

FLEXIBLE NANOCOMPOSITE ORGANIC PV CELLS

Workshop

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PHOTOVOLTAIC TITLE

➤ **Goal :**

- ✓ Efficiently convert solar energy to electricity utilizing nanocomposite materials on flexible, lightweight substrates

➤ **Challenges**

- ✓ Increase efficiency from < 3% to > 20%
- ✓ Use plastic or fabric substrates
- ✓ Bend around _” radius (roll-up)
- ✓ Transparent electrode
- ✓ Heterojunction stability

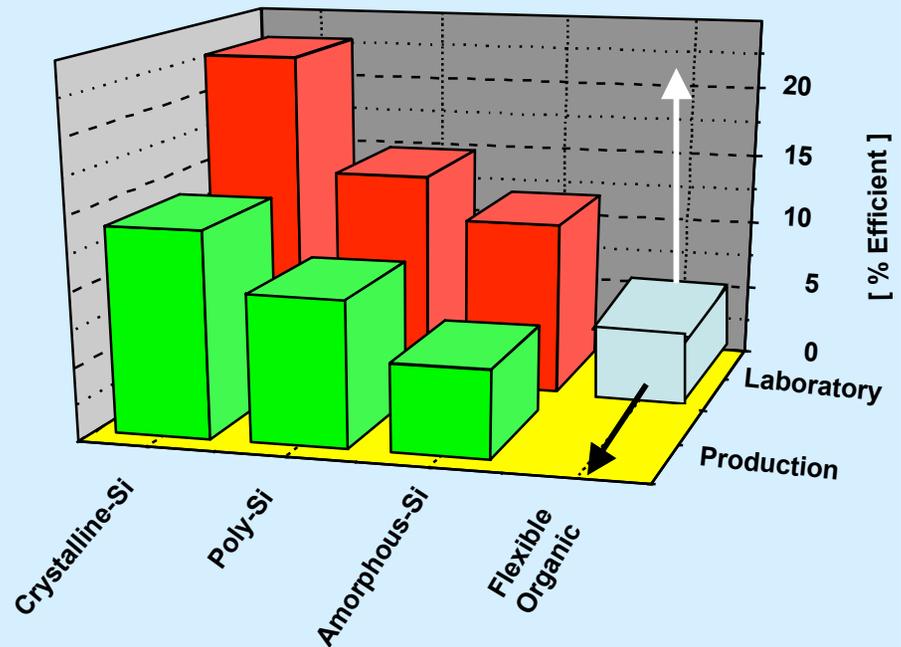
➤ **Operational Impact :**

- ✓ 200 X increase in power / weight
 - ❖ Longer operating time before resupply
 - ❖ Increased sustainability
 - ❖ Greater mobility

