Ubiquitous Electronics: Why Now?

- **20% Consumer**
- **29% Consumer**
- **39% Consumer**

**Future Drivers**
- Video Recorders
- Personal Computer
- Cell Phones
- Broadband Internet
- Flexible Displays (TV)
- Intelligent Clothing
- Wearable computing
- Autonomous Homes

**Year**
- 1973
- 1981
- 1987
- 1995
- 1997
- 1999
- 2001
- 2003
- 2005
- 2007

**Cost per megabit**
- **Transistors per Person**

- **Limiting Consumer Growth**
- **Form Factor**

- **Flexible Displays (TV)**
- **Intelligent Clothing**
- **Wearable computing**
- **Autonomous Homes**
Ubiquitous Electronics
Developing Technology

Flexible Displays
• Truly wearable computer interface
• Several different technologies still compete
• Major technological obstacles to overcome

Radio Frequency ID (smart) Tags
• Can be placed practically anywhere
• Will revolutionize tracking & inventory
• Major economic impact
• Currently too expensive

Organic Optoelectronics
• Tunable electronic properties, ease of processing
• Extend current range of semiconductors
• Under development for displays, logic and lighting
Ubiquitous Electronics
Challenges

Nascent technology

• Competing paradigms (silicon, organics)
• Spans wide range of materials and processing
• Future technology path undecided
• Innovative, integrative training needed
Ubiquitous Electronics: Challenges

- Compatibility with commodity materials (plastic, paper, textiles, …)

- Low-cost manufacturing (print electronic circuits like a newspaper)

- Environmental friendliness (starting materials, manufacturing, final product must be green)
Technology Platform

Large-area organic light emitting diodes for lighting

- Plastic substrates and encapsulation
- Efficient light-emitting coatings
- Patterning the organic and the metals
- Imaging of device functions
Technology Platform

Organic transistors for smart RF-ID tags

- Patterning of various materials
- Plastic substrates and encapsulation
- Growth of crystalline organic films
- Characterization of device functions
Polymeric Substrates

• flexibility
• robustness
• conducive to roll-to-roll manufacturing
  – ultimate method for delivering low cost

• For roll-to-roll manufacturing polymeric substrates need to be significantly improved in
• dimensional stability
• barrier properties to oxygen and water
• surface adhesion to both organic, inorganic and metallic layers
• free from contaminants/surface and internal defects
Polymer Substrates

- Polyethylene terephthalate (PET)
- Polyethylene naphthalate (PEN)
- Polycarbonate (PC)
- Polyethersulfone (PES)
- Polycyclic Olefin (PCO)
- Polyimide (PI)
<table>
<thead>
<tr>
<th></th>
<th>PET</th>
<th>PEN</th>
<th>PC</th>
<th>PES</th>
<th>PCO</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE ppm/°C</td>
<td>15</td>
<td>13</td>
<td>60</td>
<td>54</td>
<td>74</td>
<td>17</td>
</tr>
<tr>
<td>Tr (%)</td>
<td>&gt;85</td>
<td>&gt;85</td>
<td>&gt;90</td>
<td>90</td>
<td>91</td>
<td>Y</td>
</tr>
<tr>
<td>Water (%)</td>
<td>0.14</td>
<td>0.14</td>
<td>0.2-0.4</td>
<td>1.4</td>
<td>.03</td>
<td>1.8</td>
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<tr>
<td>E (GPa)</td>
<td>5.3</td>
<td>6.1</td>
<td>1.7</td>
<td>2.2</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>225</td>
<td>275</td>
<td>NA</td>
<td>83</td>
<td>50</td>
<td>231</td>
</tr>
<tr>
<td>Use T °C</td>
<td>150</td>
<td>200</td>
<td>150</td>
<td>220</td>
<td>-</td>
<td>350</td>
</tr>
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</table>
Barrier Layers

- development of effective, high performance barrier materials has been one of the critical technology hurdles in the manufacture and commercial development of flexible electronics
- barrier layers protect organic circuit elements against moisture and oxygen
  - barrier layers need to be
    - impermeable
    - mechanically flexible
    - optically transparent
    - chemically resistant
    - adhere well to the substrate.
Permeability of Oxygen

- PET: $10^{-9}$ cm$^2$/sec @ 20 °C
- SiO$_2$: $10^{-15}$ cm$^2$/sec @ 1500 °C
<table>
<thead>
<tr>
<th></th>
<th>OTR cm3/m2 per day per atm</th>
<th>WVTR g/m2 per day</th>
<th>Method</th>
</tr>
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<tbody>
<tr>
<td>PET</td>
<td>80</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>PET/SiOx</td>
<td>2</td>
<td>1</td>
<td>Evaporation</td>
</tr>
<tr>
<td>PET/Al</td>
<td>0.5</td>
<td>0.5</td>
<td>Evaporation</td>
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</table>
Nanotechnology to the rescue?
Why Care About Nano?

- Little word with big potential
- Speculation about a seismic shift in science and engineering
- Implications in ethics, economics, day-to-day life
- Panacea for all ills?
- Next Industrial Revolution?
- Next step in biological & chemical warfare?
- Opportunity to create next species to replace humanity?

So What?

