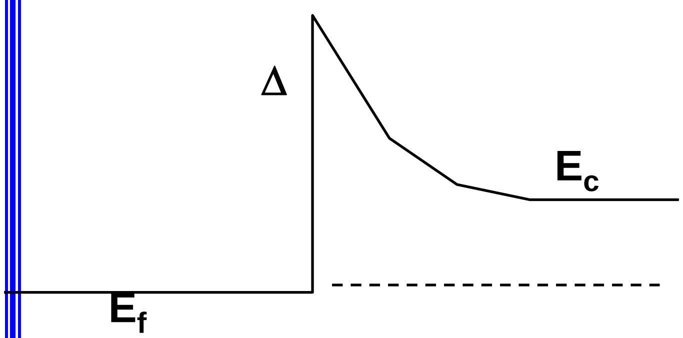
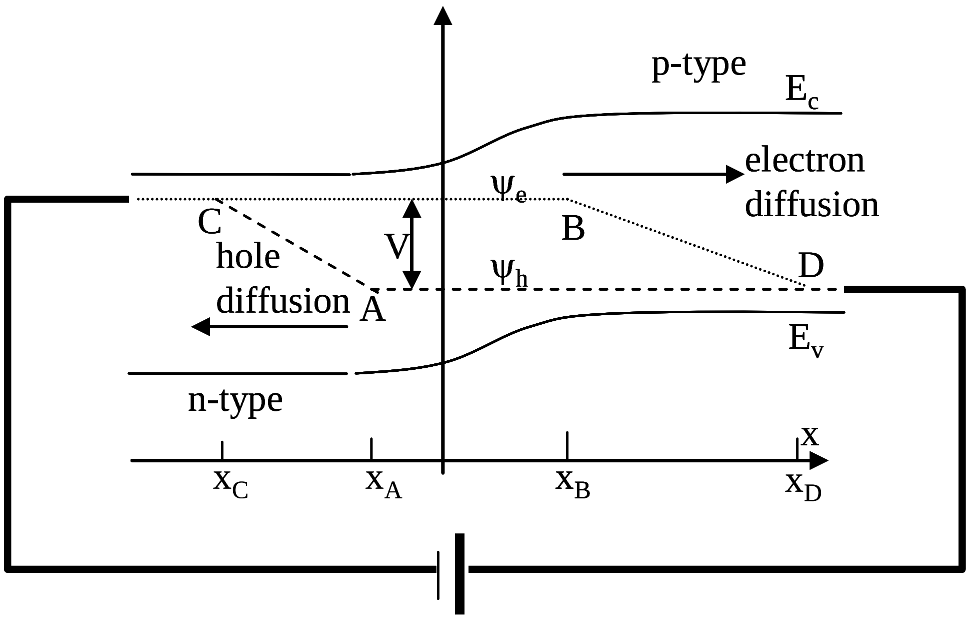
Lecture 7 Solar Cells

- review
- solid-state thermionics
- solar cells: basic principle
- solar cells: maximum efficiency
- factors impacting efficiency
- different types of cells

Compare Schottky diode and pn diode





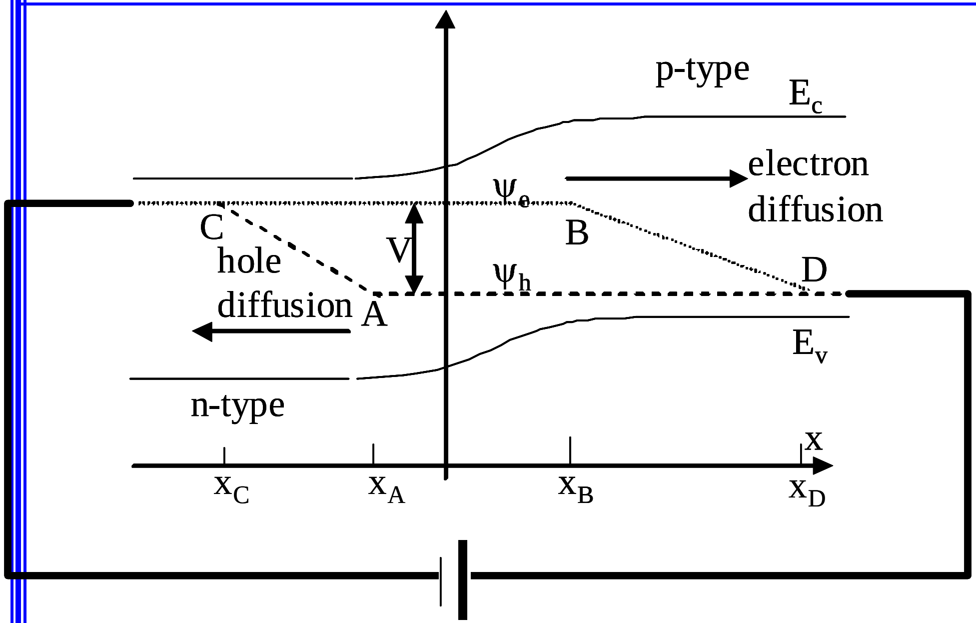
$$J = J_s\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

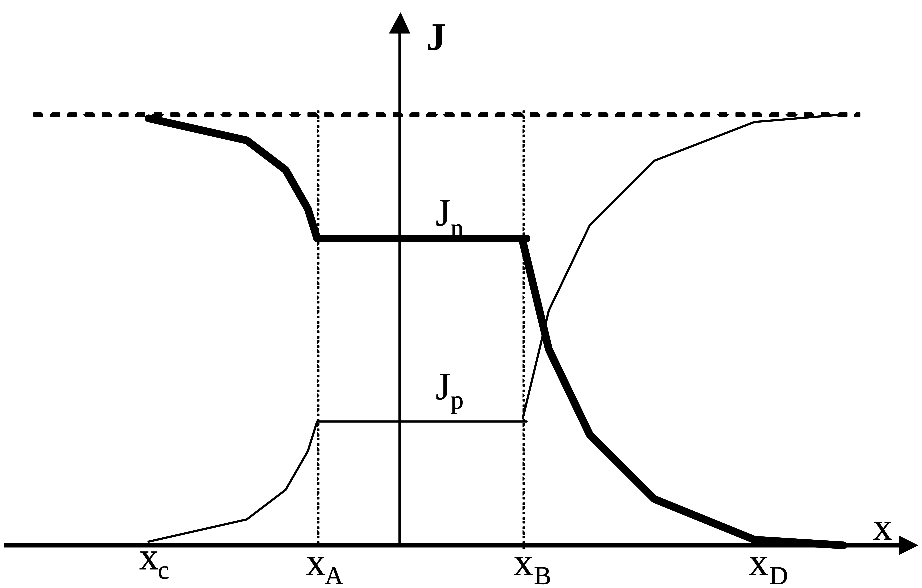
$$J = J_s\left(e^{eV/k_B T} - 1\right)$$

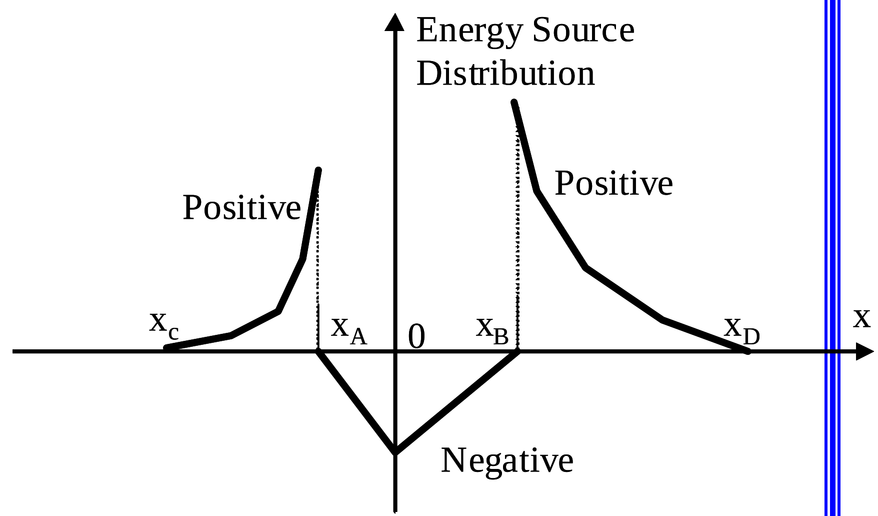
$$J_s = AT^2 \exp\left(-\frac{\Delta}{k_B T}\right)$$

$$J_s = eN_c N_v\left(\frac{1}{N_A}\sqrt{\frac{a_h}{\tau_h}} + \frac{1}{N_D}\sqrt{\frac{a_e}{\tau_e}}\right)\exp\left(-\frac{E_G}{\kappa_B T}\right)$$

