# Workshop II
# Nanotechnology and Advanced Cell Concepts

Moderators: Ryne Raffaelle and Alex Freundlich

Panel of attendees :~30





## Workshop focused on few emerging concepts(beyond tandem cells)

1. Engineering incident sun spectrum and transparency losses
   - Nano emitters (dot concentrator)
   - Surface plasmonics
   - Up converters
   - Down converter
2. Intermediate band solar cells
   - Efficiency projections (detail energy balance projections)
   - Inserting 0,1 and 2D semiconductor structures in solar cells
3. Polymer and hybrid cells
   - Nanotubes/dot polymers
   - Exciton dissociation

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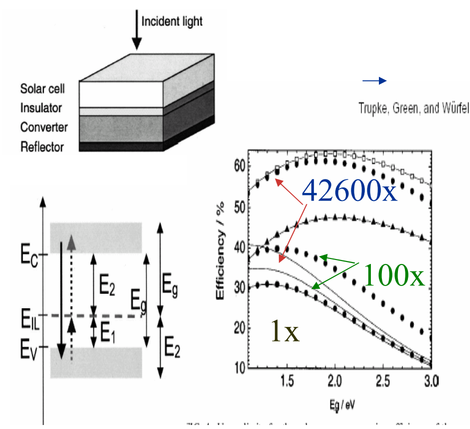
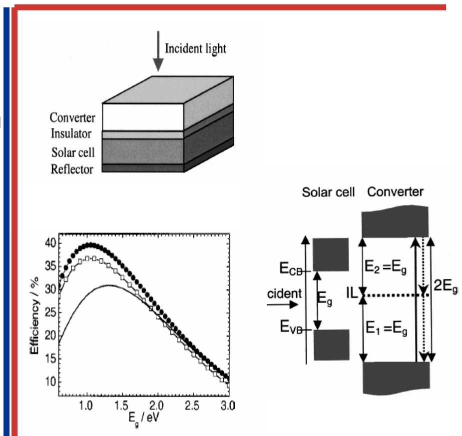
## 1-Engineering incident sun spectrum and transparency losses

$h\nu(E_1) + h\nu(E_2) \rightarrow h\nu(Eg)$




**up-conversion of sub-bandgap**

$h\nu(2Eg) \rightarrow 2\,h\nu(Eg)$




**down-conversion of sunlight**



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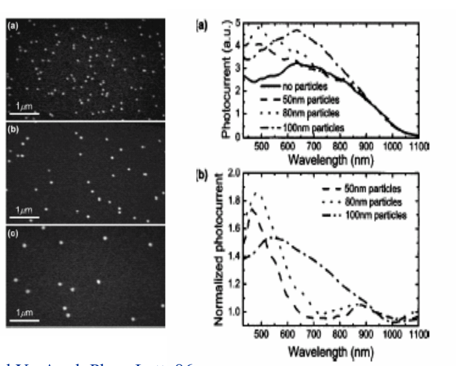
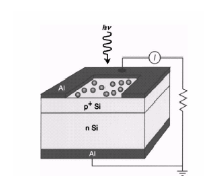
## 1-Engineering incident sun spectrum and transparency losses

**Enhanced optical absorption via surface plasmon excitation in metal nanoparticles**






Schaadt, Feng, and Yu Appl. Phys. Lett. 86, 063106 ~2005

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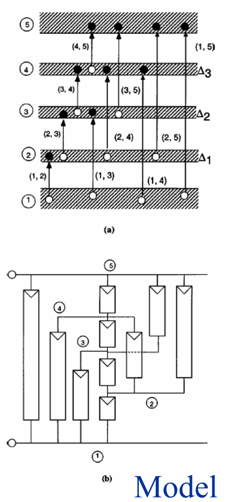
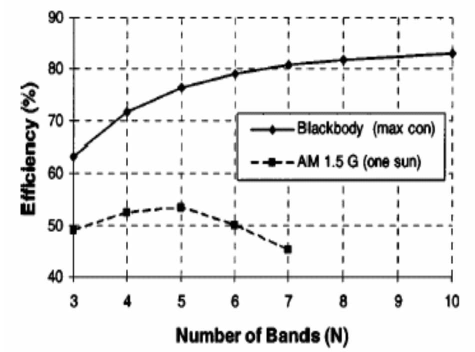
## 2- Intermediate band solar cells (IBSC), dots, wire, wells






Model assumes ideal absorption and carrier collection!



