Modelling the Organic Solar Cell

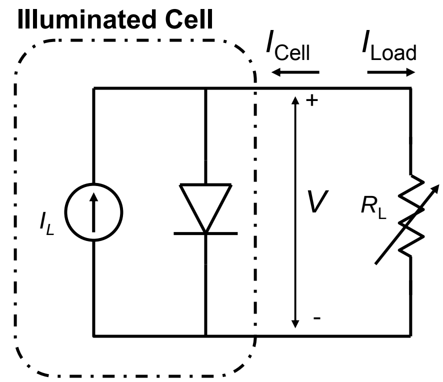
S. Sundar Kumar Iyer

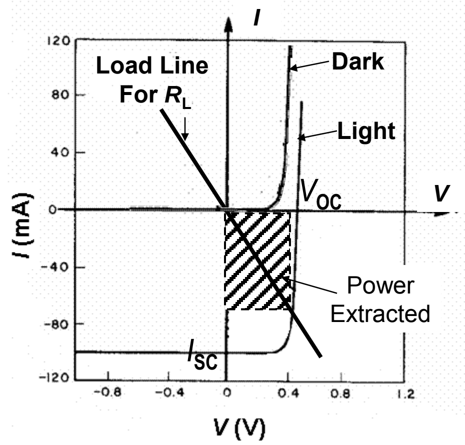
11th December, 2008

Outline

- ❑ A brief review
- ❑ Short Circuit Current
    - ■ Quantum Efficiency
- ❑ Open Circuit Voltage
- ❑ Fill Factor

Power Extracted Out Of Solar Cell





- $I_{Cell} = I_S$ [exp(qV / nkT) - 1] – I_L ; and $I_{Load}=V/R_L$
- Choose R_L to get maximum power

S.M.Sze 1991

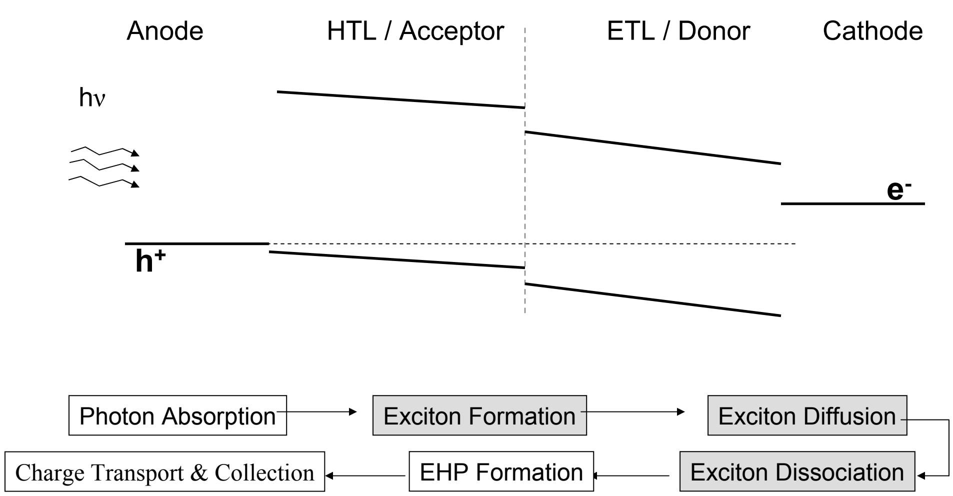
Factors Affecting Efficiency

- I_{sc} (J_{sc}) – Short Circuit Current (density)
- V_{oc} – Open Circuit Voltage
- FF – Fill Factor
- Maximum Power Output

  $P_{max} = V_{OC} \times I_{SC} \times FF$
- Efficiency

  $\eta = P_{max} \div$ Incident Light Power

Operation of Organic Solar Cells



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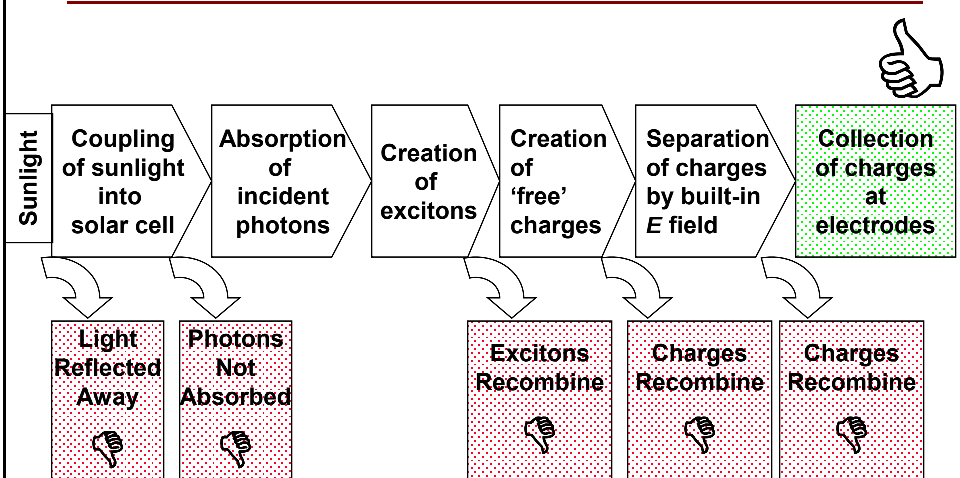
Photovoltaic Process In Organic Solar Cells