Current and Energy Distribution







Thermionic Emission and Energy Filtering

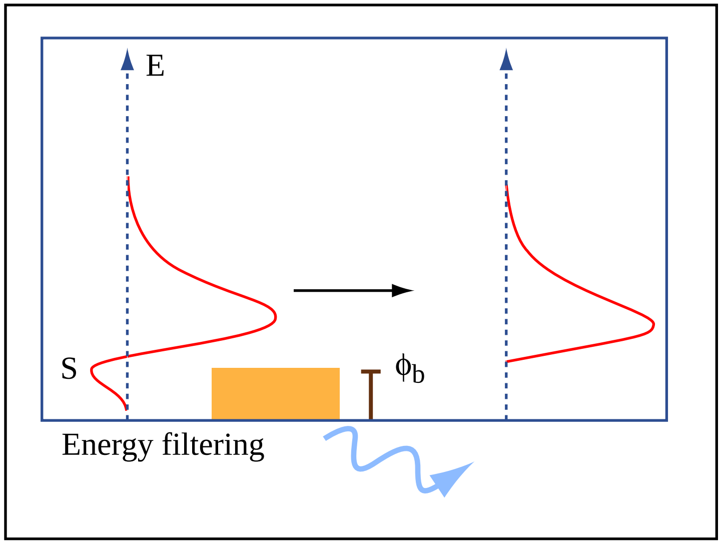
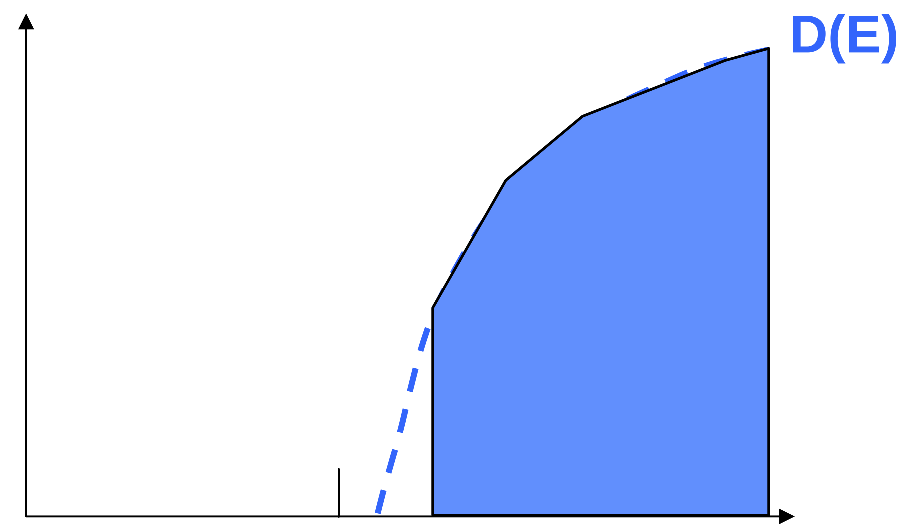
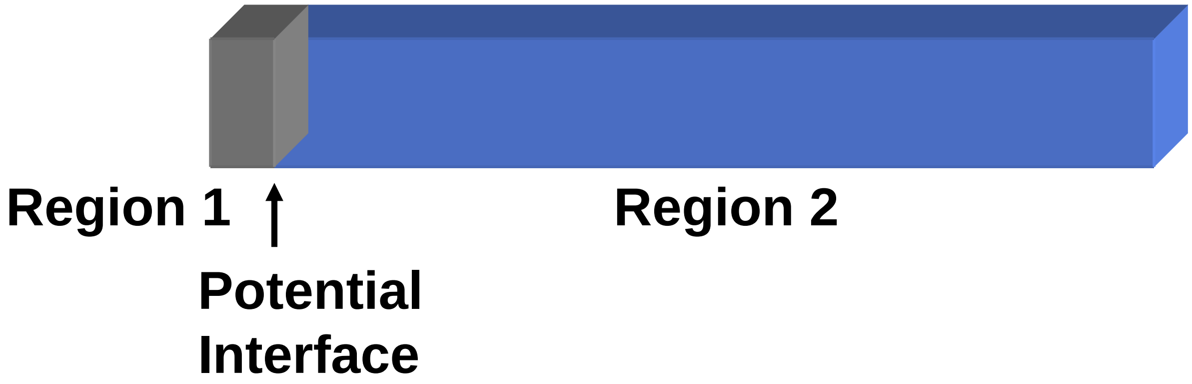


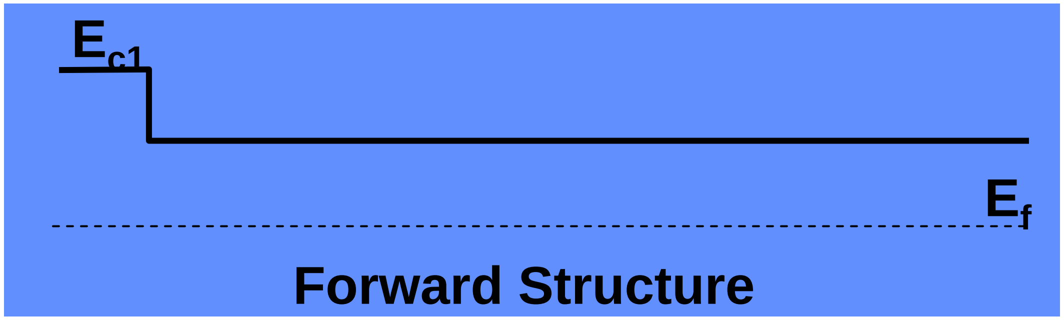
Figure by MIT OpenCourseWare.

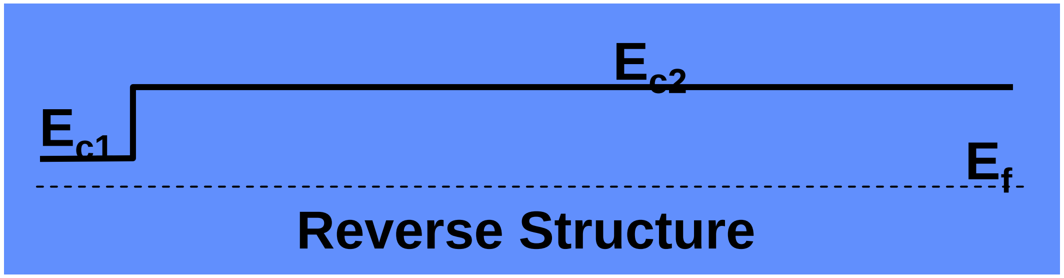


Moyzhes and Nemchinsky, Appl. Phys. Lett., 73, 1895-1897 (1998).
Shakouri and Bowers, Appl. Phys. Lett., 71, 1234 (1997).

Potential-Step Amplified Thermal-Electrical Energy Converter





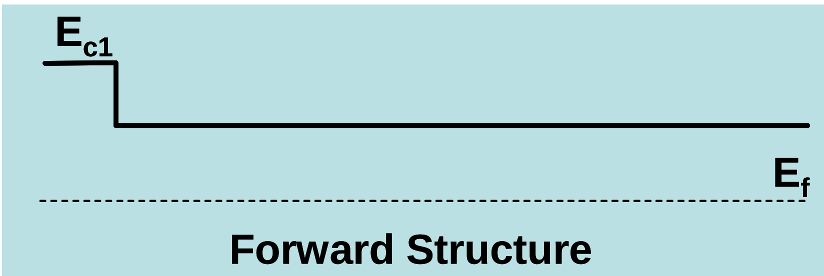


ICT'02

Sharp Interface: Electron Mean Free Path > Space Charge Region

Single Carrier Transport

Amplification of Temperature Discontinuity



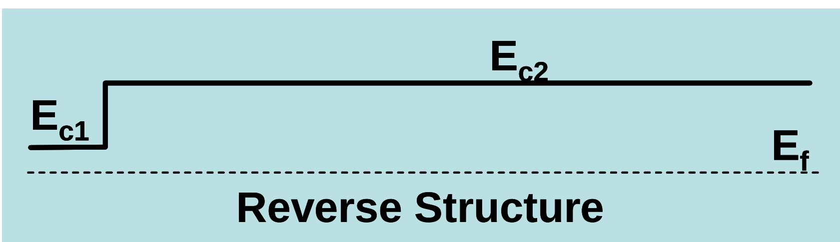
Forward Structure

$$J_{R,f} = AT_{e1}^{\;2}\, \mathrm{e}^{-(E_{c1}-E_{f1})/(\kappa_B T_{e1})}$$

$$\left(T_{e1}-T_{e2}\right)_f \propto -\frac{k_{e2}}{J_{R,f}}\frac{dT_{e2}}{dx}$$

$$\left(T_{e1}-T_{e2}\right)_f \sim e^{\Delta/(\kappa_B T_e)}\Lambda_{e2}\frac{dT_{e2}}{dx}$$

Amplification Factor



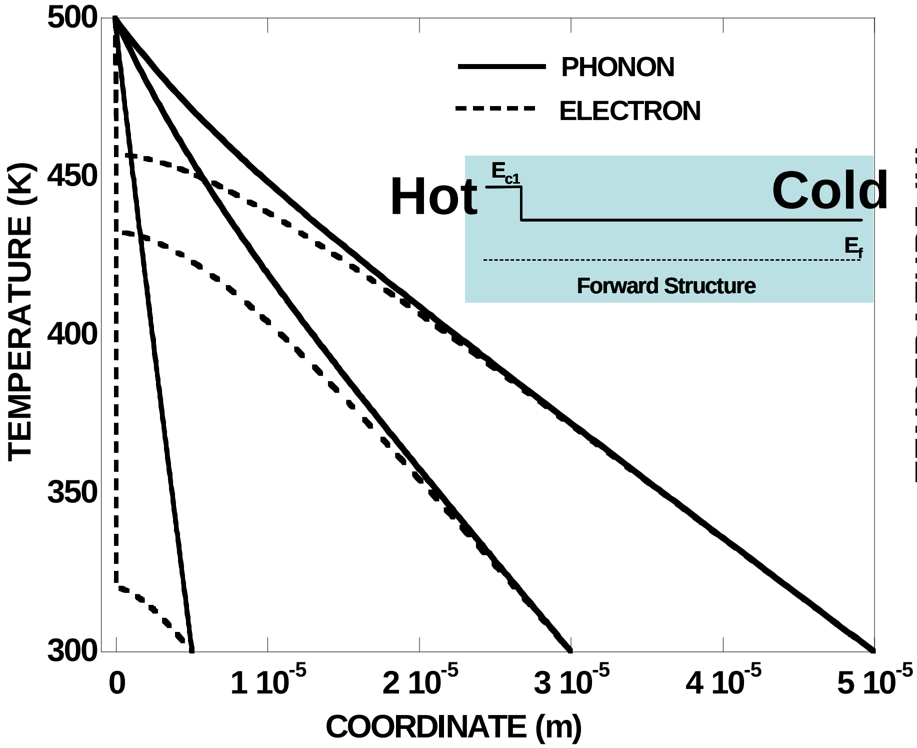
Reverse Structure

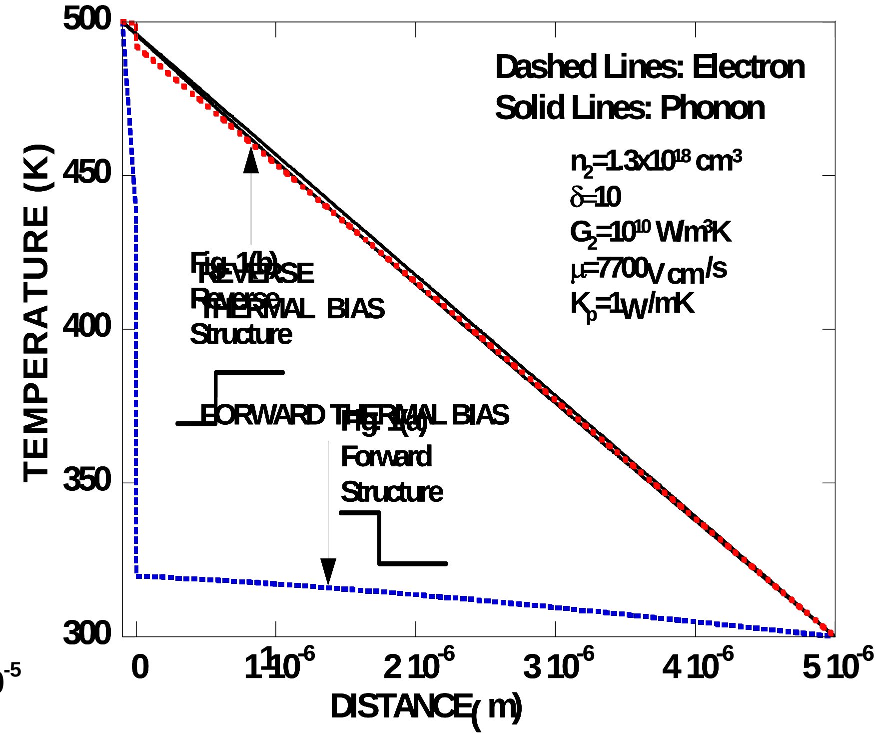
$$\left(T_{e1}-T_{e2}\right)_r \propto -\frac{k_{e2}}{J_{R,r}}\frac{dT_{e2}}{dx}$$

