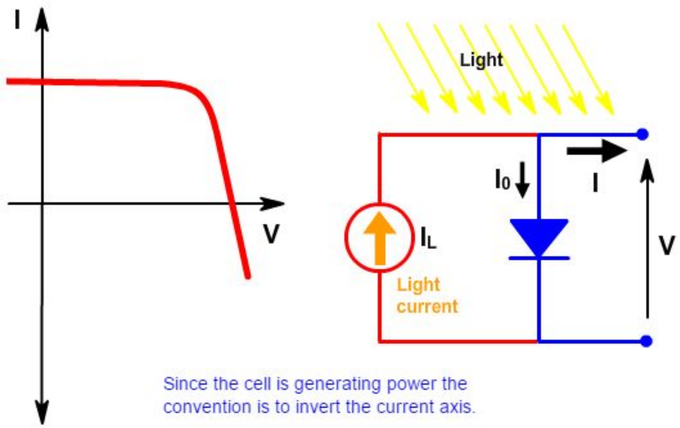
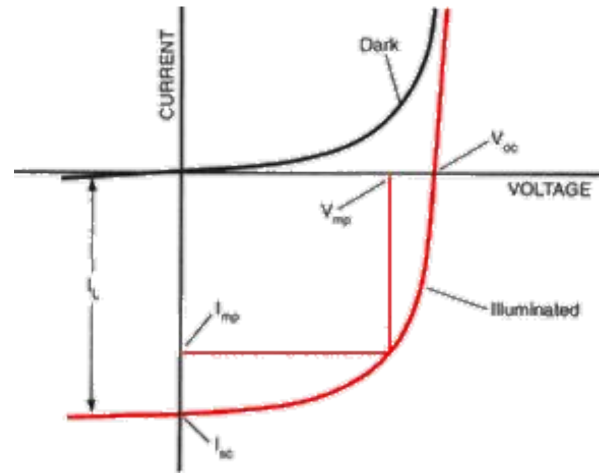
# Solar cell I-V curve



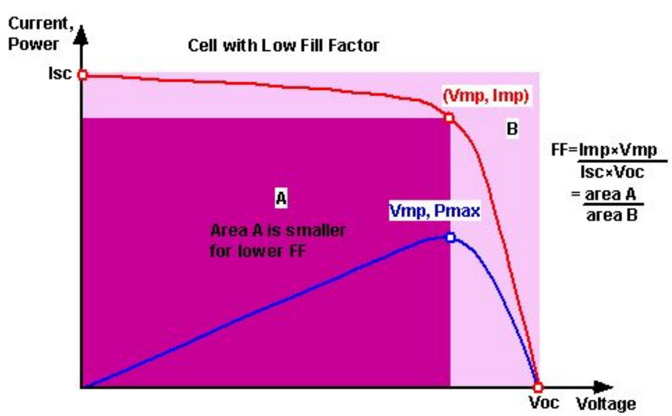

The effect of light on the current-voltage characteristics of a p-junction.

