Printed Electronics Research at Georgia Tech Manufacturing Institute

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and Georgia Tech Manufacturing Institute
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Interdisciplinary Research Institutes at Georgia Tech

President
Executive VP Research
Provost
Executive VP Administration

30+ basic research centers
Academic programs

Electronics & Nano
Manufacturing
Materials
People & Technology
Renewable Bioproducts
Robotics & Int. Machines
Strategic Energy
Sustainable Systems

IRI Characteristics
- "Outward facing"
- Establish key partnerships with industry and government
- Translational and interdisciplinary research
Preliminary Design of GTMI Operating System

1. Advanced Materials
2. Advanced Processes Enablers (design, infrastructure, policy, MEP, SCRL,...)
3. Intellectual leadership in basic research
4. Translational leadership for accelerated campus-wide synergy and interdisciplinary readiness
5. Deployment leadership with stakeholders to commercialize innovative products and services
6. Readiness & Commercialization
7. Sector Products
8. Requirements Validation "Pull"
9. xRL
10. xRL

Grand Challenges: Cross-Cutting Technology Areas for Advanced Manufacturing

- Advancing Sensing, Measurement, and Process Control
- Advanced Materials Design, Synthesis, and Processing
- Visualization, Informatics, and Digital Manufacturing Technologies
- Sustainable Manufacturing
- Nanomanufacturing
- Flexible Electronics Manufacturing
- Biomanufacturing and Bioinformatics
- Additive Manufacturing
- Advanced Manufacturing and Testing Equipment
- Industrial Robotics
- Advanced Forming and Joining Technologies
Grand Challenges: Cross-Cutting Technology Areas for Advanced Manufacturing – Related to Printed/Flexible Electronics

- Advancing Sensing, Measurement, and Process Control
- Advanced Materials Design, Synthesis, and Processing
- Visualization, Informatics, and Digital Manufacturing Technologies
- Sustainable Manufacturing
- Nanomanufacturing
- **Flexible Electronics Manufacturing**
- Biomanufacturing and Bioinformatics
- Additive Manufacturing
- Advanced Manufacturing and Testing Equipment
- Industrial Robotics
- Advanced Forming and Joining Technologies

*Over half of the challenges are related to Printed/Flexible Electronics*

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Printed and Flexible Electronics: An Enabling Technology for Revolutionary Products

**Nokia Concept Phone:**

*Morph*
Transformative Printed Electronics Research at GTMI

- Printed Electronics for Smart Materials with Advanced Sensing
- Integration of 3D Printing and Printed Electronics
- Printed Electronics for Medical Applications
- ICME-based PE Process Modeling, Monitoring and Control for High Quality and Repeatable Manufacturing
- Scalable Manufacturing for Printed Electronics

GTMI’s Printed Electronics Capabilities Highlights

- Optomec Aerosol Jet® Printing (AJP) system with high resolution printing (~10µm printed line width and nanometers thickness)
- Characterization tools for materials and printed devices
- Printed electronics prototypes fabricated at GTMI with the AJP system: strain, temperature and gas sensors, pressure sensors and actuators, organic transistors, RFID tag, high frequency antenna, and energy storage devices

Optomec AJP 300
PE System at GTMI

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Prototypes/Samples Printed at GTMI

- Strain sensor array printed with silver ink
- Interconnects linked with IC chip pins
- RFID tag on silicone
- Temperature sensor printed with carbon nanotubes
- RFID tag and antenna array on carbon fiber prepreg
- High frequency antenna

We Have Worked with a Wide Range of Ink and Substrate Materials

**Inks**
- Metal NP
- CNT
- Graphite
- CNT-Silver NP
- Polyimide

**Substrates**
- Polyimide (Flexible Films)
- Carbon Fiber Prepreg (Composites)
- 3D Flexible Surface
- Coated Surface
- 3D Printed Part

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Application Case: Direct Printing of Sensors on Laminate for Composite Manufacturing Process and Finish Component Structural Health Monitoring

Objectives

- Print strain and temperature sensors directly on prepregs and embed them into composite laminates
- Investigate the effects of sensors embedment on composite mechanical properties
- Monitoring of manufacturing process and structural health of composites with printed sensors

Prepreg: unidirectional carbon fiber/epoxy

Experimental Procedure

Prepreg preparation → Sensor printing → Composites fabrication

Printing quality → Mechanical integrity → Sensing performance
Inter-laminar Shear Strength of Various Composite Panels

Takeaway
10% pre-cure retained full mechanical performance

<table>
<thead>
<tr>
<th>Composite Sample Type</th>
<th>ILSS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Raw (0% cured) prepreg with printed sensor</td>
<td>40.63±1.52</td>
</tr>
<tr>
<td>2. Pre-cured (10%) prepreg with printed sensor</td>
<td>40.88±1.27</td>
</tr>
<tr>
<td>3. Fully-cured prepreg with printed sensor</td>
<td>22.41±1.13</td>
</tr>
<tr>
<td>4. CFRP without sensor</td>
<td>41.13±0.78</td>
</tr>
</tbody>
</table>

