm

Resistivity: \(2.5 \times 10^4 \, \Omega\)-cm
UHV Deposition

- Nanofabrication in UHV provides the most defined environments for constructing and characterizing organic molecular electronic devices.
- Many epitaxial processes occur in vacuum.

PDDT on SiO$_2$ written in
- UHV (1 x 10$^{-10}$ Torr)
- Height = ~ 20 nm (8 MLs)
- Linewidth = ~ 150 nm (fwhm)

First example of DPN in UHV!
Highly Sensitive Reading

150 nm — 30 nm

Sensitivity Response Surface

Cantilever Heating Power, mW

Sensitivity, μV/nm

10^7

10^6

10^5

10^4

10^3

10^2

10^1

10^0

10^-1

10^-2

10^-3

10^-4

10^-5

10^-6

Cantilever Heater Power, mW

Resolution, nm/Hz^{1/2}

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Scaling to High Throughput

- Large arrays of heater-cantilevers have been fabricated for data storage - IBM Millipede.

10 nm pixels
10 MHz
$10^4$ cantilevers
100% Fill

300 mm wafer
2 Hours
Faster than FIB or E-Beam!!!
Summary

• We have deposited semiconducting, insulating, and conducting materials with 50 nm later resolution and molecular thickness resolution.

• Heated cantilevers capable of parallel writing and metrology.

• This technology could be used for mask inspection, writing, and repair; prototyping; and small volume nanoelectronics manufacture.