$$\boxed{I_{sc} = -I_L}$$




$$I = I_0\left[\exp\left(\frac{qV}{kT}\right)-1\right]-I_L$$

$$V_{OC} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0}+1\right)$$

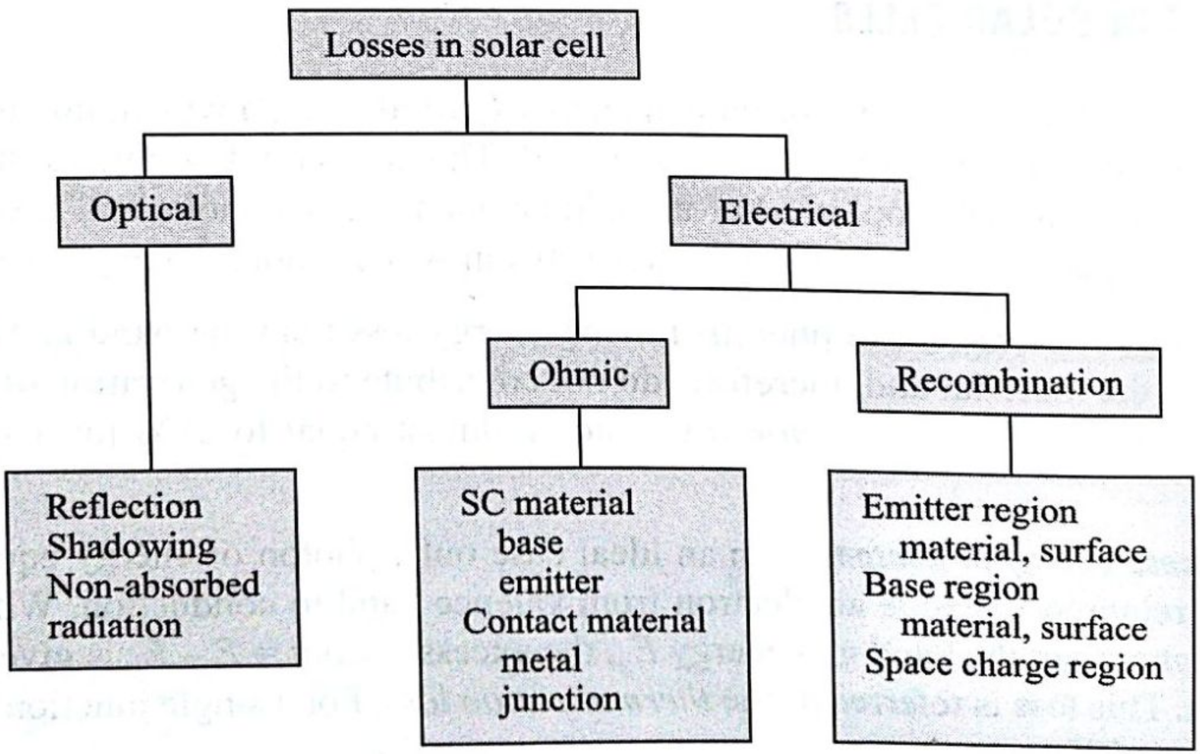



$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$$

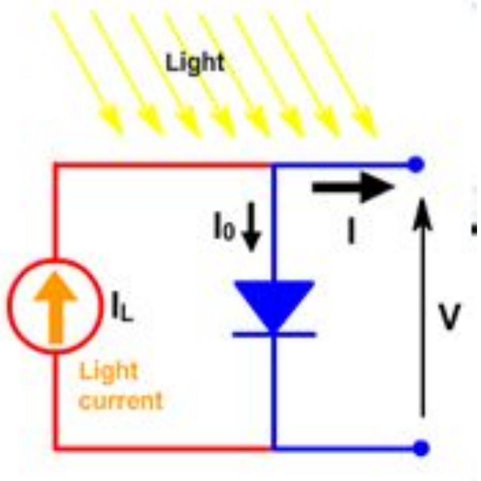
$$\eta = \frac{V_{OC}I_{SC}FF}{P_{in}}$$

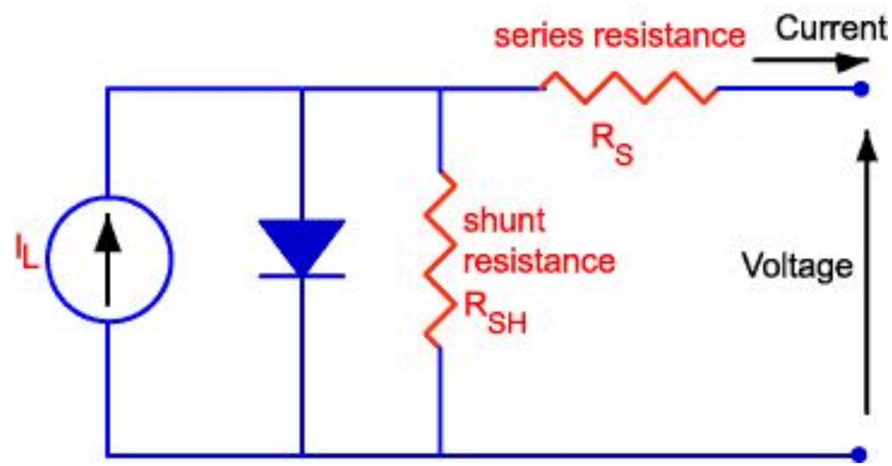
# Losses in Solar Cell:

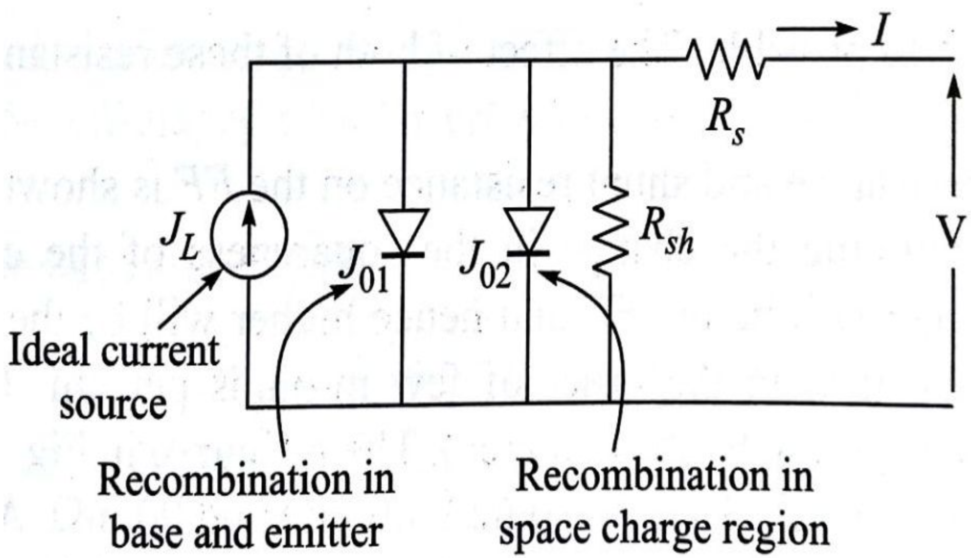
1. low energy photon/High energy photon
2. Reflection loss/incomplete absorption
3. Metal coverage
4. Voltage loss
5. Fill factor loss
6. Recombination losses



# Model of solar cell

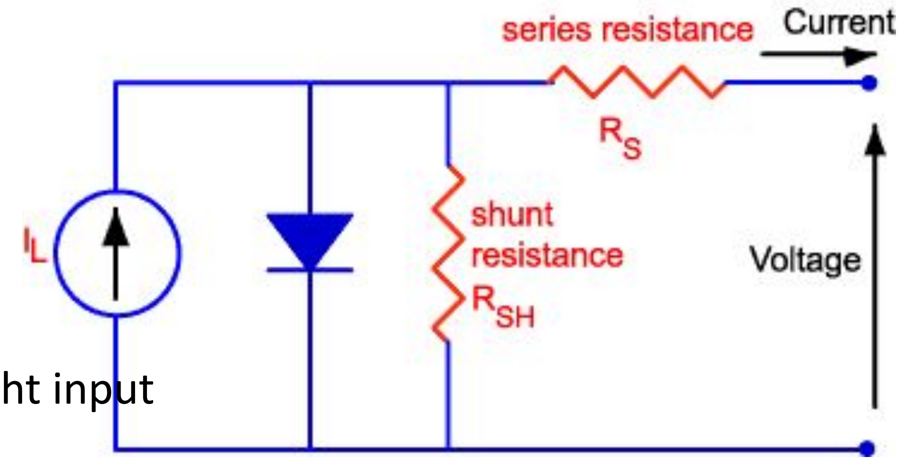


# Parasitic Resistances

The parasitic resistance: Sum of all resistance due to all component through which current is flowing as well as crustal defect and impurity