Printed Electronics-Based Strain Sensor Performance

Cyclic tests of strain and resistance change as a function of time for printed strain sensor embedded in composites

<table>
<thead>
<tr>
<th>Type of Strain Gauge</th>
<th>Gauge Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printed Gauge</td>
<td>2.2 ± 0.06</td>
</tr>
<tr>
<td>Commercial Metal Gauge</td>
<td>~ 2</td>
</tr>
</tbody>
</table>

Strain sensing test apparatus

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Design Validation of Composite Space Structures with Embedded Strain Sensors

- Carbon fiber composite hinge for deployable radiator
- Three AJP strain sensors embedded in the hinge for design optimization and FEA model validation
- Testing under various mechanical and temperature loadings

Prototype composite hinge with embedded strain sensors

Integrated Composite Design, Manufacturing Process Monitoring and Service with Printed Electronics

Finished Product Structural Health Monitoring

Manufacturing Process Monitoring

Design Model Validation

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A Case for Medical Applications of Additive Manufacturing Technology: Heart Valve Phantom

- Models for patient education
- Physical objects for medical imaging and computational models validation
- Models for pre-surgery planning and practice

Medical Applications of Multi-Material 3D Printing Technology

- Mimic human heart valve structure and conditions for pre-surgery planning, patient education and medical device (e.g. stent) evaluation
- Multi-material 3D printing allows fabrication of valve prototypes with matching mechanical behavior and conditions (such as calcium deposition)

In collaboration with Drs. M. Vannan and Z. Qian of Piedmont Hospital

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Integration of 3D Printing and Printed Electronics Technologies for Medical Applications

CT Scan → CAD/STL Models → Multi-Material 3D Printing → Printed Valve

Strain/Deformation Measurement → 3D Printed Valve with PE Strain Sensors on Surface → AJP Printing

In collaboration with Drs. M. Vrinstein and Z. Qian of Piedmont Hospital

Printing of Strain Sensors on Aortic Valve Using Aerosol Jet Printing

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Demonstration of Strain Sensing for Aortic Valve

Next Generation of Personalized Prosthetic Products and Services

- Usage data will be shared among hospitals, care providers and practitioners for effective healthcare for veterans
- Insurance claim criteria developed from usage data analysis will be used as quantitative standards
- Manufacturing and materials database will be shared with socket manufacturers

In collaboration with GT-ADP and Georgia State University

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Integration of 3D Printing and Printed Electronics for Smart Materials Fabrication

Measurement of Printed Sensors Conductivity Before and After Transfer

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Substrate of Printed Pattern</th>
<th>Adhesive Layer</th>
<th>Thickness of Printed Pattern (μm)</th>
<th>Resistance between Electrodes (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before Transfer</td>
</tr>
<tr>
<td>1</td>
<td>PTFE</td>
<td>No</td>
<td>2.15±0.07</td>
<td>8.8</td>
</tr>
<tr>
<td>2</td>
<td>PTFE</td>
<td>No</td>
<td>1.89±0.11</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>PTFE</td>
<td>Yes</td>
<td>2.81±0.13</td>
<td>12.8</td>
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<tr>
<td>4</td>
<td>PFA</td>
<td>No</td>
<td>2.06±0.09</td>
<td>9.6</td>
</tr>
<tr>
<td>5</td>
<td>PFA</td>
<td>Yes</td>
<td>2.63±0.11</td>
<td>13.4</td>
</tr>
</tbody>
</table>
Testing of Performance of Transferred Sensor

Consistent Performance after 1,000 load cycles

Scalable and Continuous Manufacturing of Smart Materials
Collaborative Project: Fabrication of CNT-based High Sensitivity Gas Sensors for Homeland Security Applications

- Long-term monitoring of chemical vapors
- Standoff detection
- Low vapor pressure of explosives requires high sensitivity
  - 10 ppb for TNT, 10 ppt for explosives (RDX, PETN)
- Deployed on buildings, vehicles, clothing, tickets
  - Low cost, small size
- AJP printed sensors outperform those by other manufacturing processes (5X sensitivity)

In collaboration with Dr. Judy Song, Electro-Optical Systems Lab, Georgia Tech Research Institute

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Collaborative Project: Printing of High Frequency Transmission Lines and Conformal Antenna

In collaboration with Dr. John Frigo, Polymers of GT-ECE

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Collaborative Project: 3D Packaging by Vias Filling

In collaboration with Dr. John Papapolymero of GT-ECE

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  • Dr. Ben Wang, GT-ISyE and GTMI
  • Dr. Kevin Wang, GTMI

• Graduate Assistants:
  • Scott Chang GT-ISyE and GTMI
  • Charles Wu, GT-MS&E and GTMI
Integration of Nanomaterials and Printed Electronics Technologies:
RFID and antenna printed on carbon nanotube buckypaper

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Questions & Comments

Thanks!

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