Solar Cells

Wei E.I. Sha (沙威)

College of Information Science & Electronic Engineering
Zhejiang University, Hangzhou 310027, P. R. China

Email: weisha@zju.edu.cn
Website: http://www.isee.zju.edu.cn/weisha

Course Overview

1. Sun Spectrum
2. Types of Solar Cells
3. P-N Junction Solar Cells
4. J-V Response and Characteristic Parameters
5. P-I-N Junction Solar Cells
6. Tandem Solar Cells
7. Circuit Model
8. Device Design
9. Organic Solar cells

Ref:
Enke Liu, Semiconductor Physics, Chapter 10;
Shun Lien Chuang, Physics of Photonic Devices, Chapter 15.
https://www.pveducation.org/

1. Sun Spectrum (1)

spectral irradiance

The spectral irradiance as a function of photon wavelength (or energy), denoted by F, is the most common way of characterizing a light source. It gives the power density at a particular wavelength. The units of spectral irradiance are in W m^{-2} μm^{-1}.

radiant power density

The total power density emitted from a light source can be calculated by integrating the spectral irradiance over all wavelengths or energies

$$H = \int_0^{\infty} F(\lambda) d\lambda$$

black-body radiation

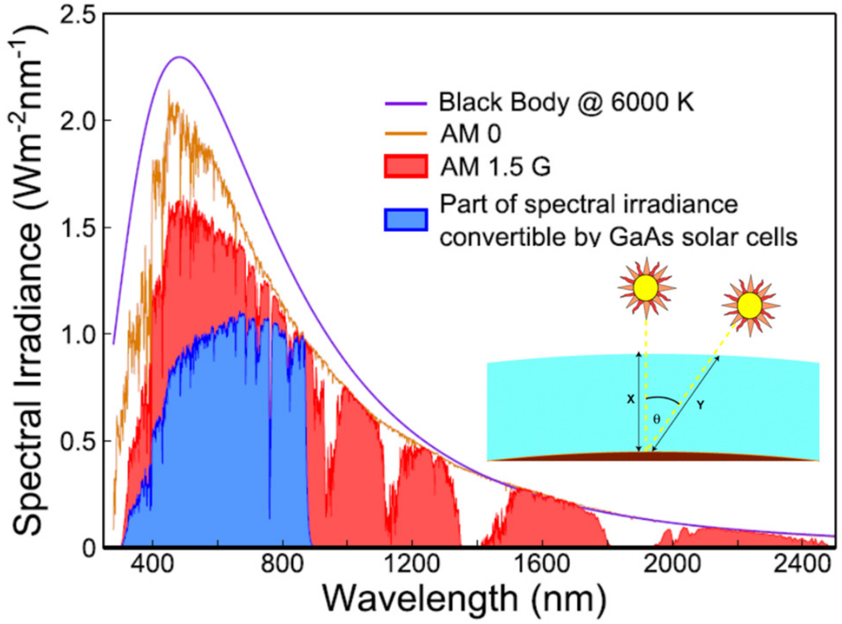
Many commonly encountered light sources, including the sun and incandescent light bulbs, are closely modelled as "blackbody" emitters. A blackbody absorbs (emits) all radiation incident on (out of) its surface and the radiation is based on its temperature.

1. Sun Spectrum (2)

black-body irradiance

$$F(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$

$H = \sigma T^4$ σ: Stefan-Boltzmann constant

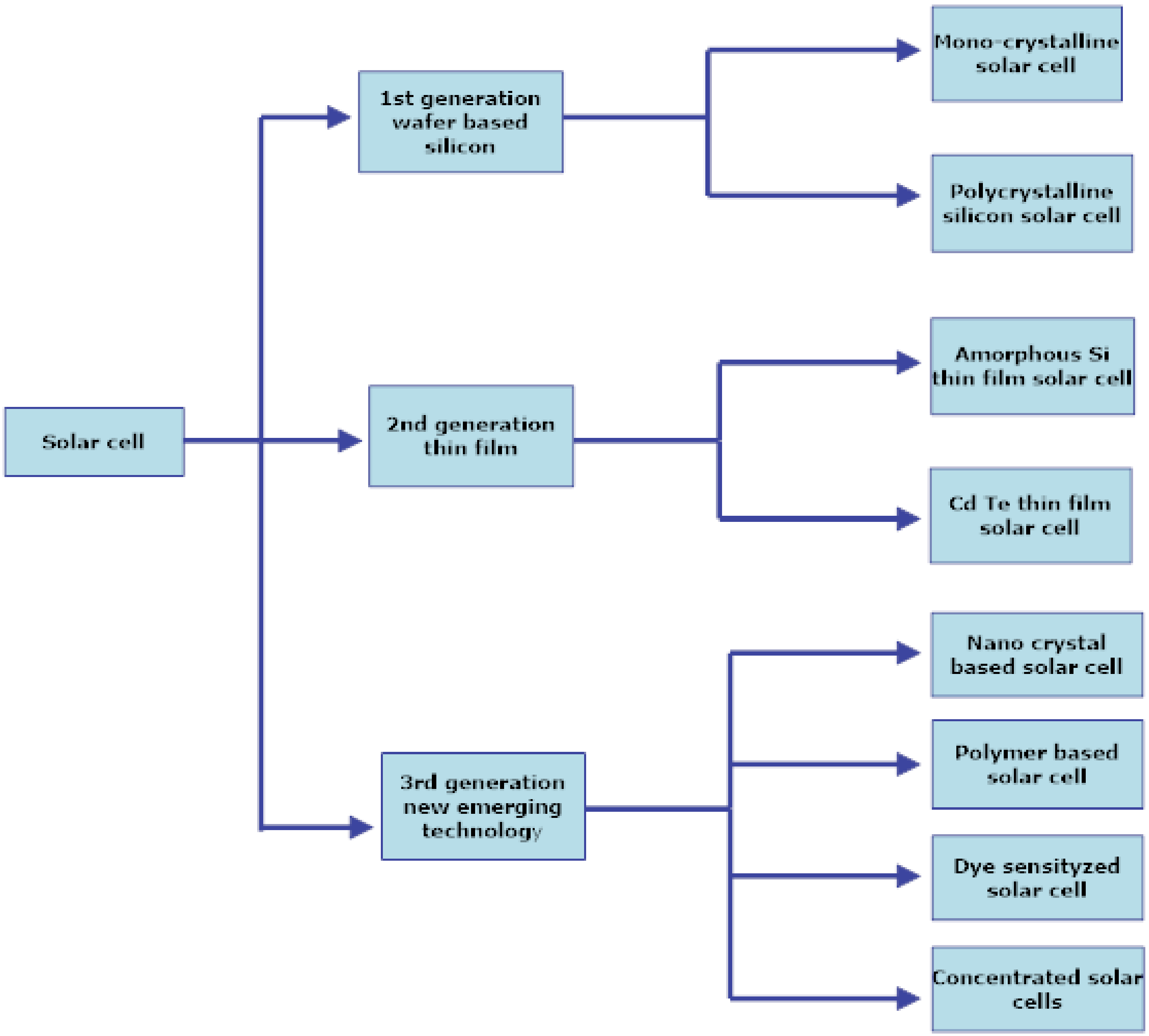


1. AM 0: The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length. AM 0 is the spectrum outside the atmosphere, approximated by the 5,800 K black-body radiation.

2. AM1.5: 1.5 atmosphere thickness, corresponds to a solar zenith angle θ of 48.2 degree (overall yearly average for mid-latitudes). Solar industry has been using AM1.5 for all standardized testing or rating of terrestrial solar cells or modules.

3. AM1.5G: G means global, which includes direct sunlight and diffused sunlight. This spectrum integrated over all wavelengths amounts to 1000 W/m^2.

