Printed Electronics
Salvation or Snake-oil?

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Options
• Stop Printing!
• Fight!
• Find new markets and opportunities
• Rethink Printing
  – High throughput, multilayer, deposition tool
  – Functional not/(in addition to) visual

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My Passion
Why Functional Printing?

• Large area
• High throughput (volume)
• Flexible substrates
• Additive

How to pattern a layer

Silicon Process Printing

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False Hopes

• Nanotechnology
  – “A trillion dollar industry by 2015”
    (M. Roco, NSF, 2001)
• RFID
  – “Trillions of devices per year”
    (~2003)!

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3D Printing Headlines

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More Market Inflation

• “The market for printable electronics will generate estimated revenues of over $7 billion (U.S.) in 2010”
  – Actual ~ $2 B
• 3D Printing
  – The relative factor
  – Manufacturable?
  – Low volume

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Lao Tzu (c. 604 - 531 B.C.)

- Those who have knowledge, don’t predict
- Those who predict, don’t have knowledge

Forecasting

- Never make predictions, especially about the future. Casey Stengel

“Killer” apps? (IDTechEx data)

- Billion dollar industries
  - OLED Displays 15.7 (not printed)
  - Sensors 6.42
    - Glucose > 6
  - Conductive inks 2.2
  - Electrophoretic Displays (E-ink) Sales peaked in 2011

Current Status (IDTechEx)

- Not yet profitable
- Largest suppliers are profitable
- 2014 total: $26.4bn
- Printed: 20.56bn (growing to $31.2bn in 2024)

“Killer” apps?

- OLED Lighting (not Displays)
  - The US has invested $17.5 Billion in incentives/loans:
    - 4.1 GW of capacity
    - 0.4% penetration

Current Technologies & Profitability (IDTechEx)

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Technology</th>
<th>Technology Status 2014</th>
<th>Profitability (IDTechEx Comment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displays</td>
<td>OLED displays</td>
<td>Not printed</td>
<td>Weak prospects</td>
</tr>
<tr>
<td></td>
<td>Electrophoretic</td>
<td>Printing fine</td>
<td>Market is in decline</td>
</tr>
<tr>
<td></td>
<td>Displays</td>
<td>Printed</td>
<td>Strong prospects</td>
</tr>
<tr>
<td>Lighting</td>
<td>OLED lighting</td>
<td>Printed</td>
<td>Strong prospects</td>
</tr>
<tr>
<td>Powering</td>
<td>OPV, DSSC</td>
<td>Some printed</td>
<td>Weak prospects</td>
</tr>
<tr>
<td>System Components</td>
<td>Sensors and Actuators</td>
<td>Ready printed</td>
<td>Strong prospects</td>
</tr>
<tr>
<td></td>
<td>Conductive ink</td>
<td>Not printed</td>
<td>Weak prospects</td>
</tr>
</tbody>
</table>

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I’m from the government and I’m here to help you!

Manufacturing Innovation Institutes
- America Makes (The National Additive Manufacturing Innovation Institute), August 2012
- Power America (Next Generation Power Electronics Manufacturing Innovation Institute), January 2014
- Institute for Advanced Composites Manufacturing Innovation (IACMI), January 2014
- Digital Manufacturing & Design Innovation Institute (DMDII), February 2014
- Lightweight Innovations for Tomorrow (LIFT, Lightweight Modern Metals Manufacturing Institute), February 2014

Flexible Hybrid Electronics MII
The Department of Defense will lead a competition for a new public-private manufacturing innovation institute in flexible hybrid electronics, combining $75 million of federal investment with $75 million or more of private investment. The modern world is filled with electronics: computers, cell phones, sensors, and literally trillions of small devices that make American lives better, if somewhat busier. The vast majority of these electronic devices are made up of rigid, rigid-circuit boards. But in the world around us, most things are not flat or boxy; our bodies, the environment, the vehicles that transport us all tend to reflect an organically derived shape with plenty of curves and flexibility. Flexible hybrid electronics combine advanced materials that flex with thinned silicon chips to produce the next generation of electronic products seamlessly integrated into the things around us. These include items as diverse as comfortable, wireless medical monitors, stretchable electronics for robotics and vehicles, and smart bridges capable of alerting engineers at the first sign of trouble. For the nation’s warfighters, these new technologies will make warfare more effective and improve mission effectiveness. For example, intelligent bandages and smart clothing will alert soldiers to first signs of injury or exhaustion; structural integrity sensors will offer real-time damage assessment for helicopters or aircraft after engagement; and small, unattended sensors will give soldiers greater situational awareness.