$$\left(T_{e1}-T_{e2}\right)_f \sim \Lambda_{e2}\frac{dT_{e2}}{dx}$$

No Amplification

Two-Temperature Modeling Results



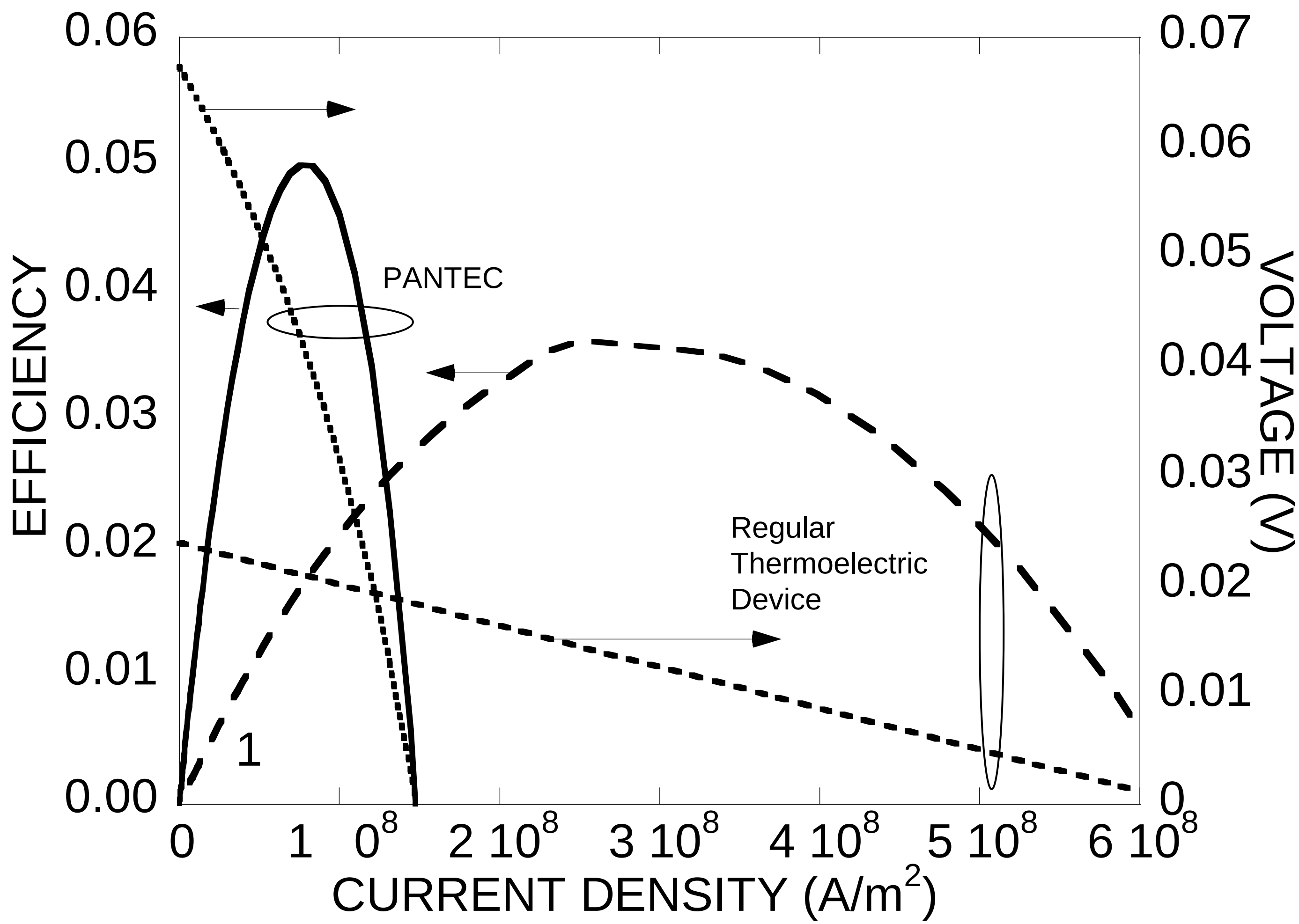


$$\frac{\Delta}{\kappa_B T} = 8.3$$

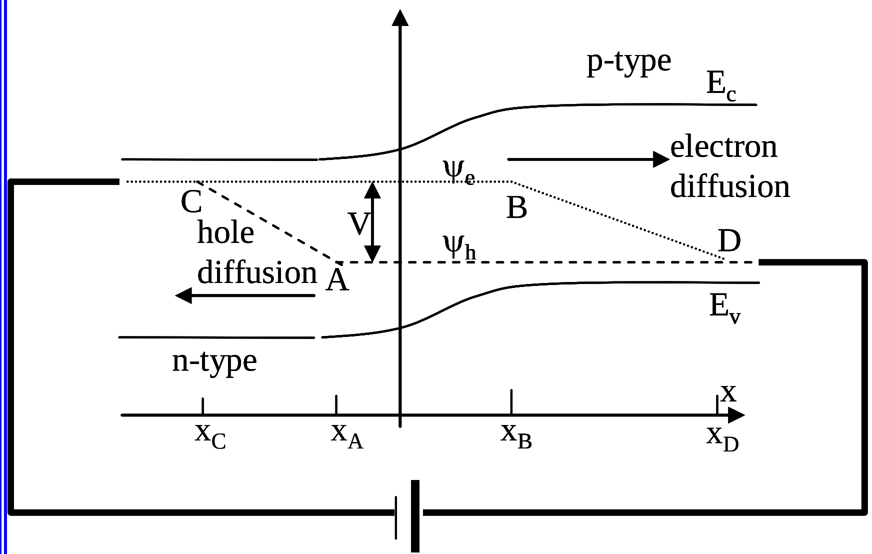
μ=20,000 cm^2/Vs; m*=0.014 m$_e$; G=10^{10} W/m^{3}K

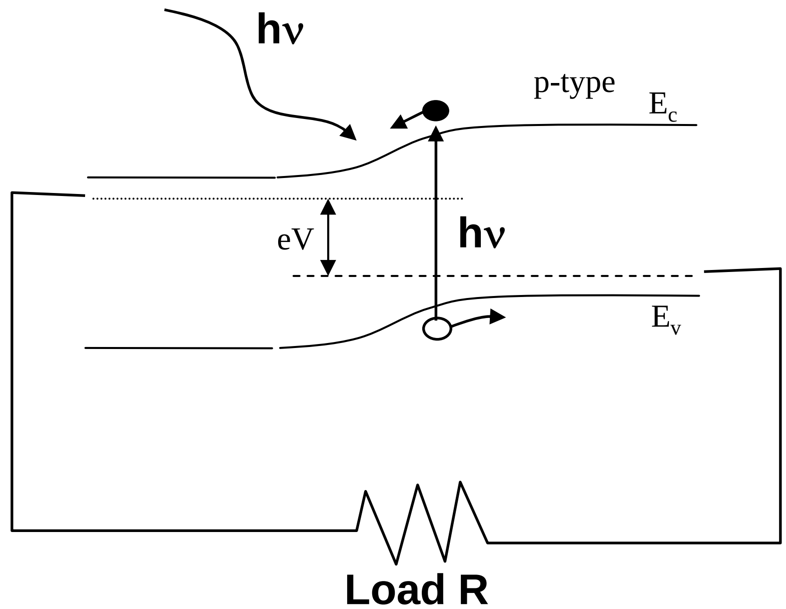
k$_p$=1W/mK; n$_2$=3.18x10^{17} cm^{-3}; n$_1$=5.8x10^{16} cm^{-3}

Power Generation Efficiency



Photovoltaic Cells





$$J = J_s\left(e^{eV/k_BT} - 1\right)$$

$$J = J_s\left(e^{eV/k_BT} - 1\right) - J_L$$

$$J_s = A\exp\left(-\frac{E_G}{\kappa_B T}\right)$$

J_L --- Excitation due to photon
Short Circuit Current

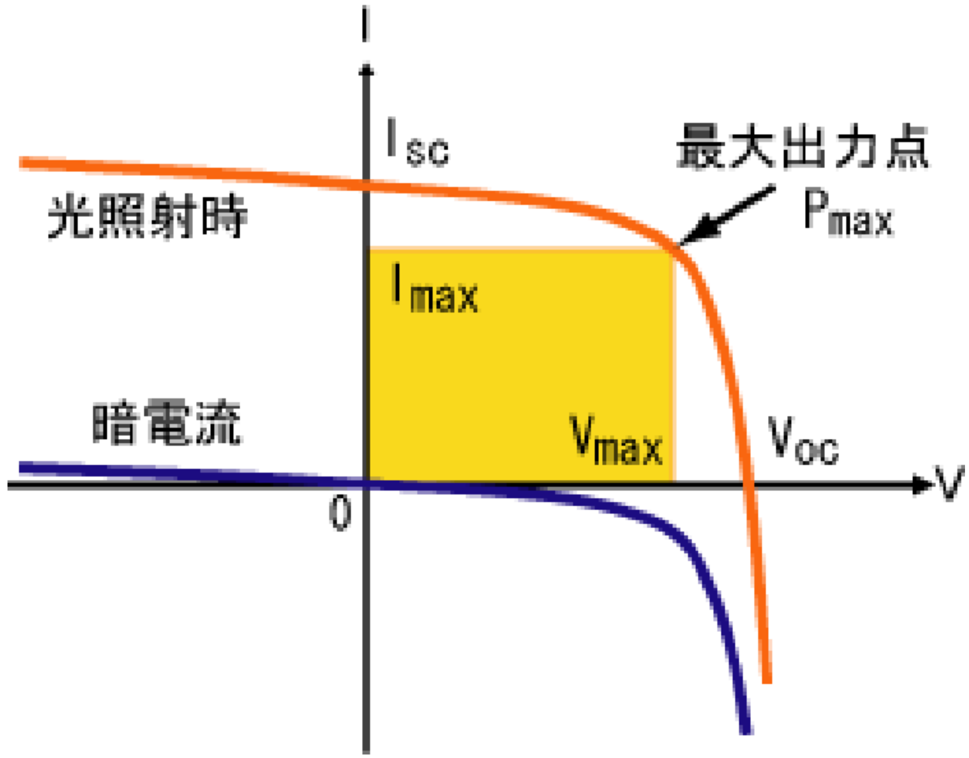
Solar Cell: Open Circuit Voltage

$$V_{oc} = \frac{\kappa_B T}{e} \ln\left(\frac{J_L}{J_s} + 1\right)$$

$$J_s = A \bullet \exp\left(-\frac{E_G}{\kappa_B T}\right)$$

$$V_{oc} \approx \frac{E_G}{e} - \frac{\kappa_B T}{e} \ln\left(\frac{A}{J_G}\right)$$

