How to Win in High-Volume Manufacturing of Flexible/Printed Electronics

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Before Beginning

- Overview of nascent flexible/printed electronics industry and the opportunity space – Why we should be positive
- What to worry about (why other technologies will remain competitive)
- My background:
  - Research:
    - Nitto Denko: Materials for electronics and display applications, including OLED emitters, photorefractive polymers, compensating films, refreshable holographic display
    - Optically active and conducting polymers
  - Beyond the lab:
    - Sloan Fellowship at Stanford Business School, 2004-05
    - Assorted business development and marketing roles in startups in solar energy, biotech and quantitative marketing
    - FlexTech Alliance (Trade Association), Director, Tech. Marketing
Outline

• Brief technical bit
• Define the terminology
• Demand and technology drivers
• Attention-getting markets
• Market predictions and opportunities
  – Drivers
  – A case study on market growth
• Satellite views on technology development
The Technical Portion

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Video Digitiser MkII: Sheet 1

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Electronics products are becoming larger – no longer just “micro” or “nano”

Performance requirements (ruggedness, low-weight, power savings, shape) demand that products be flexible and deformable

Flexible solar cells on ultra-thin steel foil (Energy Conversion Devices)

Transistors on plastic transparent substrate (Penn State University)
Flexible & Printed Electronics
“More or Less than Moore”

- A departure from self-fulfilling focus on transistor density (↑performance, ↓unit cost)
- Focus on enabling appropriate functionality at low cost

<table>
<thead>
<tr>
<th></th>
<th>Flexible &amp; Printed</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transistors</td>
<td>Thousands</td>
<td>Billions</td>
</tr>
<tr>
<td>Feature Sizes</td>
<td>10’s of microns</td>
<td>10’s of nm</td>
</tr>
<tr>
<td>Cost of Fab</td>
<td>$5-200 M/fab</td>
<td>$2-3 B/fab</td>
</tr>
<tr>
<td>Performance</td>
<td>Low</td>
<td>High</td>
</tr>
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</table>
The Definition Problem With Flexible and Printed Electronics
Printed Electronics
A Convergence of Two Worlds
(manufacturing innovation – cost reduction)
Flexible Electronics
Enabling Ubiquitous Electronics
(feature innovation – value creation)

Auto Heads-Up and Dash
Integrated Display

Magazine with Integrated Display

Portable, Self-powered Command Center
Warring Manufacturing Philosophies

Roll to Roll vs. discrete substrate

• All IC and Display manufacturing today is with discrete substrates
  – Glass substrates are extremely large
  – Batch processes, multiple steps, lots of thermal cycling
• Roll to Roll processing offers continuous flow of process
  – Can be modularized for different unit steps or integrated into complete line
Opportunities in Flexible and Printed Electronics (Overview)
Demand Drivers

• Lower Cost
  – Bill of Goods
  – Mfg Complexity
  – Economies of Scale

• New Features/Usability
  – Flexible/Conformable
  – Thickness – new apps
  – Durability
  – Weight
  – Power budget
Flex/Printed Electronics Timeline

1ST GENERATION
Passive Components
- Capacitors, resistors, conductors, inductors
- RFID antenna

2ND GENERATION
Active Printed Components
- TFTs for ePaper, eBook
- Thin-film Solar Cell
- μ-Battery

3RD GENERATION
Completely Printed Active Devices
- Color Display w/TFT-PLED
- Complete RFID circuit
- SRAM, CPU

Source: Nanogram corporation
Flexible/Printable Devices

- Aveso display
- Siemens OLED
- Precisia antenna
- TFE memory
- Dimatix circuit board
- Plastic Logic i-ink
- PolyIC integrated circuit
- Power Paper battery
- Dupond OLED
- Konarka solar cell
Photovoltaics

PV Production Growth Rate: 60% y/y (and increasing)
Thin-film PV Growth Rate >100% y/y
Long-term literally hundreds of square kilometers(!) of devices
Flexible/Portable (OLED) Lighting

Portable Lighting

OSRAM-Mauer OLED Lamp
Flexible Digital Displays

Reflective
Bi-stable “zero power”

Emissive
Efficient low power

Electrophoretic Ink

Phosphorescent OLED

Cholesteric Liquid Crystal

Thin Film Transistor (TFT) Pixel Cross Section on Flexible Substrate
Flexible Displays in Product Packaging/Marketing

- Esquire October issue featured active display on newsstand editions
10 Year Prediction

