Printed Electronics: Manufacturing Technologies and Applications

Chuck Zhang

School of Industrial & Systems Engineering (ISyE) and Georgia Tech Manufacturing Institute (GTMI)

May 12, 2014

Georgia Tech Manufacturing Institute

Presentation Outline

- Introduction to Georgia Tech Manufacturing Institute
- Overview of printed electronics technology and applications
- Aerosol Jet® Printing (AJP) process
- Application case studies

The information presented herein cannot be duplicated or extracted without permission from GTMI

Factory Information Systems

Composites/ Nano-Composites Manufacturing

Precision Machining

Printed Electronics Research

Additive Manufacturing

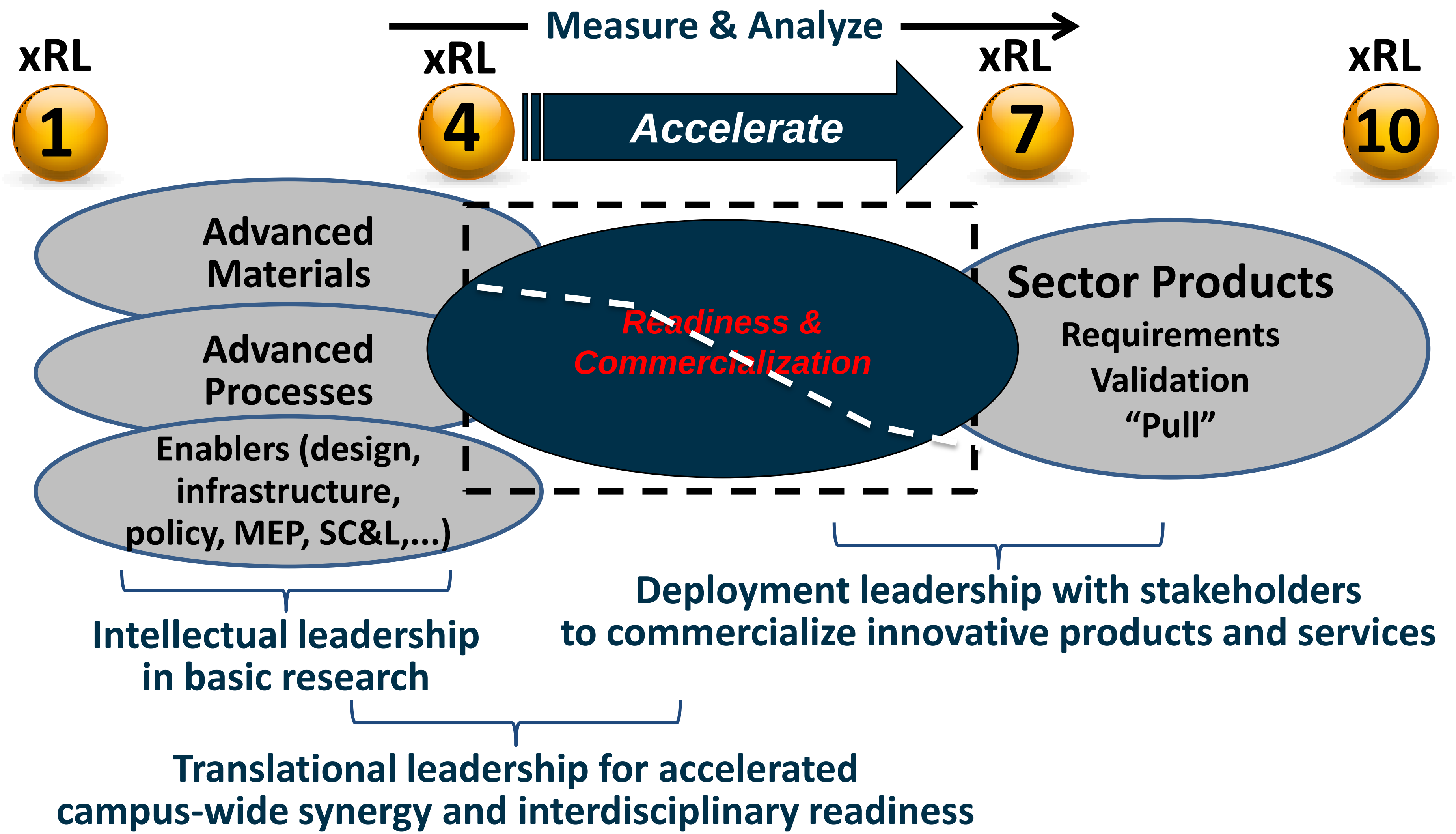
Sustainable Design & Manufacturing

Model-Based Systems Engineering

- Industrial Design
- Precision Machining
- Nano & Bio & Energy
- Composites/ Nano-Composites Manufacturing
- Factory Information Systems
- Public Policy

- Robotics
- Additive Manufacturing
- Sustainable Design & Manufacturing
- Supply Chain & Logistics
- Model-Based Systems Engineering
- Enterprise Innovation Institute

Preliminary Design of GTMI Operating System



Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

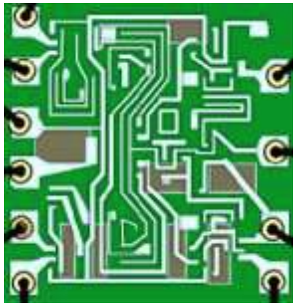
Translational Research in Additive Manufacturing at GTMI

- Additive manufacturing/3D printing process and equipment development (e.g., metal, polymer and composites part manufacturing)
- Computational modeling and simulation of additive manufacturing/printed electronics processes
- Advanced materials development for additive manufacturing/printed electronics
- Application development and demonstration of additive manufacturing/printed electronics

The information presented herein cannot be duplicated or extracted without permission from GTMI

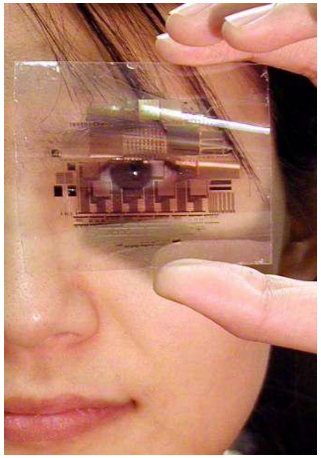
Technology Revolutions in Electronics

Past

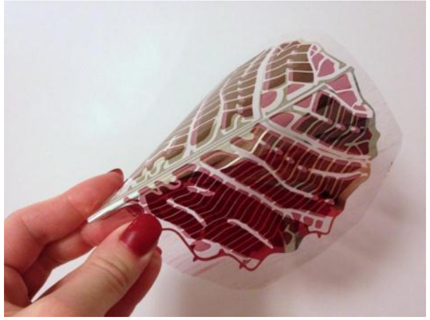


Current

Future – Beyond Silicon (Printed Electronics)



Organic circuits on polymeric substrate



Flexible solar cells

Thin flexible battery

e-paper

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

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

Report To The President on Capturing Domestic Competitive Advantage In Advanced Manufacturing, Executive Office of the President, President's Council of Advisors on Science and Technology, July, 2012.

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

Report To The President on Capturing Domestic Competitive Advantage In Advanced Manufacturing, Executive Office of the President, President's Council of Advisors on Science and Technology, July, 2012.

Georgia Tech Manufacturing Institute

Flexible Electronics Manufacturing

- ***Technologies for flexible electronics manufacturing will be major differentiators in the next generation of consumer and computing devices.***
- ***Some of these devices are expected to be among the fastest growing product categories over the next decade.***

Report To The President on Capturing Domestic Competitive Advantage In Advanced Manufacturing, Executive Office of the President, President's Council of Advisors on Science and Technology, July, 2012.

Printed Electronics Technology

- Printed electronics (PE) technique allows electronic and photonic devices to be fabricated using printing-based techniques, such as screen printing or inkjet, with conducting or semiconducting inks.
- PE can print resistors, condensers, transistors, interconnects, and most other electronic components in conventional circuits, on a wide range of substrates, like cloth or plastic.
- A fast growing advanced manufacturing technology.

Ink jet PE machine

Roll-to-roll screen printing machine

The information presented herein cannot be duplicated or extracted without permission from GTMI

Motivation for Printed Electronics

- **Printing can be a fast and inexpensive process** (e.g. newspaper)

  "inkjet, pad printing, screen, gravure, flexo, offset, ..."

- Therefore, printing processes may also **enable inexpensive electronics for new applications** (RFID tags, e-paper, disposable electronics, ...)
  - Printing often simplifies conventional processes

Printable electronics market:
~$12 bn (2011)
~$30 bn (2013) ?
(Nanomarkets.net)

parc
Palo Alto Research Center

Georgia Tech Manufacturing Institute

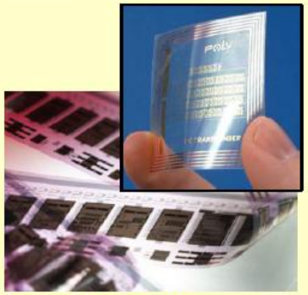
Printed Electronics Applications

- Some examples

Duracell: Battery tester

Power Paper: battery

Cypak: Intelligent Pharmaceutical Packaging



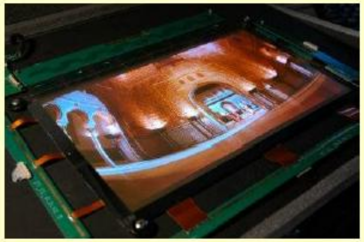
PolyIC: RFID

Konarka: Solar cell

Pelikon: EL displays

Plastic Logic: e-paper

CSG: via etching



CDT: OLED displays

parc
Palo Alto Research Center

Georgia Tech Manufacturing Institute

Major Applications of Printed Electronics

Differentiating Factors:

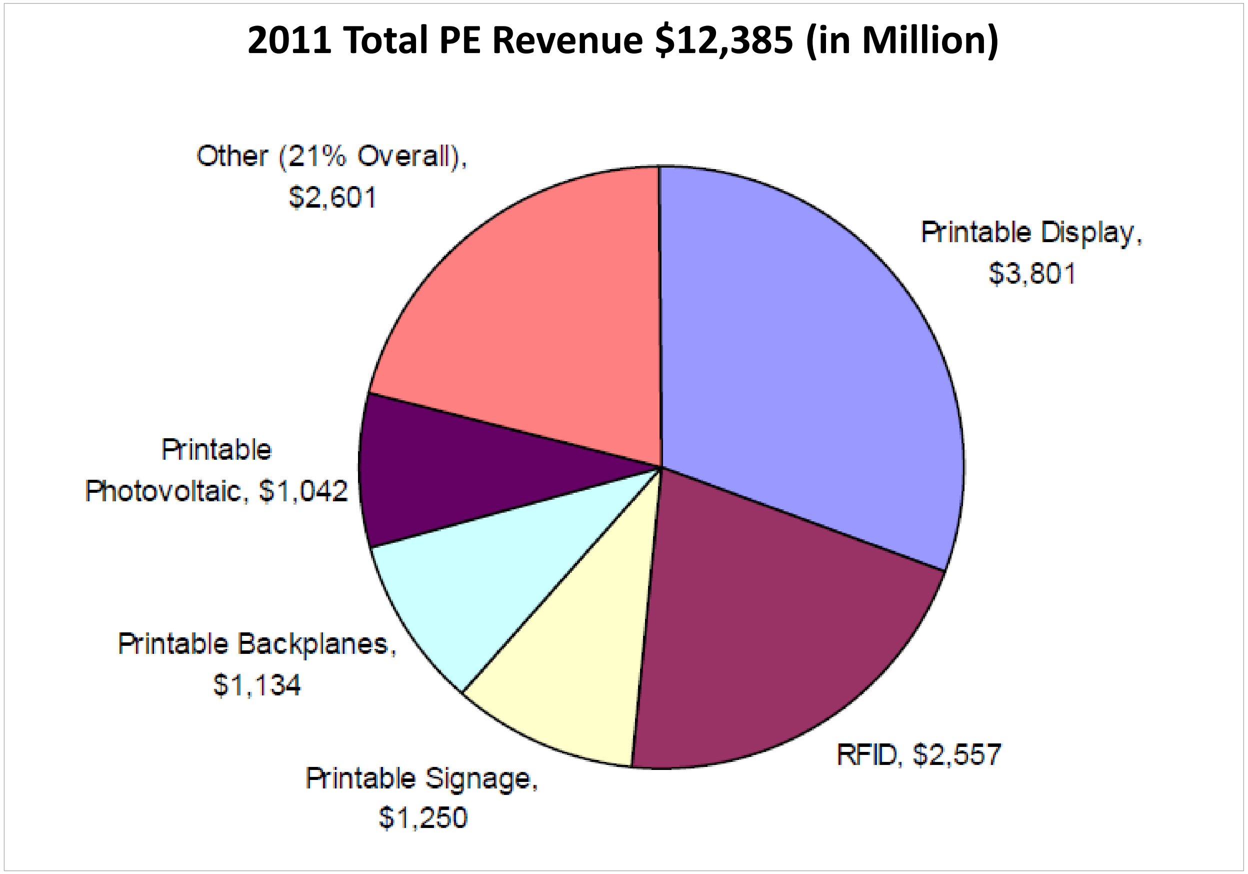
- Functions (e.g., flexibility)
- Manufacturing tool
- Customization
- Low cost