IV Characteristics of Solar Cell



From S.M. Sze, Physics of Semiconductor Devices, 2nd Ed., p.795

Maximum Power Output

$$W_e = J_e V = J_s V\left(e^{eV/k_B T} - 1\right) - J_L V$$

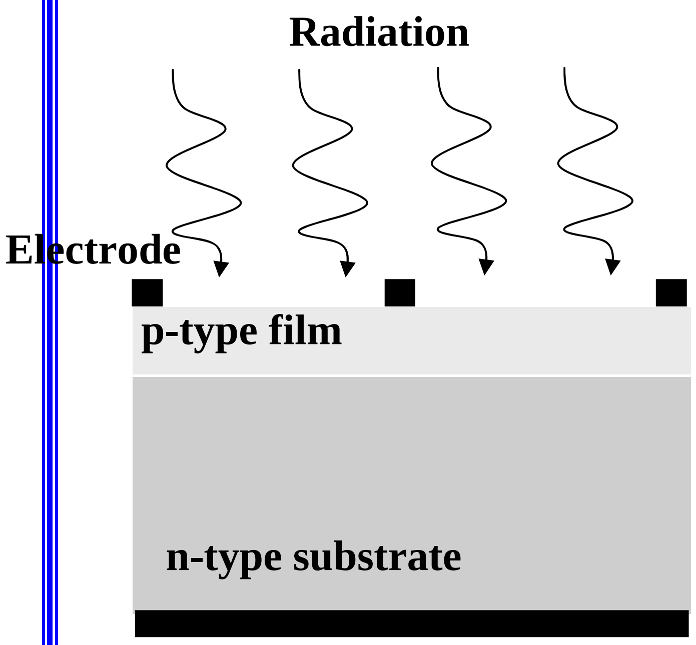
Find maximum: $dW_e/dV=0$

$$J_m = J_s \frac{eV_m}{\kappa_B T} \exp\left[\frac{eV_m}{\kappa_B T}\right] \approx J_L\left[1 - \frac{eV_m}{\kappa_B T}\right]$$

$$V_m = \frac{\kappa_B T}{e} \ln\left(\frac{J_L / J_s + 1}{1 + eV_m / (\kappa_B T)}\right) \approx V_{oc} - \frac{\kappa_B T}{e} \ln\left(1 + \frac{eV_m}{\kappa_B T}\right)$$

Fill Factor: $$F = \frac{J_m V_m}{J_L V_{oc}}$$

Source Term



$$J_L = eF_{se} \int_{E_G/\hbar}^{\infty} (1 - R_\omega) \frac{I_{b\omega}(T,\omega)}{\hbar\omega} d\omega$$

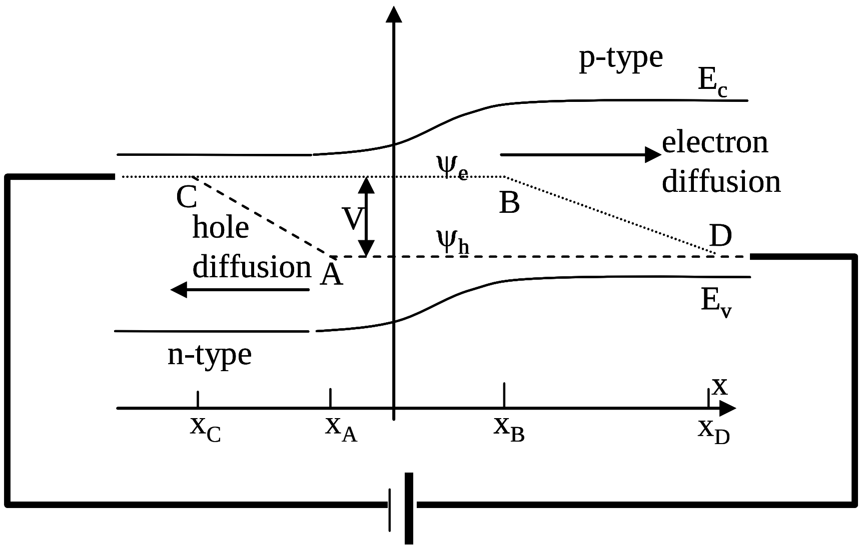
Fraction of solar radiation reaching earth
One photon generates one electron-hole pair

$$\eta = \frac{JV}{I_s}$$

← Incident solar radiation flux

Question: what is the maximum possible efficiency?

Schokley-Quisser Limit



$$J = J_s\left(e^{eV/k_BT} - 1\right) - J_L$$

$$J_s = eN_cN_v\left(\frac{1}{N_A}\sqrt{\frac{a_h}{\tau_h}} + \frac{1}{N_D}\sqrt{\frac{a_e}{\tau_e}}\right)\exp\left(-\frac{E_G}{\kappa_B T}\right)$$

- **If we do not include nonradiative recombination at all, there is still radiative recombination in the pn junction.**
- **When a voltage develops across the pn junction, the average number of photons per mode is:**

$$f(T,\omega) = \frac{1}{\exp\left(\frac{\hbar\omega - eV}{k_BT}\right) - 1}$$

Shockley, W. and Queisser, H.J., Journal of Applied Physics, 32, 510 (1961).
Henry, C.H., Journal of Applied Physics, 51, 4494 (1980).

Schokley-Quisser Limit

Recombination Current

$$J_r = \frac{e(n^2+1)}{4\pi^2 c^2} \int_{E_g/\hbar}^{\infty} d\Omega\, \omega^2 \exp\left(\frac{eV - \hbar\omega}{kT}\right)$$

$$\cong A \exp\left(\frac{eV - E_g}{kT}\right),$$

$$A \simeq \frac{e(n^2+1)\, E_g^2\, kT}{4\pi^2 \hbar^3 c^2} = 5693 E_g^2 \frac{\text{A}}{\text{cm}^2}.$$

n---Refractive index

$$J_L = eF_{se} \int_{E_G/\hbar}^{\infty} (1 - R_\omega) \frac{I_{b\omega}(T,\omega)}{\hbar\omega} d\omega = eF_{se} \int_{E_G/\hbar}^{\infty} \frac{I_{b\omega}(T,\omega)}{\hbar\omega} d\omega$$

Ideal Device

$$J = A\exp\left(\frac{eV - E_g}{k_B T}\right) - J_L$$

Image removed due to copyright restrictions.
Please see Fig. 3 in Henry, C. H.
"Limiting Efficiencies of Ideal Single and Multiple Energy Gap Terrestrial Solar Cells." *Journal of Applied Physics* 51 (August 1980): 4494-4500.

Follow same efficiency analysis to maximize efficiency

Henry, C.H., Journal of Applied Physics, 51, 4494 (1980).

Multijunction Cells

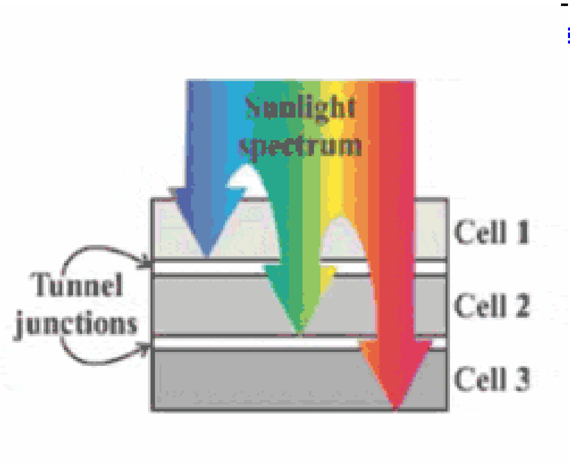
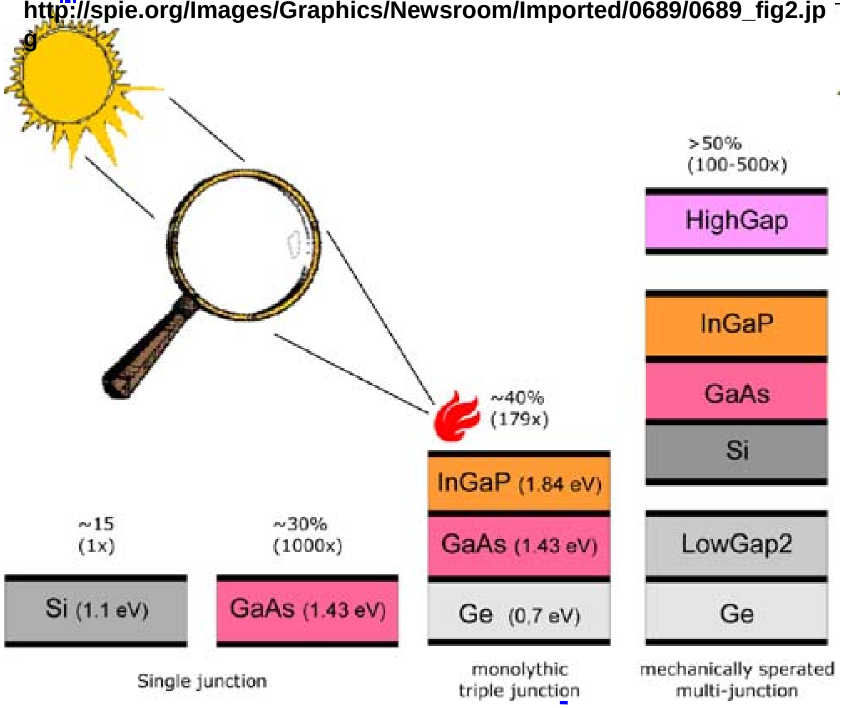