He really means Flexible Hybrid Electronics
- Sensors can be printed too!
- (Including these two)
- Energy
- Workers
- Innovation
Global Challenges

- Air
  - Sensors
- Water
  - Sensors
  - Filtration/Purification
- Food
  - Sensors
- "Green"
  - Additive Deposition
  - Additive Manufacturing

Global Challenges (PE Contributions)

- Energy
  - Storage
  - Batteries
  - Supercapacitors
  - Production/Harvesting/Transduction
  - Solar
  - Vibration
  - RF
  - More efficient Devices
    - OLED Displays
    - LED Lighting

Ambient RF energy harvesting using printed metamaterials

Bruce E. Kahn
Clemson University

And now, for something completely different
Energy Harvesting (Scavenging)

- Means of powering electronic devices by scavenging many low-grade ambient, or “wasted” energy sources such as environmental vibrations, human power, thermal gradients, or pressure gradients, and their conversion into useable electrical energy.
- Potentially attractive as replacements for primary batteries in low power applications.

Ambient RF Energy Harvesting Publications (IEEE)

- TV
- Radio
- Cellphone
- Wi-Fi networks
- Base stations
- Routers
- Communications devices
Why Harvest RF?

- Can reuse broadcast RF
  - 1 uW is a fraction of 10 mW Zigbee (Bluetooth, WiFi)
- Ubiquitous in urban environments
  - Day and night
  - Inside and out
- Stationary or mobile
- No added energy cost
- Industrial design
  - RF goes through most materials
  - Can reuse antennas

Computing Energy Efficiency

Mobile Phone Subscriptions

- More people around the world have cell phones than ever had land-lines
- There are nearly as many mobile subscriptions as there are people on earth

Cell Phone Statistics

Trends

- Power efficiency
- RF availability
- RF → DC efficiency
- RF energy harvesting

RF Power Spectrum at City Location

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RF Power Density (London)

Frequency Bands

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>DTV</td>
</tr>
<tr>
<td>850/900</td>
<td>GSM (US/Europe)</td>
</tr>
<tr>
<td>1800/1900</td>
<td>GSM (US/Europe)</td>
</tr>
<tr>
<td>2100</td>
<td>3G</td>
</tr>
<tr>
<td>2400</td>
<td>WiFi, Bluetooth</td>
</tr>
<tr>
<td>5000</td>
<td>WiFi</td>
</tr>
</tbody>
</table>

AM (MW) Radio Transmitters

AM Radio Stations

http://fmscan.org/coverage.php?band=mw

Metamaterials

- “Artificially” engineered structures that exhibit properties not found in naturally occurring materials.
- Assemblies of multiple individual elements fashioned from conventional materials, but the materials are usually constructed into repeating patterns, often with microscopic structures.
- Properties are derived not from the compositional properties of the base materials, but from their structures.

Inspired by Nature
Properties of metamaterials are mostly dependent on their geometry.

Metamaterial Applications

• Negative refractive index
  – Bend light “backwards”
• Invisibility cloak
  – Make things “disappear”
• Flat lenses
• Superlenses
  – Resolution beyond diffraction limit

Metamaterial Advantages for RF EHA’s

• Wide bandwidth
• Multiband absorption
• Electrically small (can be 10X smaller than conventional)
• Could absorb > 3X more energy than similar size rectenna

Multiple Frequency Absorption

Why Print RF metamaterials

• Critical dimensions
  – sub mm
• Large area
• Easy to control spacings
• Flexible
• Thin
• Lightweight
  – Rollable, stowable, foldable
Available Power Density

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Handheld</th>
<th>Wi-Fi router</th>
<th>GSM Base Station</th>
<th>AM Radio Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>800-900</td>
<td>0.1</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>1800-2400</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>2400-3000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>3000-4000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>4000-5000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>5000-6000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
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<tr>
<td>6000-7000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
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<tr>
<td>7000-8000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>8000-9000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>9000-10000</td>
<td>0.535</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Needs
- Large Area
- High Efficiency