2. Types of Solar Cells (1)



CIGS solar cell

(quantum dots)

→ **perovskite solar cells**

2. Types of Solar Cells (2)

1. First Generation Wafer Based Silicon Cells

Silicon wafer based technology is the oldest and most popular due to its highest power efficiency.

2. Second Generation Thin Film Solar Cell

Second generation thin film solar cells are much more economical when compared to first generation silicon wafer solar cells. Thin film solar cells are not made up of any crystal. They are made by depositing a thin layer of silicon that is deposited on a base material like metal or glass. Light absorbing layer of silicon wafer cell is around hundreds of μm (~200 μm) thick while light absorbing layer of thin film solar cell is quite thin (1-5 μm).

3. Third Generation Solar Cells

It is the new technology that has evolved in the market now-a-days but are not studied deeply.

targets:

easy fabrication, low cost, stable (long lifetime, temperature/humidity insensitive), large area, environmental friendly

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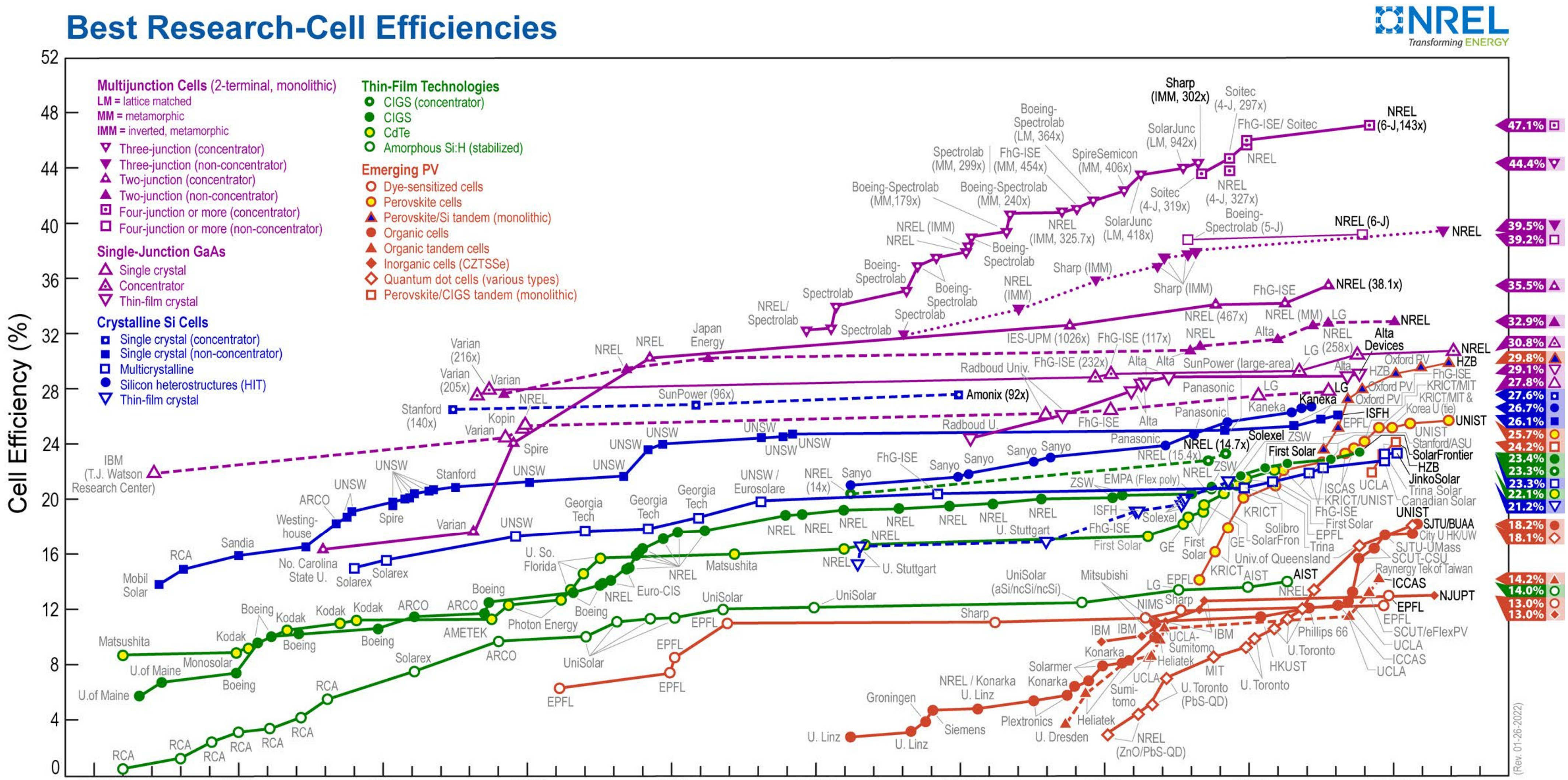
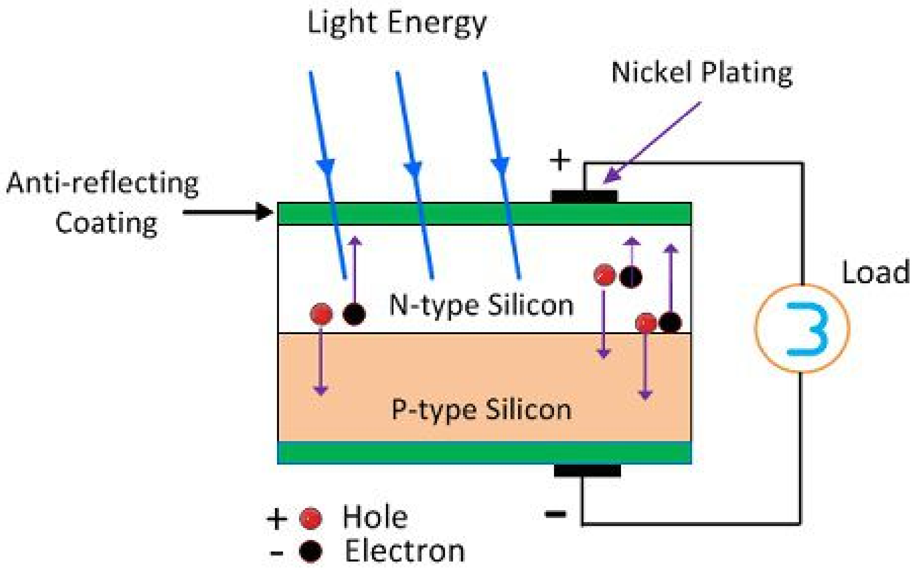
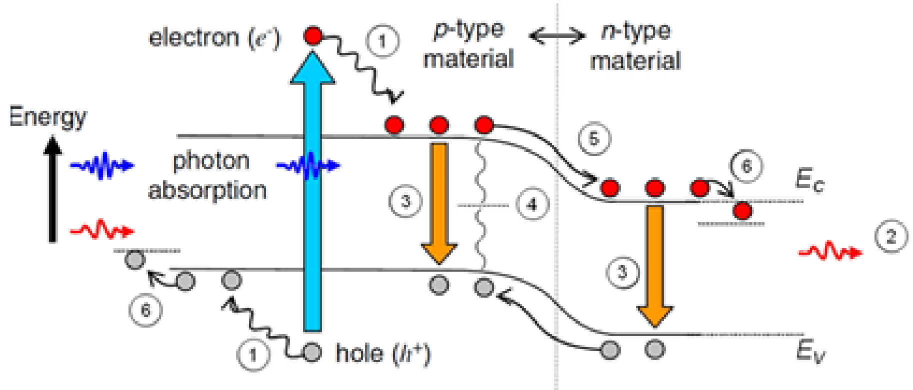
2. Types of Solar Cells (3)



https://www.nrel.gov/pv/cell-efficiency.html

3. P-N Junction Solar Cells (1)





1. the generation of light-generated carriers;
2. the collection of the light-generated carries to generate a current;
3. the generation of a photovoltage across the solar cell; and
4. the dissipation of power in the load and in parasitic resistances.