Applications:

- RFID
- OLED display
- OLED lighting
- Organic solar cells
- Systems on foil (smart packaging, polytronics)
- Sensors
- Energy storage devices
- Biomedical devices

The information presented herein cannot be duplicated or extracted without permission from GTMI

A Big Market with Tremendous Growing Potential



A recent report by IDTechEx predicts the PE market will reach $330B in 2027

Data from NanoMarkets LLC
www.idtechex.com/ope

Georgia Tech Manufacturing Institute

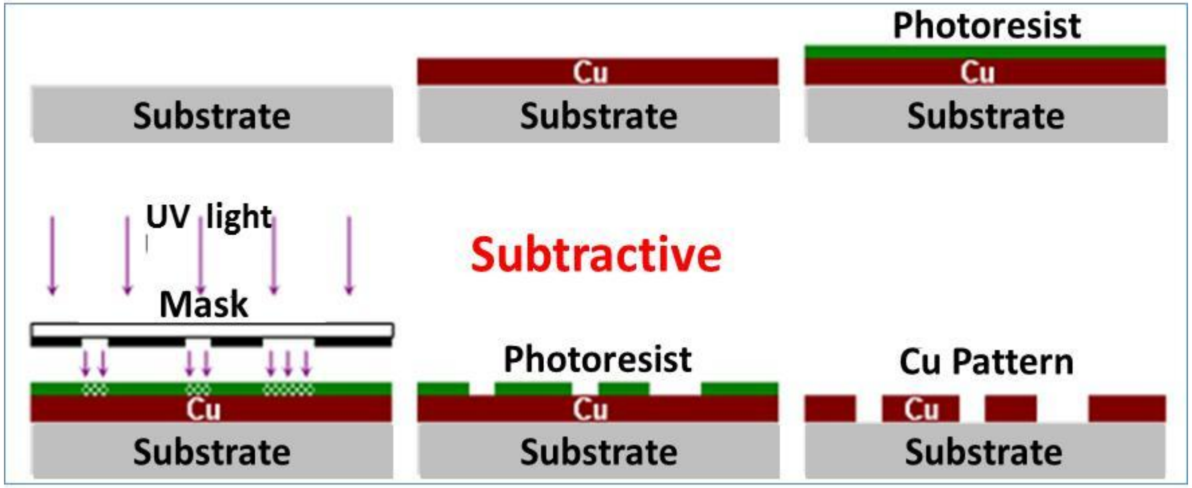
The information presented herein cannot be duplicated or extracted without permission from GTMI

Nokia Concept Phone:

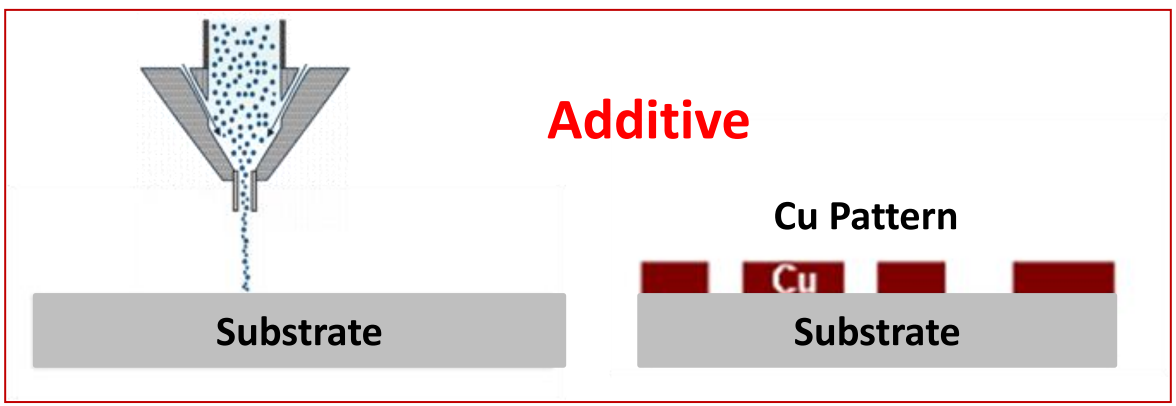
Morph

The information presented herein cannot be duplicated or extracted without permission from GTMI

Traditional CMOS vs. Direct Write PE



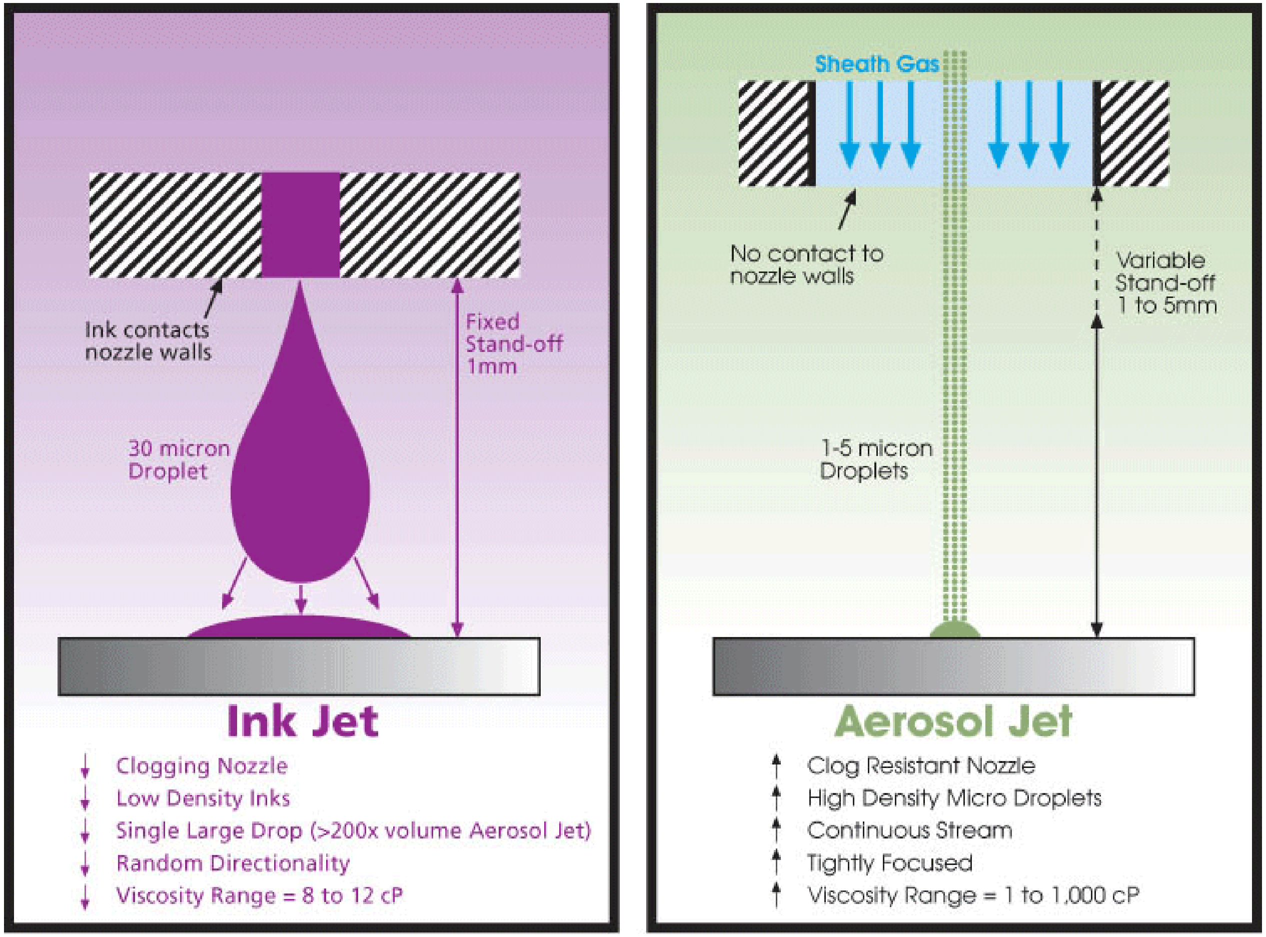
- High equipment investment
- Lengthy, complex process steps
- High production volume to justify equipment/process cost



- 3D curvature surfaces
- Rapid production
- Cost independent of production lot size
- Environmentally friendly

The information presented herein cannot be duplicated or extracted without permission from GTMI

Two Commonly Used PE Processes: Ink Jet Printing and Aerosol Jet® Printing

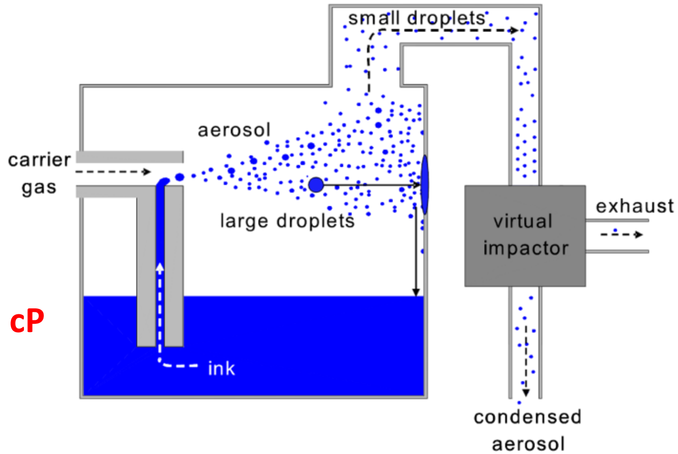


Georgia Tech Manufacturing Institute

www.optomec.com

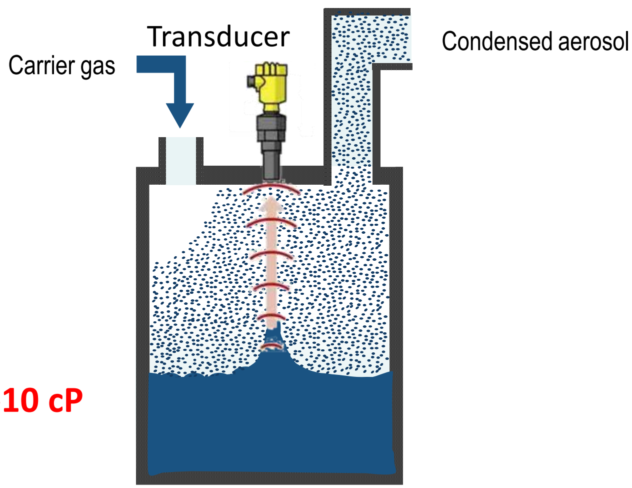
Aerosol Jet Printing Process

Pneumatic Atomization



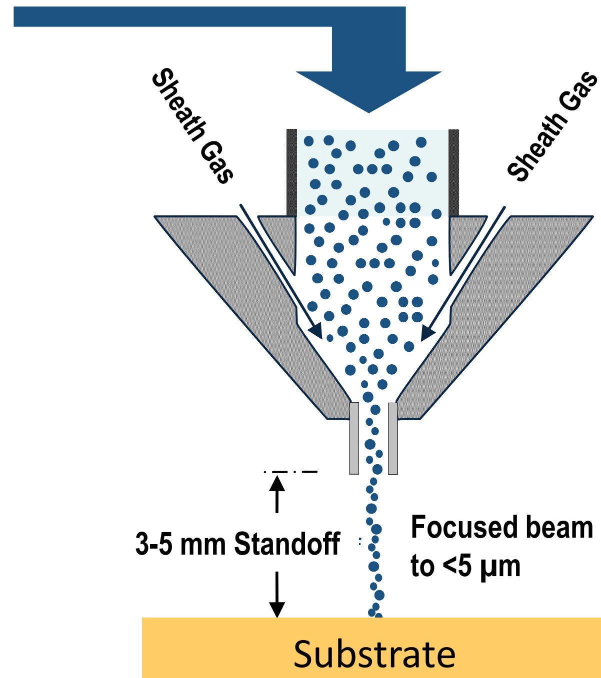
Ink viscosity: 1-2,500 cP

Ultrasonic Atomization



Ink viscosity: 0.7-10 cP

Printing Head



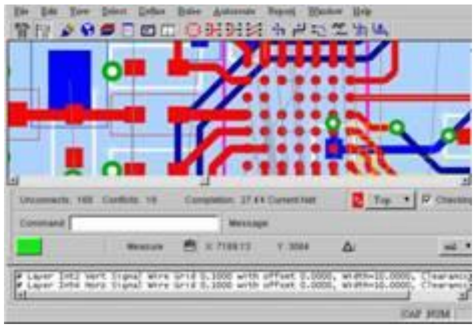
Nozzle Output:
Small Aerosol Droplets ~ 1-5um
Up to 0.25 microliter/sec dispensing speed
<10-150 µm line width printing capability