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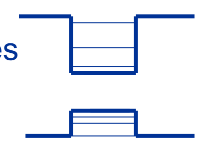
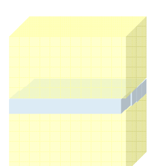
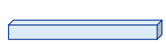
## Multiple "intermediate levels"/confined states available in low dimensional structures

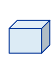




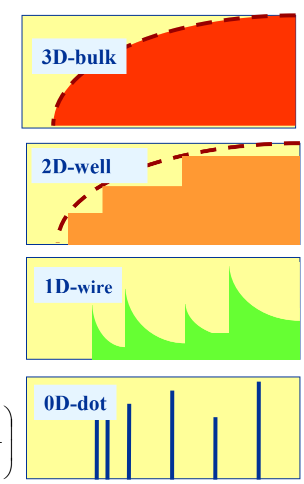
$$E_{nz} = \frac{\hbar^2 \pi^2}{2m_{e,h}} \left( \frac{n_z^2}{L_z^2} \right)$$



$$E_{nx,nz} = \frac{\hbar^2 \pi^2}{2m_{e,h}} \left( \frac{n_x^2}{L_x^2} + \frac{n_z^2}{L_z^2} \right)$$



$$E_{nx,ny,nz} = \frac{\hbar^2 \pi^2}{2m_{e,h}} \left( \frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2} \right)$$



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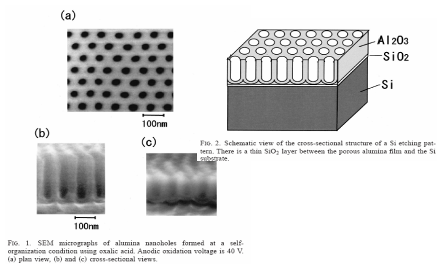
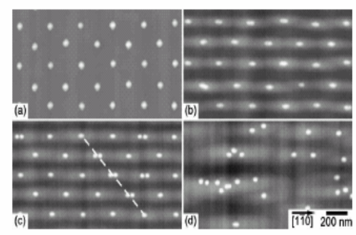
## Large palette of sophisticated materials under development

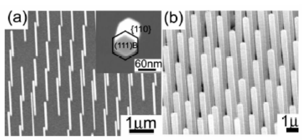
Epi Templates (PAM, InP wire on Au nano particles)

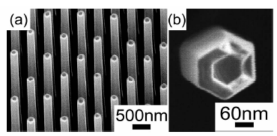



Ordered or self assembled

III-V nonwires and nanotubes



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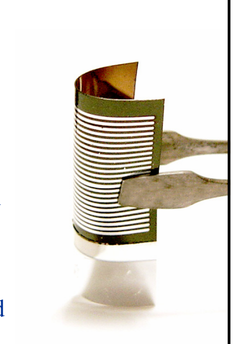
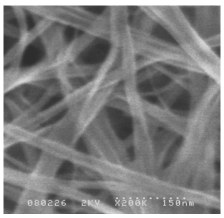
## Nano-Polymeric PV

1. **Photon Absorption** – suitable bandgap polymer/and additives to capture significant portion of solar spectrum
2. **Exciton Diffusion** – limited diffusion lengths (~10 nm) of polymeric exciton necessitates sufficient device structure or appropriate weight fractions of material additives
3. **Exciton Dissociation** – sufficient difference in potential energy levels to overcome the exciton binding energy for electron-hole dissociation
4. **Carrier Transport** – high hole conductivity in the polymer and high electron conductivity in material additives