1, 2: absorption above band-gap/thermalization below band gap/transmission

3, 4: radiative recombination, nonradiative recombination

5, 6: minority carriers are diffused and extracted across the junction, voltage drop at the contacts.

3. P-N Junction Solar Cells (2) — Photocurrent

The first process is the absorption of incident photons to create electron-hole pairs. The e-h pairs will be generated in the solar cell provided that the incident photon has an energy greater than that of the band gap.

However, electrons (in the *p*-type material), and holes (in the *n*-type material) will only exist, on average, for a length of time equal to the minority carrier lifetime before they recombine. If the carrier recombines, then the light-generated photocarriers is lost and no current or power can be generated.

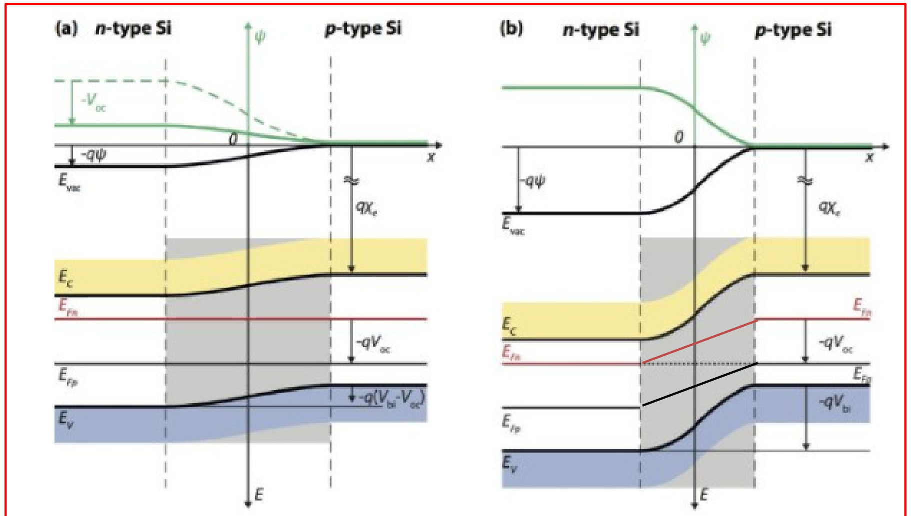
In the second process, the photocarriers are separated by the electrostatic field existing at the p-n junction. If the light-generated minority carrier reaches the p-n junction, it will be swept across the junction by the E-field, and then becomes majority carrier.

The collection probability of carriers generated in the depletion region is almost unity as the e-h pair are quickly swept by the E-field and are collected. Away from the junction, the collection probability drops. If the carrier is generated more than a diffusion length away from the junction, then the collection probability of this carrier is quite low. Similarly, if the carrier is generated closer to a region such as a surface with higher non-radiative recombination than the junction, then the carrier will recombine.

3. P-N Junction Solar Cells (3) — Photovoltaic Effect

In order to generate power, a voltage must be generated, which is known as the "photovoltaic effect". Collection of photocarriers causes a movement of electrons (holes) to the n-type (p-type) side of the junction. Under short circuit conditions, there is no build up of charge, as the carriers exit the device as light-generated current.

If the photocarriers are prevented from leaving the solar cell, then the collection of the carriers causes an increase in the number of electrons (holes) on the n-type (p-type) side of the p-n junction. This collection creates an electric field at the junction which is in opposition to that already existing at the junction, thereby reducing the net electric field (similar to the forward-bias P-N junction). Under open circuit conditions, the net E-field is almost equal to zero and the net current is zero.



open circuit **short circuit**

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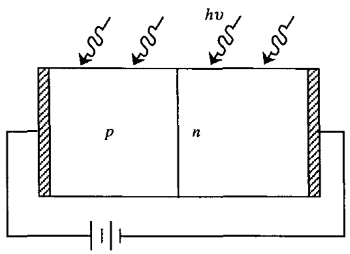
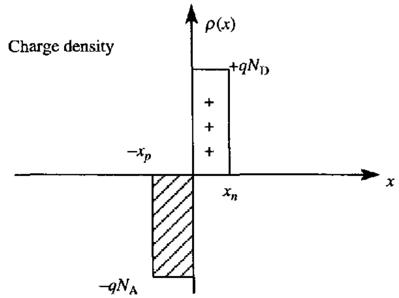
4. J-V Response and Characteristic Parameters (1)





n-side of the diode

$$D_p \frac{\partial^2}{\partial x^2}\delta p_n - \frac{\delta p_n}{\tau_p} = -G_0 \qquad \delta p_n(x_n) = p_{n0}(e^{qV/k_BT} - 1) \qquad \delta p_n(+\infty) = G_0\tau_p$$

$$\delta p_n(x) = \left[p_{n0}\left(e^{qV/k_BT} - 1\right) - G_0\tau_p \right] e^{-(x-x_n)/L_p} + G_0\tau_p \qquad J_p(x) = -qD_p \frac{\partial}{\partial x}\delta p_n(x)$$

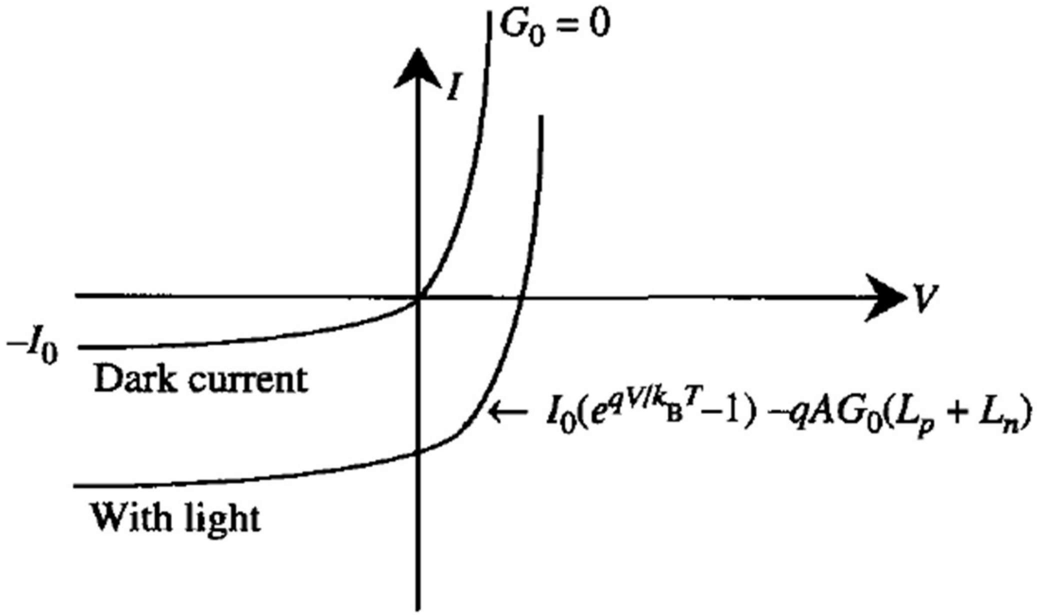
$$J_p(x_n) = q\frac{D_p}{L_p} p_{n0}\left(e^{qV/k_BT} - 1\right) - qG_0L_p$$