Image removed due to copyright restrictions.
Please see the schematic of a tandem PV cell in Pentland, William. "Solar Energy's Bleeding Edge - Breakthrough PV Research Projects." CleanBeta Blog, June 22, 2008.

http://www.solarserver.de/solarmagazin/images/Imagen1_web.gif

http://cleantechlawandbusiness.com/cleanbeta/wp-content/gallery/cache/314__520x420_tandempv.jpg

http://spie.org/Images/Graphics/Newsroom/Imported/0689/0689_fig2.jpg



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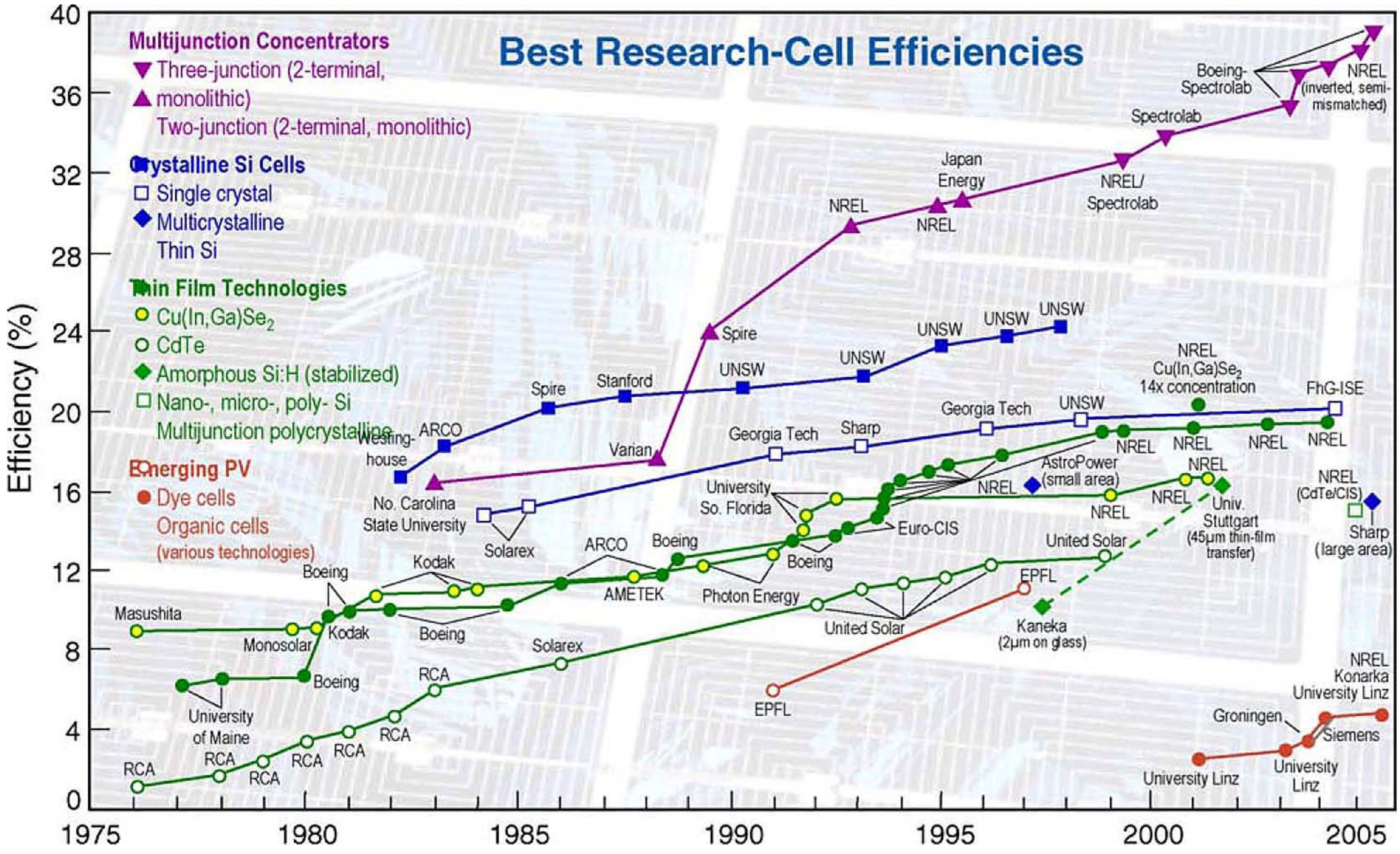
Please see Fig. 4 in Henry, C. H. "Limiting Efficiencies of Ideal Single and Multiple Energy Gap Terrestrial Solar Cells." *Journal of Applied Physics* 51 (August 1980): 4494-4500.

Henry, C.H., Journal of Applied Physics, 51, 4494 (1980).



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Challenge: Recombination

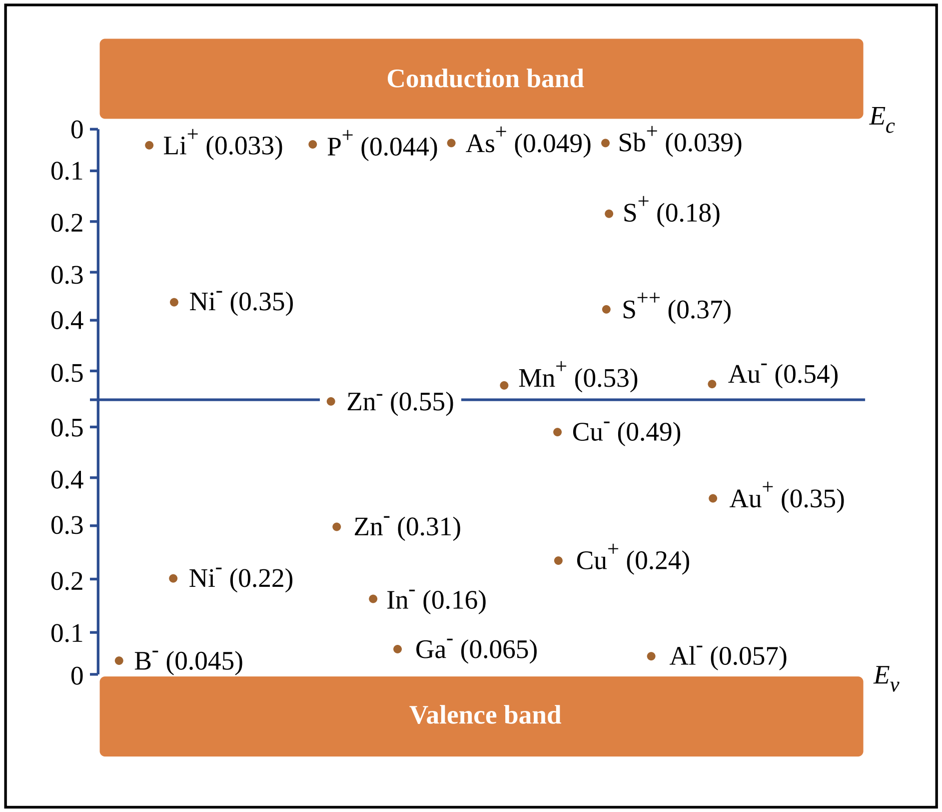


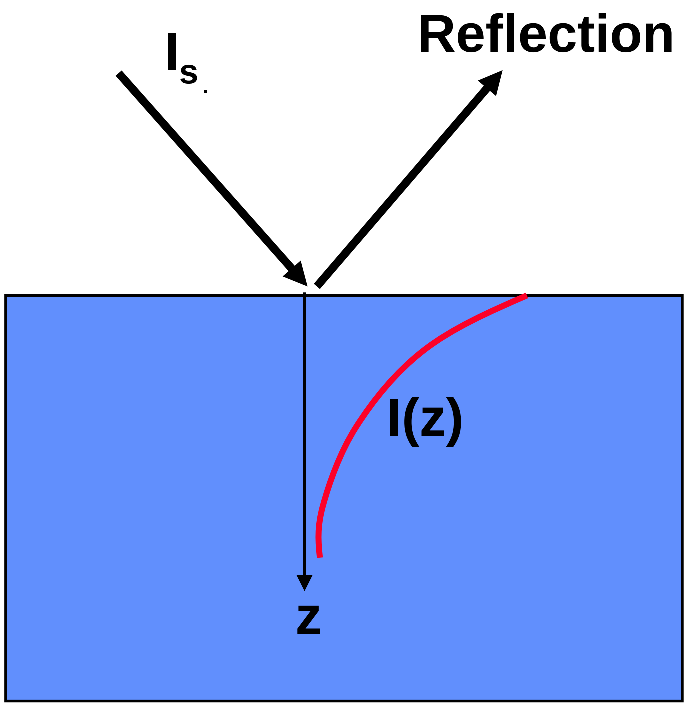
Figure by MIT OpenCourseWare.