less weight
larger area



Photovoltaic Technology Efficiency

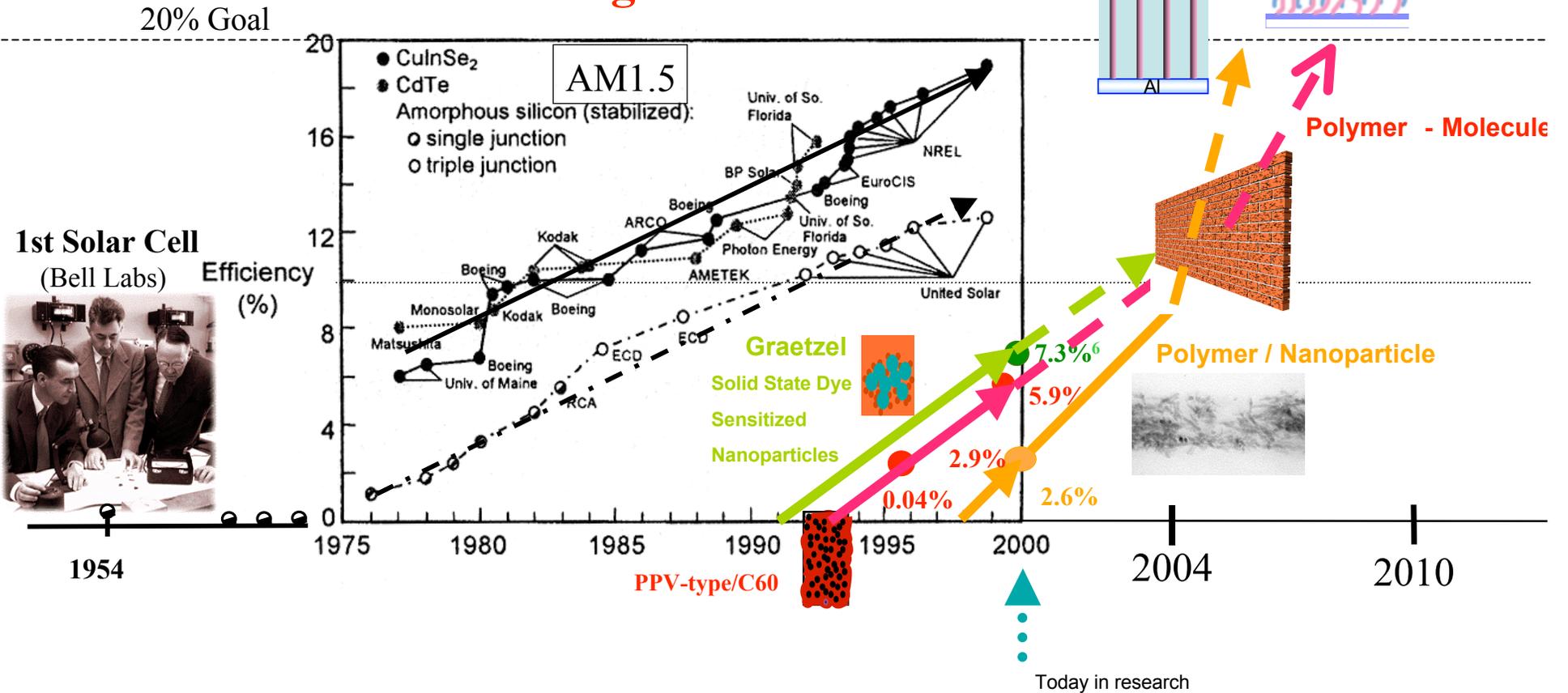


Decreasing Cost
Increasing Area

10% efficiency = 100 W / m²
 a-Si: 10 kg / m² \$ 50 – 100 / m²
 Organic: 0.1 kg / m² \$ 2 – 5 / m²

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Historical Progress of Photovoltaics



Can the Combination of Nanocomposite Technology and Polymer Science Yield Efficiencies > 20% on Flexible Substrates