Georgia Tech Manufacturing Institute

www.optomec.com

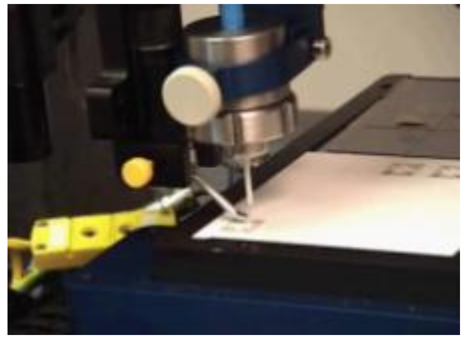
Aerosol Jet Process (Art to Part)

Design



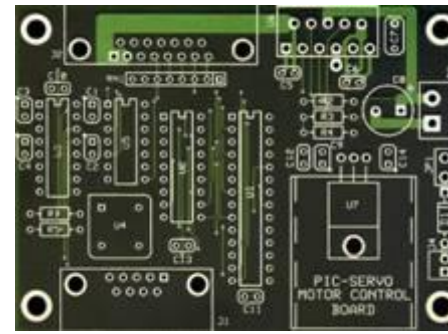
- CAD Model
- Convert to DWG file
- Tool paths generated with Optomec software

Process



- Liquid raw material
- Create fine (femto Litre) aerosol
- Focus to tight beam (~10µm)
- Post-process (dry, cure, sinter, etc.)

Part



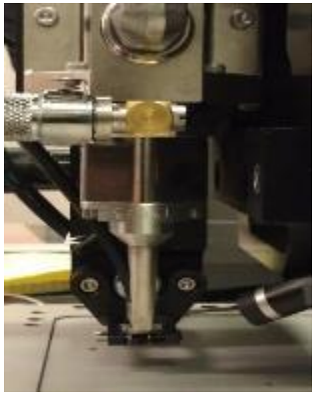
- Fine line traces
- Conformal printing
- Embedded passives
- Interconnects
- Coatings

The information presented herein cannot be duplicated or extracted without permission from GTMI

AJP Deposition Process

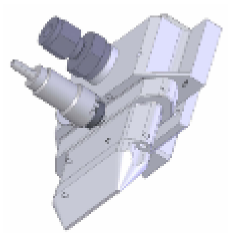
Fine Feature Printhead

- Fine Features from ~10µm to >200um
- Thicknesses ranging from 100nm to microns (material dep.)
- 5 interchangeable nozzle sizes
  - 100, 150, 200, 250, 300µm
- Integrated dispense shutter



Wide Feature Printhead

- Features from ~500µm to ~2.5mm
- Thicknesses ranging from 100nm to microns (material dep.)
- 3 standard nozzle sizes
  - 0.75mm round, 1.5 & 3.0mm slotted
- Integrated dispense shutter



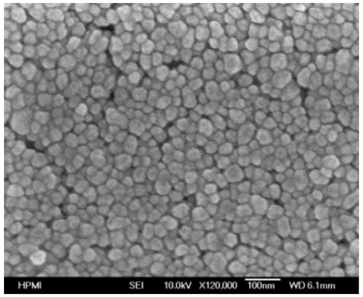
1 to 5cm Wide Nozzle Heads
(In Development)

Georgia Tech Manufacturing Institute

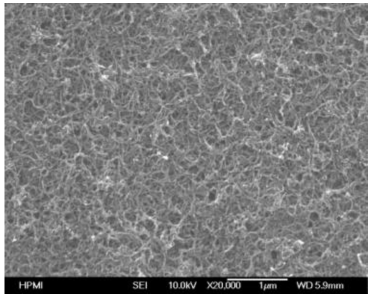
Optomec

Wide Ranges of Ink and Substrate Materials

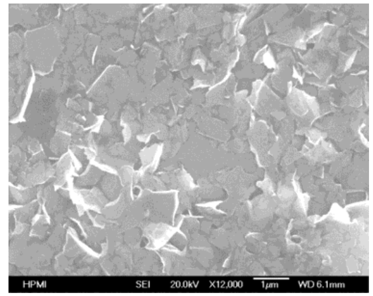
Inks



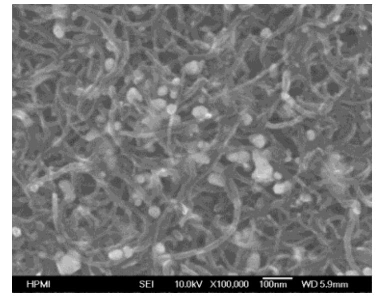
Metal NP



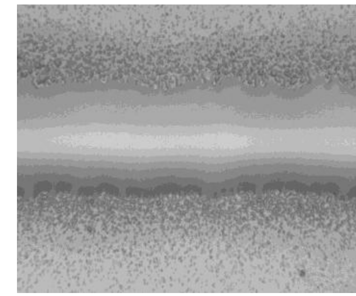
CNT



Graphite

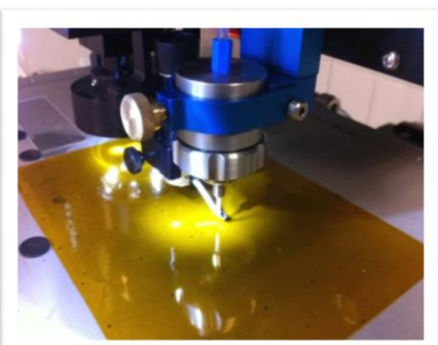


CNT/Silver NP

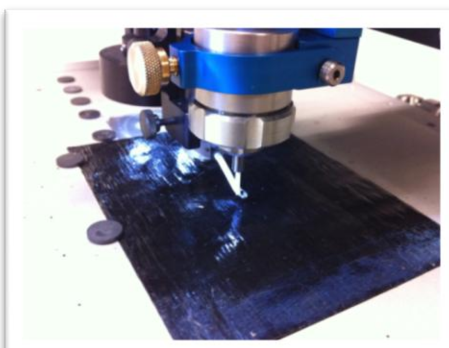


Polyimide

Substrates

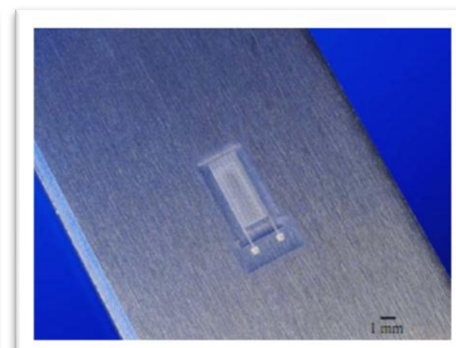


Polyimide
(Flexible Films)



Carbon Fiber Prepreg
(Composites)

3D Surface



Metal

Georgia Tech Manufacturing Institute

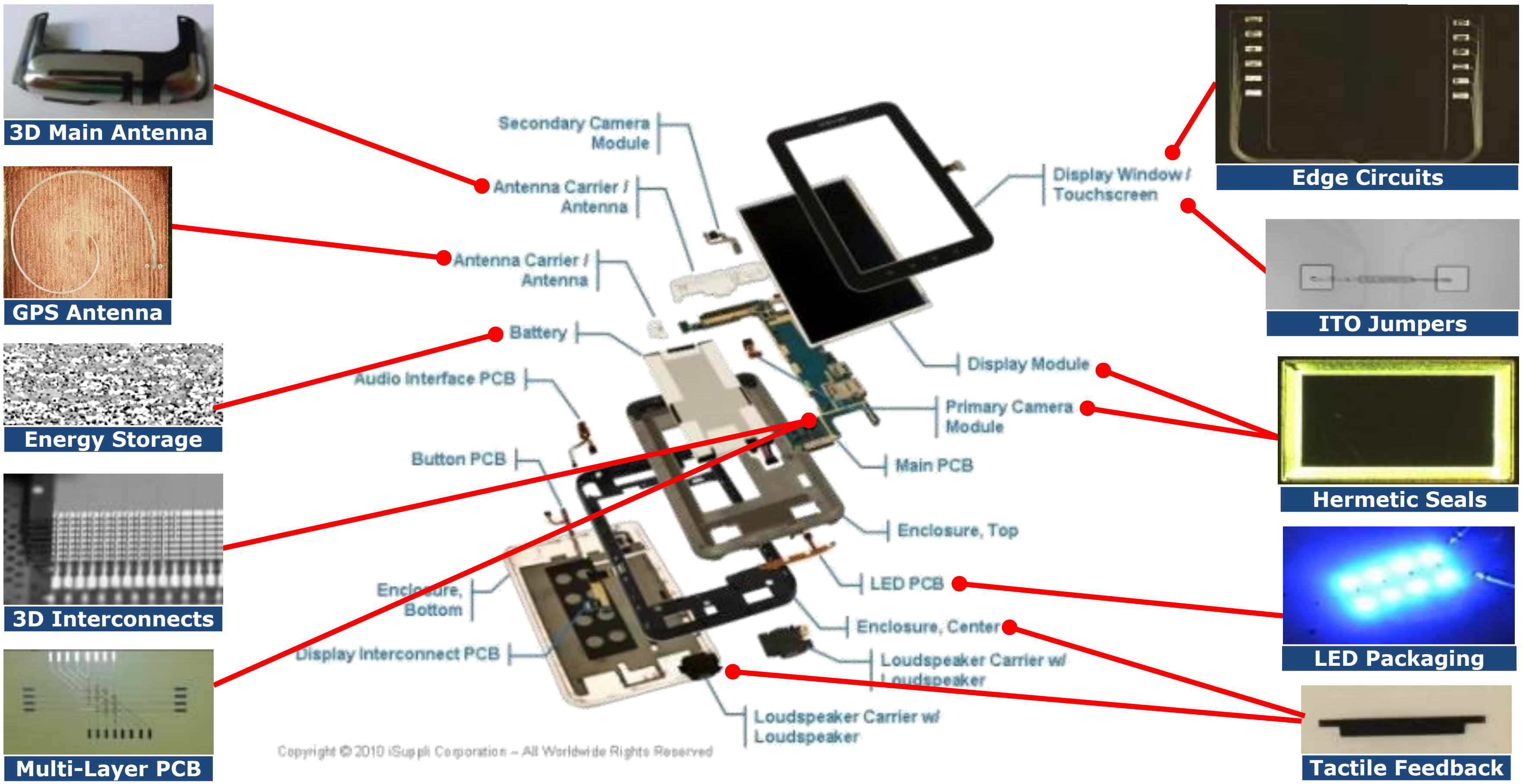
The information presented herein cannot be duplicated or extracted without permission from GTMI

Ink Materials Availability

Metal Inks	Resistor Inks	Non-Metallic Conductors
An Cuig (Pt)	Acheson (carbon)	Brewer Science (SWCNTs)
Applied Nanotech (Ag, Cu, Ni, and Al)	Asahi (carbon)	Heraeus (PEDOT:PSS)
Clariant (Ag)	DuPont (carbon and ruthenate)	NanoIntegris (SWCNTs / MWCNTs)
DuPont (Ag)	Lord (carbon)	SouthWest Nano (SWCNTs / MWCNTs)
Henkel (AG)	Methode Development (carbon)	**Semiconductors**
Intrinsiq (Cu)	**Dielectrics and Adhesives**	Aldrich (organic semiconductors)
Novacentrix (Ag, Cu)	Aldrich (polyimide)	Alfa (organic semiconductors)
Paru (Ag)	BASF (PVP)	Merck (organic semiconductors)
Resin Designs (AgE)	DuPont (Teon AF)	NanoIntegris (SWCNTs)
Sun Chemical (Ag)	Henkel (adhesives)	**Reactive Chemistries**
UTDots (Ag, Au, Pt)	Loctite (adhesives)	Rohm & Hass (Enlight)
Xerox (Ag)	Norland (UV adhesives)	Shipley (photo and etch resists)