## Optical Losses:

Light generated current itself proportional to light input

## Recombination Losses:

By diode itself, connected to the parallel of current flow in opposite direction

## Ohmic Losses:

### Series Resistance (Rs): Effect on $I_{sc}$

Sum of all resistance in the path of current flow

### Shunt Resistance (Rsh): Effect on Voc,

Due to leakage across P-N junction/ crystal defect/impurities

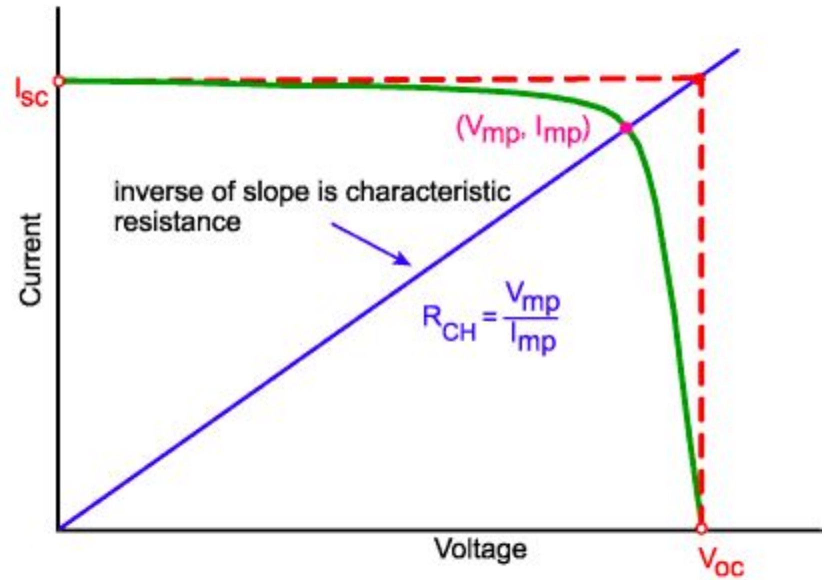
# Resistive Losses
## Characteristic Resistance

- The characteristic resistance of a solar cell is the output resistance of the solar cell at its maximum power point.
- If the resistance of the load is equal to the characteristic resistance of the solar cell, then the maximum power is transferred to the load and the solar cell operates at its maximum power point.

- It is a useful parameter in solar cell analysis, particularly when examining the impact of parasitic loss mechanisms.

The characteristic resistance of a solar cell is the inverse of the slope of the power line, can be given as:

$$R_{CH} = \frac{V_{MP}}{I_{MP}}$$

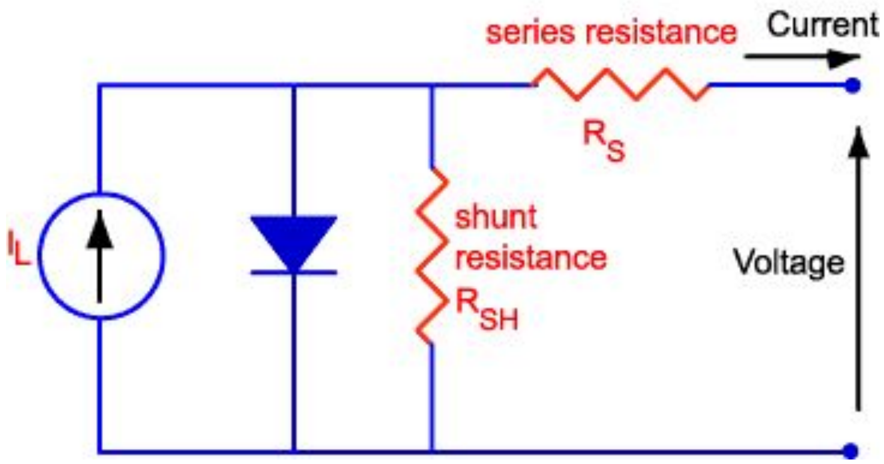



It can alternately be given as an approximation where: $$R_{CH} = \frac{V_{OC}}{I_{SC}}$$

# Effect of parasitic Resistances

Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances.