Some Key Questions

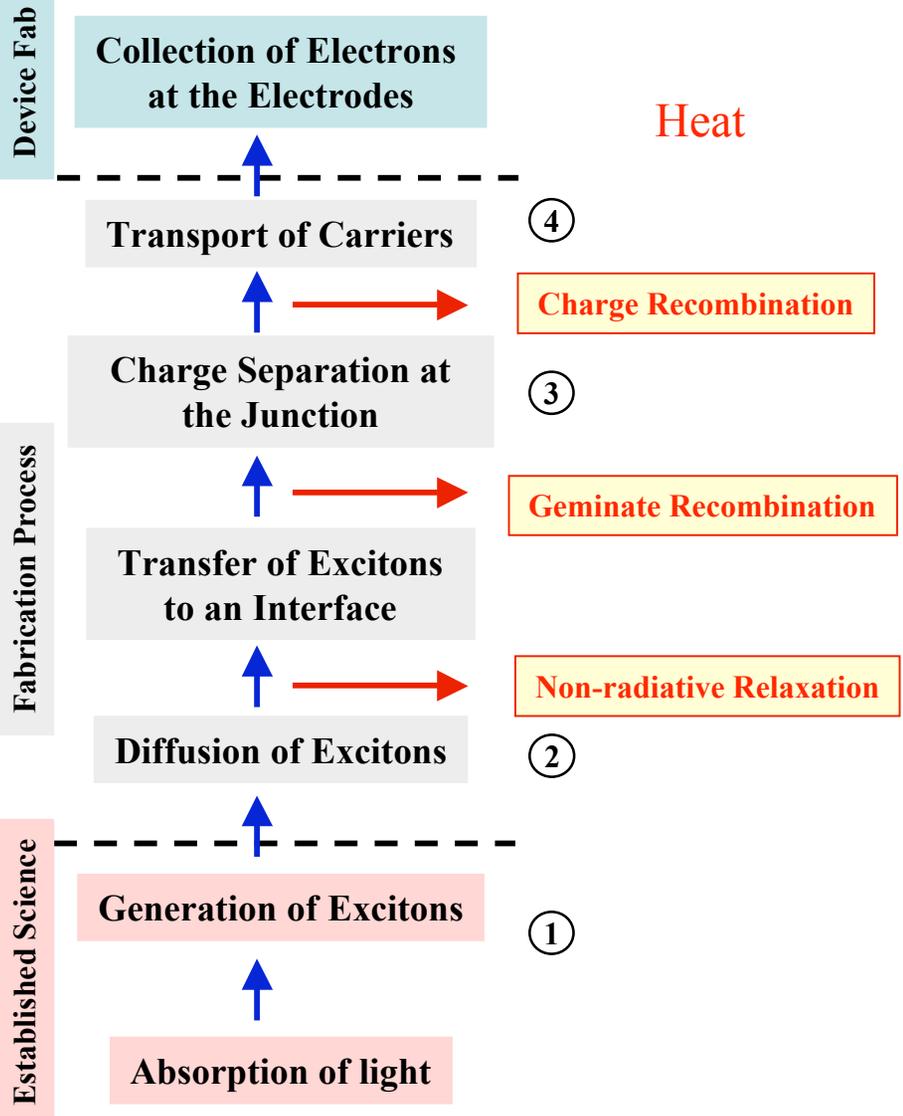
- Why are organic PVs as good as they are and can they get better?
 - ✓ Need to translate chemistry speak to EE speak
 - ✓ What are the mechanistic differences? What are the + /- ??
 - ✓ What about the mechanism don't we understand?
- How to achieve the “stereo-regularity” for increased efficiency?
- How to keep the nanocomposite or all polymer structure stable?
- How can we / do we measure the intrinsic performance of the key design parameters ?
- How can we measure / picture the internal 3D morphology of the final device?



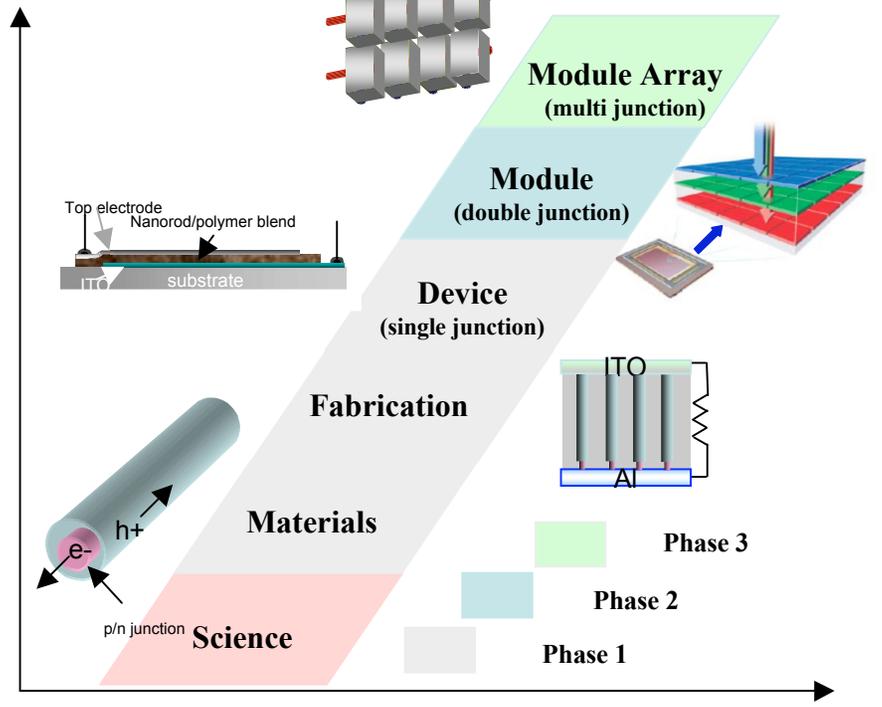
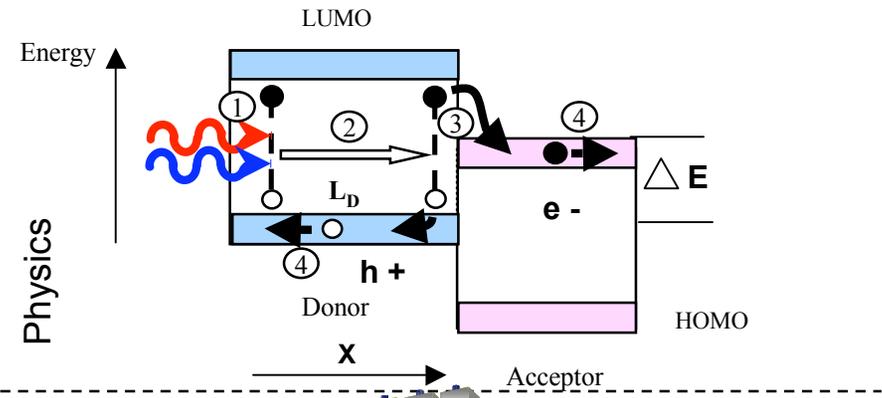
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Conversion of Solar Energy into Electricity