Partial Listing from Optomec

Application Case: "Print Me a Phone" (The Economist)



Active customer projects in the above areas, and more…

Georgia Tech Manufacturing Institute

Optomec

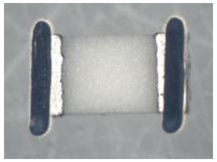
Aerosol Jet: Early Adopter Examples

Smartphone Display Manufacturer

- MEMS Packaging:
  - Hermetic Seal Rings
  - ***vs. Photolithography***
  - Less Cost
  - Higher Yield

Smartphone OEM Supplier

- 3D Antenna - Smartphone/Tablet
  - ***vs. LDS***
  - Lower Cost
  - Better Performance
  - More Environmental

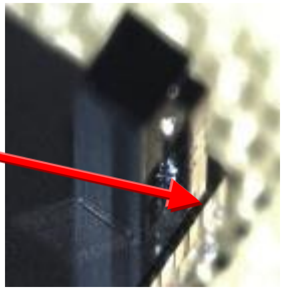


Defense Contractor

- Die/Component Attach
  - ***vs. Dispensers***
  - Higher Density (50um)
  - Higher Yield
  - Recessed Substrates

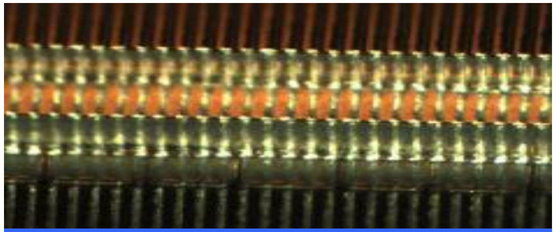
Disk Drive Manufacturer

- Micro-Underfill
  - ***vs. Dispensers***
  - Higher Density (15um)
  - High Standoff
  - Vertical Chips



Aerosol Jet: 3D Integration for Semi Packaging

- Stacked Die: Staggered Chips Conformal Interconnects
  - *vs. Wirebonding*

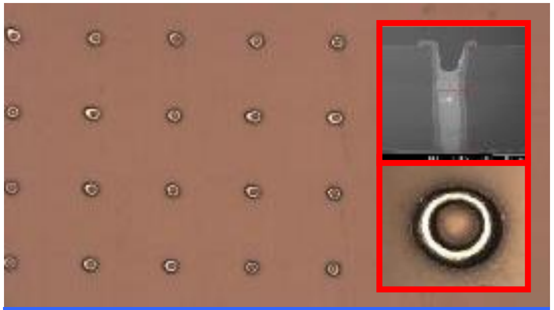


25um / 50um 3D Interconnects

- Stacked Die: Aligned Chips Vertical Interconnects
  - *vs. Wirebonding*

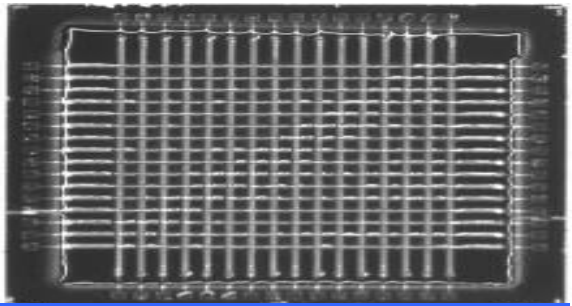
25um / 100um Sidewall Interconnects

- Via Filling
  - *vs. Plating*



75um dia x 300um Deep

- Printed Interposer
  - *vs. Silicon (Wafer Processing)*



3 Layer Cross-Over Circuit

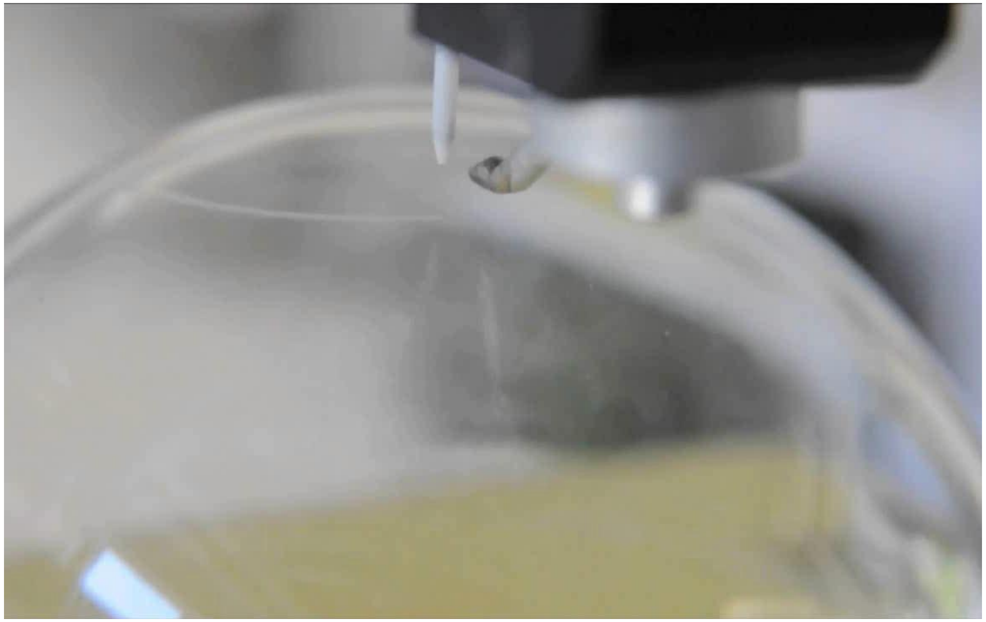
Georgia Tech Manufacturing Institute

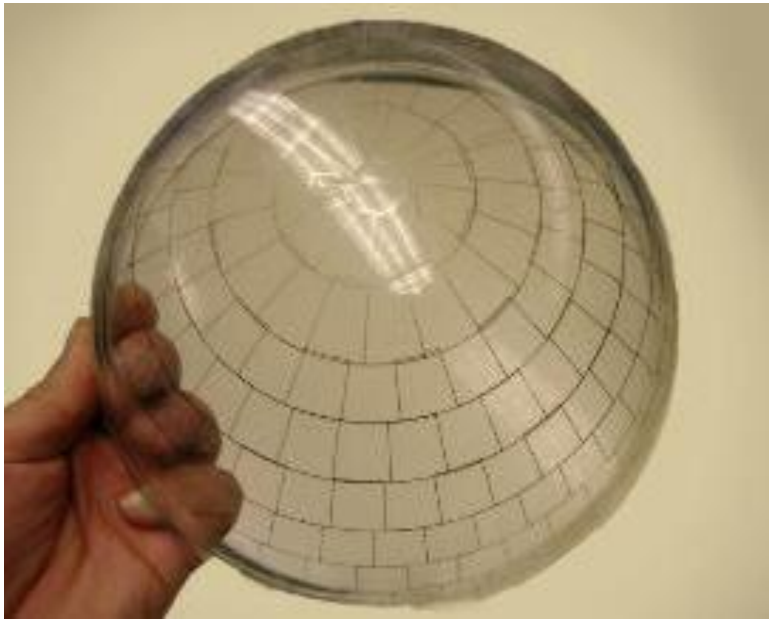
3D Printed Antenna: Video of Production System

- **Coordinated 5-axis capability, based on commercial CNC Machine Tool**
  - **Software Utilities to assist with multi axes toolpath generation**
  - **Typically 2+1 or 3+2 Axes mode, enabled by AJ's insensitivity to stand-off/angle**

Functionalized 3D Plastic Parts: Defense

EMI Shielding Printed onto a Dome



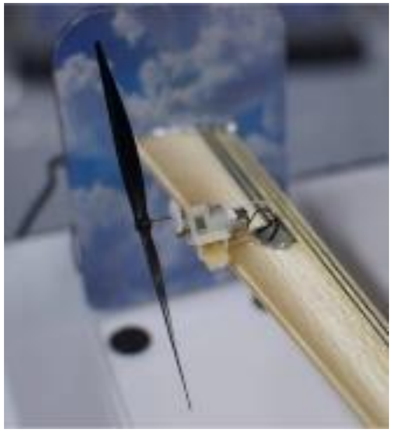


OPTOMEC®
Additive Manufacturing Systems—from NANO to MACRO™

Georgia Tech Manufacturing Institute

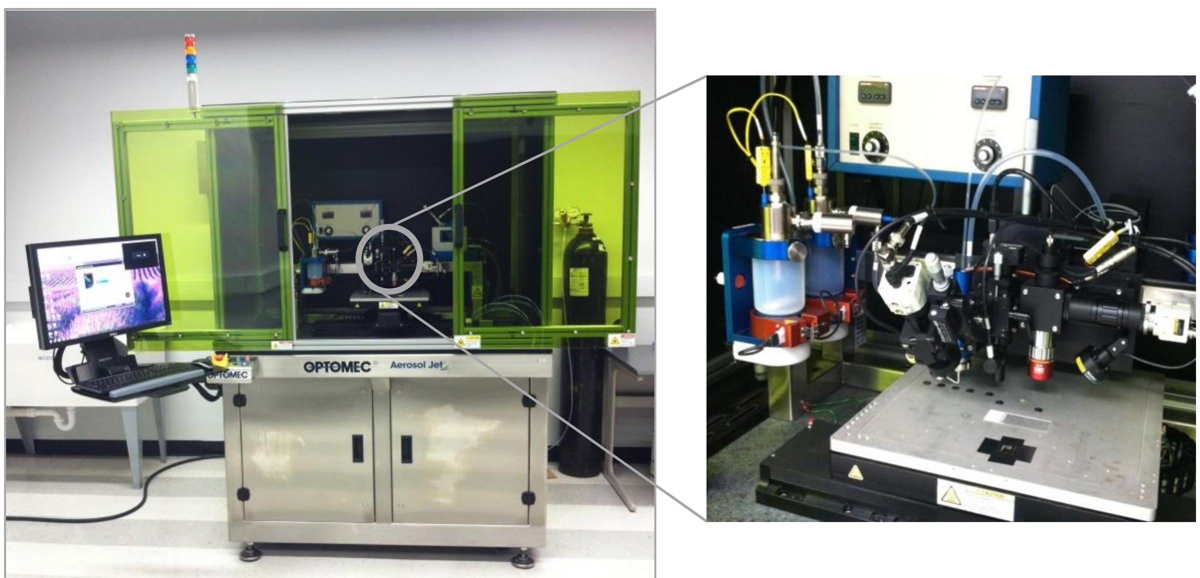
Functionalized 3D Plastic Parts: Aerospace

- **Joint Project of Aurora Flight Sciences, Optomec and Stratasys**
  - Fully Printed Wing Structure & Electronics
  - FDM Process Prints Wing using Aerospace Grade Material
  - Process Prints Sensor, RF Antenna and Power Circuits on Wing
  - Demonstrated at DMC Conference
- **Advantages**
  - Lighter Weight, Higher Performance
  - Conformal Electronics, More Payload
  - Fully Functional RP & RM
  - Simplified Electro-Mechanical Integration
  - Point of Use Repair + Reconfiguration



Aerosol Jet Printing Setup at GTMI

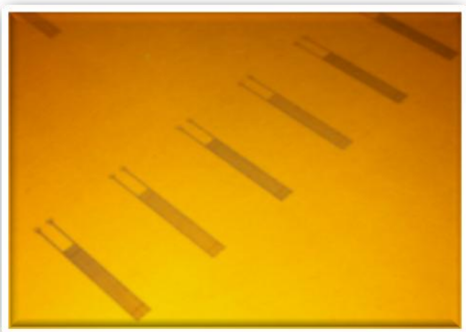
- **An Optomec AJP-300 System was acquired and installed in March 2013**
- **Prototype printed electronics fabricated at GTMI with the AJP system include strain and temperature sensors, organic transistors/pressure sensors, high-sensitivity gas sensors, RFID tags, supercapacitors, and high frequency antenna**



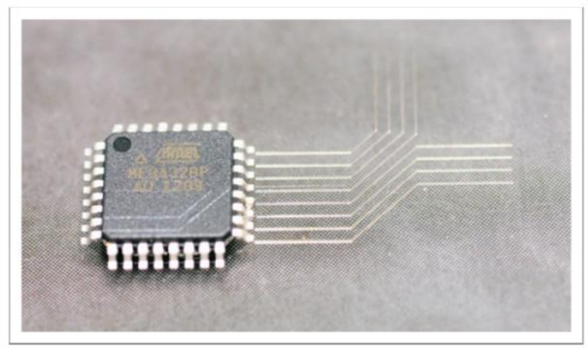
Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