The most common parasitic resistances are series resistance and shunt resistance.

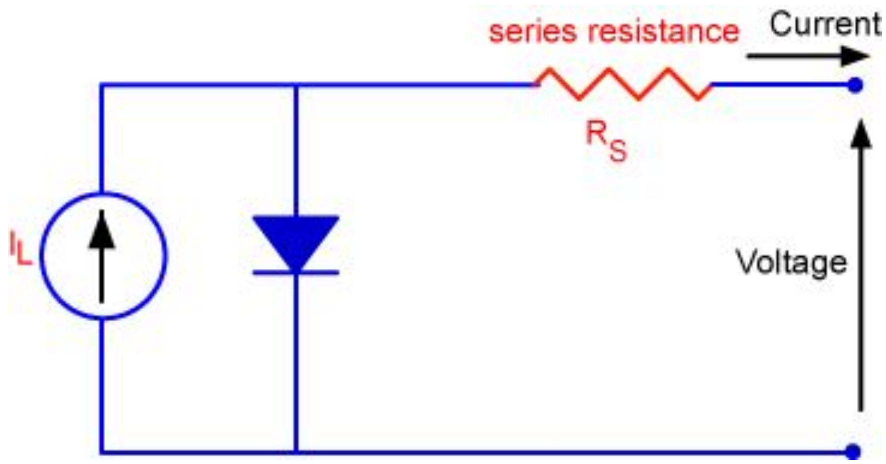



Rs: as low as possible
Rsh: as high as possible

In most cases and for typical values of shunt and series resistance, the key impact of parasitic resistance is to reduce the fill factor.

Both the magnitude and impact of series and shunt resistance depend on the geometry of the solar cell, at the operating point of the solar cell.

# Series Resistance




Series resistance in a solar cell has three causes:

