Plasmonic Solar Cells

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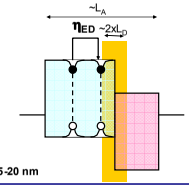
Introduction

Overall Quantum Efficiency

Fundamental problem: $L_D << 1/\alpha$

(1) $\eta_A > 50\%$
(2) $\eta_{ED} \sim 10\%$
(3) $\eta_{CT} \sim 100\%$
(4) $\eta_{CC} \sim 100\%$

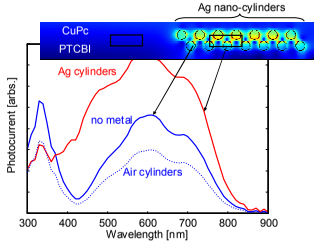


Exciton diffusion length ~ 5-20 nm

$$\eta_{EQE} = \eta_A \cdot \eta_{ED} \cdot \eta_{CT} \cdot \eta_{CC} \sim 10\%$$

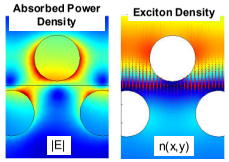
Plasmonic Solar Cell

- Simple model system: Ag cylinders in DA solar cell
- Model: optical absorption + exciton diffusion
- Exciton quenching at Ag interface not modeled



Mechanisms

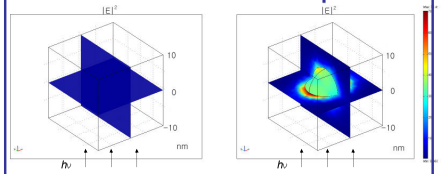
Localized photon absorption near the DA interface:
- Increase optical electric field near the DA interface within an exciton diffusion length



- Increased exciton diffusion length

Localized Fields

Localized Photon Absorption

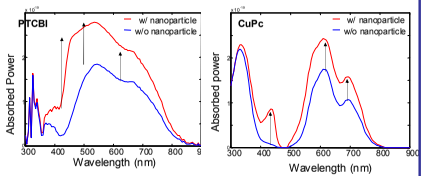


Finite Element Method
Nanoparticle: Ag (radius = 5nm)
Organic: copper phthalocyanine (CuPc)
Wavelength: 450nm

Maximum exciton generation rate $\propto |E|^2$: ~70 times enhancement

Calculated absorbed power enhancement: $\frac{3.5e-20}{7.0e-21} \cong 5$ times

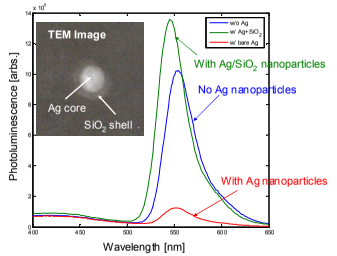
Broadband Resonance: Increased Absorption Near and Off Resonance



- Substantial increase in optical absorption near plasmon resonance of the Ag nanoparticles
- Even off-resonance: scattered field enhance absorption

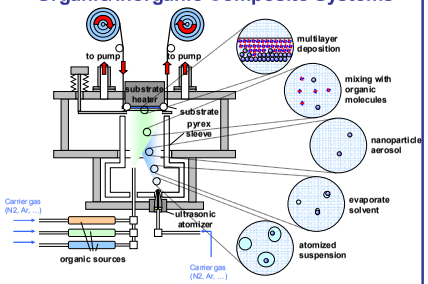
Reduced PL Quenching

- Ag/SiO_2 particles embedded in organic thin films enhance absorption
- SiO_2 shell is essential (bare Ag particles leads to PL quenching)



Deposition Technology

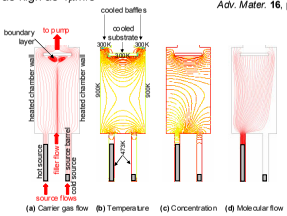
Deposition Technology for Organic/Inorganic Composite Systems



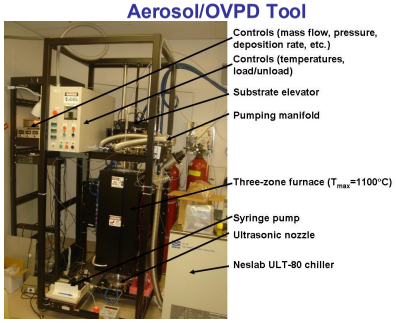
Why Use Vapor Phase?

- Materials use efficiency >50%
- Multilayers
- Additional degrees of freedom in controlling nanostructure (pressure, temperature, gas flow)
- Rates as high as 1μm/s

Shtein, Peumans, Benziger and Forrest, *Adv. Mater.* **16**, p.1615 (2004).



