Organic and Hybrid Organic-Inorganic Materials and Devices for Integrated Photonics

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Outline

• Science Fiction Becoming Reality
• From Inorganic to Organic & Hybrid Materials
• Organic & Hybrid Integrated Photonics
• Challenges & Opportunities
• Future Outlook
Science Fiction Becoming Reality

Provide new ways to interface with technology

Enable new, custom functionality in systems

Want more than a display

- Sensing
- Detection
- Processing
- Imaging
- Power

Nano Energy,
DOI:10.1016/j.nanoen.2014.06.017
Advantages:
- High-speed response
- Efficient conversion of light energy
- Stability over time

Disadvantages:
- Expensive for large area
From Inorganic to Organic/Hybrid Materials

Small Molecules

Advantages:
• Efficient conversion of light energy
• Custom optical properties
• Amenable to large-area, flexible form factors

Disadvantages:
• Unstable over time due to environment

Polymers

Lowest Unoccupied Molecular Orbital (LUMO)

Highest Occupied Molecular Orbital (HOMO)

Conduction band ($\pi^*$)

Valence band ($\pi$)
Hybrid materials benefit from the combinations of disparate properties in the organic and inorganic constituents that can be combined to create new materials with tailored characteristics.
Films in a Copper Indium Gallium Selenide (CIGS) thin film solar cell:

a. Mo film deposited by thermal evaporation.
b. CIGS film deposited by thermal evaporation or sputtering.
c. ITO film deposited by sputtering.

Deposition Methods for Inorganic and Metallic Films:
- Chemical vapor deposition (CVD): thin films formed by chemical reaction in vapor phase from precursors.
- Physical vapor deposition (PVD): electron/thermal evaporation, sputtering, pulsed laser deposition.
Polymers can be conductive

Organic Light Emitting Diode (OLED)  Organic Photovoltaic (OPV)

Emerging Applications

Organic Field Effect Transistor (OFET)

Protective layer: corrosion resist

Coated steel sheets – the manufacturing process

Traditional Applications

Organic coating
Priming paint
Anticorrosive paint
Metallic coating
Steel core

Priming paint
Anticorrosive paint
Metallic coating

Nobel Prize in Chemistry for 2000

Alan J. Heeger, University of California at Santa Barbara, USA,
Alan G. MacDiarmid, University of Pennsylvania, Philadelphia, USA,
Hideki Shirakawa, University of Tsukuba, Japan

"for the discovery and development of conductive polymers"

Plastics that conduct electricity

We have been taught that plastics, unlike metals, do not conduct electricity. In fact plastic is used as insulation round the copper wires in ordinary electric cables. Yet this year’s Nobel Laureates in Chemistry are being rewarded for their revolutionary discovery that plastic can, after certain modifications, be made electrically conductive. Plastics are polymers, molecules that repeat their structure regularly in long chains. For a polymer to be able to conduct electric current it must consist alternately of single and double bonds between the carbon atoms. It must also be ‘doped’, which means that electrons are removed (through oxidation) or introduced (through reduction). Those ‘holes’ or extra electrons can move along the molecule – it becomes electrically conductive. Heeger, MacDiarmid and Shirakawa made these seminal findings at the end of the 1970s and have subsequently developed conductive polymers into a research field of great importance for chemists as well as physicists. The area has also yielded important practical applications. Conductive plastics are used in, or being developed industrially for, e.g. anti-static substances for photographic films, shields for computer screens against electromagnetic radiation and for “smart” windows (that can exclude sunlight). In addition, semi-conductive polymers have recently been developed in light-emitting diodes, solar cells and as displays in mobile telephones and mini-format television screens. Research on conductive polymers is also closely related to the rapid development in molecular electronics. In the future we will be able to produce transistors and other electronic components consisting of individual molecules – which will dramatically increase the speed and reduce the size of our computers. A computer corresponding to what we now carry around in our bags would suddenly fit inside a watch.
Defining characteristic of photonic devices is the need for layered materials to control the emission, absorption, and transmission of photons.

Next Generation Solar Cells

Silicon-Organic Hybrid Laser

http://nanotechweb.org/cws/article/indepth/59390

Nature Communications, DOI: 10.1038/ncomms10864, 2016
Solution-processed deposition techniques involve three steps:

a) Preparation of target materials solution.
b) Spread the solution onto the substrate.
c) Evaporation of the solvent and film formation.