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I_{sc}: Short Circuit Current

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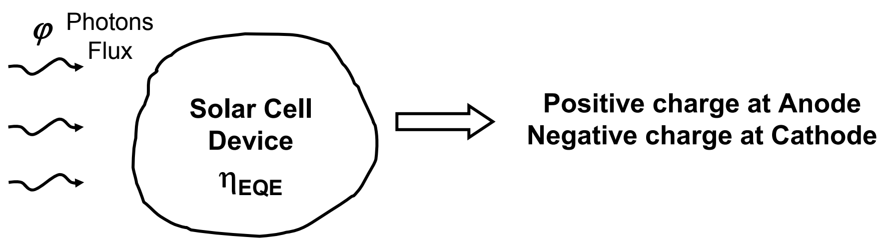
Short Circuit Current & Quantum Efficiency



$$I_{sc} = \varphi\, \eta_{EQE}\, q\, A$$

I_{sc} : Short Circuit Current when electrodes are shorted (A)

φ : Photon flux (# of phontons s^{-1} m^{-2})

A: Area of device

η_{EQE} : External Quantum Effieiency = $\eta_{O} \cdot \eta_{A} \cdot \eta_{ED} \cdot \eta_{CT} \cdot \eta_{CC}$

q : Electron charge (C)

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Quantum Efficiency

$\eta_{EQE} = \eta_O \cdot \eta_A \cdot \eta_{ED} \cdot \eta_{CT} \cdot \eta_{CC}$
$= \eta_O \cdot \eta_{IQE}$

η_{EQE} : External Quantum Efficiency
η_{IQE} : Internal Quantum Efficiency
η_O : Optical efficiency
η_A : Light Absorption Efficiency
η_{ED} : Excition Diffusion Efficiency
η_{CT} : Charge Transfer Efficiency
η_{CC} : Charge Collection Efficiency

η_{EQE} is the percentage of incident photons that result in carries contributing to short circuit current

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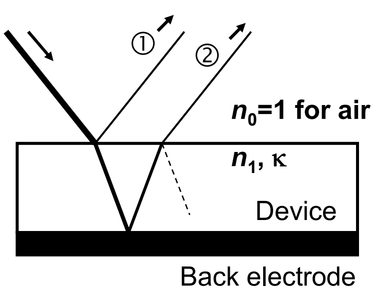
Optical Efficiency η_O

η_O



- Optical losses maybe due to
  - Reflection at the surface ①
  - Unabsorbed light leaking out ②
- Solutions
  - Anti Reflection Coating (ARC)
  - Texturing the top surface
  - Concentrators

η_O = 1-R where

$$R = \frac{(n_1-n_0)^2 + \kappa^2}{(n_1+n_0) + \kappa^2}$$

n_i : refractive index of medium i
κ: attenuation coefficient in device

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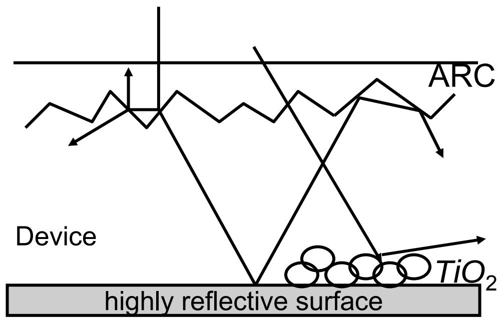
Light Trapping

η_o



- Surface modification
- Anti-reflection coating
- Nanoparticles such as TiO_2

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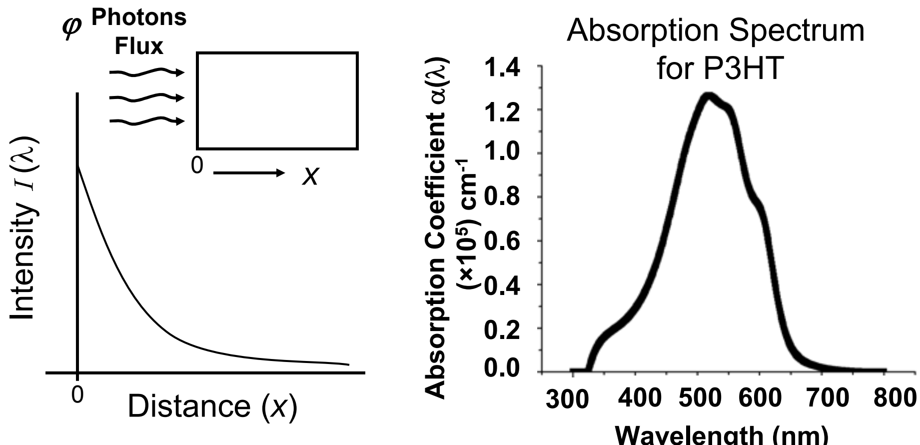
Light Absorption