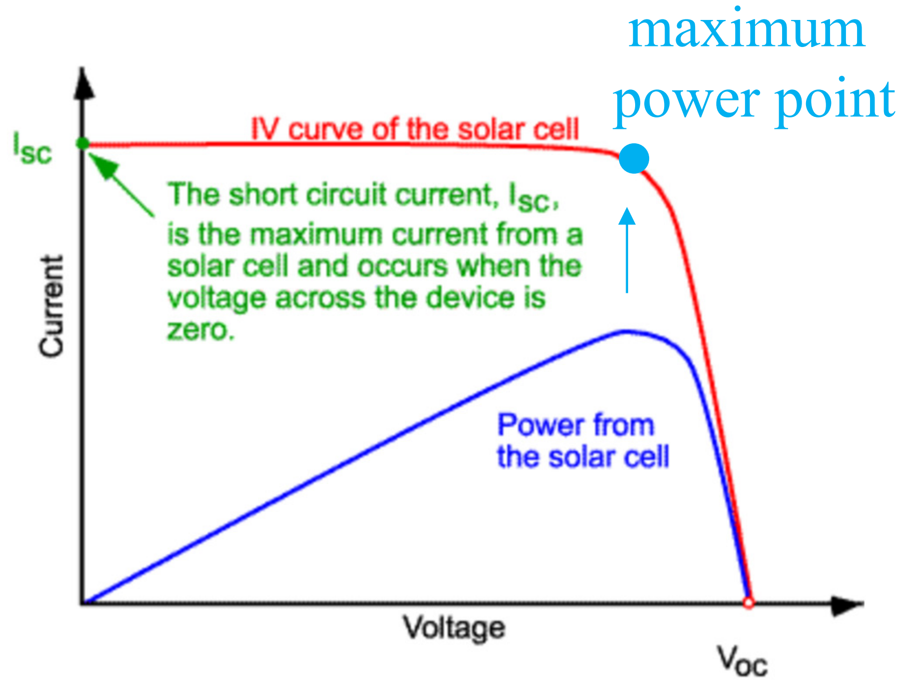
p-side of the diode

$$J_n(-x_p) = q\frac{D_n}{L_n} n_{p0}\left(e^{qV/k_BT} - 1\right) - qG_0L_n$$

$$J = J_n(-x_p) + J_p(x_n) = \left(q\frac{D_n}{L_n} n_{p0} + q\frac{D_p}{L_p} p_{n0} \right)\left(e^{qV/k_BT} - 1\right) - qG_0(L_n + L_p) = J_0\left(e^{qV/k_BT} - 1\right) - J_{ph}$$

4. J-V Response and Characteristic Parameters (2)

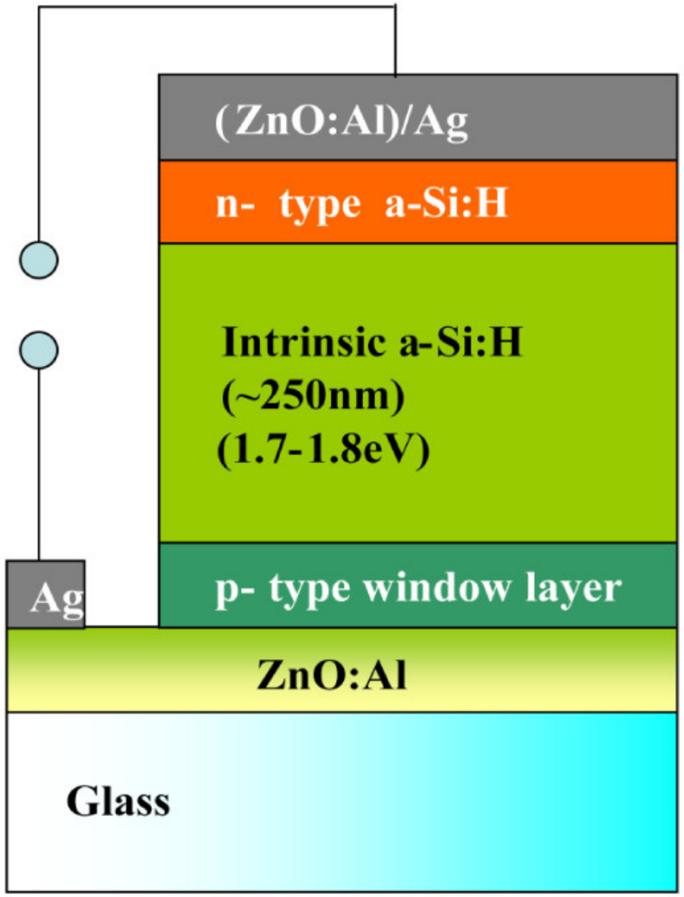




1. Short-circuit current I_{sc}, is the current through the solar cell when the voltage across the solar cell is zero.
2. Open-circuit voltage V_{oc}, is the maximum voltage available from a solar cell, and this occurs at zero current.
3. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}.
4. Power conversion efficiency of a solar cell is determined as the fraction of incident power (area of cell * 1000 W/m^2) which is converted to electricity.

5. P-I-N Junction Solar Cells

For P-N junction solar cells, optical absorption within the diffusion lengths L_p and L_n is small. To enhance the absorption (J_{sc}) of the solar cell, an intrinsic region used as the major absorption layer is added.

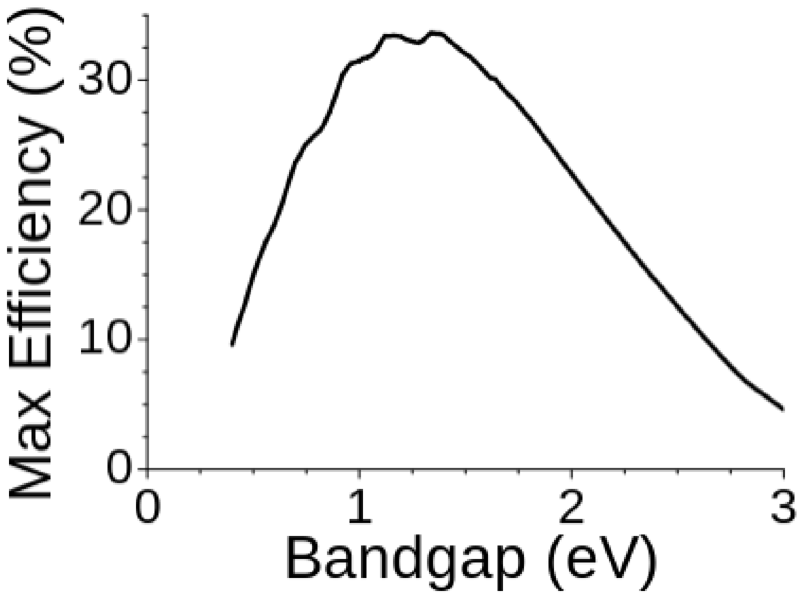


The p- and the n-layer are used to create the E-field in the i-layer, in which the light is absorbed. When an absorbed photon generates an electron-hole pair, the electron will move towards the n-layer and the hole to the p-type layer. For p-i-n structure, the absorption is not limited by the diffusion lengths.

6. Tandem Solar Cells (1)

Spectrum loss: The dominant loss mechanism of a solar cell is the inability to harvest all of the power in the Sunlight due to the fact that the photons must have enough energy to overcome the bandgap of the material.

On the other hand, photons with more energy than the bandgap, say blue light, initially excite an electron to a state high above the bandgap, but this extra energy is lost through relaxation process. This lost energy turns into heat, which further increases the spectrum loss. According to the Shockley-Queisser limit, the maximum efficiency for a single-bandgap material is about 34%.