- **Deep levels**
- **Dangling bonds**
- **Grain boundaries**

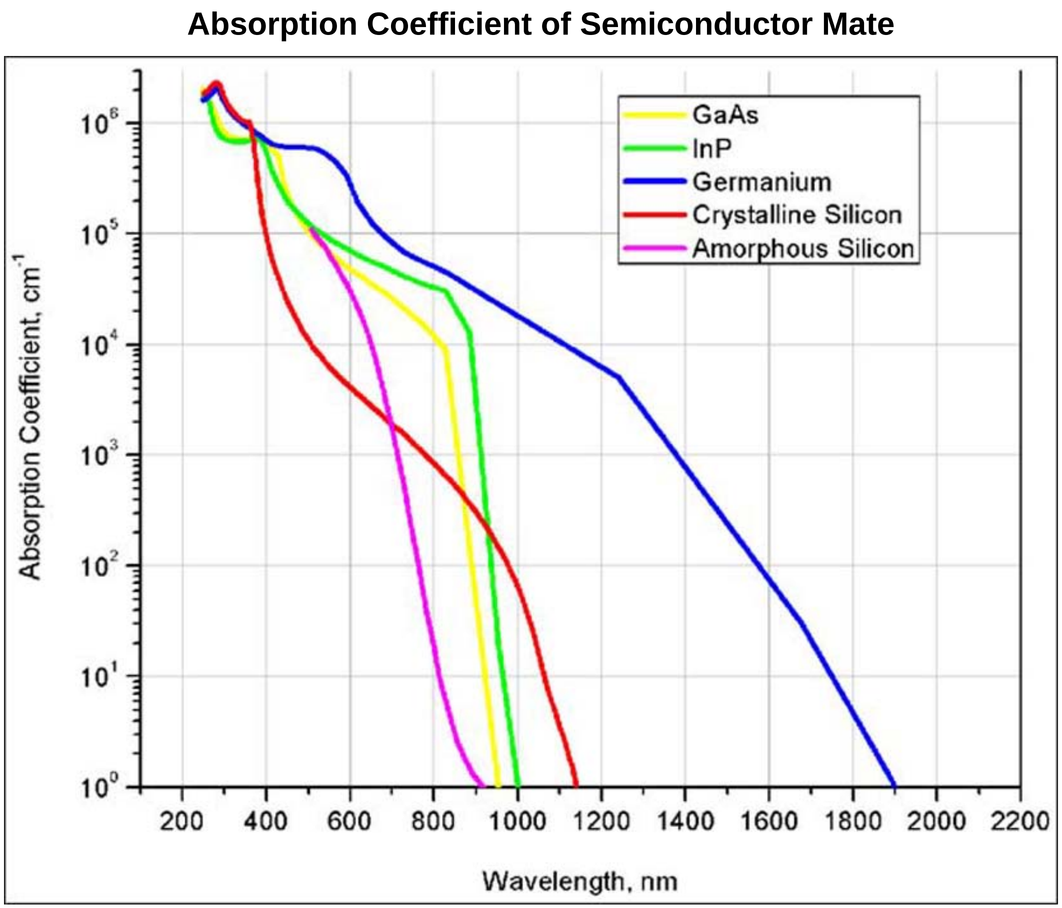
- **Purify**
- **Single crystals**

http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT-Delhi/Semiconductor%20Devices/LMB2A/3b.htm

Photon Absorption



$$I(z) = I_s e^{-\alpha z}$$



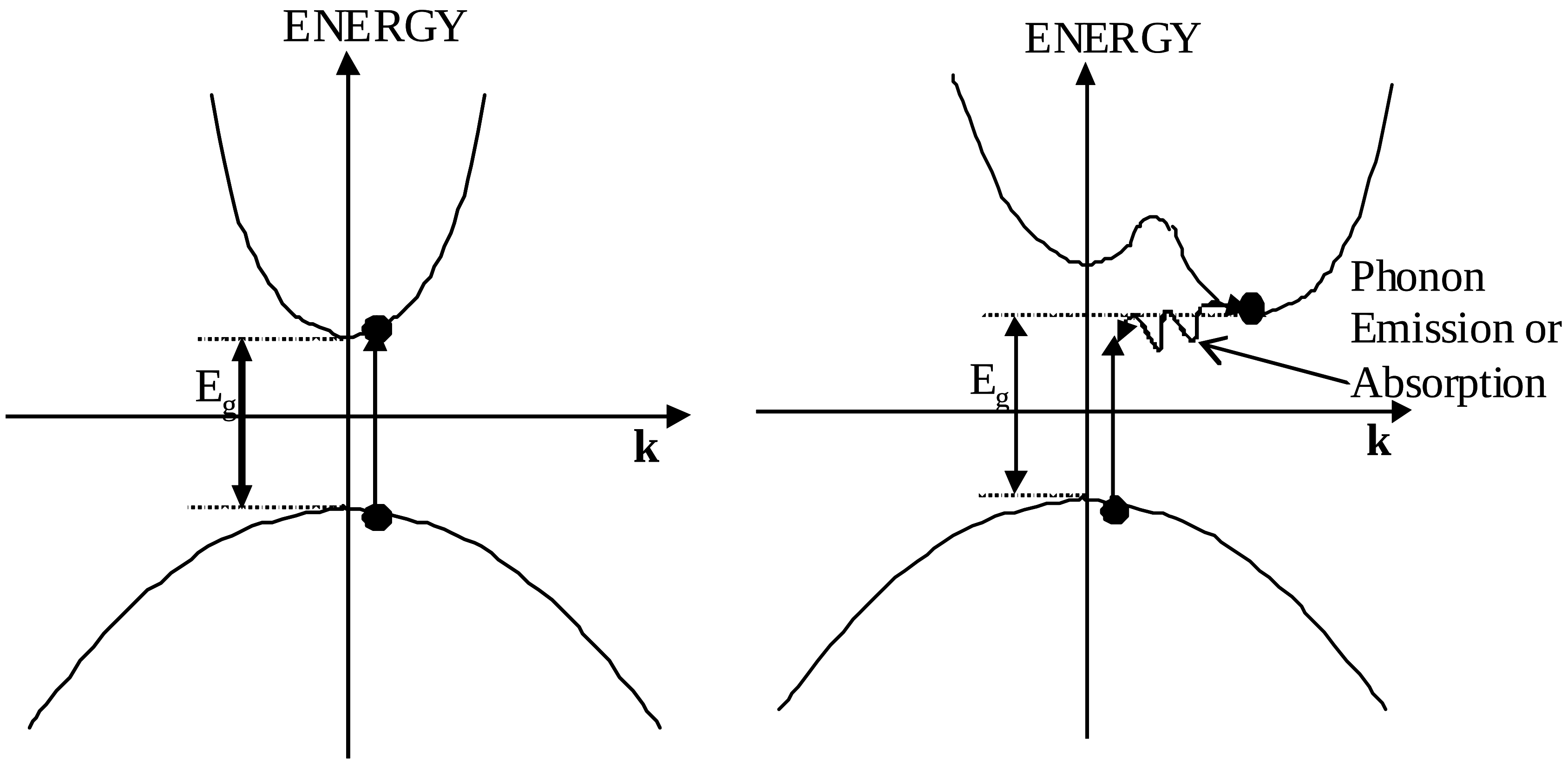
Courtesy of Christiana Honsberg and Stuart Bowden. Used with permission.

α--- absorption coefficient

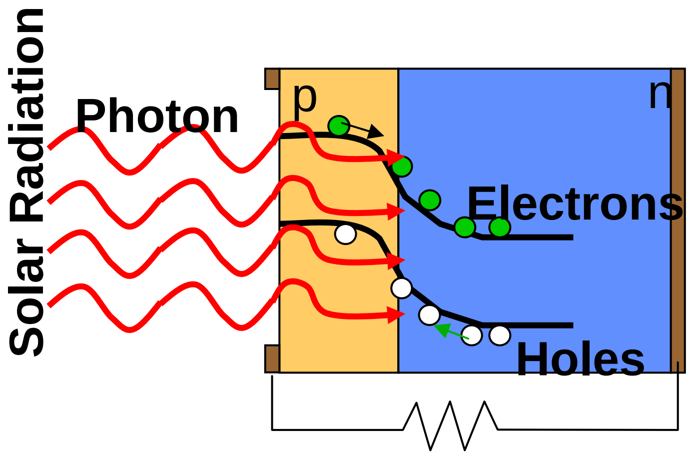
δ=1/α---penetration depth

(H.J Moller, 1993)