η_A



$$I(\lambda,x) = I(\lambda,x=0)\exp(-\alpha x)$$

$\varphi = I(\lambda,x) / (hv/\lambda)$

h : Plank's constant

c : Speed of light

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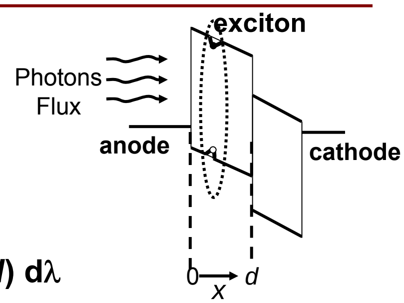
Absorption Efficiency η_A

η_A



$$\eta_A = 1 - \frac{\int_{\text{Full spectrum}} (hv/\lambda)^{-1} I(\lambda) \exp(-\alpha(\lambda)d)\, d\lambda}{\int_{\text{Full spectrum}} (hv/\lambda)^{-1} I(\lambda)\, d\lambda}$$

$$= \frac{\text{Number or photons absorbed}}{\text{Number of photons incident}}$$

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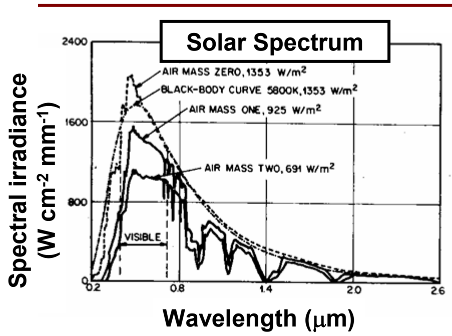
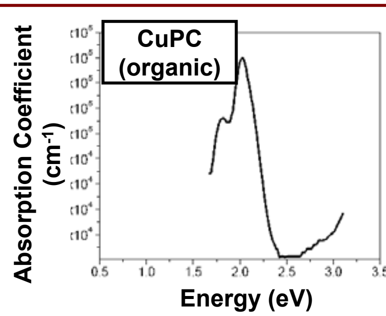
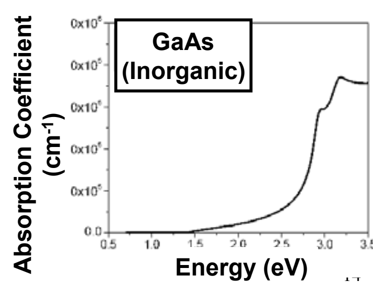
Absorption in Active Layer

η_A







- Organics absorb in a band
- High absorption coefficient
- η_A is high for thick films

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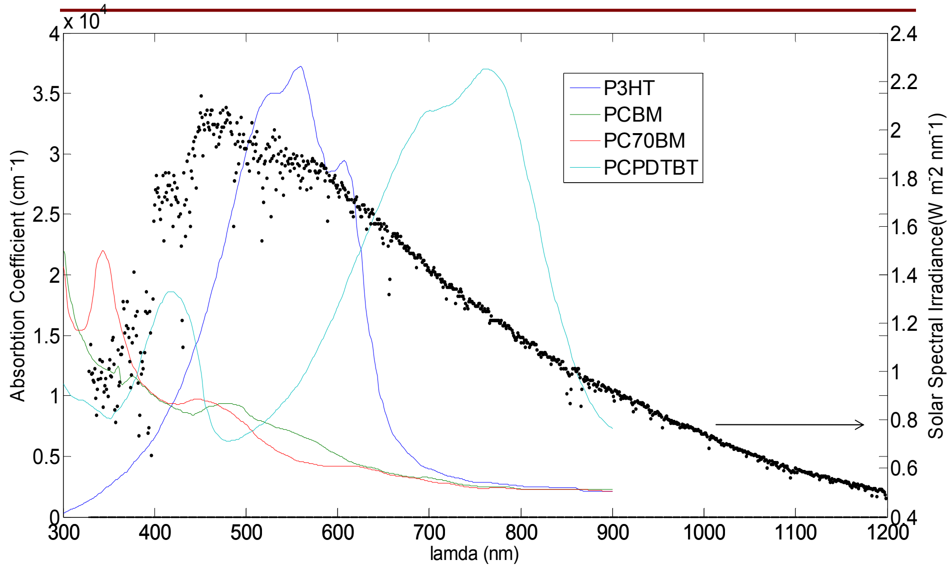
Absorption Spectrum