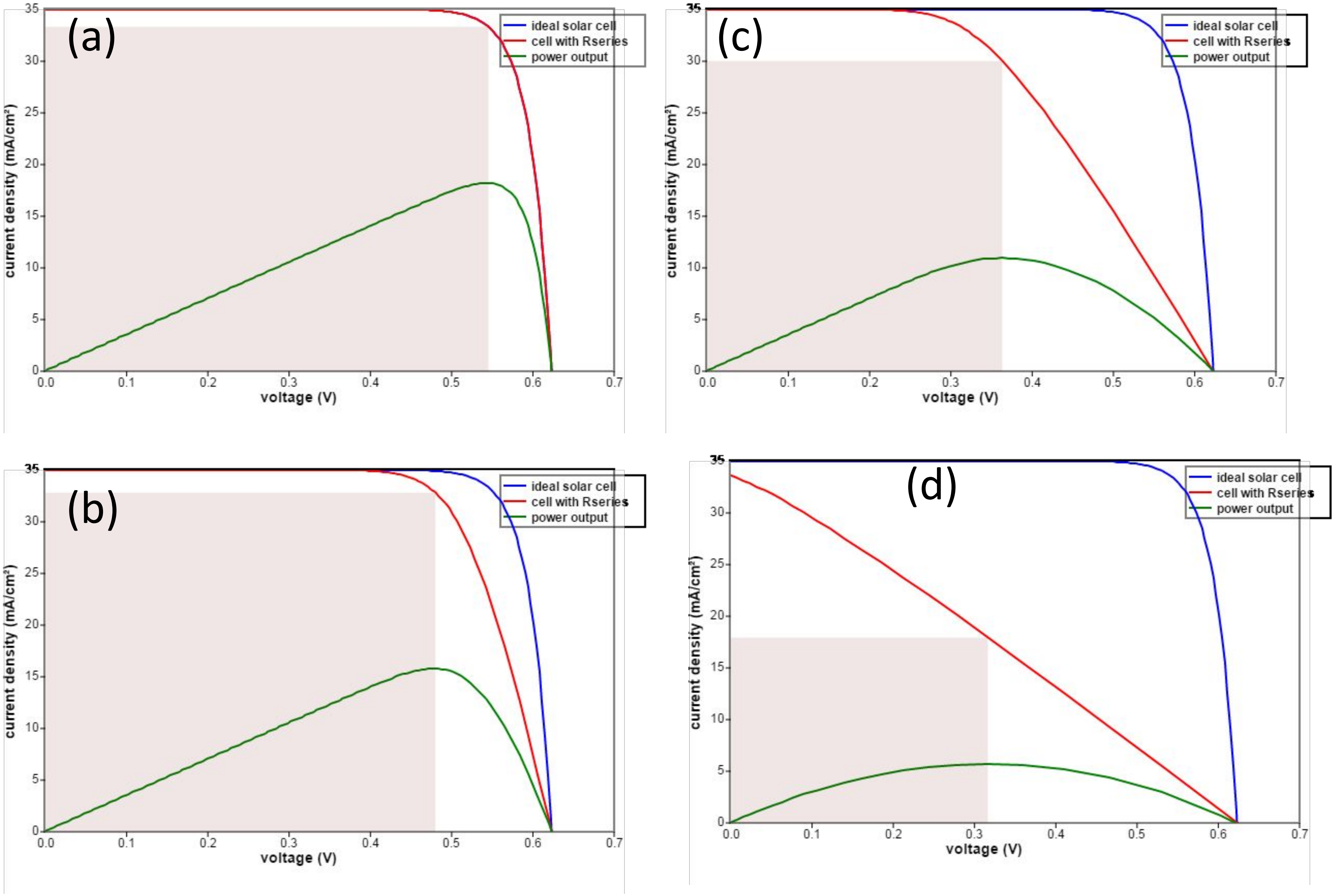
- the movement of current through the emitter and base of the solar cell;
- the contact resistance between the metal contact and the silicon; and
- the resistance of the top and rear metal contacts.

The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.

$$I = I_{sc} - I_o[e^{q(V+IR_s)/nkT} - 1]$$

# Effect of Series resistance on *I-V* curve

**With increasing series resistance**



Series resistance does not affect the solar cell at open-circuit voltage since the overall current flow through the solar cell, and therefore through the series resistance is zero.

However, near the open-circuit voltage, the *I-V* curve is strongly effected by the series resistance.

A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the *I-V* curve at the open-circuit voltage point.

An equation for the FF as a function of series resistance can be determined by noting that for moderate values of series resistance, the maximum power may be approximated as the power in the absence of series resistance minus the power lost in the series resistance. The equation for the maximum power from a solar cell then becomes:

$$P'_{MP} \approx V_{MP} I_{MP} - I_{MP}^2 R_S = V_{MP} I_{MP}\left(1 - \frac{I_{MP}}{V_{MP}} R_S\right) = P_{MP}\left(1 - \frac{I_{SC}}{V_{OC}} R_S\right)$$

$$P'_{MP} = P_{MP}\left(1 - \frac{R_S}{R_{CH}}\right)$$

defining a normalized series resistance as; $r_S = \dfrac{R_S}{R_{CH}}$

$$P'_{MP} = P_{MP}(1 - r_S)$$

Assuming that the open-circuit voltage and short-circuit current are not affected by the series resistance which allows the impact of series resistance on FF to be determined;

$$P'_{MP} = P_{MP}(1 - r_S)$$

$$V'_{OC} I'_{SC} FF' = V_{OC} I_{SC} FF(1 - r_S)$$

$$FF' = FF(1 - r_S)$$

In the above equation the fill factor which is not affected by series resistance is denoted by $FF_0$ and FF' is called $FF_S$. The equation then becomes;

