Flexible Electronics
from Silicon Wafers to Flexible Plastic
Flexible and Printed Electronic Materials and Devices

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Chemistry Department
Materials Science & Engineering Program
Director
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State University of New York at Binghamton
The U.S. Early Adopter for Flexible Displays

The Air Force had announced a complementary program using OLED on SS

Source: John Pellegrino (ARL) and Darrel Hopper (AFRL)
i3 Electronics, Inc

**Rich Heritage**

- **IBM**
  - Microelectronics division

- **Endicott Interconnect Technologies**
  - Founded 2002
  - Acquisition of IBM Endicott by local investment group
  - Expanded on technology and customer base

- **i3 Electronics**
  - Founded in 2013
  - Acquired assets of Endicott Interconnect Technologies
  - Dedicated to high reliable and complex technology
Center for Advanced Microelectronics Manufacturing
Agenda

• Advanced electronics packaging
  – Materials and processing are key

• Flexible electronics
  – Patterning: photolithography to printing
  – Unsupported substrates for R2R manufacturing
  – Flexible glass

• Next generation flexible electronics
  – Imprint lithography & multi layer alignment
  – Eliminate vacuum and high temperature (?)
  – Additive driven self assembly
Why Roll-to-Roll (R2R) Manufacturing?
R2R can lead to reductions in cost.

Center Objectives

- Fabrication of specialty prototype large-area flexible electronic substrates for members and sponsors.
- R2R vacuum deposition, photolithography, wet and dry processing of flexible, unsupported, thin film based active, passive electronic devices and advanced interconnect technology.
- Evaluate flexible R2R substrate materials and process capability.
- Specify, design, develop and build future tool and processing equipment.
- Development of materials and processes for inkjet printed electronics.
Flexible Electronics: materials, tool and application space

Substrates
- Glass panel (as a standard)
- PET film
- PI film
- PEN film
- Corning’s Willow flexible glass
- Metals (Cu, SS, etc...)
- Others

Technology
- Fine circuitry
  - single & double sided
  - single & multilayer
  - registration & overlay
- Sensors
  - environmental
  - biometric
- Medical
  - catheter technology
  - implantable
  - diagnostic
- Passive displays
- Lighting
- Optical waveguides
- Solar energy conversion
- Active devices
- Active display backplanes

Design & Fabrication

Processing (R2R & Panel)
- Vacuum deposition
- Photolithography
- Wet/dry processing
- Slot-die coating
- Ink-jet printing
- Aerosol ink-jet printing

CAMM
Flexible Electronics for a Variety of Customers and Applications

Solar Cells

Production and Prototyping for a Number of Customers for a Variety of Applications

Power Conversion Modules

Fingerprint Sensors

Wafer Probing & 2.5D / 3D Chip Interposer
# Patterning

<table>
<thead>
<tr>
<th>Technique</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Printing</td>
<td>50-100 µm</td>
</tr>
<tr>
<td>Flexography</td>
<td>40 µm</td>
</tr>
<tr>
<td>Gravure Printing</td>
<td>15 µm</td>
</tr>
<tr>
<td>Inkjet Printing</td>
<td>20-50 µm*</td>
</tr>
<tr>
<td>UV Lithography (365 nm)</td>
<td>250 nm</td>
</tr>
<tr>
<td>Vacuum UV Lithography (248 nm)</td>
<td>120 nm</td>
</tr>
<tr>
<td>Deep UV Lithography (193 nm)</td>
<td>80 nm</td>
</tr>
<tr>
<td>Extreme UV Lithography (10-124 nm)</td>
<td>~20 nm</td>
</tr>
<tr>
<td>e-beam Lithography</td>
<td>10-20 nm</td>
</tr>
<tr>
<td>Soft Lithography</td>
<td>~20 nm</td>
</tr>
</tbody>
</table>

*10-30 µm with optimization between ink & substrates

Inkjet Printing Fabrication of Electronic Devices

Dimatix DMP-2831
Optomec M3D 300
Xennia Xenjet 5000

RFIDs
Solar Cells
Nanoelectronics

Organic electronics
PCBs & interconnects
Gas sensors

Bio-sensors
3D packaging

Howard Wang, Binghamton University
What is Photonic Curing?