η_A



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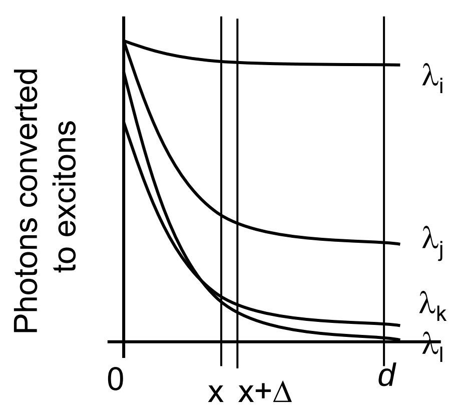
Exciton Distribution in Irradiated Material

η_{ED}



$$\xi(x) = \int_{\text{Full spectrum}} (hv/\lambda)^{-1} I(\lambda) \exp(-\alpha(\lambda)x)\, d\lambda$$

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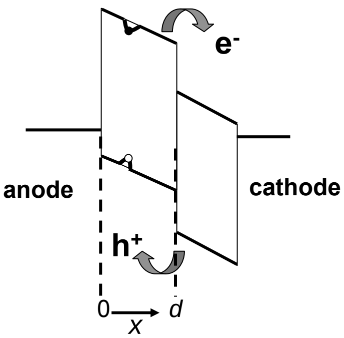
Excition Dissociation Efficiency - η_{ED}

- Excitons are neutral
- Concentration of surviving exitons at x' is

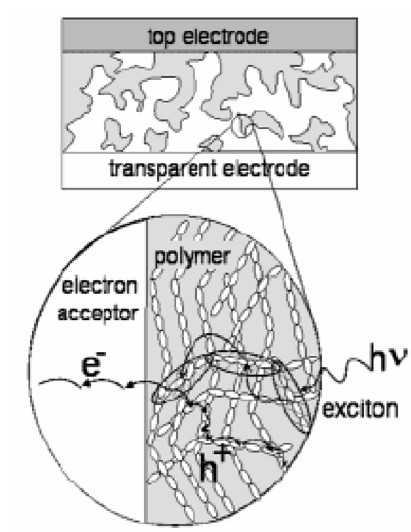
$$\xi\,(x+x') = \tfrac{1}{2}\,\xi\,(x)\,\exp(-x'/L_D)$$

  - L_D is the average exciton diffusion length
- Likely location of dissociation is the interface



$$\eta_{ED} = \frac{\int_0^d \tfrac{1}{2}\,\xi\,(x)\,\exp(-(d-x)/L_D)\,dx}{\int_0^d \xi\,(x)\,dx} = \frac{\text{Excitons reaching interface}}{\text{Number of excitons created}}$$

η_{ED} in Bulk Heterojunction Device



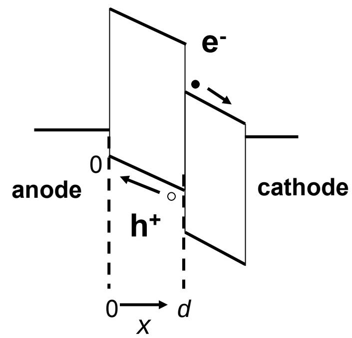
$\eta_{ED} \approx 1$

Charge Transfer Efficiency - η_{CT}

- Electrons and hole drift towards electrodes
- On the way, they may get trapped/recombine
- Concentration of surviving charge will be

  $n(t) = n(t = t_0)\, exp(- t / \tau)$

  - τ is the average charge liftime



- Time needed for charge to reach the electrode

  $T_{transit} = d \div [\mu(\mathcal{E})\, \mathcal{E}]$

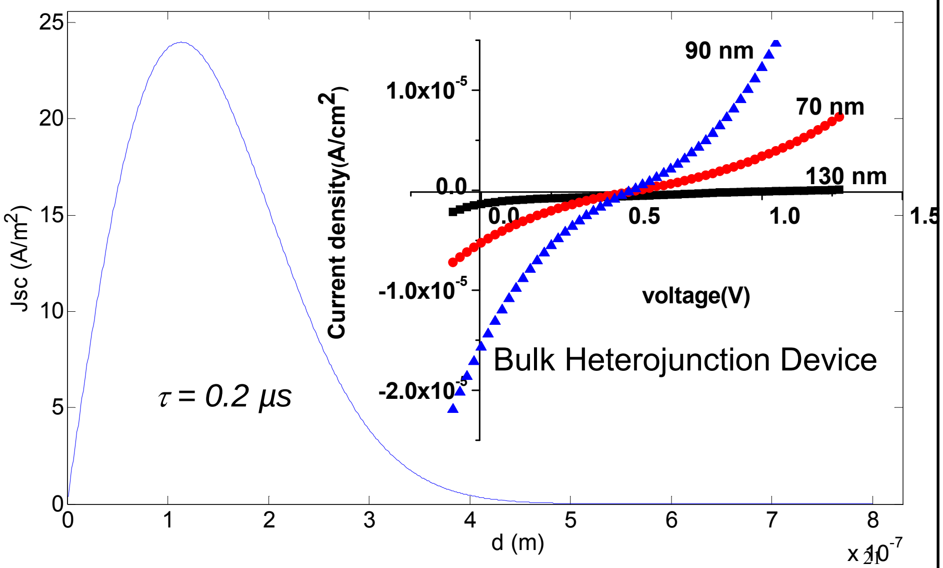
- $\eta_{CT} = exp(- T_{transit} / \tau) = \dfrac{\text{\# charges reaching electrode}}{\text{\# conducting charges created}}$