Depositing films in a “dry” state could address these challenges.
“Dry” physical vapor deposition enables:

- tailored material composition
- novel film structure
- heterostructure design
- use of same process, regardless of thin-film material or substrate

**Parameter Space:**
1. Target composition
2. Chamber pressure
3. Substrate temperature
4. Growth distance
5. Fluence

Emulsion-based, Resonant Infrared Matrix-Assisted Pulsed Laser Evaporation (RIR-MAPLE)
### Challenges & Opportunities

**Polymer Distributed Bragg Reflector (DBR)**

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
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<tbody>
<tr>
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PMMA: 8nm RMS roughness, n=1.49
P3HT: 13nm RMS roughness, n=2.0

16-layer DBR of polymers with similar solubility demonstrated!
First Organic Solar Cell using UV-MAPLE Deposition

Voc (V) 0.32
Jsc (mA/cm²) 0.33
FF 0.28
Efficiency 0.03%

Challenges & Opportunities

Hydrophobic Polymers: Effect of Primary Solvent

**Alkyl aromatic solvents**

- Toluene (a)
- o-Xylene (b)
- Pseudocumene (c)

**Chlorinated aromatic solvents**

- Chlorobenzene (d)
- o-Dichlorobenzene (e)
- 1,2,4-Trichlorobenzene (f)

Decreasing vapor pressure and solubility-in-water
## Challenges & Opportunities

### Hydrophobic Polymers: Effect of Primary Solvent

<table>
<thead>
<tr>
<th>Primary Solvents</th>
<th>P3HT roughness (nm)</th>
<th>Voc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
<th>Rs (Ohm*cm²)</th>
<th>Rsh (Ohm*cm²)</th>
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</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>105.33</td>
<td>0.61</td>
<td>7.79</td>
<td>38.7</td>
<td>1.84</td>
<td>24.52</td>
<td>142.86</td>
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<tr>
<td>o-Xylene</td>
<td>61.97</td>
<td>0.63</td>
<td>8.33</td>
<td>39.3</td>
<td>2.06</td>
<td>21.92</td>
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<td>Pseudocumene</td>
<td>51.17</td>
<td>0.63</td>
<td>8.58</td>
<td>44.5</td>
<td>2.42</td>
<td>17.07</td>
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<td>Chlorobenzene</td>
<td>41.33</td>
<td>0.63</td>
<td>8.85</td>
<td>45.4</td>
<td>2.51</td>
<td>15.84</td>
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<tr>
<td>o-Dichlorobenzene</td>
<td>19.37</td>
<td>0.64</td>
<td>10.47</td>
<td>44.8</td>
<td>2.99</td>
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<td>1,2,4-Trichlorobenzene</td>
<td>11.87</td>
<td>0.63</td>
<td>10.62</td>
<td>48.8</td>
<td>3.27</td>
<td>14.11</td>
<td>325.26</td>
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For a simple solar cell material system, the device efficiency for RIR-MAPLE processing is comparable to devices fabricated using solution-based processing.

W Ge, NK Li, RD McCormick, E Lichtenberg, YG Yingling, AD Stiff-Roberts, ACS Applied Materials & Interfaces 8 (30), 19494-19506, 2016
Challenges & Opportunities

Hybrid Nanocomposites

Pyridine-CdSe/PCPDTBT (80% CdSe loading)

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<th>Spin Cast</th>
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<tbody>
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<td>(c)</td>
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<table>
<thead>
<tr>
<th>RIR-MAPLE</th>
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<tbody>
<tr>
<td>(d)</td>
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<td>(f)</td>
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</table>

Challenges & Opportunities

Silver Nanoparticles

W. Ge, T. B. Hoang, M. H. Mikkelsen, A. D. Stiff-Roberts, Appl Phys A 122, 824 (2016).

Hybrid Perovskites

Collaborator: Maiken Mikkelsen, Duke

Collaborator: David Mitzi, Duke
Future Outlook

NAE Grand Challenge: Restore and Improve Urban Infrastructure
Future Outlook


NAE Grand Challenge: Develop Carbon Sequestration Methods
Future Outlook

NAE Grand Challenge: Engineer Better Medicines

Future Outlook

Organic & Hybrid Integrated Photonics

1) Design New Materials
   • Non-toxic
   • Earth-abundant
   • Custom functionality

2) Improve Device Performance
   • Hybrid materials integration
   • Reliability
   • Lifetime

3) Scale-up Fabrication
   • Materials synthesis (high volume, sustainable)
   • Thin-film processing (high throughput, large area, high yield)
   • Life-cycle assessment (from raw materials to waste products)
Thank you!