Photonic Curing

- Using carefully timed and controlled flashlamps to heat only the surface and not the entire thickness of the material. Exposure time is usually less than 1 millisecond.
- Allows use of high-temp materials on low-temp substrates.
- Organic and inorganic inks (including ITO, Si)
- Polymer, paper, glass
What is needed to manufacture electronic devices on flex?

- Silicon-like flexible substrates with perfectly clean, flat and defect free surfaces
- Methods to handling and convey unsupported substrate materials
- Strategies to prevent contamination and defects (scratches) at each step
- Substrate dimensional stability up to 300 or 400 °C
  - The higher the temperature, the better
- Materials deposition schemes: dielectric, semiconductor, conductors etc...
  - Vacuum deposition (evaporation, PVD or CVD), liquid thin film coating
  - Dielectrics with low leakage currents ($10^{-10}$ A)
  - High break down voltages (20 V & up)
- Patterning and pattern registration capability down to 1 μm or better
  - Photolithography or multi-pass printing (such as Gravure)
  - Etching of dielectrics, semiconductors and conductors
- Ability to repeat processes sequentially between 3 to 8 times without yield loss
- Methods to inspect, test (and repair) devices over 10-100’s of feet
Substrates Requirements

- Cost
- Low coefficient of thermal expansion
- Low shrinkage
- Tolerate higher processing temperatures
- Surface chemistry, roughness & cleanliness
- Barrier
- Solvent resistance
- Moisture resistance
- Clarity
- Rigidity
- Conductive layers
- Commercial availability
- Substrates for more demanding applications
  - likely to be hybrid multilayer organic/inorganic structures

Challenges with Plastic Substrates for Electronics

- Limited process temperature ranges (<< 300°C)
  - Limits TFT device processes and backplane performance
- Poor dimensional stability with varying process temperatures, stress and relative humidity
  - Limits pattern resolution for multi-step photolithography
  - Very difficult to make high resolution display circuits
- Permeable to diffusion of oxygen and water vapor
  - Major problem for OLEDs displays that degrade even in low levels of oxygen & water
  - Require complex and costly multilayer barrier coatings to limit diffusion to less than $10^{-5}$ gm/cm²/day
Comparison of SS & Flexible Other Substrates

<table>
<thead>
<tr>
<th>Property</th>
<th>Stainless-Steel</th>
<th>Plastics (PEN, PI)</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (μm)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Weight (g/m2)</td>
<td>800</td>
<td>120</td>
<td>220</td>
</tr>
<tr>
<td>Safe bending radius (cm)</td>
<td>4</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>RTR processable?</td>
<td>yes</td>
<td>likely</td>
<td>unlikely</td>
</tr>
<tr>
<td>Visually transparent?</td>
<td>no</td>
<td>some</td>
<td>yes</td>
</tr>
<tr>
<td>Max process temp (°C)</td>
<td>1000</td>
<td>180, 300</td>
<td>600</td>
</tr>
<tr>
<td>TCE (ppm/°C)</td>
<td>10</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>200</td>
<td>5</td>
<td>70</td>
</tr>
<tr>
<td>Permeable O₂, H₂O?</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Coeff Hydrolytic Exp (ppm/%RH)</td>
<td>none</td>
<td>11, 11</td>
<td>none</td>
</tr>
<tr>
<td>Pre-bake required?</td>
<td>no</td>
<td>yes</td>
<td>maybe</td>
</tr>
<tr>
<td>Planarization necessary?</td>
<td>yes</td>
<td>maybe</td>
<td>no</td>
</tr>
<tr>
<td>Buffer layer necessary?</td>
<td>yes</td>
<td>yes</td>
<td>maybe</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>high</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Thermal conductivity (W/m·°C)</td>
<td>16</td>
<td>0.1-0.2</td>
<td>1</td>
</tr>
<tr>
<td>Plastic encapsulation substrate thickness</td>
<td>8x</td>
<td>1x</td>
<td>5x</td>
</tr>
<tr>
<td>Deform after device fabrication</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

Organic Photovoltaic Device Collaboration between Corning, CAMM, and CAPE (WMU)