Factors Affecting η_{ED}

- Choice of Electrodes
- Thickness of active layer(s)
- Morphology and Phase in active layer

Effect of Charge Carrier Lifetime

η_{ED}



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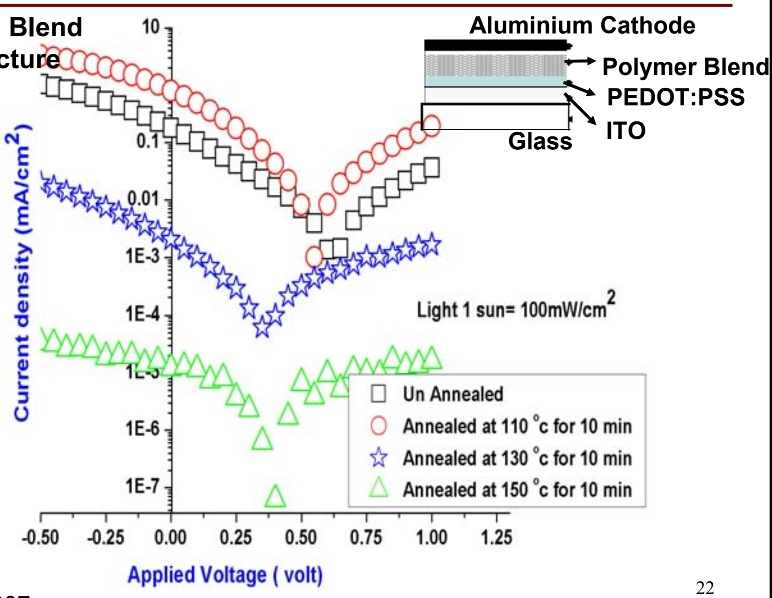
Effect of Post Process Anneal

η_{ED}

P3HT: PCBM Blend Heterostructure



Vinod Pagare 2007

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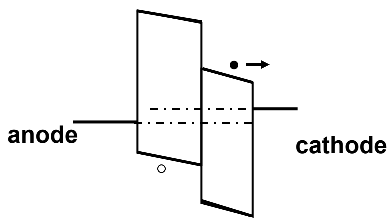
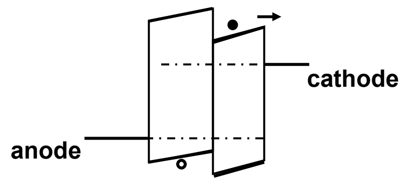
η_{CC}

Charge Collection Efficiency - η_{CC}

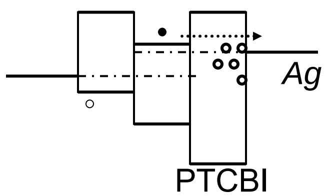
At low biases



At higher biases (>V_{FB})



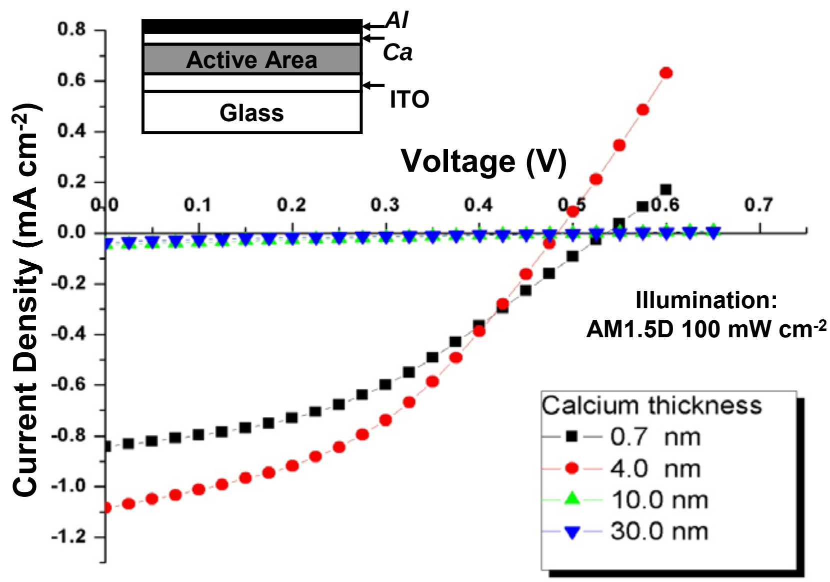
Tunnel through EBL



- **Charge collection may be affected by**
  - **Internal fields**
  - **Traps**
  - **Exciton Blocking Layer (EBL)**