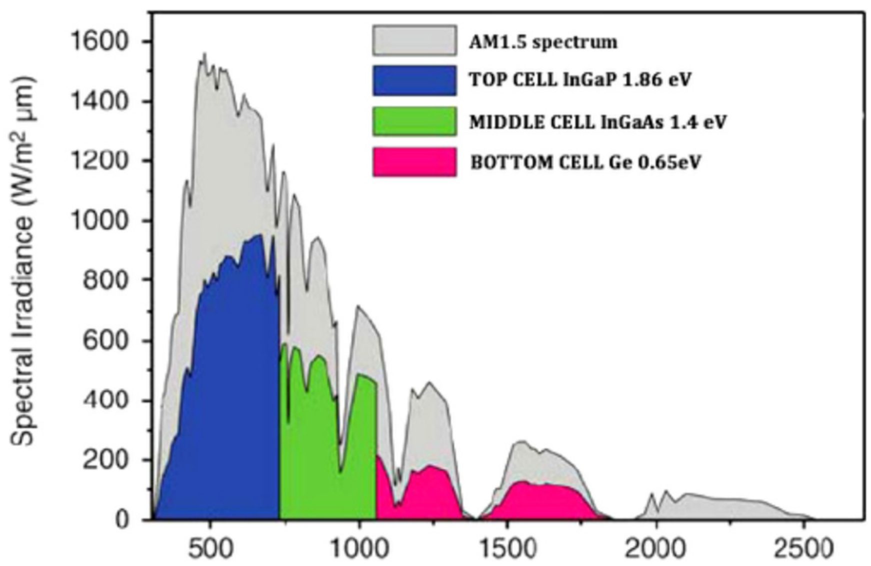


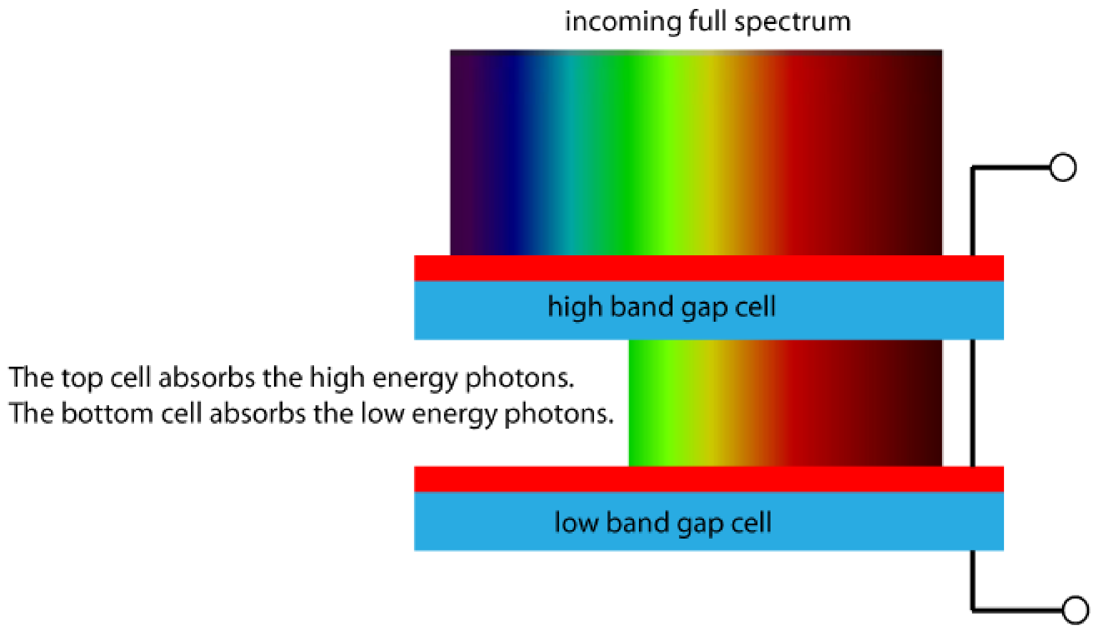
Why is silicon good for solar cells?

The efficiency limit occurs at a band gap of 1.34 eV. Silicon bandgap of 1.1 eV is close to the value.

6. Tandem Solar Cells (2)

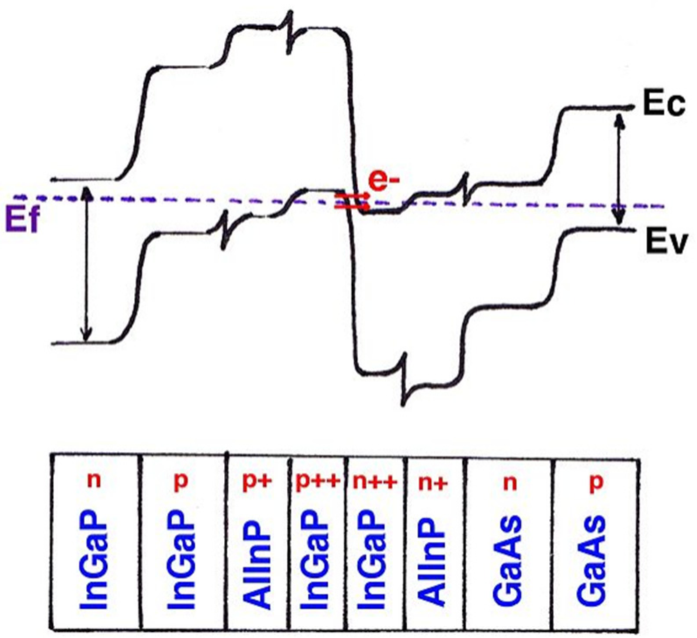
Tandem solar cells: Cells made from multiple materials layers can have multiple bandgaps and will therefore respond to multiple light wavelengths, capturing and converting some of the energy that would otherwise be lost to relaxation. This means that you can make a multi-junction cell by layering the different materials on top of each other, shortest wavelengths (biggest bandgap) on the "top" and increasing through the body of the cell.