FlexTech, 2008

- Sensors
- e-Paper
- Lighting
- Integrated Devices
- Equipment
- OLED
- Energy

Hybrid Manufacturing
Demo/Rigid Devices

R2R & Flexible
Wide adoption
Cumulative Revenues to 2017

- Energy: $76.7B
- OLED Equipment: $49.1B
- Lighting Integrated Devices: $42.0B
- e-Paper: $23.2B
- Sensors: $18.1B
- Sensors: $13.0B
- Sensors: $9.7B

FlexTech, 2008
## Recent Venture Investments

<table>
<thead>
<tr>
<th>Device Companies</th>
<th>Materials Companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add-Vision</td>
<td>Kovio</td>
</tr>
<tr>
<td>Konarka</td>
<td>Cambrios</td>
</tr>
<tr>
<td>Nanoident*</td>
<td>Coled Technologies*</td>
</tr>
<tr>
<td>ORFID*</td>
<td>Novaled**</td>
</tr>
<tr>
<td>OrganicID *</td>
<td>Nanogram</td>
</tr>
<tr>
<td>Plastic Logic</td>
<td>Plextronics</td>
</tr>
<tr>
<td>E Ink</td>
<td>Vitex Systems</td>
</tr>
<tr>
<td>PolyIC*</td>
<td>Sumation*</td>
</tr>
<tr>
<td>Polymer Vision</td>
<td>Nanosolar**</td>
</tr>
</tbody>
</table>

* size of investments have not been disclosed,
** could also be considered a device company
Notes on Venture Investments

• List is loaded - strong VC investment in production facilities (especially Europeans)

• Materials are perennial VC favorite

• More than 50 funded thin-film PV startups, at least 10 in excess of $100M

• Display and Mfg investments are out of favor
LCDs – A Case Study

- Electro-optic effect discovered at RCA
- Flat LCD TV proposed
- First LCD Demo (TN)
- Sharp LCD Calculator
- First Color TFT LCD
- First commercially available LCD TV (Seiko, 2”)
- First LCD ViewCam
- First commercially successful LCD TV
- LCD TV sales exceed CRT sales (>100M units)

1962
1963
1967
1971
1973
1979
1985
1992
2002
2008

Promising Research
Niche Product
Mass Market

Discovery
Materials Development
Process Development
Supply Chain Development

Entrenched Product
Strong Opportunity Areas

- Sensors
- Novelty/Toy
- Medical
- E-paper
- Authentication
- Wearable Electronics
- Product Packaging
What Makes Them Attractive

- Creates market rather than competing in existing market (no entrenched substitutes)
- Niche markets with mass market potential
- Electronics is a small part of product cost
- Solves a problem that can’t be easily addressed by existing technology
- Fits into an existing supply chain
Technology Development Opportunities

Materials
- Barriers/Dielectrics
- Conducting Inks
- Flexible substrates

Processes
- R2R Coating
- Printing and Patterning
- Registration/Inspection

Devices/Integration
- Diodes
- Sensors/Detectors
- Thin-film transistors

Products
- Smart Bandages & Clothing
- Sensor Networks
- Photovoltaics

Markets
- Military – Information and Awareness
- Medical – Monitoring and Implants
- Energy – Storage and Harvest
Some Less Attractive, but Large, Markets

General Lighting

Display Replacements
- Cell phone
- TV

iLED + waveguide ≡ OLED
What Makes Them Unattractive

- Competes with existing commodity product
- Large existing production infrastructure
- Doesn’t leverage existing production
- Solves a problem that can be addressed by existing technology
First Cost of Light for Various Sources in 2007

<table>
<thead>
<tr>
<th>Light Source</th>
<th>2007 First Cost of Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent Lamp (A19 60W)</td>
<td>$ 0.30 per klm</td>
</tr>
<tr>
<td>Fluorescent Lamp (F32T8)</td>
<td>$ 0.60 per klm</td>
</tr>
<tr>
<td>High-Intensity Discharge (250W MH)</td>
<td>$ 2.00 per klm</td>
</tr>
<tr>
<td>Compact Fluorescent Lamp (13W)</td>
<td>$ 3.50 per klm</td>
</tr>
<tr>
<td>ILED (1W Cool White)</td>
<td>$ 25.00 per klm</td>
</tr>
<tr>
<td>OLED (2008, Osram-Mauer)</td>
<td>$ 1,000,000.00 per klm</td>
</tr>
</tbody>
</table>
Picking a Technology Winner
A Few Items to Consider