η_{CC}

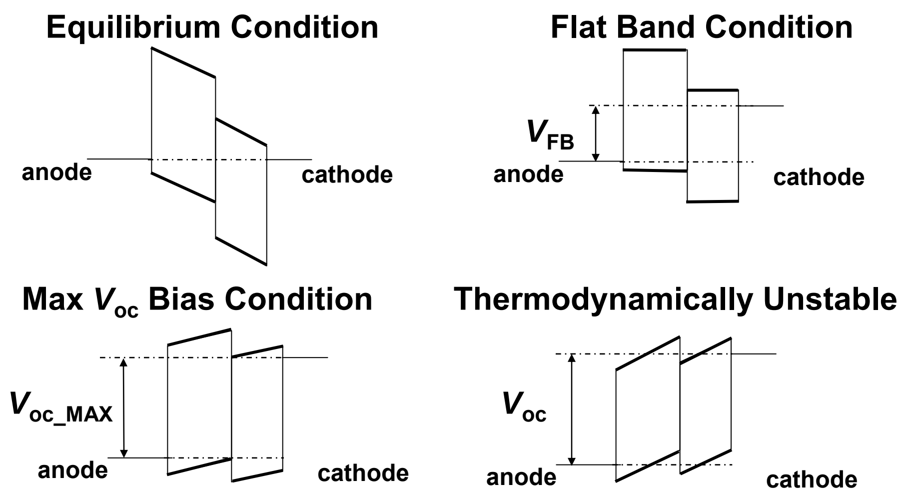
Cathode Thickness Variation



Nitin Sahai 2008

V_{oc} : Open Circuit Voltage

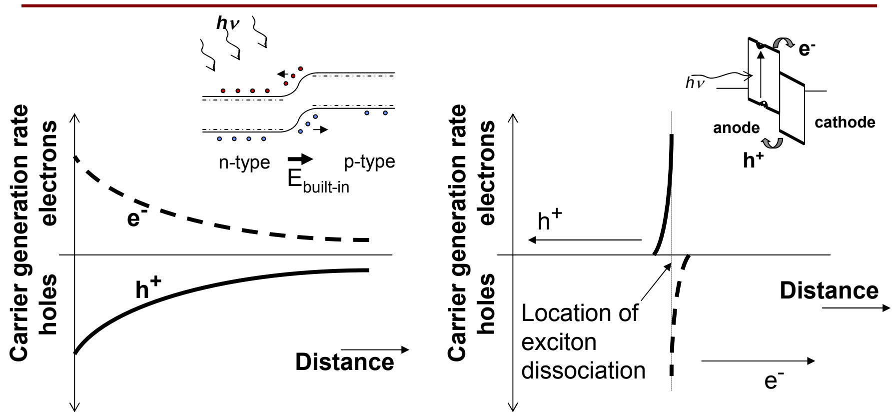
Maximum Open Circuit Voltage



$V_{oc\_MAX} = \phi_{LUMO\_A} - \phi_{HOMO\_D}$;

$V_{oc} = \phi_{LUMO\_A} - \phi_{HOMO\_D} - 2kT \ln (g_D/p_D)$

Higher V_{oc} in Organic Solar Cells

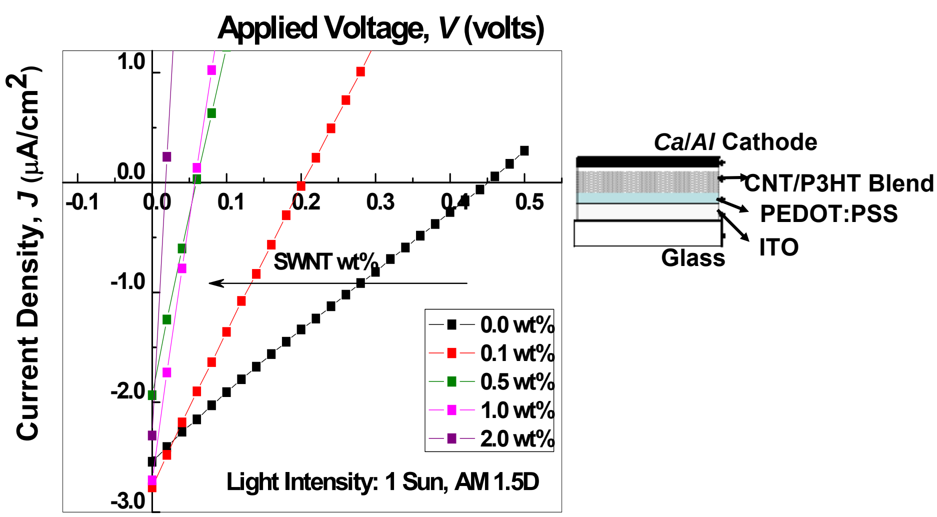


Inorganic *p-n* junction Solar Cell
• Charge separation field has to overcome diffusion tendency of electron or hole to separate the charges