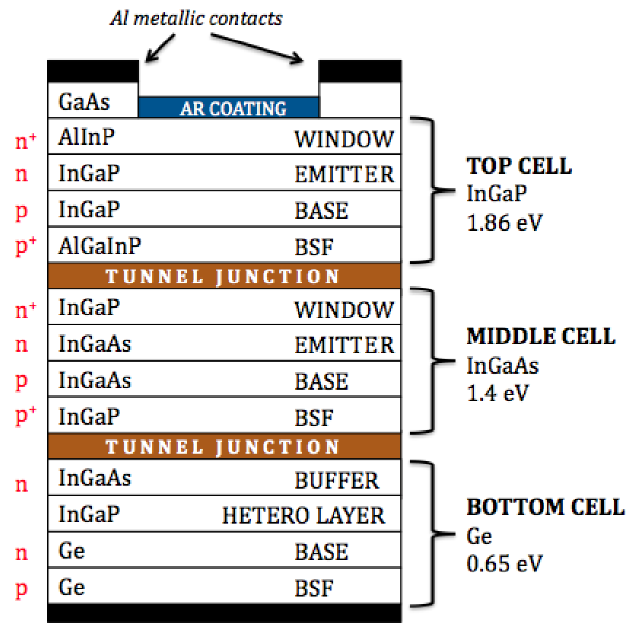




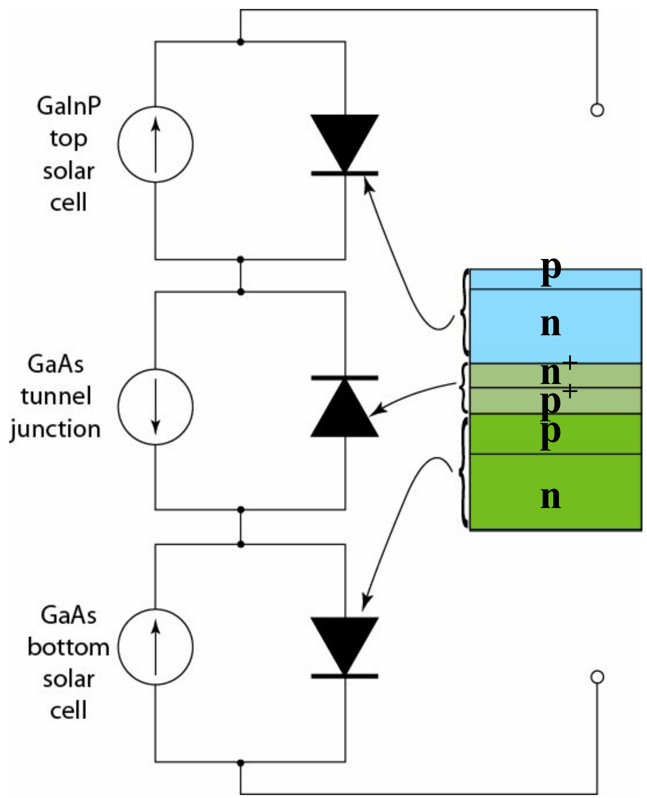
6. Tandem Solar Cells (3)

<u>Interconnecting layer</u> in tandem solar cells, which is important for device efficiency, shall meet the following requirements: (1) <u>electrically</u>, it should form <u>ohmic contact</u>; (2) <u>optically</u>, it should have <u>transparency</u> as high as possible. The highly-doping <u>tunnel junction</u> could provide a low electrical resistance and optically low-loss connection between two subcells.

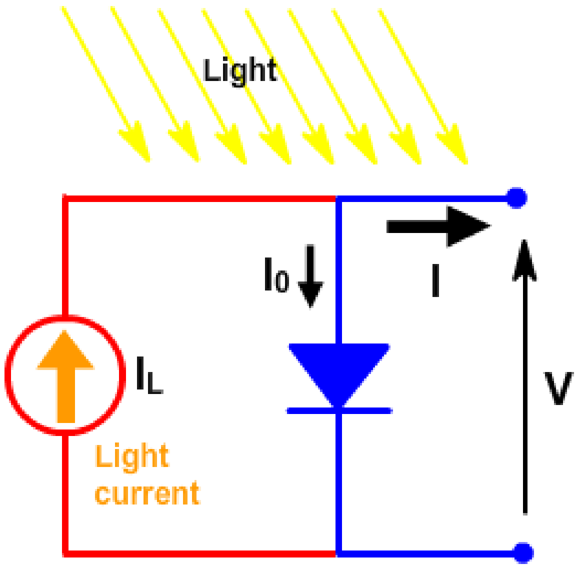




circuit model



Ideal circuit model for solar cells



$$I = I_L - I_0\left(e^{qV/(mk_BT)} - 1\right)$$

$$m \approx \begin{cases} 1, & \text{bimolecular recombination} \\ 2, & \text{SRH recombination} \\ 2/3, & \text{Auger recombination} \end{cases}$$

ideality factor

$$V_{oc} = \frac{mk_BT}{q}\log\left(1+\frac{I_L}{I_0}\right) \approx \frac{mk_BT}{q}\log\left(\frac{I_L}{I_0}\right)$$

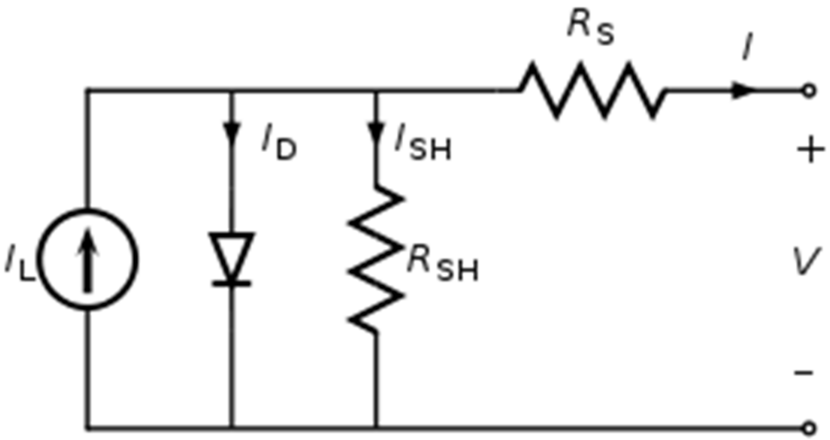
open-circuit condition (assume n≈p) α=1 (SRH), 2 (Bimolecular), 3 (Auger)

$$G_L \approx R \approx \gamma n^{\alpha} \quad G_0 = R_0 = \gamma n_i^{\alpha} \quad np \approx n^2 = n_i^2 \exp\left(\frac{E_{Fn}-E_{Fp}}{k_BT}\right) = n_i^2 \exp\left(\frac{qV_{oc}}{k_BT}\right)$$

$$V_{oc} \approx \frac{k_BT}{q}\log\left(\frac{n^2}{n_i^2}\right) \approx \frac{2}{\alpha}\frac{k_BT}{q}\log\left(\frac{G_L/\gamma}{G_0/\gamma}\right) = \frac{2}{\alpha}\frac{k_BT}{q}\log\left(\frac{J_L}{J_0}\right)$$

7. Circuit Model (2)

Practical circuit model for solar cells



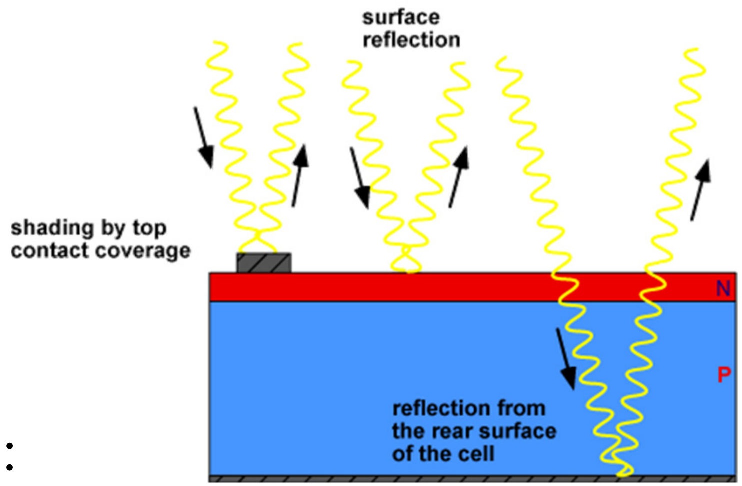
$$I = I_L - I_0\left[\exp\left(\frac{q(V+IR_S)}{mk_BT}\right)-1\right]-\frac{V+IR_S}{R_{SH}}$$

https://www.pveducation.org/pvcdrom/solar-cell-operation/series-resistance
https://www.pveducation.org/pvcdrom/solar-cell-operation/shunt-resistance

series resistance R_S: resistance in the current path, such as contact resistance, surface contact/sheet resistance (electrode-semiconductor and semiconductor-semiconductor interface), etc.

shunt resistance R_{SH}: leakage (short-circuit) path of current (leakage current along edge of solar cells)

8. Device Design (1)



Optical Loss

Optical losses will lower the short-circuit current.