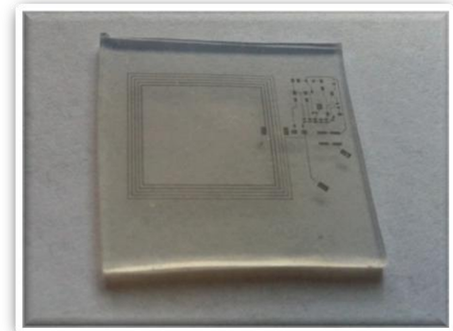
Prototypes/Samples Printed at GTMI



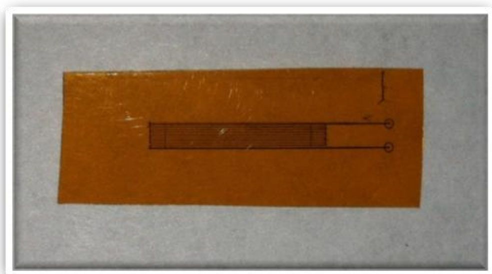
Strain sensor array printed with silver ink



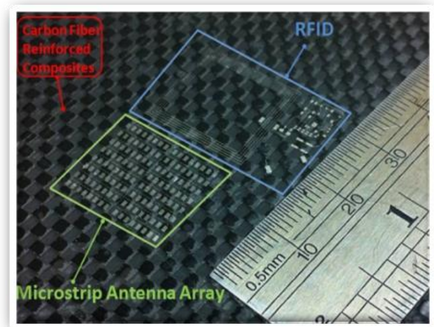
Interconnects linked with IC chip pins



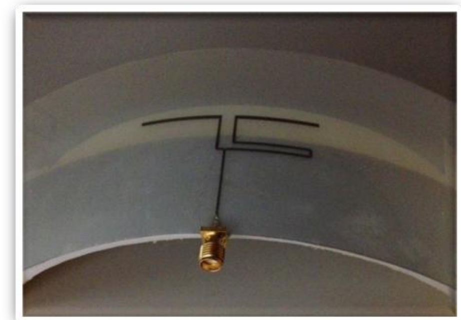
RFID tag on silicone



Temperature sensor printed with carbon nanotubes



RFID tag and antenna array on carbon fiber prepreg



High frequency antenna

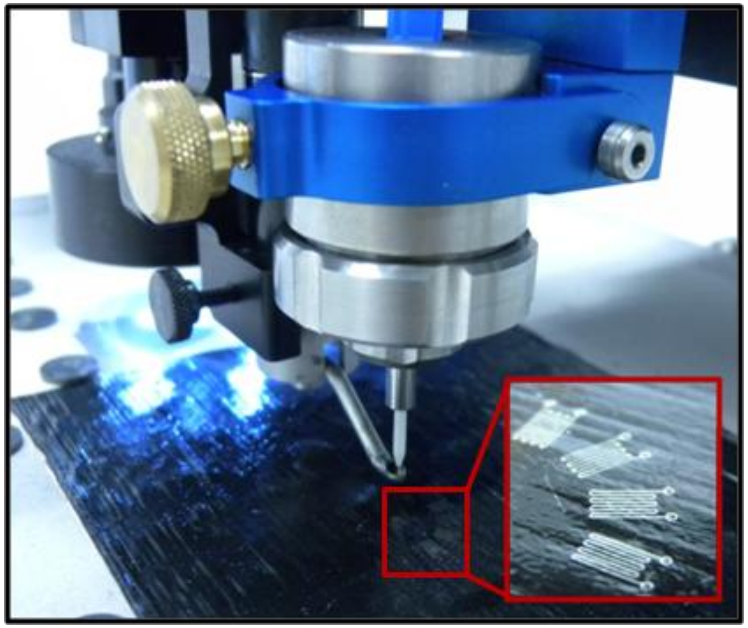
Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

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

Objectives

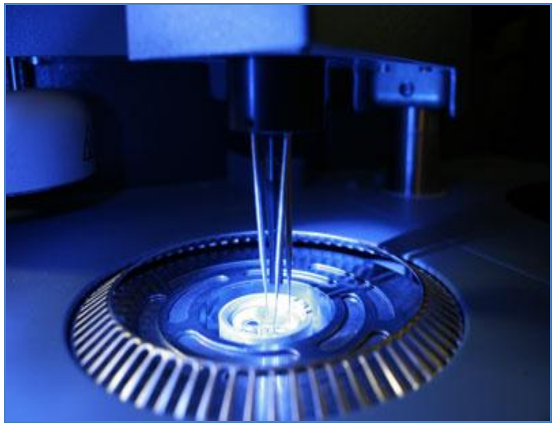
- **Print strain and temperature sensors directly on prepregs and embed them into composite laminates**
- **Investigate the effects of sensors embedment on composite mechanical properties**
- **Monitoring of manufacturing process and structural health of composites with printed sensors**

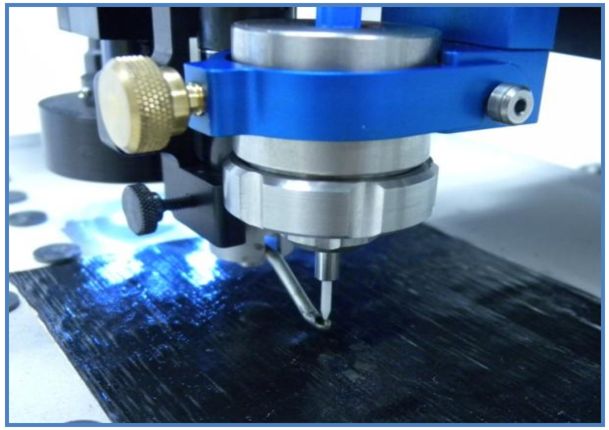


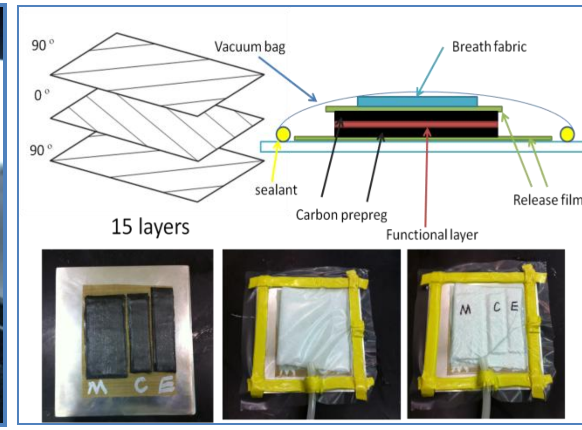
- **Prepregs: unidirectional carbon fiber/epoxy**

The information presented herein cannot be duplicated or extracted without permission from GTMI

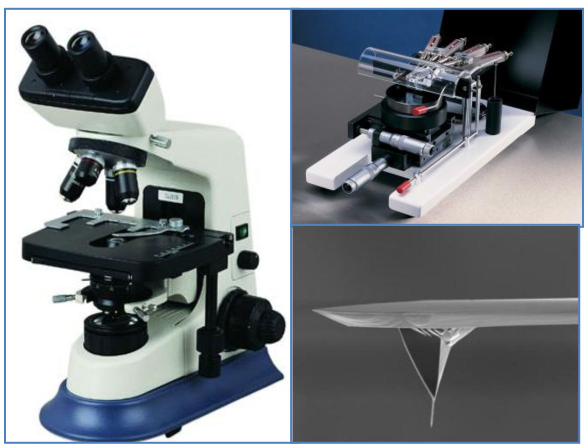
Experimental Procedure

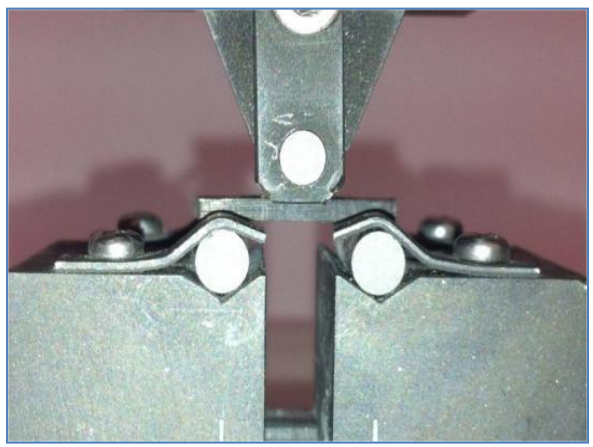


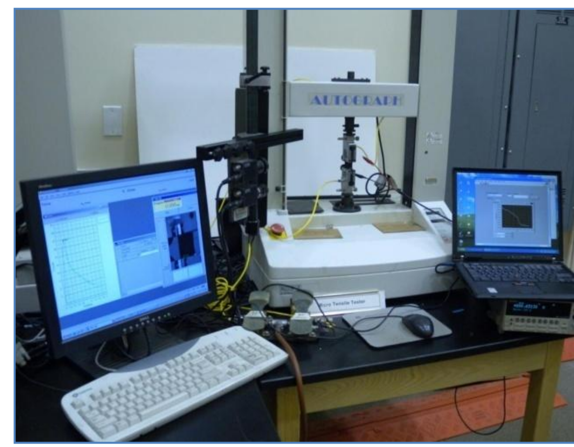




Prepreg preparation → **Sensor printing** → **Composites fabrication**







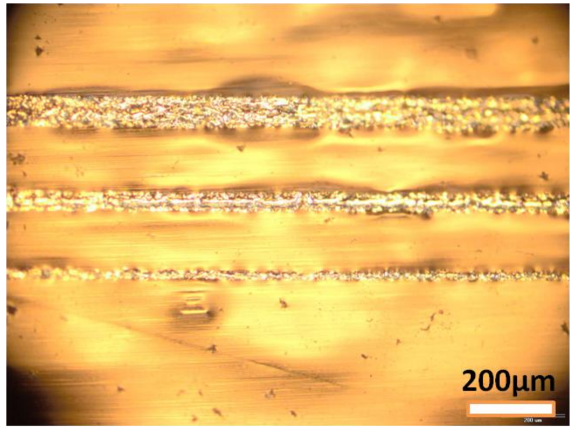
Printing quality → **Mechanical Integrity** → **Sensing performance**

Georgia Tech Manufacturing Institute

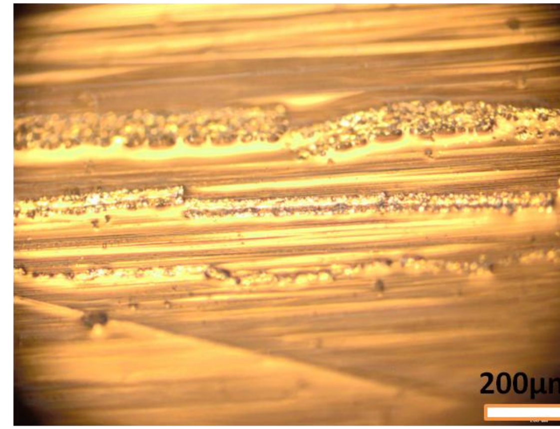
The information presented herein cannot be duplicated or extracted without permission from GTMI

Effect of Curing on AJP Sensors

Printed lines on <u>raw</u> prepreg:
- **Poor printing quality**
- **Patterns washed out**

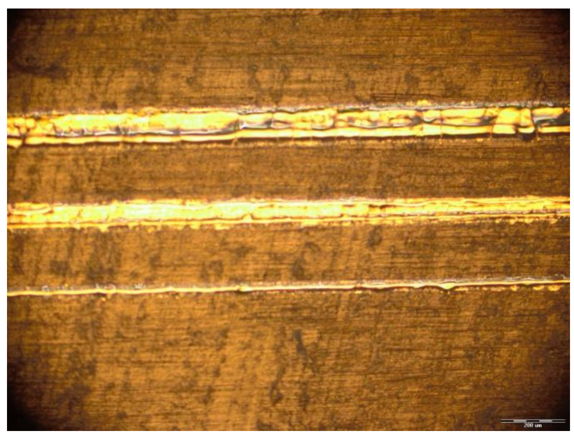


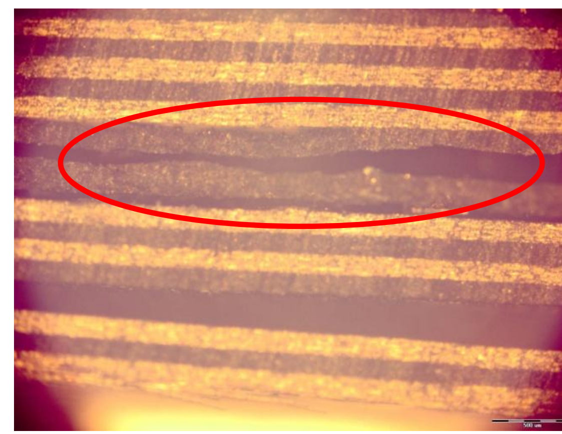
Before curing



After curing

Printed lines on <u>fully-cured</u> prepreg
- **Mech. degradation**
- **Delamination**