Organic hetero-junction Solar Cell
•Charge separation field is aided by the diffusion tendency of hole and electron

B. Greg 2003

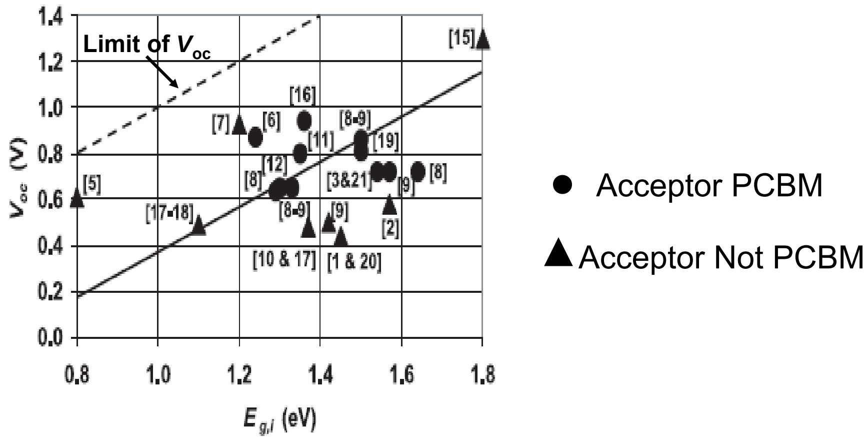
Lower R_{sh} Lowers V_{oc}



Arun Tej Mallajosyula 2008

V_{oc} in P3HT Based Solar Cells

Sample of 22 Bulk Heterojunction Solar Cells



B. Minnaert and M. Burgelman 2007

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Fill Factor

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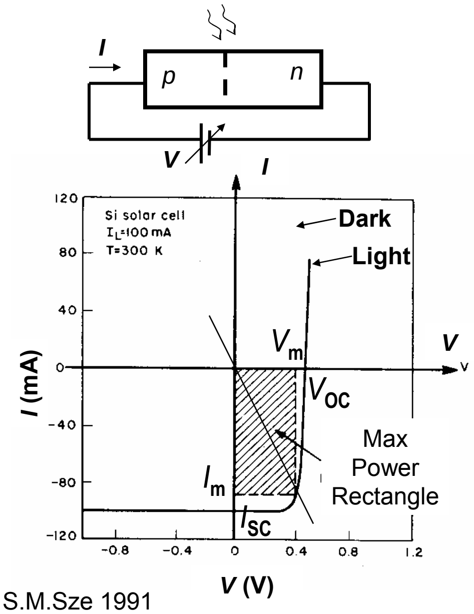
Fill Factor Definition



- Fill Factor FF is the ratio of area of maximum rectangle fitted in the 4th quadrant *I-V* and the product of V_{OC} and I_{SC}
- FF = $(V_m \cdot I_m) / (V_{oc} \cdot I_{sc})$

S.M.Sze 1991

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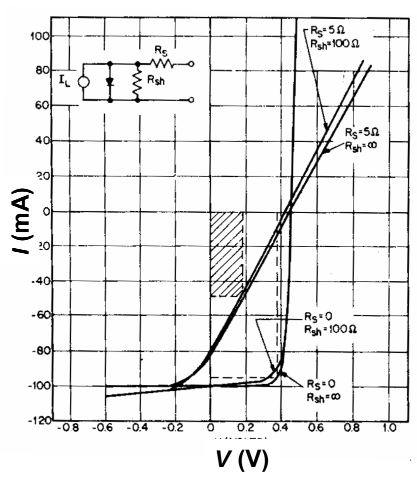
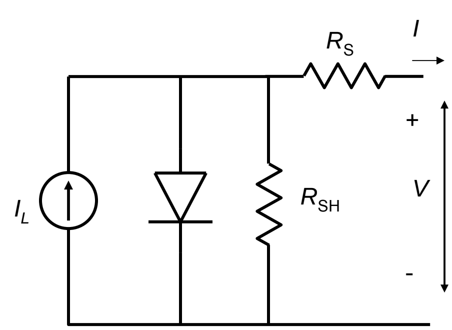
Model for Solar Cells (Traditional)





- Series resistance causes ohmic loss
- Shunt resistance cases charge separated to recombine