There are a number of ways to reduce the optical losses:

1. Top contact coverage of the cell surface can be minimised (although this may result in increased series resistance).

2. Anti-reflection coatings can be used on the top surface of the cell.

3. The optical path length in the solar cell may be increased by a combination of surface texturing and light trapping.

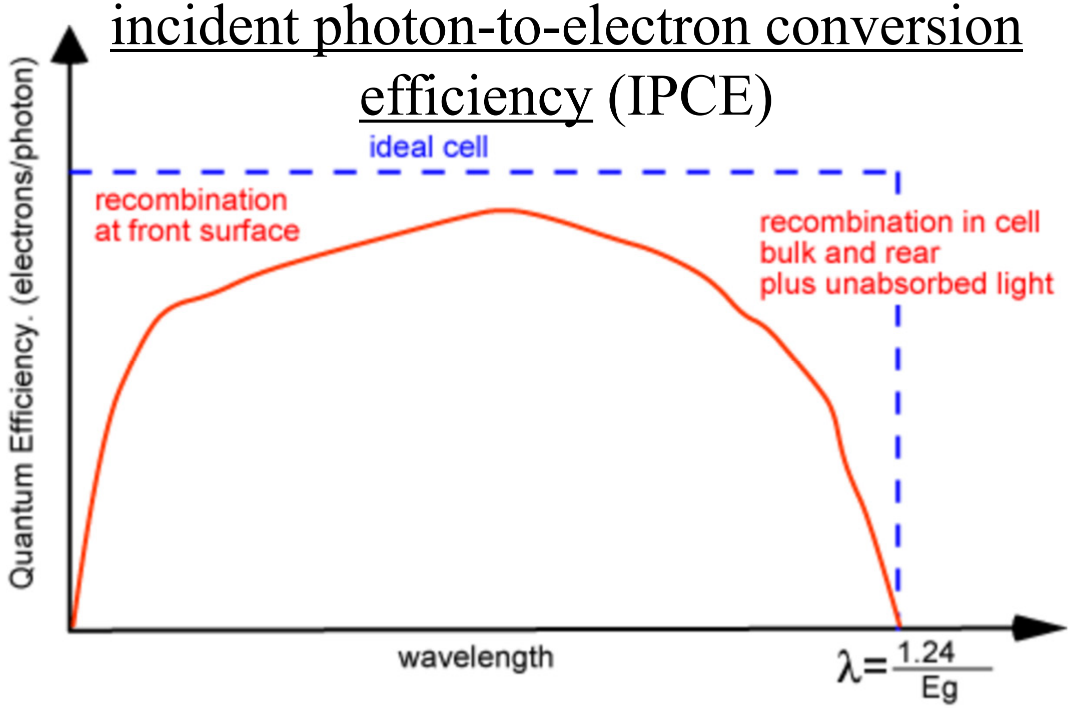
4. The solar cell can be made thicker to increase absorption (although light that is absorbed more than a diffusion length has a low collection probability and will not contribute to the short circuit current; open-circuit voltage will decrease).

8. Device Design (2)

Nonradiative Recombination Loss

Nonradiative recombination losses affect both *short-circuit voltage* and *open-circuit voltage*. Typically, recombination at the surface (surface recombination) or in the bulk of the solar cell (bulk recombination) are the main areas of recombination.

incident photon-to-electron conversion efficiency (IPCE)



IPCE/QE: ratio of the number of carriers collected to the number of photons of a given energy incident on

Blue light has a high absorption coefficient and is absorbed very close to the front surface, it is not likely to generate minority carriers that can be collected if the front surface is a site of high recombination. Similarly, a high rear surface recombination will primarily affect carriers generated by infrared light, which can generate carriers deep in the device.

8. Device Design (3)

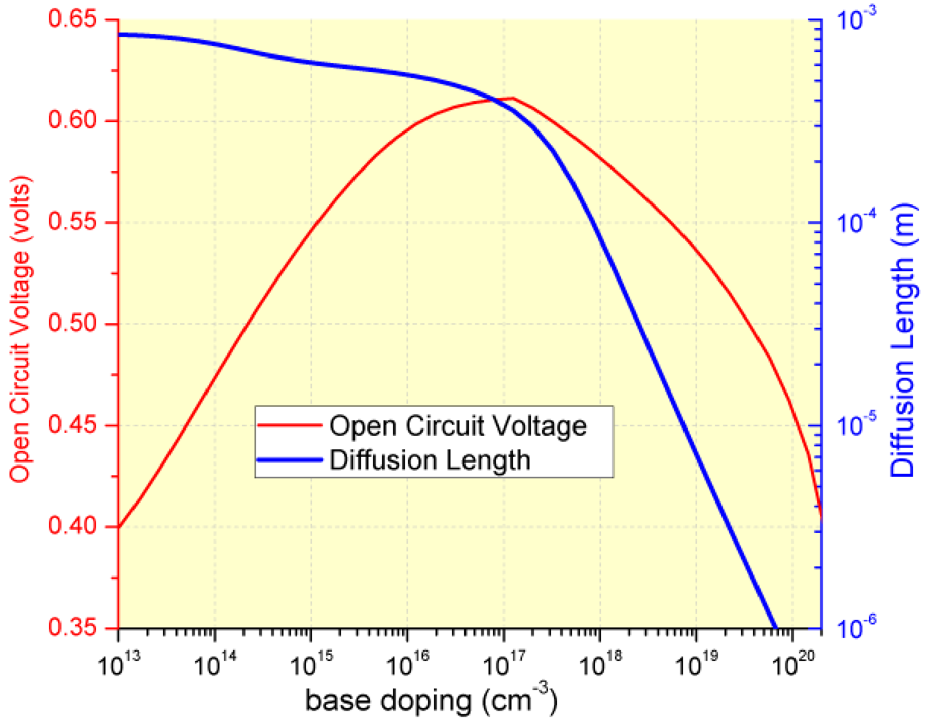
Open-circuit voltage can be improved by the following schemes

1. Minimizing the equilibrium minority carrier density by increasing the doping reduces dark current.

2. To minimize recombination and achieve a high voltage, a high diffusion length is required.

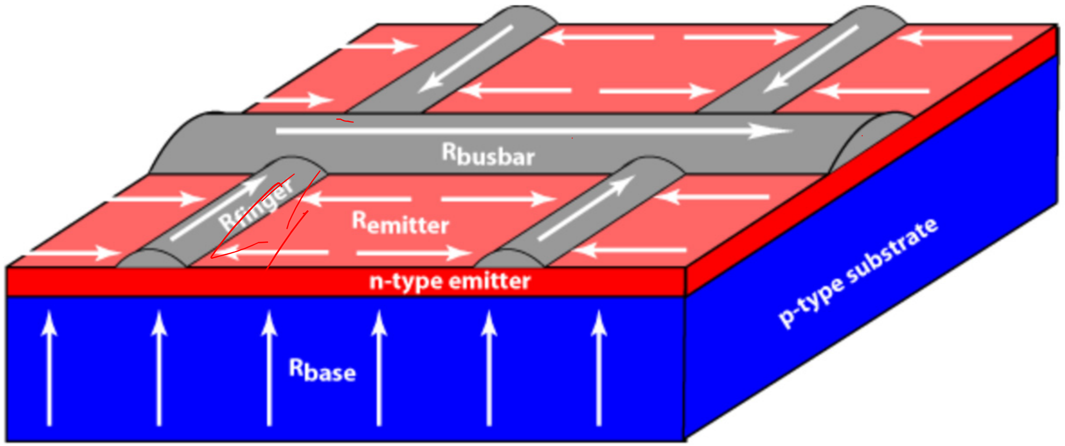
3. The impact of surface recombination is reduced by passivating the surfaces.