After curing

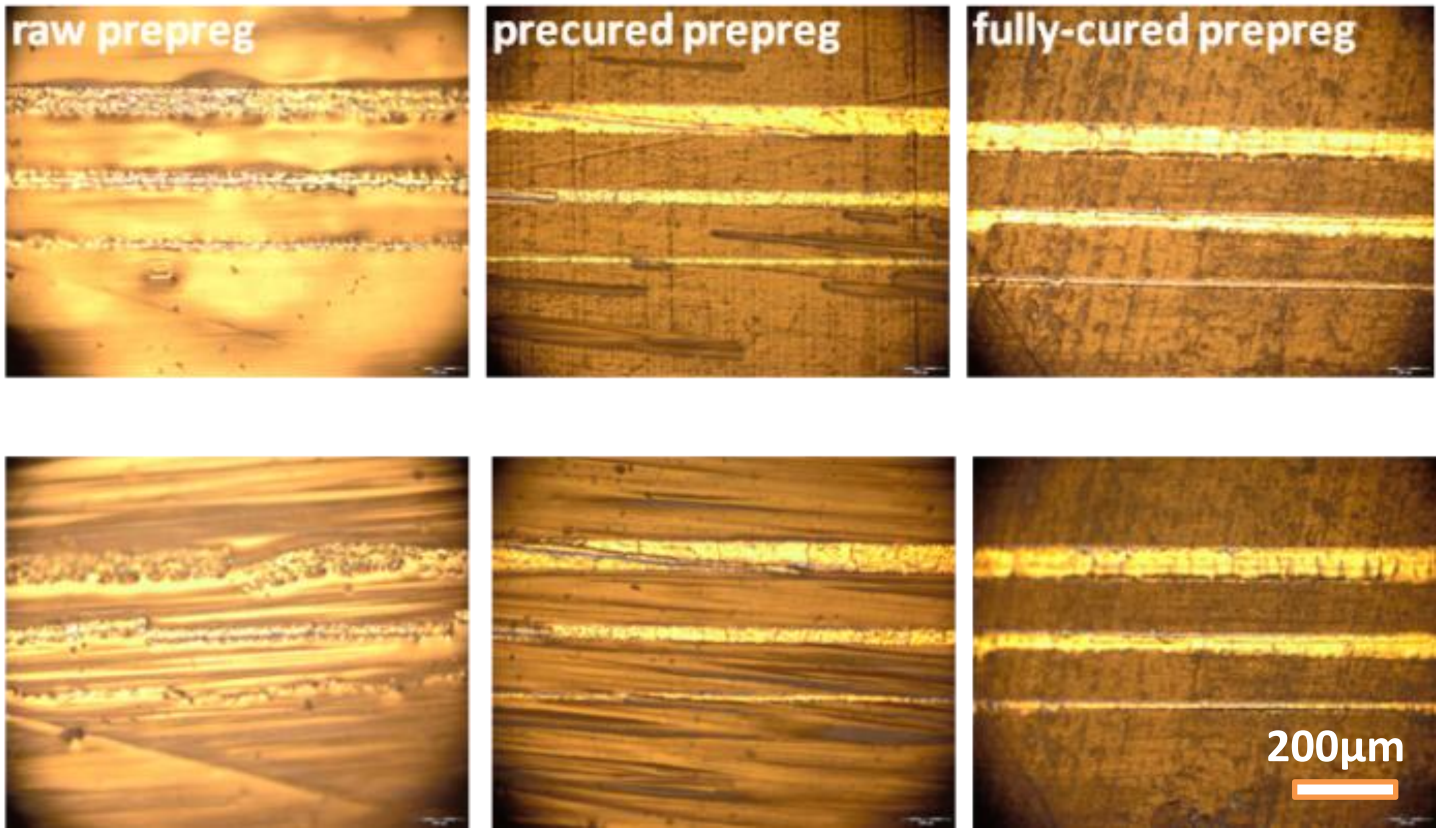

Cross-section of composites with embedded printed layers

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

Printing Quality on Different Substrates

	Raw prepreg: no precuring	Precured prepreg: 10 min, 180ºC	Fully-cured prepreg: 360 min, 180ºC
Before curing			
After curing			



Poor sensing performance

Acceptable sensing capability with unaffected mechanical performance

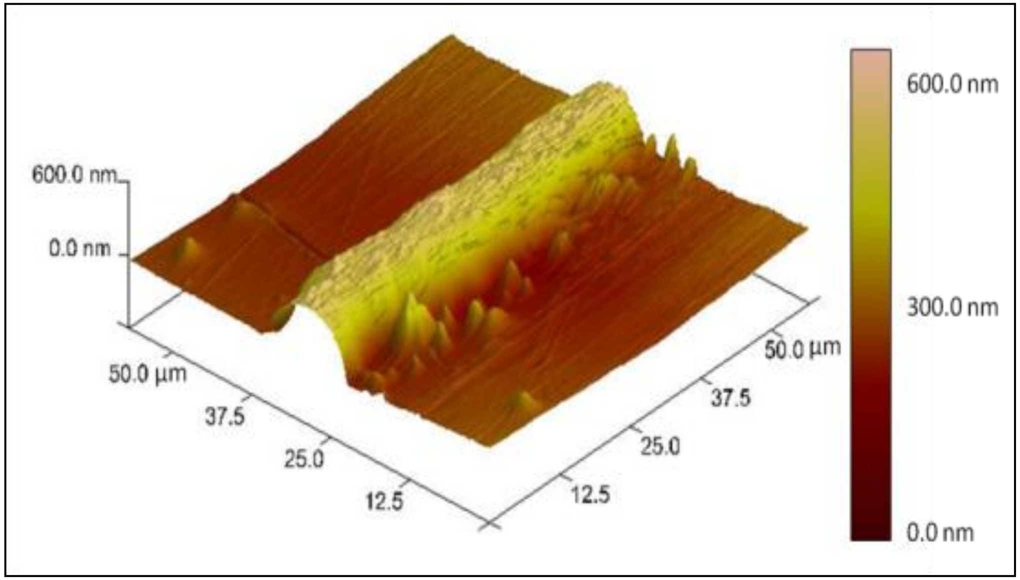
Compromised Mechanical performance

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

AFM and Electrical Resistivity Measurements

Sample Type	Mean Electrical Resistivity ($10^{-6}\Omega\cdot cm$)
1. Printed line on raw (0%) prepreg	Printed lines washed out
2. Printed line on fully-cured (100%) prepreg	5.5 ± 0.4
3. Printed line on pre-cured (10%) prepreg	12.7 ± 1.4



Takeaway

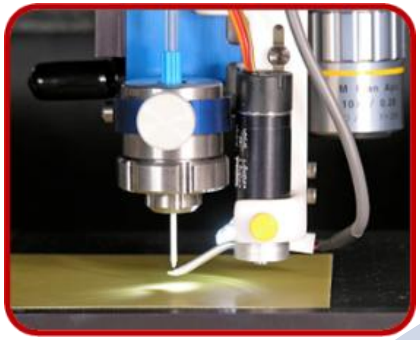
10% pre-cure resulted in certain, but acceptable, loss in electrical conductivity

Georgia Tech Manufacturing Institute

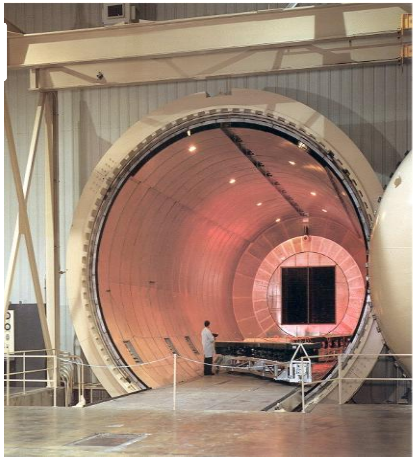
The information presented herein cannot be duplicated or extracted without permission from GTMI

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

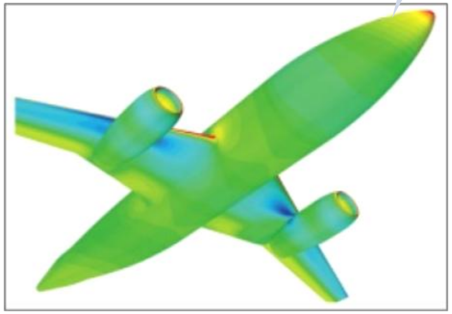
Embedded Printed Sensors in Composites



Finished Product Structural Health Monitoring



Manufacturing Process Monitoring



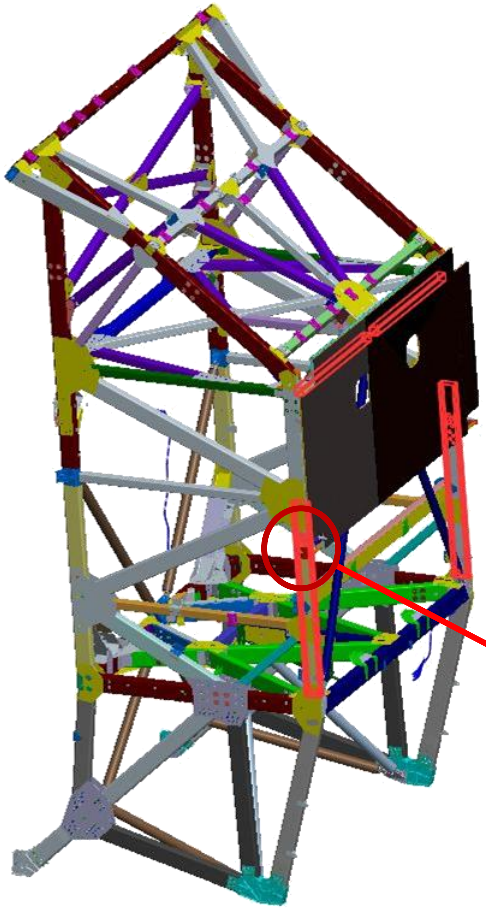
Design Model Validation

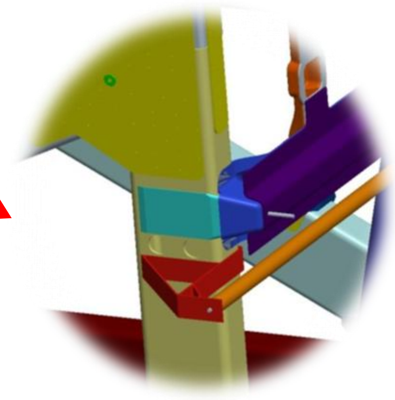
Georgia Tech Manufacturing Institute

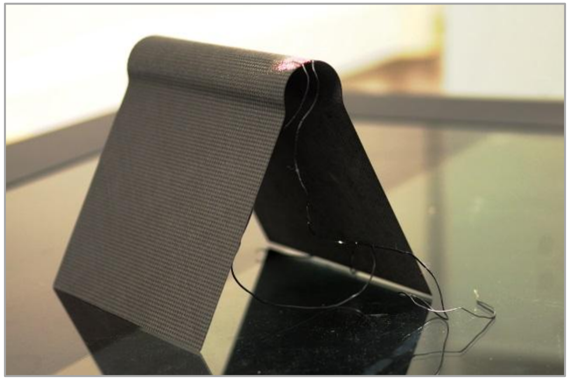
The information presented herein cannot be duplicated or extracted without permission from GTMI

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

In collaboration with Genesis Engineering Solutions, Inc.