S.M.Sze 1991

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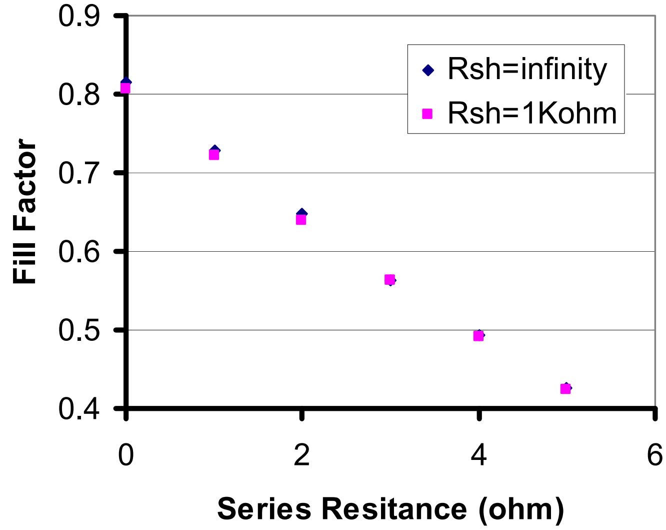
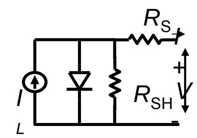
Variation in FF with R_s





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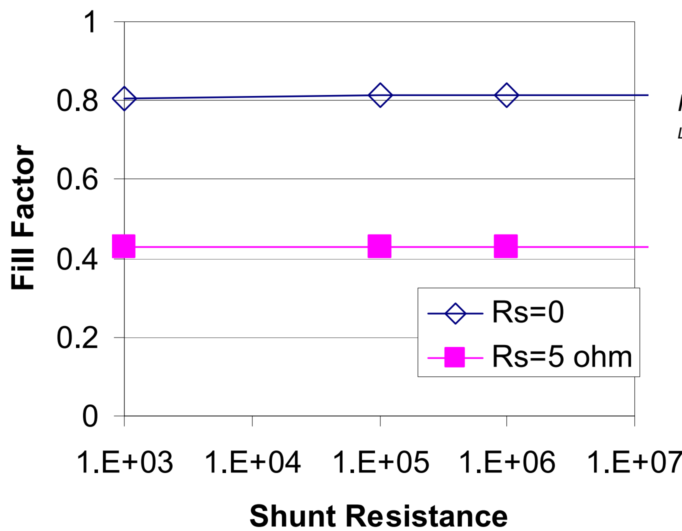
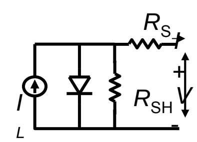
Variation in FF with R_{sh}





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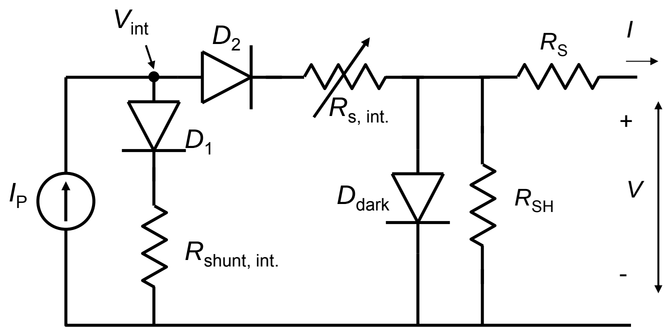
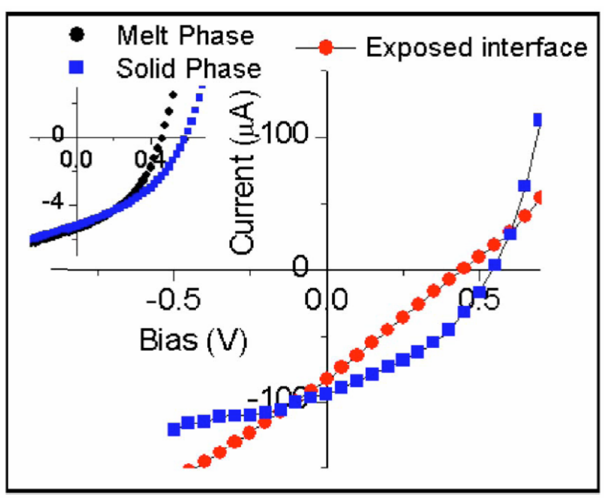
Organic Solar Cell Model



- I_L is a function of voltage
- Exciton generation I_P is a constant
- $R_{shunt, int}$ will account for exciton recombination
- $R_{s,int}$ will account for extraction of e^- and h^+ to electrodes

B. Mazhari 2006

Contacts Effect Fill Factor



Gupta 2008

We Discussed …

- Calculating Efficiency of a Solar Cell
- Short Circuit Current
  - Quantum Efficiency
- Open Circuit Voltage
- Fill Factor

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