1) Design OPV device structure
   - CAPE, Corning, CAMM

2) Fabricate flexible glass web
   - Corning

3) Roll-to-roll ITO deposition and pattern
   - CAMM, Corning
     - 125 Ω/□, ~83% transmission @ 550nm
     - R2R pattern with Azores, wet etch ITO film

4) Cut device substrates into sheets
   - Corning

5) Sheet-fed functional layer printing
   - CAPE, Corning

6) Device testing
   - CAPE, Corning


Dual Rotary Si (2% Al) Targets
Elevated Temperature ITO Sputtering

- Glass web: 330mm width, >40m length
- Deposition with GVE Optilab system
  - 175°C deposition temperature
  - 0.3m/min web speed
- Multilayer sequential deposition of SiO_x/ITO
  - 50 nm thick SiO_x (AlO_x) intermediate passivation layer (reactive sputter with O_2)
  - 50 Ω/sq ITO layer, 70 nm thick
  - Thin film stack not optimized for transmission
- 3% sheet resistance variation on glass web
  - 280mm width x 10m length measured
Photolithography and Patterning
Azores 6600 Step and Repeat System
with Northfield Automation handlers

Step and repeat
~ 50 x 50 mm (2 x 2 in) expose area

R2R patterned Al on PET
Photolithography Overlay Study

- 5 mil substrate – GVE SiO$_x$ deposition on both sides of substrate for passivation
- Two Al metal layers with SiO$_x$ spacer in between deposited sequentially in the GVE tool
- Photoresist for both layers slot die coated at Frontier Industrial – Dow Shipley S1811
- Photoresist developed and stripped and Al etched in Hollmuller R2R wet processing tool
- Vacuum bake performed following first layer patterning step
Overlay Alignment

Approximately 20 feet of 1 and 2 mm overlay samples run, >100 samples picked at random and averaged

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>-0.27</td>
<td>0.52</td>
</tr>
<tr>
<td>Absolute Value</td>
<td>0.64</td>
<td>0.8</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Positive</td>
<td>1.10</td>
<td>1.50</td>
</tr>
<tr>
<td>Max Negative</td>
<td>-1.50</td>
<td>-1.30</td>
</tr>
</tbody>
</table>

Better than expected and suitable for device fabrication
Etched In Time: EITI LPS 2500 DF

Funded by: Flex Tech Alliance / ARL
Designed for use with CAMM GVE R2R Optilab system

Process capability
- Linear plasma source
- Plasma pre-clean prior to sputtering
- Reactive ion etcher (RIE)
- Plasma etch of oxides/nitrides
- Typical process gases: SF$_6$, CHF$_3$, C$_4$F$_8$, He, Ar, N$_2$ and O$_2$

Status
- Module fabrication and initial testing (completed)
- Initial process development (completed)
- Etch rates and uniformities have been established for silicon dioxide, silicon nitride, a-Si, photoresist and Si
- Application and process development underway
R2R patterned a-Si on PEN versus Si wafer

a-Si on PEN

Si wafer (at 45° tilt)
R2R Patterning Summary

• Successfully patterned features unsupported films down to 3 µm
• Demonstrated layer to layer accuracies of less than 1 µm using 5 mil plastic film.
• Patterned 5-10 µm sized features in a-Si films using EITI RIE module
• Demonstrated processes with positive and negative tone resists
• Current work includes R2R etch processes for SiO$_x$, SiN$_x$, a-Si:H and IGZO.
Energy Conversion Devices Defect Inspection

ECD and Integral Vision’s Defect Inspection System provides digital-optical inspection of web material during all stages of processing.

The $1.3M project was funded by ECD, Integral Vision and the United States Display Consortium (USDC) using Army Research Laboratory appropriated funding to advance the capability of U.S. industry in the flexible microelectronics market.