Photovoltaic Physics



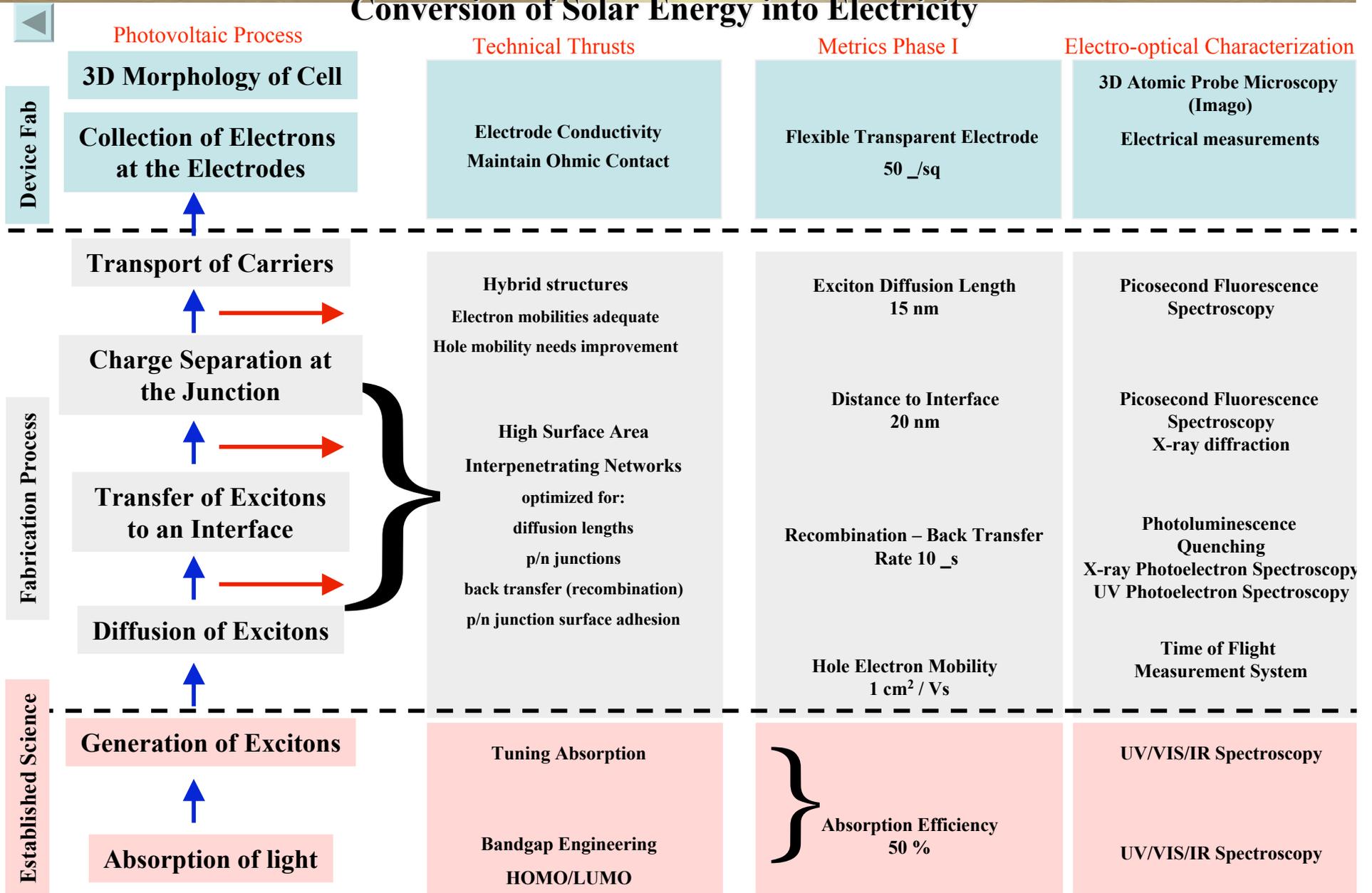
Heat





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Conversion of Solar Energy into Electricity





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Conversion of Solar Energy into Electricity

Materials Development

Photovoltaic Process

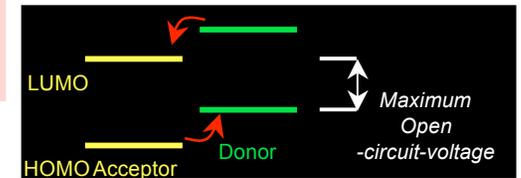
Absorption of light



Generation of Excitons

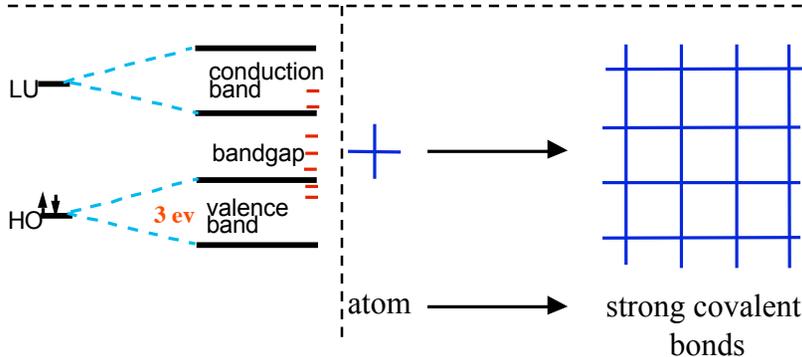
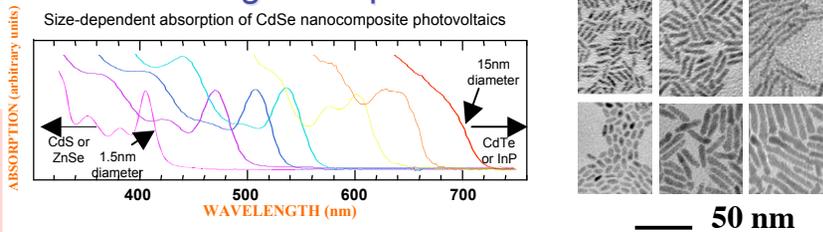