Direct vs. Indirect Semiconductors



Thin and Thick Dilemma



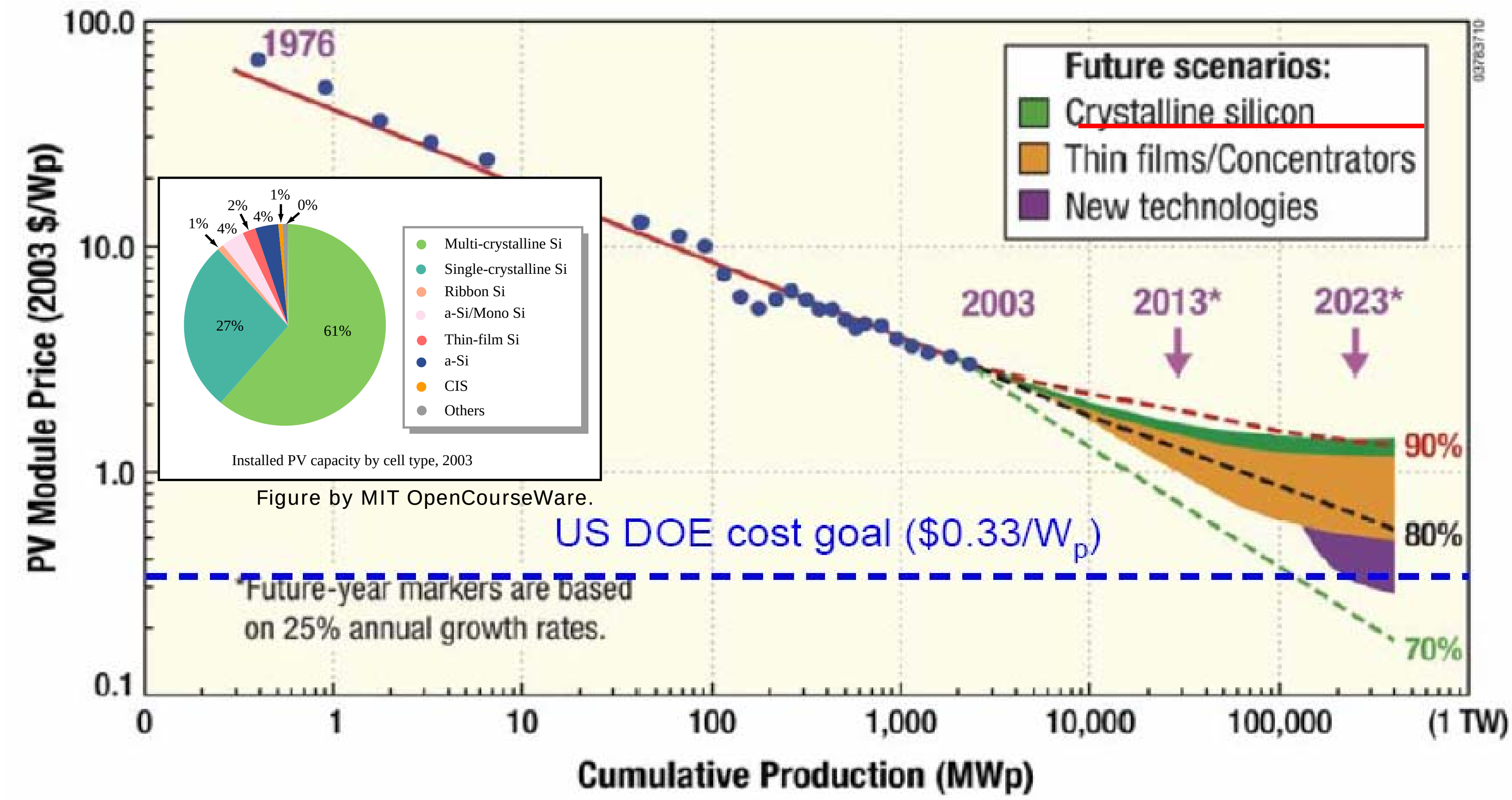
For Light Capture

- Crystalline Si: >100 μm
- Amorphous Si: ~ 1 μm

For Charge Transfer

- Thinner is better

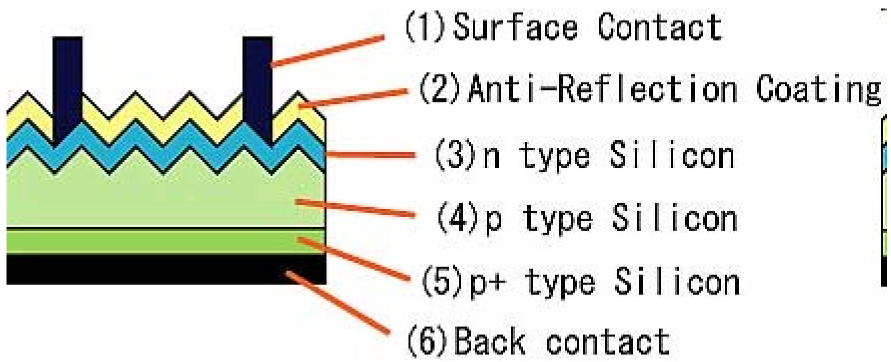
Issue of Cost



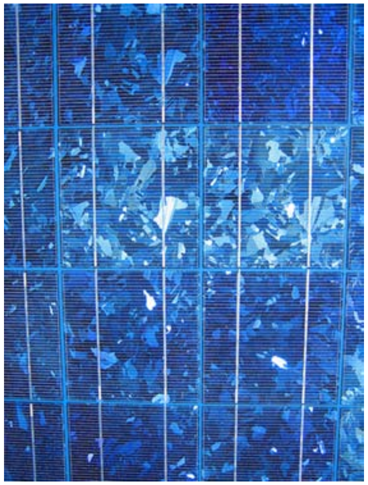
Courtesy of Thomas Surek. Used with permission.

Single Crystalline and Polycrystalline Si Cells

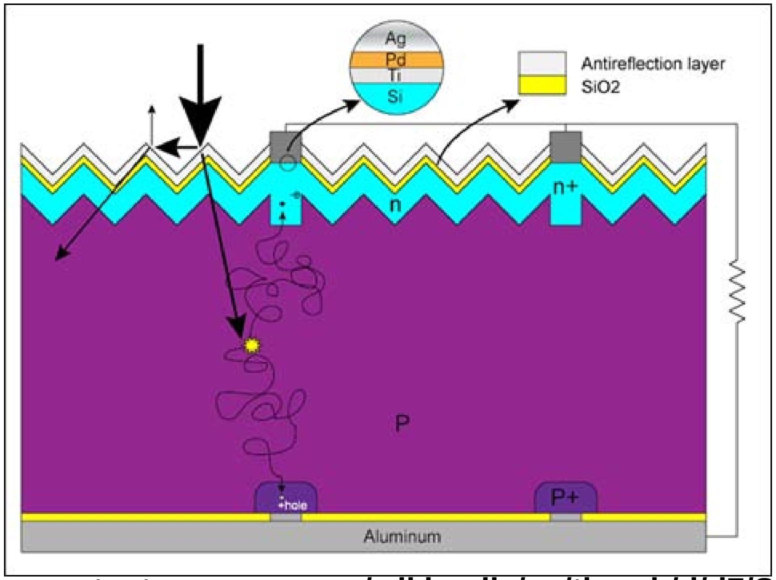
http://solarpowernotes.com/images/single-solar-cell.png



http://i.ehow.com/images/GlobalPhoto/Articles/5282425/CellStructure-SiCrystal-eng_Full.jpg

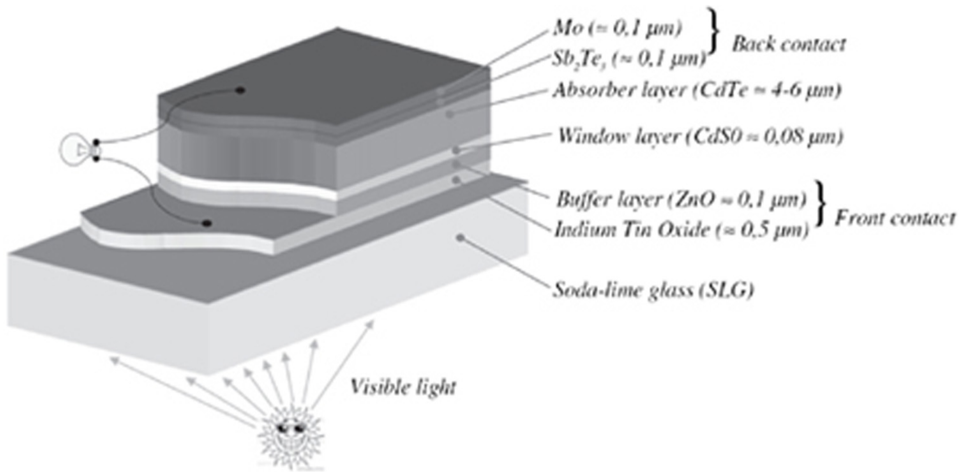


http://www.k2solar.com/images/sb10067558az-001.jpg



http://wpcontent.answers.com/wikipedia/en/thumb/d/d7/Silicon_Solar_cell_structure_and_mechanism.svg/400px-Silicon_Solar_cell_structure_and_mechanism.svg.png

Thin Film Solar Cells



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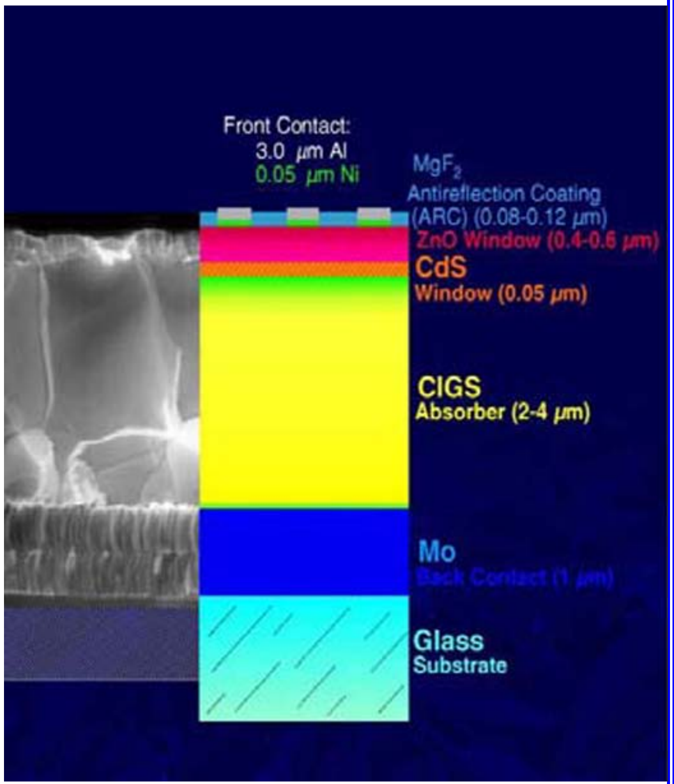

http://www.informaworld.com/ampp/image?path=/713610945/713984434/001f0003.png

Courtesy of EERE.

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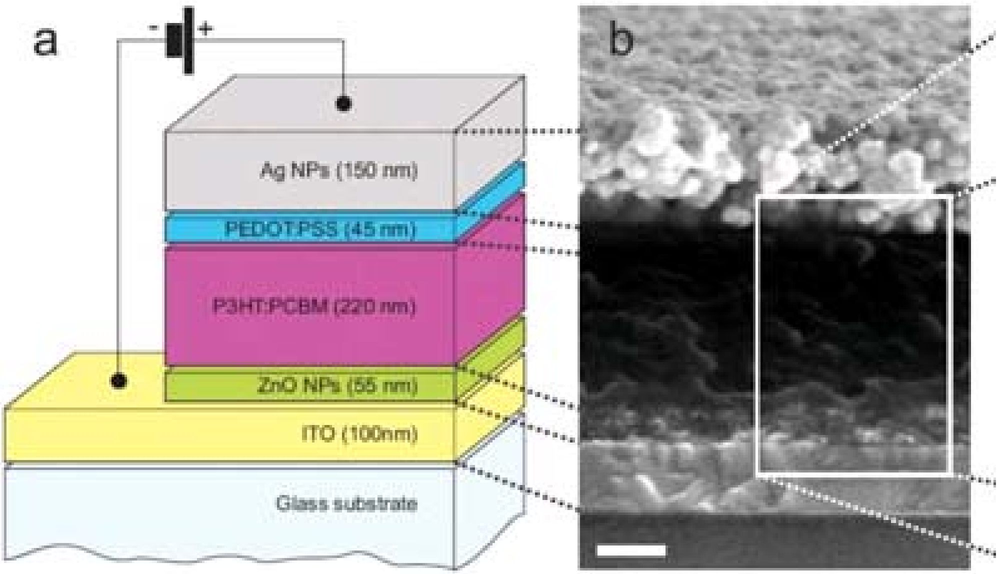
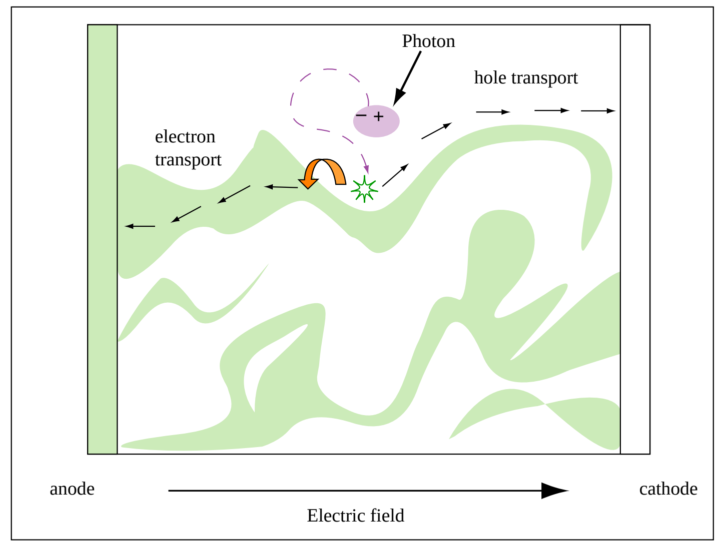
http://www.aps.org/publications/apsnews/200504/images/fig2_triple_junction_cell.jpg