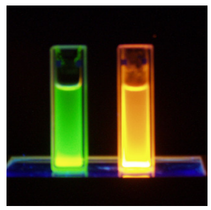


# Nanomaterials for Polymeric PV

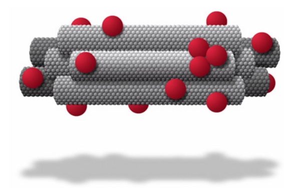
- High electron affinity for polymer exciton dissociation
- SWNTs have extremely high electrical conductivity
- Optical absorption properties which can be tuned by size
- SWNTs have tremendous aspect ratio (low percolation threshold in polymer)



Single Wall Carbon Nanotubes (SWNTs)



CdSe Quantum Dots (QDs)

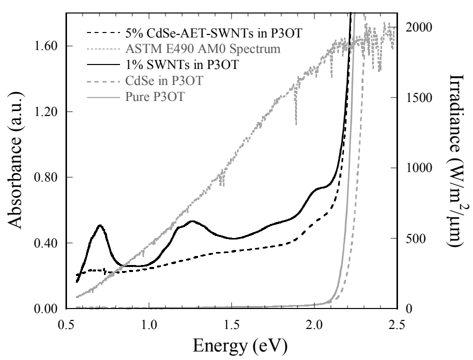


QD-SWNT Complex





# Optical Absorption vs. AM0



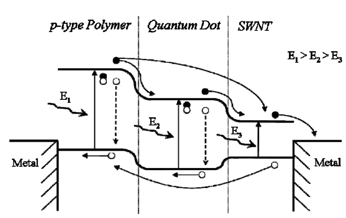

- Ability to enhance AM0 absorption through nanomaterial diameter tuning

QD [5]

$$\Delta E_g = \frac{h^2}{8d_{QD}^2}\left(\frac{1}{m_e^*}+\frac{1}{m_h^*}\right)$$

SWNT [6]

$$E_g = \frac{2a_{c-c}\gamma_o}{d_{SWNT}}$$




[5]E. Kucur, J. Riegler, G.A. Urban, T. Nann, J. Chem. Phys. 119 (2003) 2333-2337.
[6]H. Kataura, Y. Kumazawa, Y. Maniwa, I. Umezu, S. Suzuki, Y. Ohtsuka, Y. Achiba. Synth. Met. 103 (1999) 2555-2557.

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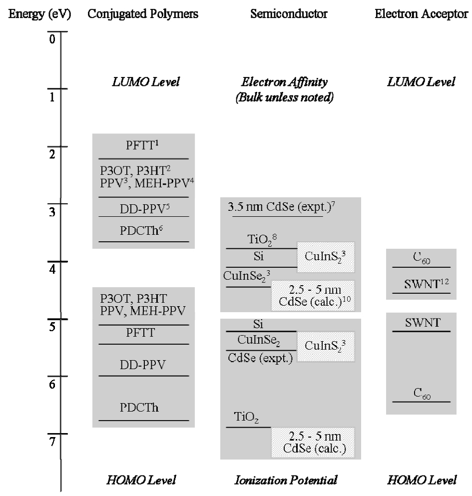
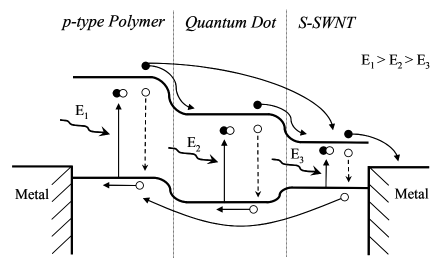
# QD-SWNT-Polymeric Solar Cells