$$FF_S = FF_0(1 - r_S)$$

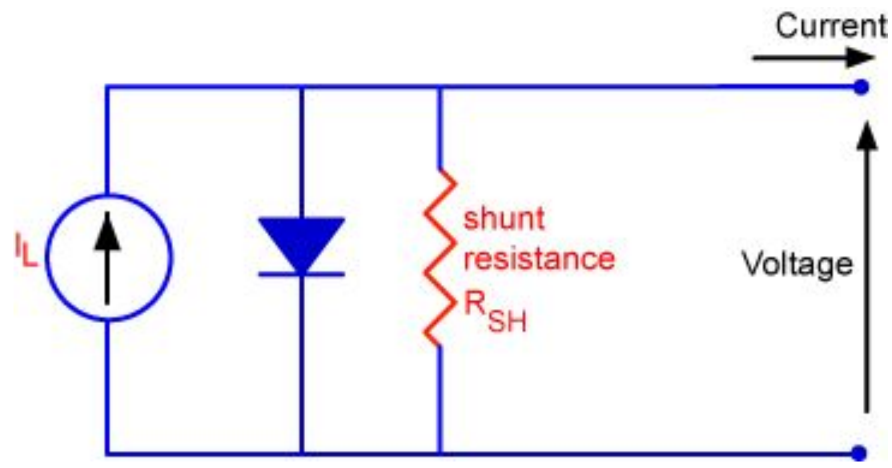
An empirical equation, which is slightly more accurate for the relationship between $FF_0$ and $FF_S$ is;

$$FF_S = FF_0(1 - 1.1 r_S) + \frac{r_S^2}{5.4}$$

which is valid for $r_s < 0.4$ and $v_{oc} > 10$, where $v_{oc}$ *is* $V_{oc}$*/(kT/q) i.e., Open circuit voltage normalized to the thermal voltage.*

# Shunt Resistance

Significant power losses caused by the presence of a shunt resistance, $R_{SH}$, are typically due to manufacturing defects, rather than poor solar cell design.




Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current.

Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell.

The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact.

In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large.

The equation for a solar cell in presence of a shunt resistance is:

$$I = I_{sc} - I_o[e^{qV/nkT} - 1] - \frac{V}{R_{sh}}$$

The impact of the shunt resistance on the fill factor can be calculated in a manner similar to that used to find the impact of series resistance on fill factor. The maximum power may be approximated as the power in the absence of shunt resistance, minus the power lost in the shunt resistance. The equation for the maximum power from a solar cell then becomes;

$$P'_{MP} \approx V_{MP} I_{MP} - \frac{V_{MP}^2}{Rsh} = V_{MP} I_{MP} (1 - \frac{V_{MP}}{I_{MP}} \frac{1}{R_{sh}}) = P_{MP} (1 - \frac{V_{OC}}{I_{SC}} \frac{1}{R_{sh}})$$

$$P'_{MP} = P_{MP} (1 - \frac{R_{CH}}{R_{sh}})$$

Defining a normalized shunt resistance as; $r_{SH} = \frac{R_{SH}}{R_{CH}}$

Assuming that the open-circuit voltage and short-circuit current are not affected by the shunt resistance allows the impact of shunt resistance on FF to be determined as;

$$P'_{MP} = P_{MP} \left(1 - \frac{1}{r_{SH}}\right)$$

$$V'_{OC} I'_{SC} FF' = V_{OC} I_{SC} FF \left(1 - \frac{1}{r_{SH}}\right)$$

$$FF' = FF \left(1 - \frac{1}{r_{SH}}\right)$$

In the above equation of FF, the fill factor which is not affected by shunt resistance is denoted by $FF_0$ and FF' is called $FF_{SH}$. The equation then becomes;