- **Established Science**
 - Strong absorbers in the visible and near-infrared
 - Bandgap engineer LUMO & HOMO

Bandgap Engineering HOMO/LUMO



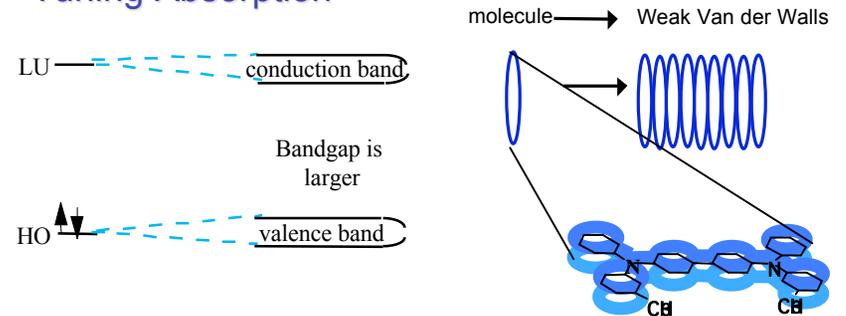
Inorganic Semiconductors

Tuning Absorption



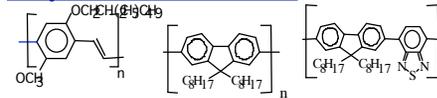
- Very broad conduction band allows broad delocalization
- Broad bands due to strong covalent interactions
- Width of band is proportional to carrier mobilities (all things being equal)
- Free electron drifts long distances over lattice