## *Energy Level Diagrams*

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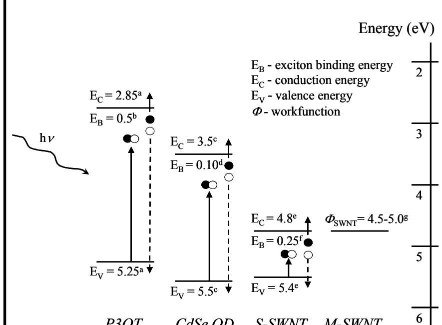
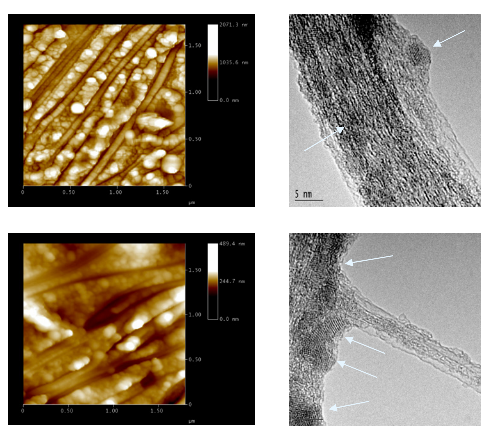
# CdSe-SWNT Complexes




B.J. Landi, S.L. Castro, H.J. Ruf, C.M. Evans, S.G. Bailey, R.P. Raffaelle, Solar Energy Materials & Solar Cells. (2004) in press.

## *Microscopy*



AFM TEM

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## Questions

What are the fundamental challenges?
Modeling? Detail balance calculations predict efficiencies beyond 60%(but they neglect photon absorption and carrier transport issues)
Do we understand the device Physics at play?

What are the practical challenges?
Material and device fabrication issues (crystal growth, doping,…)?
Relevance to Space PV?





## Workshop II
## Nanotechnology and Advanced Cell Concepts

### Panel Discussions

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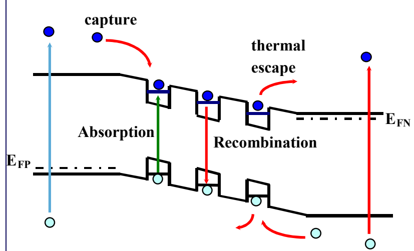
## Other Discussion during tutorial portion

### Quantum dot/well/wire Devices

- How do we connect QD/Q wires to quickly sweep the generated carriers away and prevent them from recombining?




- Still in very early stages

### Polymer/hybrid PV

- Stability in space (vacuum, UV and radiation) is yet to be proven
- Nanotubes can assist in exciton separation
- Exciton separation in QD goes back to the ability to remove carriers from the dot/tube.

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## Panel discussion

- **Dots/Wells being implemented in middle cell of tandem to increase the current and radiation hardness**
  - o Will the few percent gain be worth the complexity?
  - o Cost/Benefit will rule the market and research
  - o Will this require exotic materials?
  - o Can increased cell life mitigate initial cost?
  - o Where do you get the funding to research/develop?

- **Unlike tandem cell physics, which is well understood, none of these new technologies (QD, polymer, etc) are fully understood on a fundamental level.**
  - o Current funding/development forces product before understanding
  - o How do you improve a product you don't understand?

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## Panel discussion

- **Every factor is idealized for efficiency calculations. It is difficult to accurately predict practical efficiency without a real understanding of the technology.**
- **Practical analysis of this technology is needed in order to determine areas of loss to the theoretical efficiency.**
- **Quantization frustrates thermal loss.**
  - temperature stability
- **Quantum wires in a-Si:**
  - Various sizes of wires to spread out collection spectrum
  - Polymeric substrates
  - Bandgap Engineering
- **What degradation happens in host material**
  - Large number of design parameters(Doping, Cladding)

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## Panel Conclusions

**Roadblocks/Challenges**

1. Theory and fundamentals (lack of detailed design rules)
2. Apparent Complexity
3. Research Funding

**Opportunities/Advantages**

1. Simpler, Cheaper, Easy Approaches (e.i. nano-Xtals,..)
2. Relative Efficiency Enhancements (spectral tuning, temp. coefficients, radiation tolerance)
3. Enter Through Heritage (III-Vs,…)
4. Enabling for Thin Films
5. Mission Enabling (e.i. 77K radioisotope/PV battery)
6. Mission Critical Applications (i.e. laser beaming,sensing,….)
7. Synergy with Other Tech. (Optoelectronics,..etc)
8. Expansion of Materials Palette for PV

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