Polymer Cells





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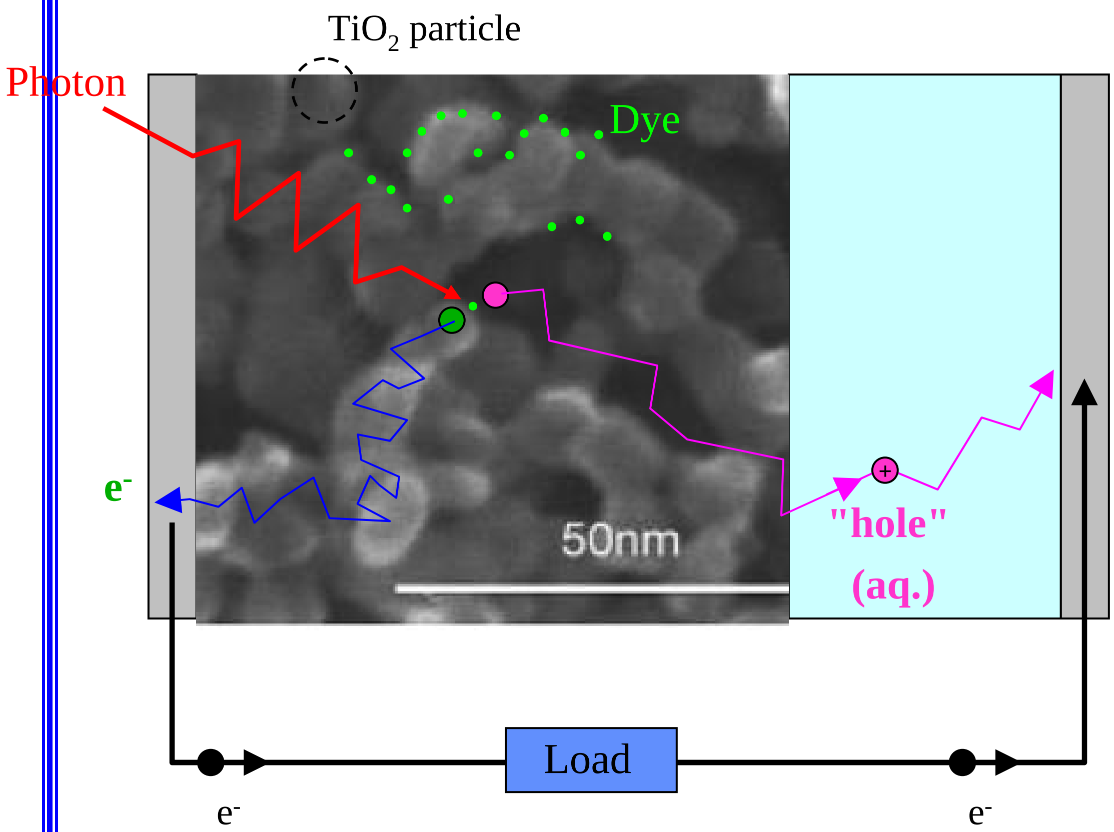
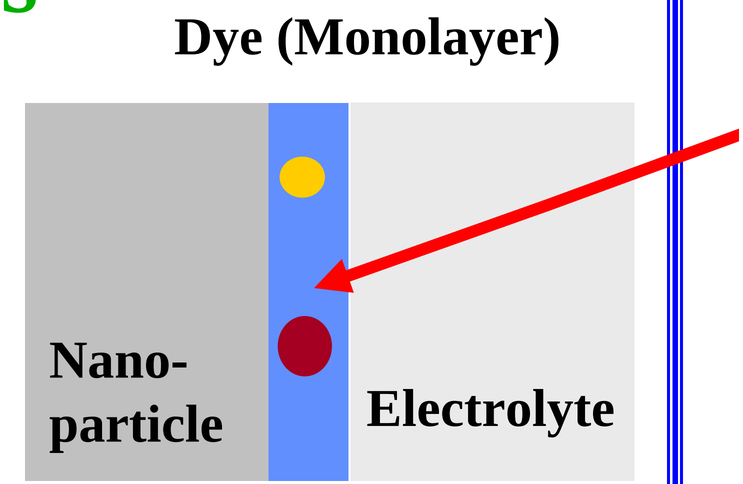
http://www.pvsociety.com/photo/158/158157-Three_different_views_of_IMEC_s_spray_coated_organic_solar_cell.jpg

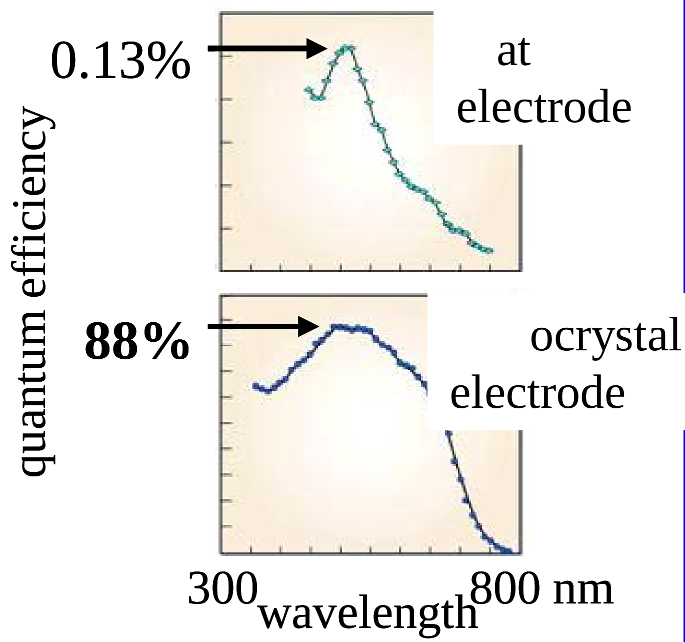
Courtesy of IMEC. Used with permission.

http://crg.postech.ac.kr/korean/UserFiles/Image/pics/opv6.jpg

Grätzel Cells



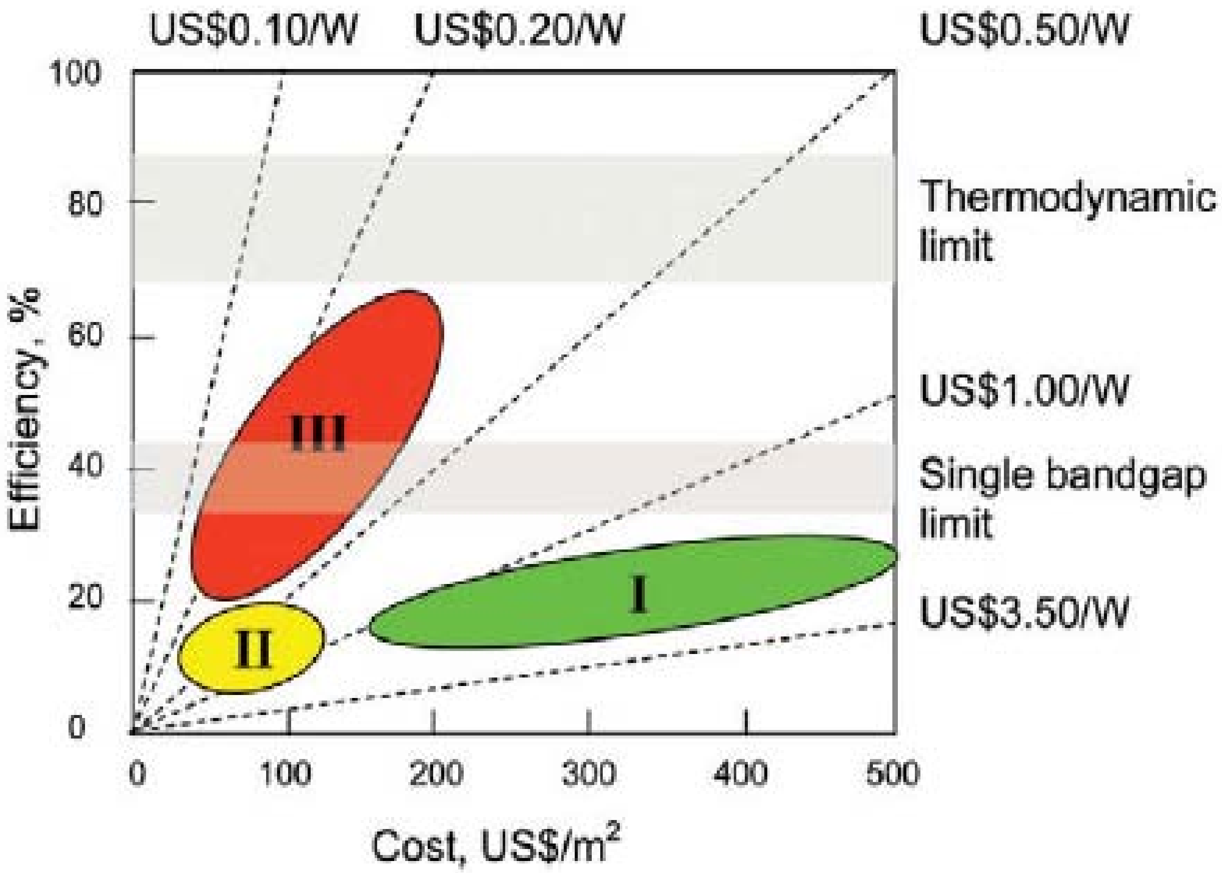




PV Efficiency: ~11% (~7% module)
Hydrogen Generation: ~5%

Grätzel, Nature, 2001.

Trends in Solar PV



(Source: Martin Green)

Can we bring Si into Gen. III paradigm?

2.997 Direct Solar/Thermal to Electrical Energy Conversion Technologies
Fall 2009