Tuning Absorption

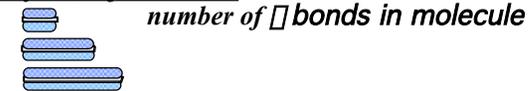


Organic

Vary chemical structure



Vary size of molecule



Vary molecular environment

Neutral excited state, & charge carrier states undergo strong polarization interactions with surrounding molecules; E_g function of molecular packing/orientation



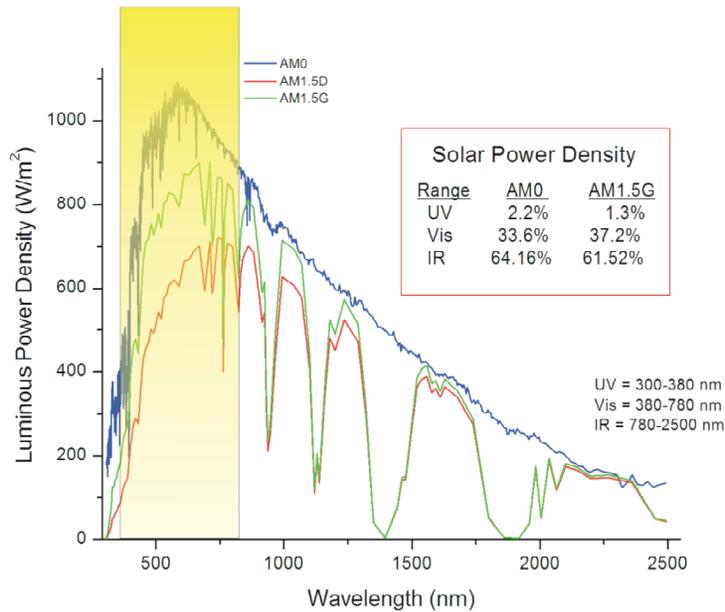
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Factors Affecting PV performance

These are the major focus of this program

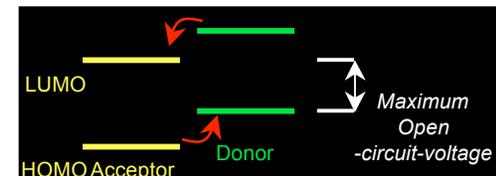
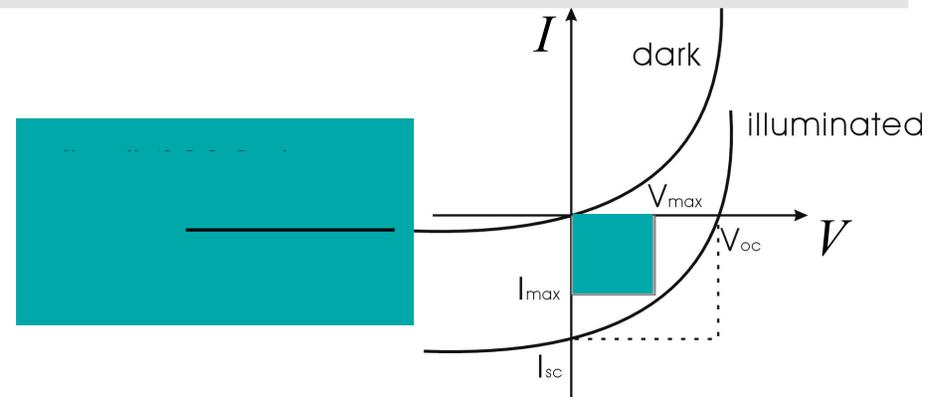
$$\text{Energy conversion efficiency} = \frac{\text{electrical power generated}}{\text{incident optical power}} = \eta = \frac{P_{\max}}{P_{\text{solar}}} = FF \frac{I_{\text{sc}} V_{\text{oc}}}{P_{\text{solar}}}$$

Active spectral region for current organic solar cell technology



Highest performance organic cells show ~3% power conversion efficiency while absorbing < 35% of the solar spectrum