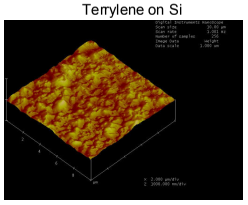
Aerosol/OVPD Tool



Thin Film by Aerosol Deposition

- Can deposit films at very low solubility (e.g. 0.0001wt%)
- 10nm roughness for 100nm films

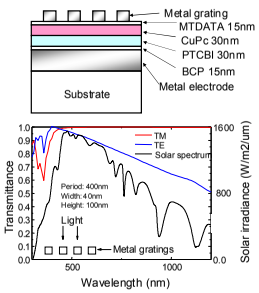
Terrylene on Si



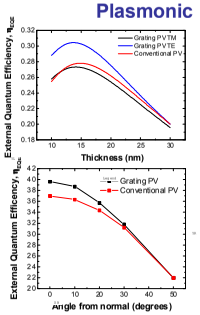
Metal Grating Electrodes

Metal Gratings in Solar Cells

- Conventional transparent electrodes such as Indium-Tin-Oxide (ITO) are problematic:
  - Expensive
  - Brittle (crack when bent)
  - Resistive OR transparent
  - Cannot be deposited on top of organic
- Metals are cheap (e.g. Ag) in thin film form and very conductive but opaque
- Can we nanostructure metals such that they become optically transparent without losing conductivity?

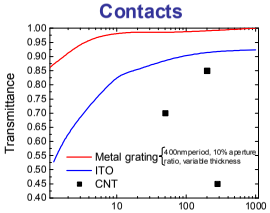


Plasmonic Enhancement



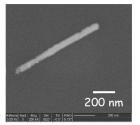
- Due to interference and localization of electromagnetic energy.
- Short circuit current increases by 7% for TE mode
- Overall performance is better up to 50 degrees.

Metal Gratings are Very Good Transparent Contacts

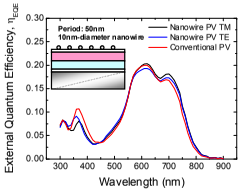


- Transmittance depends on geometrical factors, such as grating period, aperture ratio, thickness, etc.
- For both TM and TE polarizations, transmittances is better than that of ITO for comparable sheet resistance

Scaling Behavior: 10nm-Diameter Nanowires

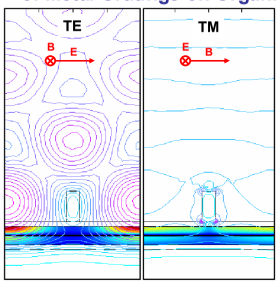


Scanning electron micrograph of Ag nanowire grown in ion-track-etched polycarbonate by electroplating (courtesy of M. Brongersma)



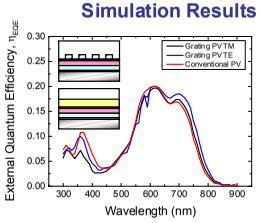
- Metal nanowire networks are nearly ideal transparent, yet conductive electrodes
- Compare favorably to CNT networks
- Device fabrication
  - Synthesis by electrodeposition in ion-track-etched polycarbonate membranes
  - Spin-on or spray-on deposition

Near-Field Effects: Finite-Element Simulations of Metal Gratings on Organic Solar Cells



- Calculation of:
  - optical energy flow (contours)
  - optical absorption
  - exciton diffusion (colormap)
- Both TE and TM mode result in substantial absorption in organic thin film
- Metal gratings are excellent transparent contacts to solar cells

Simulation Results



- The external quantum efficiency is comparable to that of a conventional solar cell with an ITO transparent contact
- Grating organic solar cell quantum efficiency shows features related to grating coupling

Conclusions

- More excitons can be created by plasmonic effects using metal nanoparticles
- Insulator shell prevents exciton quenching
- Metal nanoparticles may accelerate exciton diffusion
- Metal core/insulator shell particles are interesting additives to organic solar cells
- Metal gratings with appropriate period and duty rate, etc. can be more transparent than conventional transparent electrodes.
- New device performance can be as good as conventional organic PV cells.
- Metal nanowires are candidates for the replacement of ITO.

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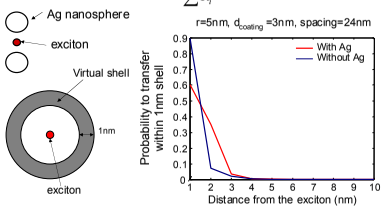
Enhanced Exciton Diffusion

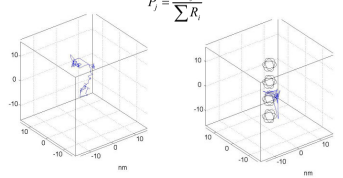
Enhanced exciton diffusion

- Exciton = oscillating dipole.
- Power absorption at point R: $R_j = \frac{dQ}{dt} = \frac{1}{2}\omega\varepsilon''|E_j|^2$
- Transfer probability: $P_j = \frac{R_j}{\sum R_i}$, ($i$ = lattice number)



Monte Carlo Simulations

1. Start at (0, 0, 0).
2. Calculate the magnitude of electric field, |E| at each 1 nm lattice grid.
3. Rate to transfer to grid j is, $R_j \propto |E|^2$
4. The probability to transfer to the grid j is, $P_j = \frac{R_j}{\sum R_i}$



Average step size: 1.3 nm

Average step size: 2.8 nm