System Attributes:

- 6" width inspection
- Bidirectional unwind/rewind interleave capability
- Target defect size: ≤1 to 5 μm
- Scratch detection: ≥1 x 10 μm
- Web location tracking
- Pass/fail sensitivity to 3 μm
- Web widths up to 24"
- Throughput speed from 24" to 120" per minute
R2R Inspection

Integral Vision (2006)
Inspection System Specifications
Four modules over 6” width
Target feature size: < 1-5 um

SunOptical Systems (2013)

**Inspection Modules**
- Integral Vision (USDC/ARL)
- SunOptical Systems
- 4D Technology (Flex Tech)
- Quality Vision International

![Diagram of inspection system]
R2R IGZO TFT on flexible substrates

Sputtered IGZO (1:1:1:4)
Sputtered gate dielectric (SiO$_x$:AlO$_x$)

$V_{ds}=5V$

$I_{on} = 200 \times 10^{-6} \text{ A}$
$I_{off} = 2 \times 10^{-12} \text{ A}$

with Bruce White, Binghamton University
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Flexible Electronics Fabrication for HPMs

- Unsupported substrates for R2R manufacturing
- Materials patterning
  - Including printing
- R2R photolithography (when needed)
- R2R deposition
- Fabricate arrays of TFTs directly on flex
- Active and Passive hybrid integration
  - Traditional electronics assembly

→ Fabricate and assemble arrays of sensors and devices directly on “bandage” like substrates
A consortium of Government, Industry, and Academic Laboratories that provides the collaborative interactions needed to more effectively develop manufacturing capabilities while enhancing product development.

**Objectives**

- Accelerate prototype to manufacturing stage of product development
- Identify large-scale manufacturers
- Collaborative teams
- Innovation
- Accelerate maturation of platform capabilities across the supply chain
- Technologies to improve performance, integration, design standards, interface standards and manufacturability of sub components & systems
Design and Manufacturing of Wearable Human Performance Monitors

Collaborators

Mark Poliks, James Turner, Steven Czarnecki, Kanad Ghose
Mohit Garg, Zhanpeng Jin, Qiong Gui
State University of New York at Binghamton

Frank Egitto, Mark Schadt
i3 Electronics, Inc.

Ana Arias, Yasser Kahn
University of California at Berkeley
Wearable HPMs

• Small-scale systems integration and packaging of multi-function wearable human performance monitors.
  – Sensing and monitoring systems are becoming increasingly common.
  – Wearable systems need to be flexible, light weight and consume little power.
  – Ultimately packaged in the format of a bandage.
  – Need to be “low” cost.
Flexible Electronic Systems for Health Monitoring

- Developing printing methods compatible with large area electronics

- Optoelectronic sensor
- Flexible power sources/storage
  - Photovoltaics
  - Batteries
  - Capacitors
- Integration with Si ICs

- Pulse Rate
- Temperature
- Blood oxygenation
- ECG
- Bio impedance

Ana Claudia Arias
Human Performance Monitor (HPM)

Infrastructure

- Power: 72 hour operation
- Sensor Interface Electronics
- Processor/Communications
  - Control functions
  - Data analysis
  - Transmission to local area network

Phase 1 Biometric Parameters

- ECG
- Heart rate
- Temperature
Printed Sensor vs Commercial Electrodes

- Identify commercially available ECG sensors
  - Shimmer 2r as benchmark
- Test the printed sensor by connecting to Shimmer 2r
- Determine the voltage level of acquired ECG signals
- Compare the signal quality between the printed sensor and clinical-grade disposable Ag/AgCl sensors.
Design Requirements

Electrical Design Requirements
• Must accommodate multiple sensors: temperature, ECG, pulse, oximeter, ...
• Support secure, low-power + low-energy communication to host
• Comply with specified form factor
• Must support 24 hours of reliable operations
• Minimize number of components

Functional Requirements
• Front-end processing needs:
  — conditioning of low-level ECG signal, noise filtering
  — selection of analog signal from multiple sources
  — amplification of signals
• Low power analog-to-digital conversion and storage of data to be transmitted
• Transmission of data to host, interpretation of host commands, derivation of heart rate etc.
Conclusions

• HPM sensors and devices can be packaged into the size of a bandage.

• HPM integration and packaging is based on a combination of printed and solder-assembled electronics.
  – HPMs measure temperature, pulse, ECG signals and eventually blood oxygen levels, collect fluids and perform analysis.
  – Integrate wireless data link to nearby devices, such as smart phones, for processing and communication.
Thank you!