Photovoltaics are an important part of a sustainable energy portfolio

- Renewable sources currently make up a small percentage of US energy
- Solar PV is currently only a small part of this

The current world energy consumption is 13 TW, or 13 trillion watts
### Photovoltaics by generation

#### Challenges for PV going forward
- Intermittency
- Cost per kWh

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<table>
<thead>
<tr>
<th>Generation</th>
<th>Characteristics</th>
<th>Materials</th>
<th>Top Efficiency (lab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>Bulk crystalline Si</td>
<td>Single crystal</td>
<td>24.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi crystal</td>
<td>20.3%</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Thin films</td>
<td>CIGS</td>
<td>18.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CdTe</td>
<td>16.5%</td>
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<tr>
<td></td>
<td></td>
<td>a-Si</td>
<td>10.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>organic</td>
<td>10.4%</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>High efficiency</td>
<td>GaInP/GaInAs/Ge</td>
<td>40.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>??</td>
<td>Target of 40-60+ %</td>
</tr>
</tbody>
</table>
Stanford PV research

Significant effort in improving efficiency in thin film solar cells (2\textsuperscript{nd} gen)

- Organic PV through CAMP
  - Bulk heterojunction solar cells
  - Dye sensitized solar cells
- Nanostructured solar cells
- Earth abundant non-toxic materials
- Plasmonics

Some work in 3\textsuperscript{rd} generation concepts

- Multijunction cells
Molecular semiconductors
- Abundant: ~100,000 tons/year
- Mature industry/markets
- Low materials cost: ~1$/g → 17¢/m²
- Low-cost manufacturing
- Non-toxic
- Stable

Polymer: solution processed
Small molecule: vacuum

\[\alpha-Si\]

Power conversion efficiency (%)

@ approx. AM1.5 100mW/cm²

α-Si data from C. Wronski

Year

CAMP 15%
Center for Advanced Molecular Photovoltaics (CAMP) at Stanford

Focus areas

- Devices
- Reliability
- Electrodes
- Synthesis
- Nanostructure engineering
- Plasmonics
- Characterization
- Transparent electrodes
- Metal Nanoparticles
- Metal Contact
- 10nm
- Transparent Contact
- nanospheres
- nanorods
Our work to date
- Radial junction vertical NW array solar cells
- Low efficiency (< 0.1 %); large reverse current for p-n junctions
- Poor NW surface passivation and Au catalysts lead to carrier recombination

New directions
- New deposited oxide surface passivation on Ge and Si NWs – reduce surface recomb. velocity
- New non-Au catalysts – reduce reverse leakage
- Study axial (e.g. GaP/Si/Ge) heterostructures for multijunction NW solar cells

Enhanced light trapping is a major benefit of using nano-structured solar cell materials rather than more reflective thin films.
Solar Cells Using Non-Toxic Abundant Materials
S. F. Bent and B. M. Clemens

• >90% of PV production is Si; just a few other materials make up the rest
• CuInGaSe₂ – 19.5% efficient – thin film architecture
• But CIGS contains In, CdTe has Cd problem…
• Cu₂ZnSnS₄ (CZTS)
  • 5.74% efficiency (Katagiri, et al)
  • 1.45 eV E₉

<table>
<thead>
<tr>
<th>Raw Material Costs</th>
<th>Relative Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu - $3.35/lb</td>
<td>Cu - 6.0 x 10⁻⁵</td>
</tr>
<tr>
<td>Zn - $1.59/lb</td>
<td>Zn - 7.0 x 10⁻⁵</td>
</tr>
<tr>
<td>Sn - $6.61/lb</td>
<td>Sn - 2.3 x 10⁻⁶</td>
</tr>
<tr>
<td>S – $0.02/lb</td>
<td>S - 10⁻⁴</td>
</tr>
<tr>
<td>Ga - $209/lb</td>
<td>Ga - 1.9 x 10⁻⁵</td>
</tr>
<tr>
<td>In - $361/lb</td>
<td>In - 2.5 x 10⁻⁷</td>
</tr>
<tr>
<td>Se - 2002 $4, 2007 $33/lb</td>
<td>Se - 5 x 10⁻⁸</td>
</tr>
</tbody>
</table>


Focus: Low cost processing methods by chemical bath deposition
Can we exploit the unparalleled light concentrating ability of metallic nanostructures?

- Light concentration by a 20 nm ∅ Al particle
- Strong interaction can be tuned to any wavelength through a proper choice of metal, particle shape, size,..

Flow of light (Poynting vector) calculated by:
C. F. Bohren, D. R. Huffman, Absorption and Scattering of Light by Small Particles, Wiley, New York 1983

- Explanation: Oscillating electric fields from light can cause electron oscillations/plasmons in the metal

- High local light intensities are attained due to the large charge displacement in the metal particle

Metal stripes enhance light absorption by
1) waveguiding 2) near field light concentration

Absorption in a 50 nm thick Si layer can be increased by almost 30% if a proper grid period is chosen