- Nanoscale is unique because macroscopic behavior meets the more exotic properties of the atomic and molecular world (e.g. quantum effects).
- Behavior is intermediate between isolated atoms/molecules and bulk materials.
- Coupling of size with properties is key.
Size/Properties
Facts About Nano

- ~800 M in research from federal gov in 03
- Political support from both sides of the aisle - NNI
- Major universities across the world are investing on nanotech
- Across many disciplines
  - Chemists, physicists, biologists, engineers, doctors, computer scientists
Facts About Nano

- Nano is big business
  - 1T market by 2015
  - Fastest-growing industry in history
  - Larger than telecom & IT combined (1998)
  - Private spending on nano 1 B

- Priority for
  - IBM
  - NEC
  - HP
  - ...
  - Start-ups
Facts About Nano

- News media
  - CNN, MSNBC
- Nobel Prize several times for Nanotech
- Feynman Prize for Nanotechnology
- Forbes Cover in 2001
  - “The Next Big Idea”
- Episodes in
  - Star Trek: The Next Generation
  - X-Files
Nanotech Companies

Number of Companies (Jan. 2004)

- Materials: 27%
- Devices: 19%
- Instruments: 18%
- Biotechnology: 19%
- MEMS: 14%
- Consulting: 2%
- Processes: 1%
- nanoMaterials: 11%
- nanoPowders: 13%
- nanoChemicals: 3%

Source: NanoinvestorNews
Nanotech VC Funding


<table>
<thead>
<tr>
<th>Year</th>
<th>Venture Capital Funding (Millions)</th>
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<tbody>
<tr>
<td>1999</td>
<td>51, 12</td>
</tr>
<tr>
<td>2000</td>
<td>145, 68</td>
</tr>
<tr>
<td>2001</td>
<td>87, 90</td>
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<tr>
<td>2002</td>
<td>190, 217</td>
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</table>

Legend:
- NanoBio
- Other Nano
Nanotech Funding
Is It Real?

- Faster-burning rocket fuel
- Automotive parts
- Tennis balls (2002 Davis Cup)
- Sunscreen lotions
Nanocomposites

• Composites are made from different classes of materials
• Combine best features from both
• Typically tradeoffs
  – Stiffness
  – impact
Polymer Nanocomposites

Spheres (0-D)

Rods (1-D)

Layers (2-D)

Network (3-D)
Nanocomposites vs. Composites

- **Inorganics**
  - soft, flexible nanoparticles
  - ...as opposed to hard, rigid macrofillers

- **Synergy**
  - effect on crystal phase/morphology of polymer
  - effect on structure/dynamics
  - ...as opposed to simple reinforcement

- **Interfaces**
  - behavior dominated by interfaces/synergy
  - ...as opposed to weighted average of bulk properties
Nanocomposites: Property Profile

Nanocomposites combine:
- stiffness – toughness
- stiffness – melt viscosity
- non-swelling – toughness
- flame resistance – ability to process
- low CTE – low modulus
- low CTE – low viscosity

Avoid property tradeoffs
Unique opportunities in new materials design
Automotive Applications

Lightweight
Stiffness/Impact strength

540,000 lbs/yr

2002 GMC Safari
Chevrolet Astro
XRD and Morphology of PVDF & Nanocomposites

![Graph showing XRD patterns of PVDF and PVDF-NC with labeled peaks at 2θ degrees.]

- PVDF: 110α, 111α, 002α, 200 / 111β, 001β
- PVDF-NC: 020α, 110α, 111α, 002α, 200 / 111β, 001β

![Morphology images of PVDF and PVDF-NC at 2µm and 1µm scales.]
Mechanical Response of PVDF Nanocomposites

![Mechanical Response of PVDF Nanocomposites](image)
Mechanical Response of PLG Nanocomposites

![Graph showing stress vs. elongation for ABPLG, ABPLG/Silica 3%, and ABPLG/30B 3% nanocomposites.](Image)
Barrier Applications

500 nm

Relative Permeability

Volume Fraction Silicate

PCL Nanocomposite

PCL Composites (conventionally filled)

A

B
Properties of CN Nanocomposites

- CNTs Volume Content (%)

- Temperature (°C)

- E' (MPa)

- log[σ (S·m⁻¹)]
Advantages of Laser Processing

- direct large amounts of energy to specific locations
- localized heating
- high heating and cooling rates ($10^9 - 10^{14}$ K/sec)
- low thermal budget
  - plastic/flexible substrates
- patterning
- fast
- large scale manufacturing (R2R)
SiO$_2$ Films

SiO$_2$ loading: 10 wt%
- glass
- SiO$_2$ on glass
- SiO$_2$ on glass laser annealed

Transmittance (%) vs. Wavelength (nm)
ITO: Transparency

Transmittance (%)
Wavelength (nm)

ITO on PET

Transmittance (%)
Wavelength (nm)

PET
ITO on PET (as-prepared)
Laser annealed at 50mJ/cm²
Laser annealed at 75mJ/cm²
Laser annealed at 100mJ/cm²
ITO: Conductivity

![Graph showing Sheet Resistance (KOhms/) vs. Number of Coatings before and after laser annealing. The graph displays two lines: one for before laser annealing (green) and one for laser annealed (red). The x-axis represents the number of coatings, and the y-axis represents the sheet resistance (KOhms/). The graph shows a decrease in sheet resistance with an increase in the number of coatings for both conditions.]
BaTiO$_3$ Films

2 theta (deg)

20 40 60
(c)
(b)
(a)
(220)
(211)
(210)
(200)
(111)
(110)(100)

Capacitance (norm.)

Electric field (kV cm$^{-1}$)

-30 -15 0 15 30
0.85
0.90
0.95
1.00
0.95
1.00
(b)

Capacitance
(norm.)

(a)
Process Modeling

![Graph showing temperature profiles](image)

- **t = 30 nm**

- Curves labeled (a) to (e) with corresponding energies:
  - 190 mJ/cm²
  - 150 mJ/cm²
  - 110 mJ/cm²
  - 70 mJ/cm²
  - 30 mJ/cm²

Graph axes:
- **$T_r (°C)$**
- **$x (cm)$**