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

Application Case: Fabrication of CNT-based High Sensitivity Sensors for Standoff Chemical Vapor Detection

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

Motivation

- Long-term monitoring of chemical vapors
  - Ammonia, hydrazine, chemical warfare agents, etc.
- 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

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

Nanomaterials-Based Sensors

- Benefits of carbon nano-materials for sensing
  - Ambient temperature operation
  - Low cost fabrication
  - Specificity to particular gas (functionalization and/or sensor array)
  - Sensor reverts back once the reaction is complete
  - Easy integration with electronics (antennas, RF modules)
  - Standoff detection using wireless operation
- Passive (battery-free) sensor operation
  - Small size, low-cost, no maintenance
- Interrogation distance up to 100m+ feasible

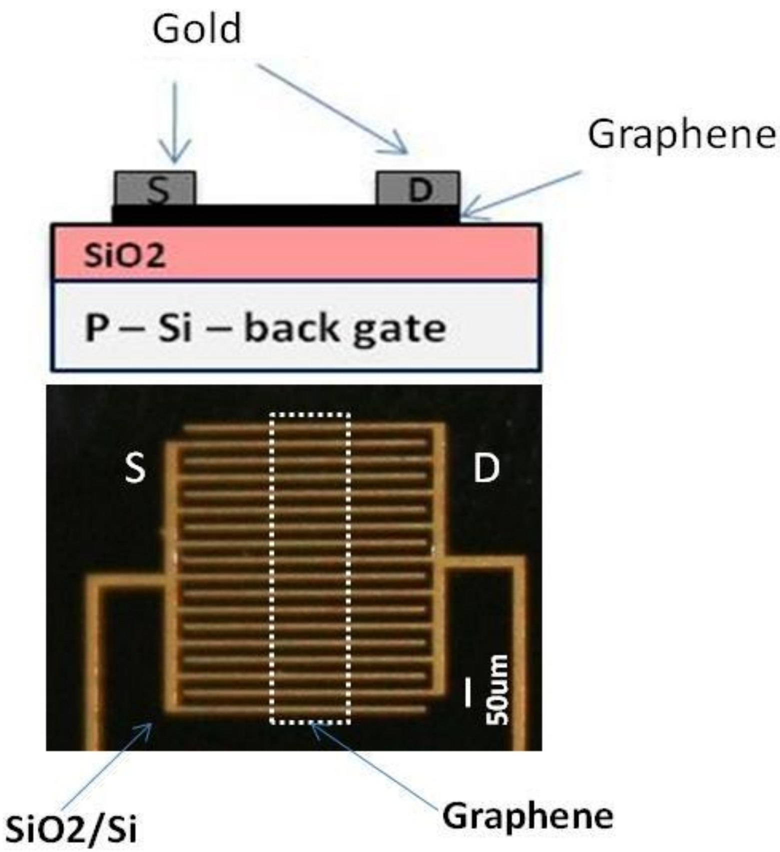
The information presented herein cannot be duplicated or extracted without permission from GTMI

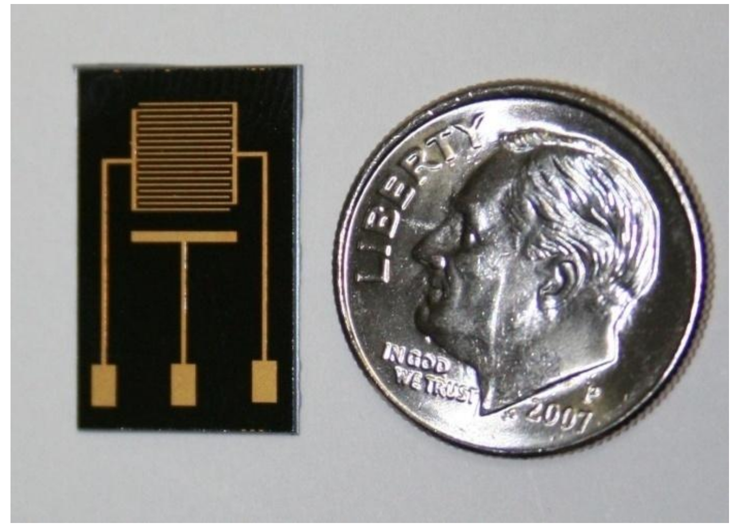
Challenges for Trace Detection

- **Low vapor pressure of explosives makes sensing difficult**
  - **10 parts per billion for TNT**
  - **10 parts per trillion for RDX, PETN**
- **Require high sensitivity to detect vapors**
- **Interference in background (selectivity)**
- **Standoff range limited by power and technology**

The information presented herein cannot be duplicated or extracted without permission from GTMI

Prototype Device





- **Two or three terminal device**
- **Chemiresistor and/or impedance measurement**
- **Currently applied to detect chemical compounds and radiation**

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

Nanomaterial-based Chemresistor Characteristics

- Sensitive
  - Up to 50 parts per billion
- Selective
  - Functions in the presence of contaminants
- Quick-response
  - Less than 1 second in exposure
- Reversible
  - Reverts back to original state
- Repeatable
  - Same response over time

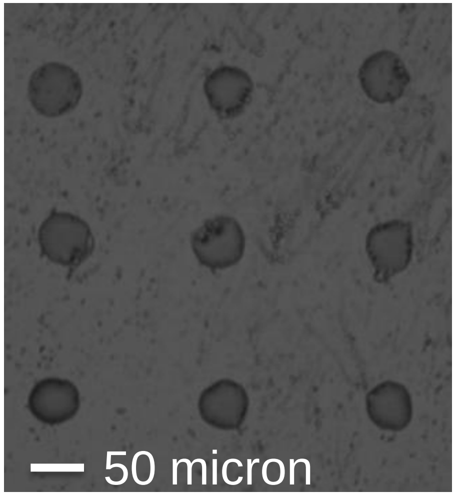
The information presented herein cannot be duplicated or extracted without permission from GTMI

Nanomaterial Sensing Film Fabrication Methods Comparison

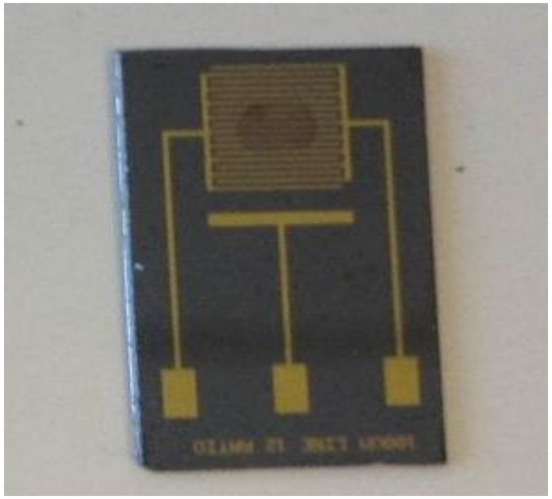
Fabrication Method	CNT Dispersion Viscosity Requirement	Process Requirements	Repeatability Quality Control	Cost
Brush Painting	None	Chemical Hood long curing time	Personnel dependent, relative lack of control	Labor
Air Spray Coating	Prefers Medium to High Viscosity Solution	Chemical Hood Face Mask & Mask for Device	Solution concentration Air pressure Spray Nozzle Selection	Labor
Spin Coating	Prefers High Viscosity Solution	Chemical Hood Mask for Device	Solution concentration High Speed Control (RPM)	Equipment
Dip Coating	Prefers High Viscosity Solution	Chemical Hood Mask for Device	Solution concentration Motor Speed Control (RPM)	Labor
Ink Jet Printing	Prefers Medium to High Viscosity Solution	Chemical Hood	Solution concentration Ink Jet Nozzle Clogging	Equipment

The information presented herein cannot be duplicated or extracted without permission from GTMI

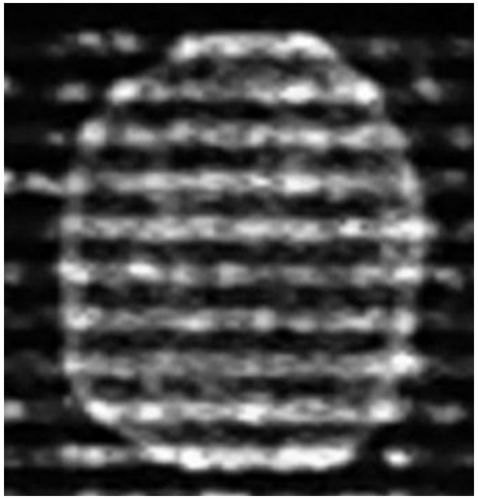
Ink-Jet Printing Results



Ink-jet printing pattern
3 x 3 array



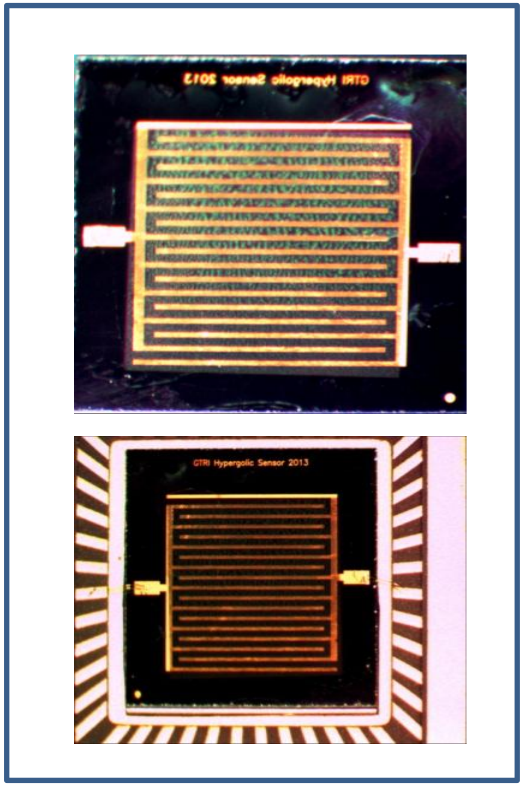
Ink-jet printed
Interdigitated Electrode
(IDE) Sensor



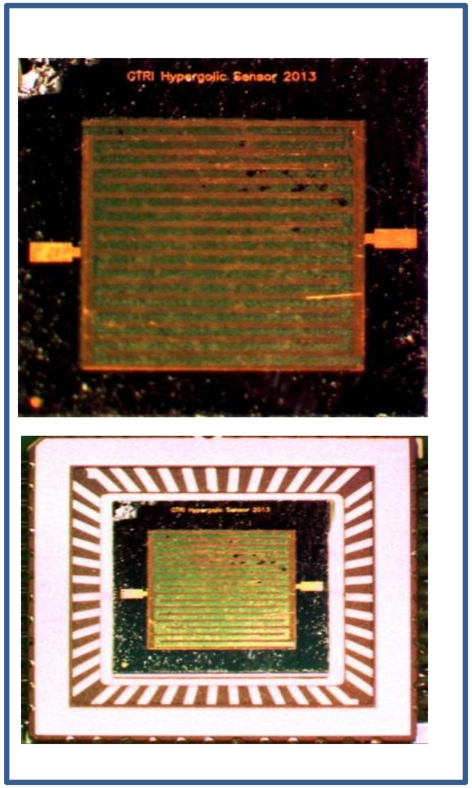
Optical Phtography
of the ink-jet printed
sensing film

The information presented herein cannot be duplicated or extracted without permission from GTMI