- I_{sc} – Short-circuit current (maximum current flow through the cell)
 - ✓ depends strongly on e- and h+ mobilities
- V_{oc} – Open circuit voltage (maximum voltage drop across the cell)
 - ✓ depends on work-functions of electrodes and relative band-offsets of e- and h+ conductors in the active region



V_{oc} (and therefore the efficiency) limited by the relative energy levels of the donor and acceptor molecules



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Semiconductor Band Gap Effects on Cell Efficiency



1.5 eV

“Ideal”
band gap



- AE – Absorption efficiency
(absorbed sunlight; spectral overlap)
 - ✓ depends on absolute absorption cross-section of the absorbing material and the width and overlap of the absorption spectrum with that of the solar spectrum
- QE – Quantum Efficiency
(absorbed photons resulting in exited free electrons)

Solar spectrum showing approximate location of 1.5 eV “Ideal” band gap



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IPV

- single junction devices
- absorbs in fixed band; poor absorbers
- low absorption depth
- generates free electron hole pairs
- large excitonic radii
- high carrier mobility
- carriers generated together in bulk *requires equilibrium* electrical potential energy difference, Φ_{bi} , for separation
- recombination in bulk
- bulk properties are important
- $V_{oc, max}$ determined by the Φ_{bi}
- greater stability
- high manufacturing cost

VS

OPV

- molecular multi-junctions
- absorption bands can be tuned; good absorber
- larger absorption depth
- generates neutral excitons
- Exciton radius 2 nm
- high exciton binding energy
- carriers generated *and* separated at the interface
- recombination at interface
- interfacial properties are important
- $V_{oc, max}$ determined by the *photo-induced* chemical potential energy difference, $\Delta\mu_{h\nu}$ and, in some cases, Φ_{bi}
- less stable
- potential low manufacturing cost

Current density is proportional to: electrical + chemical potential gradients

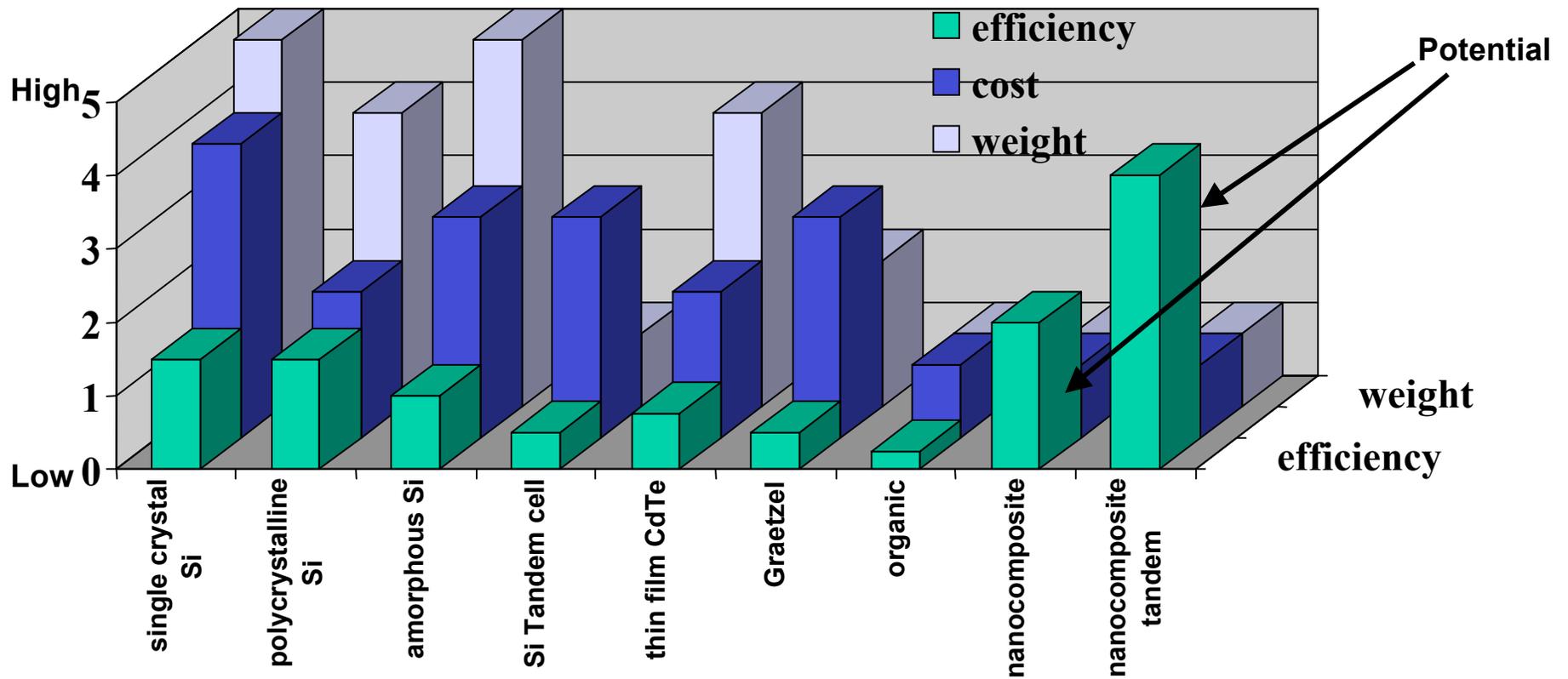
- Excitonic solar cells are unique: Carriers generated, separated and recombine at the heterointerface
- The photoinduced interfacial chemical potential difference, $\Delta\mu_{hn}$, plays a crucial role in excitonic solar cells
- Excitonic cells can be limited by short exciton diffusion lengths and/or low carrier mobilities.
- High surface area cells solve these problems but increase interfacial recombination rates
- IPV performance determined by the electrical potential energy difference, Φ_{bi}
- Φ_{bi} is the built in potential which results from electrodes with different work functions