4. Enhancing the film quality of active layer can reduce bulk recombination.



8. Device Design (4)

Parasitic Resistive Losses

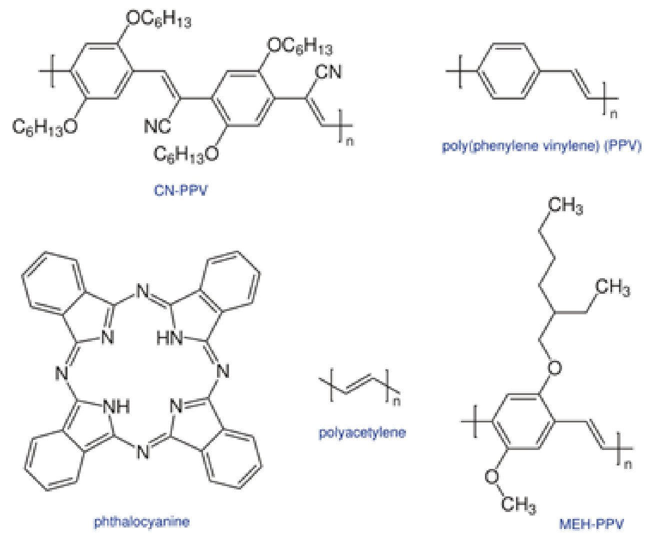


Balance between the increased resistive losses associated with a widely spaced grid and the increased reflection caused by a high fraction of metal coverage of the top surface.

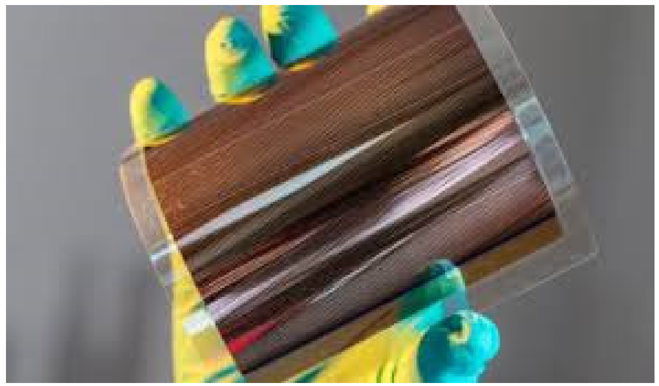
9. Organic Solar Cells (1) —— Optional

Organic solar cell is a type of photovoltaic that uses conductive organic polymers or small organic molecules as active materials.

conjugate polymer

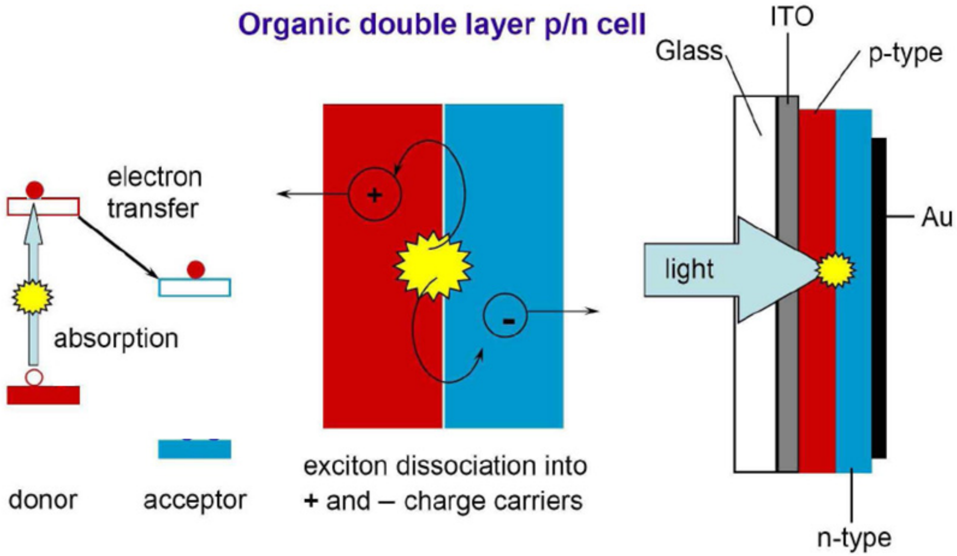


- ✓ *low-cost processing*
- ✓ *high absorption in visible light*
- ✓ *mechanically flexible*
- ✓ *grow on thin/flexible substrate*
- ✓ *large-area application*
- ✓ *environmentally friendly*
- X *low exciton diffusion length*
- X *low carrier mobility*
- X *low conversion efficiency*



9. Organic Solar Cells (2) —— Optional

planar heterojunction: the simplest organic PV device

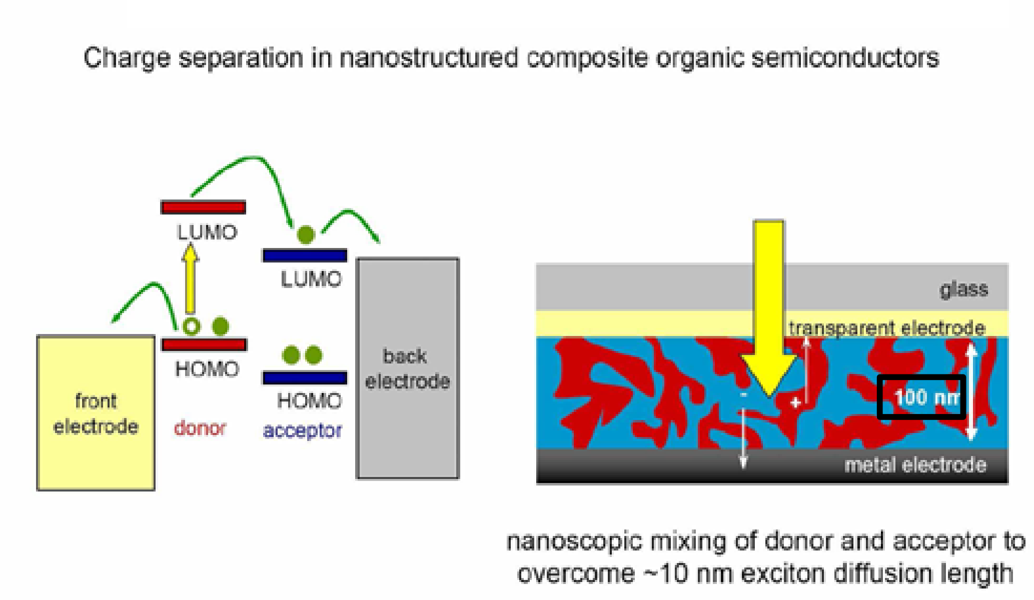


C. W. Tang, Appl. Phys. Lett. 1985, **48**, 183.

Unlike in an inorganic crystalline solar cell cell material, with its band structure and delocalized electrons, excitons in organic photovoltaics are strongly bound.

The exciton can be dissociated to electron and hole by offering a heterojunction interface. Because exciton diffusion length of just 3-10 nm, thus planar cells must be very thin, but the thin cells absorb light less well. Planar heterojunction typically uses small organic molecules as active bi-layers.

<u>bulk heterojunction</u>



R. H. Friend et al., Nature 1995, **376**, 498
A. J. Heeger et al., Science 1995, **270**, 1789

In a bulk heterojunction, a blend of electron donor and acceptor materials (typically, polymer materials) is cast as a mixture, which then phase-separates. Regions of each material in the device are separated by only several nanometers.

The domain sizes of this blend are on the order of nanometers, allowing for excitons with short lifetimes to reach an interface and dissociate due to the large donor-acceptor interfacial area. However, efficient bulk heterojunctions need to maintain large enough domain sizes to allow efficient transport of electrons and holes. Thus, <u>morphology control</u> is a key issue for the bulk heterojunction.

roll to roll process