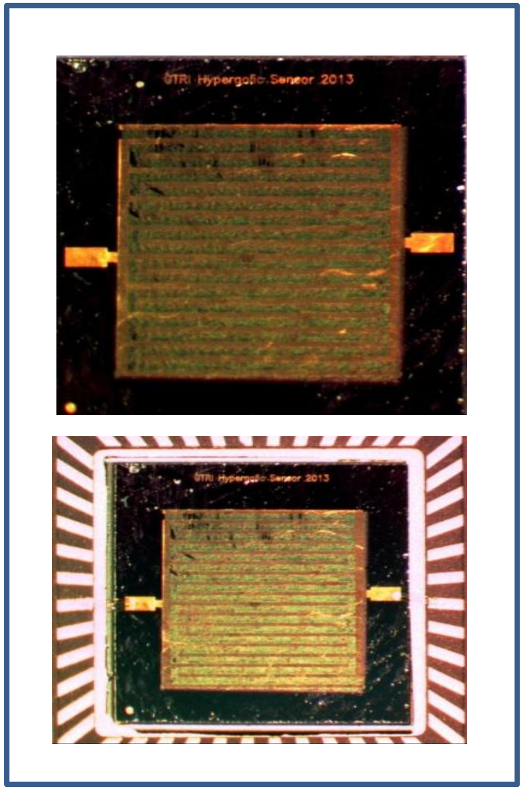
Aerosol Jet Printed Sensing Film



Sensor #1



Sensor #2

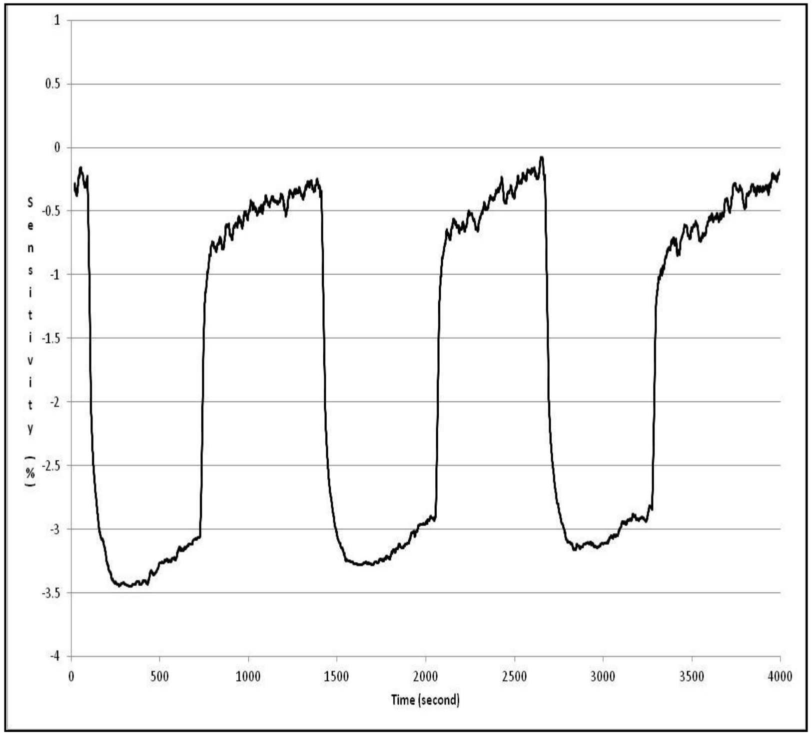


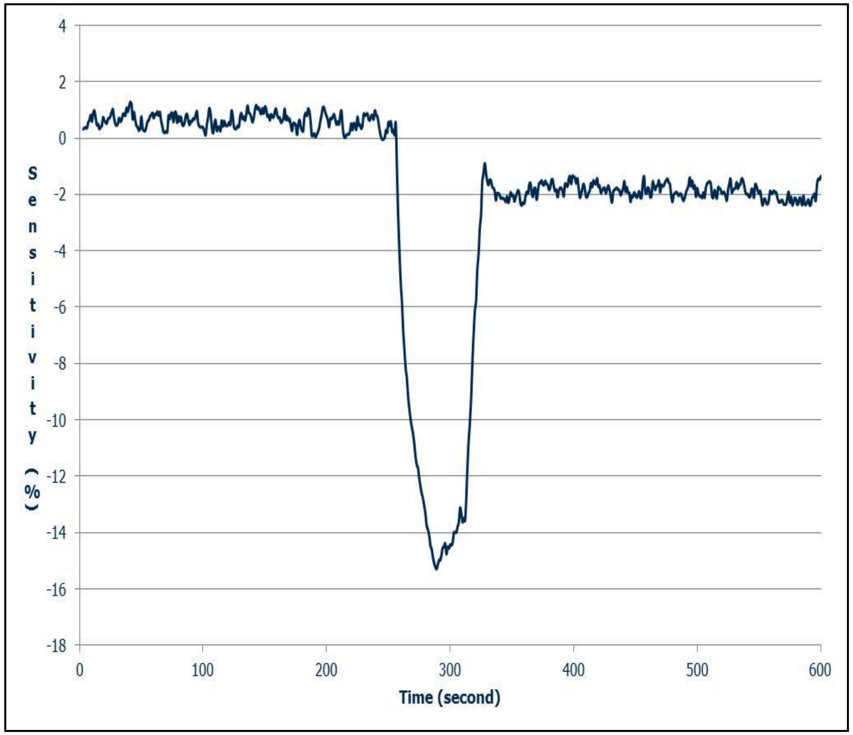
Sensor #3

Aerosol jet printed sensing film on pre-fabricated interdigitated electrodes (top). Wirebonding completed sensor packages (bottom).

The information presented herein cannot be duplicated or extracted without permission from GTMI

NO_2 Gas Sensing Comparison





Ink-jet printed sensing for 50 ppm NO2 gas **(~3.5%)**

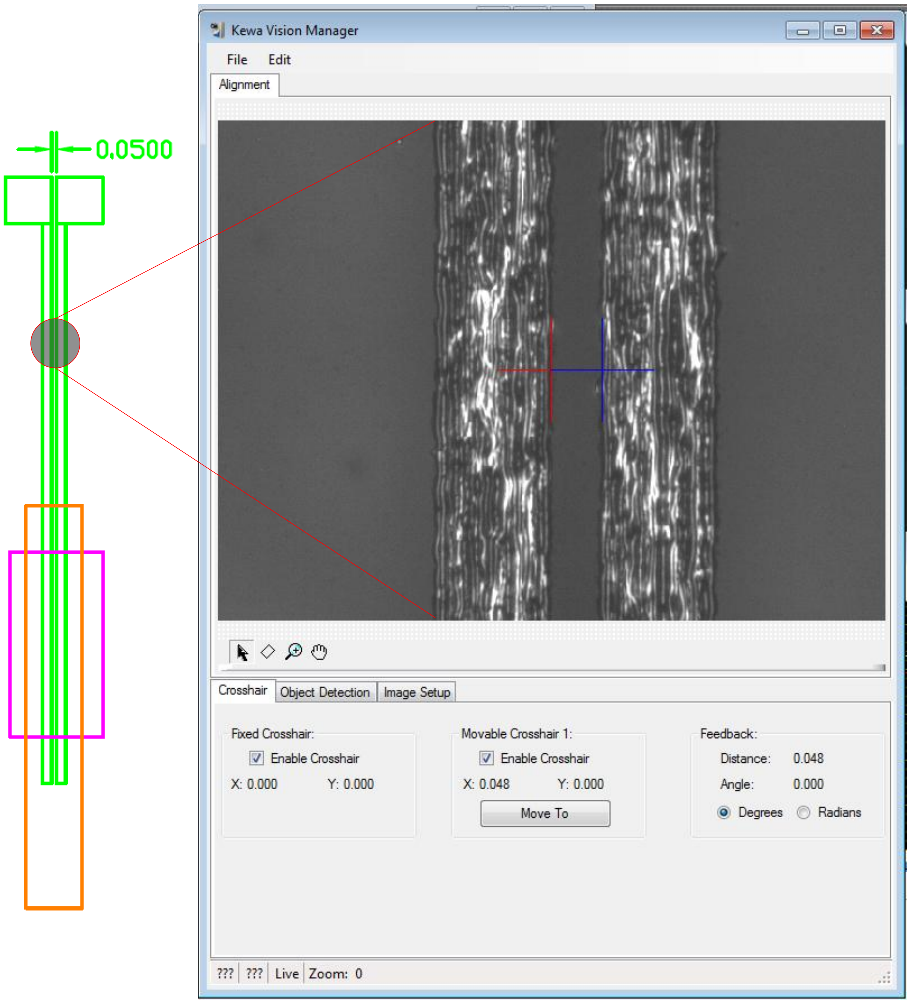
Aero-sol jet printed sensing for 20 ppm NO2 gas **(~15%)**

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

Ongoing Project: Printing of Organic Transistors

- **Uniform gate distance and low line edge roughness are required for good transistor performance**
- **Multilayer and multi-material deposition is needed**
- **AJP organic transistors performed better than those made by ink jet printing**
- **GTMI is developing process monitoring and control methods for improving printed line quality**



In collaboration with Dr. Bernard Kippelen @ GT-ECE

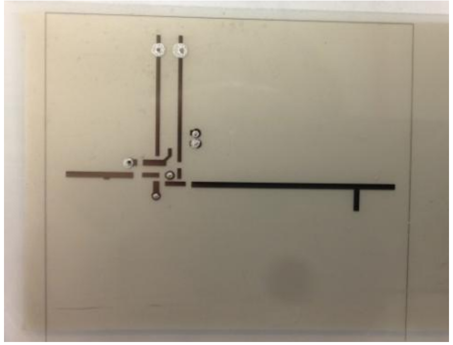
Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

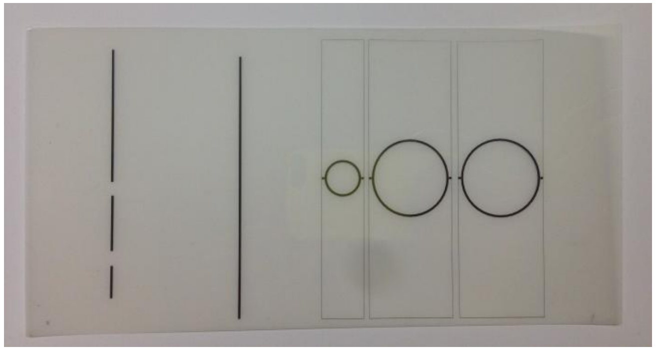
Ongoing Project: Printing of 2.4 GHz Antenna

- Fast and cost effective manufacturing compared to conventional lithography process
- Conformal antenna on various surfaces
- Low temperature processing suitable for polymer substrates
- Performance matching simulation results

Printed Antenna



Amplifier Circuit



Transmission Line &
Ring Oscillator

In collaboration with Dr. John Papapolymero @ GT-ECE

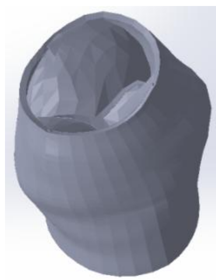
Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

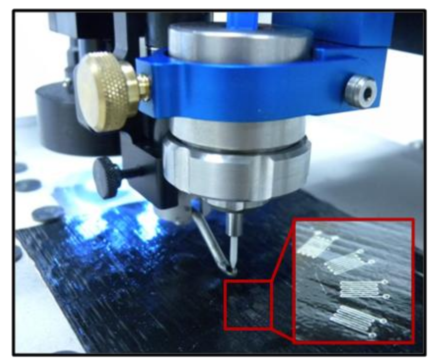
Integration of 3D Printing and Printed Electronics Technologies for Medical Applications

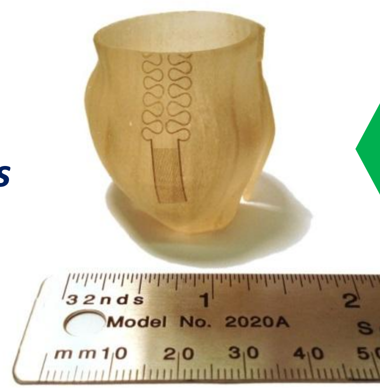
CT Scan

CAD/STL Models



Printed Valve





3D printed valve with strain sensors on surface

In collaboration with Piedmont Hospital, Atlanta

Georgia Tech Manufacturing Institute

The information presented herein cannot be duplicated or extracted without permission from GTMI

Technical Issues and Challenges for PE Manufacturing and Applications

- **Ink and Substrate Materials**
  - Ink performance during printing and curing, wetting and adhesion between ink and substrate, biocompatibility
  - Volume manufacturing
- **Manufacturing Process Monitoring and Control**
  - Process modeling, simulation and optimization (ICME)
  - Monitoring and control of key process parameters
  - Metrology and QC for PE
- **Scalable Manufacturing**
  - Scalable for production, not just prototyping
  - Complimentary to and integrated with existing manufacturing processes

The information presented herein cannot be duplicated or extracted without permission from GTMI

Technical Issues and Challenges for PE Manufacturing and Applications (Cont'd)

- **Reliability and Durability of Printed Devices**
  - **Nanoparticles behavior during service**
  - **Environmental stability**
- **Software Issues**
  - **Integration of mechanical and electronic design software for PE**
- **Integration of PE and 3D Printing**
  - **Effective algorithms for integrated PE and 3D printing**
  - **Compatibility of ink and 3D printed surfaces**
  - **Equipment with integrated PE and 3D printing capabilities**

The information presented herein cannot be duplicated or extracted without permission from GTMI

Acknowledgement

- **Sponsors and Partners:**
  - ATK
  - Department of Veterans Affairs
  - Genesis Engineering Solutions
  - Optomec (Mr. Mike O'Reilley)
  - Piedmont Hospital
  - Spirit AeroSystems
- **Research Collaborators:**
  - Dr. Bernard Kippelen, GT-ECE
  - Dr. John Papapolymero, GT-ECE
  - Dr. Judy Song, GTRI
  - Dr. Ben Wang, GT ISyE and GTMI

Georgia Tech Manufacturing Institute

Questions & Comments

Thanks!

Chuck Zhang

Tel: (404) 894-3280

Email: chuck.zhang@isye.gatech.edu