• Beware of the Hype Curve
• Cost is not a meaningful technology driver
  – Except perhaps for disruptive technology
• The Market drives technology, not the other way around
  – Inherent physical limits on existing technology Aren’t
  – Technology capabilities are predictable, even if the solutions are not
  – There is always a substitute for your solution
The Hype Curve

Visibility vs. Maturity

- Technology Trigger
- Peak of Inflated Expectation
- Trough of Disillusionment
- Slope of Enlightenment
- Plateau of Productivity

Where We Were in 2000

Where We Are Today
The Value of Cost

- Definition of “disruptive”: 10x more productive, or 10x less expensive than current technology
- Disruptive technologies:
  - Telephone
  - Telegraph
  - Radio
  - TV
  - Internet
  - Silicon microchip
- Printed Electronics is not a “disruptive” technology (although one could argue the case in medicine)
Predicting Technology Development

- Technology development is ruled by power laws.
- Over long time periods change is smooth and predictable.
- Remember that there is a lot of capital invested in entrenched technologies.
Example LEDs – Haitz’ Law
Example - Magnetic Storage

Magnetic disc technology reached “inherent physical limits” every 2-3 years starting in the mid 80’s.

Every time, the problem was quickly overcome.
Circuit Performance
Semi Ink Mobility vs. Device Features

Frequency (Hz)

Mobility (cm²/V-s)

FET Channel Dimensions
- L=1 um
- L=10 um
- L=50 um
- L=100 um
UniSolar Manufacturing Line

R2R Photovoltaic Deposition Line and Fabricated Roll
Off-the-shelf Volume Mfg

AKT SunFab
Thin-Film PV Enables Economies of Scale

AKT (AMAT) SunFab (example)
- a-Si PECVD, ~10k panel/month
- Gen 8.5 glass (5.7m² Modules)
- 55k m² of PV per month
- 40MWp annually (η=9%)
- Fixed cost/Wp = $1.75

Monthly Roll-to-Roll equivalent:
55km of 1m web (13 x 600mm rolls)

First production panels in 2h08
Upshot

(Whatever your concept of F/P E, it’s likely wrong)
Funding Flexible/Printed Electronics Research
Directed Government Funding For Flex (2001-2013)

**USA - $193M**
- NIST-ATP, $12.2M
  - 2 Projects
- DARPA, $15M
  - Mesoscopic Integrated Conformal Electronics
  - Flexible Emissive Displays
- Army, $97.3M
  - FDC, Phase I
  - FDC, Phase II pending approval
- USDC, $69.3M
  - 40+ cost-shared projects

**EU - $715M**
- FP6, $186M
  - Advanced displays
  - Flexidis
  - Micro/nano sub-systems
  - OLLA
- FP7, $183M
  - Organic display systems
  - Organic Electronics
- BRD $265M
  - Initiative Organic PV
  - OLED Initiative
  - Smart labels
- UK $79M
  - CPI/CENAMPS

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# Investor Appetites

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<tr>
<th></th>
<th>Venture</th>
<th>Corporate</th>
<th>Gov’t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Market size (TAM) (min)</strong></td>
<td>~$2B</td>
<td>$200-500M</td>
<td>$0 (Desired)</td>
</tr>
<tr>
<td><strong>Time to market (max)</strong></td>
<td>5-7 years</td>
<td>1-3 years</td>
<td>15 years</td>
</tr>
<tr>
<td><strong>Customer Base</strong></td>
<td>Diverse</td>
<td>Broader is better</td>
<td>Strategic</td>
</tr>
<tr>
<td><strong>IRR</strong></td>
<td>&gt;40%</td>
<td>≥COC (typically 13-18%)</td>
<td>5-7%</td>
</tr>
<tr>
<td><strong>Market Dynamics</strong></td>
<td>Emergent + Strong Growth</td>
<td>Predictable Cash Flows</td>
<td>Need Driven</td>
</tr>
</tbody>
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Summary

• Flexible/Printed electronics are in the marketplace (not just hype anymore)
• PV and displays drive near-term growth
  – Economy of scale catch-22
  – Enable new products in each category
• Hybrid production technologies will continue to open high margin markets
• Near-term volatility in emerging products
Contact Information

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  – Founder, Solar Red
  – kcammack@gmail.com
  – (415) 867-9065
From Hybrid to Roll-to-Roll

R2R can lead to reductions in cost. R2R can enable new applications:

- Inexpensive displays
- Large area displays
- Low cost RFID
- Remote sensors for military and commercial
- “Smart” fabrics
- Large area lighting