Ambient Power and Device Consumption

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Power density available (µW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140,000</td>
</tr>
<tr>
<td>4</td>
<td>80,000</td>
</tr>
<tr>
<td>10</td>
<td>1,600</td>
</tr>
<tr>
<td>50</td>
<td>3,200</td>
</tr>
<tr>
<td>100</td>
<td>8,400</td>
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<tr>
<td>500</td>
<td>48,000</td>
</tr>
<tr>
<td>1000</td>
<td>480,000</td>
</tr>
<tr>
<td>5000</td>
<td>160</td>
</tr>
<tr>
<td>10000</td>
<td>40</td>
</tr>
</tbody>
</table>

Recently Reported RF Powered Systems

<table>
<thead>
<tr>
<th>Year of publication</th>
<th>Device</th>
<th>Frequency (MHz)</th>
<th>Power source</th>
<th>Transmission Distance (km)</th>
<th>Battery life (h)</th>
<th>Charge time (h)</th>
<th>Battery capacity (mAh)</th>
<th>Other comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Dragonfly Biotelemetry</td>
<td>4-96 Mbps</td>
<td>ISM 902-928 MHz</td>
<td>1.31 mW</td>
<td>1.5 m range</td>
<td>2.36 x 1.88 mm die</td>
<td>4.6 x 6.8 mm flex circuit</td>
<td>Battery-free, wireless network sensor application</td>
</tr>
</tbody>
</table>

Potential Applications
- Low power devices
  - Microcontrollers, displays (e.g. E-ink), RF transceivers, and others
- Charge batteries
  - Smartphone, Bluetooth device, and other portable devices
- Battery-free wireless network sensor applications
  - Unattended ground sensors (UGS), environmental monitoring and building automation (e.g. temperature sensors)
- Military applications
  - SAR imaging, powering wearable tracking devices, and covert surveillance sensors
- Internet of Things (IoT)
  - Unattended, autonomous, self-powered machine to machine (M2M) devices

“PARC Paperclip” Design Concepts
- Coupled Split-Ring Resonator
- The metamaterial elements (2 split-ring resonators) are connected (coupled) in a racetrack configuration.
- Inductance
  - The size of SRR's
- Capacitance
  - The azimuthal gap of the SRR's
- Impedance
  - Antenna gap

Patent ApplicationFiled
“PARC Paperclip” Advantages

- High efficiency
- Wide bandwidth
- High gain
- Nearly isotropic

Performance Simulation

Energy Conversion Efficiency

This is NOT Inductive Coupling!

Antenna + Coplanar Waveguide (1x3 Array)
Hybrid Energy Harvester

Inductors
Capacitor
Diodes
Capacitor
Capacitor Bank

Demonstration 1: Continuous Discharge
• LED
• 2-3 mW
• ≥ 1.7 V

Demonstration 2: Energy Storage
• Energy is stored in capacitors
• Energy is discharged through LED when button is pressed

Skin Depth

The Team
Clemson
• Liam O’Hara
• Chip Tonkin

Tampere UT (Finland)
• Don Lupo
• Miao Li

PARC
• Printed Electronics
  – Greg Whiting
  – Ping Mei
• Metamaterials
  – Bernard Casse
  – Armin Volkel
  – George Daniel
  – Victor Liu

Sponsors
• “Most people make the mistake of thinking design is what it looks like. People think it’s this veneer – that the designers are handed this box and told, ‘Make it look good!’ That’s not what we think design is. It’s not just what it looks like and feels like. Design is how it works.” — Steve Jobs, 2003
• Don’t make fashion, make function!

The Rules

1. Silicon
   - Shear’s Rule (Jim Shear, NanoSisel)
     If it can be done with Si, it will be.
   - Rule: Rule (Shawn, DARPA)
     Don’t waste time with silicon.
   - Gomory’s: Character has a damned good rule to live by!

2. Ink jet ink
   - Hakola’s Rule (T. Hakola)
     If it is easy to formulate, it doesn’t perform well, and vice versa.
   - Inks: Inks (Shawn Jones, Printed Electronics, Ltd. UK)
     ‘Inks’ in the semiconductor industry are proportional to probability.
   - Goldberg’s Corollary
     Don’t fall for it!

3. Kahn’s Rules
   - High volume and low cost (particularly over large areas) can not be achieved at a time.
     Nature abhors a vacuum — and so do I.
   - Make it work!

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