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Competitive Analysis





Technical Barriers

Why Nanocomposite technology ?

➤ 1st problem: Excitons

- Electrons and holes bound (i.e. they form excitons). The binding energy is 0.2 – 0.5 eV. The electrons and holes can recombine before they are split by the built in electric field.
- Diffusion length L_D **short compared to absorption depth**

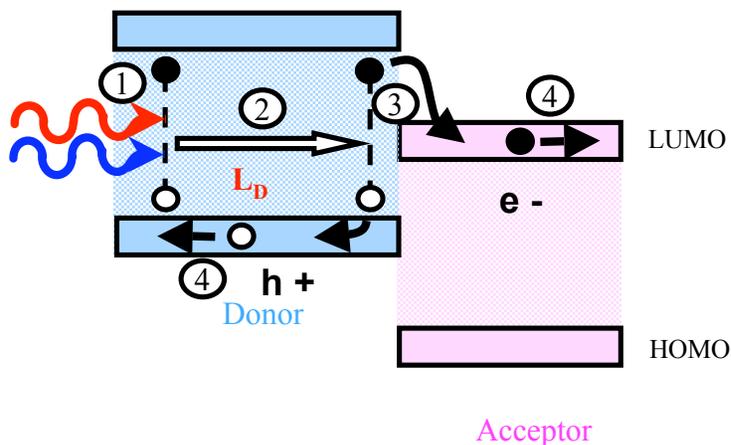
- **Absorption depth short**
- **Exciton state has long lifetime (10-100ns)**
- **Conducting materials for charge separation of electrons and holes are an atomic layer away from each other (<1nm)**

➤ 2nd problem: Low mobility

- It takes longer for an exciton to split in a low mobility material.
- It takes longer for carriers to reach electrodes. This gives them more time to recombine.
- The high resistance of the carriers leads to low efficiency.

- **Transport mobilities high due to conductivity of electrons inside a single-crystal nanowire**
 - ✓ electron mobility of >600 cm²/Vs rather than in an organic conductor (electron mobility <0.001cm²/Vs)
- **Core/shell structure improvement**
 - ✓ replace the hole-conducting polymer matrix with a hole-conducting inorganic shell on the outside of every nanorod (hole mobility >100 cm²/Vs) rather than in an organic conductor (hole mobility <1Vs).

Photoinduced Charge Transfer at a Donor (D)-Acceptor (A) Interface



- ① Exciton generation by absorption of light (depth should be large)
- ② **Exciton diffusion over $\sim L_D$**
- ③ Exciton dissociation by charge transfer
- ④ Charge extraction through carriers by the internal electric field