$$FF_{SH} = FF_0 \left(1 - \frac{1}{r_{SH}}\right)$$

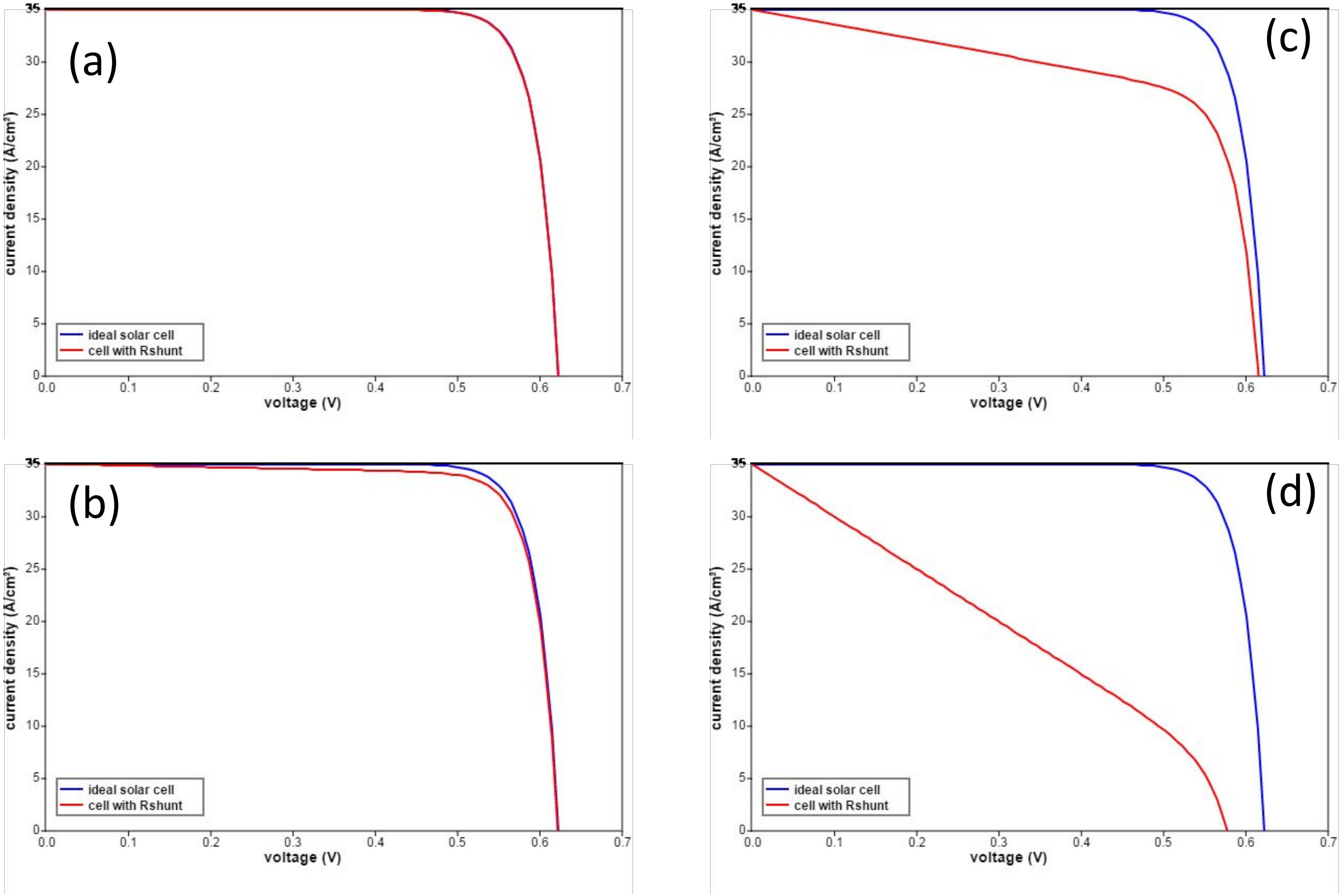
An empirical equation, which is slightly more accurate for the relationship between $FF_0$ and $FF_{SH}$ is;

$$FF_{SH} = FF_0 \left(1 - \frac{V_{OC} + 0.7}{V_{OC}} \frac{FF_0}{r_{SH}}\right)$$

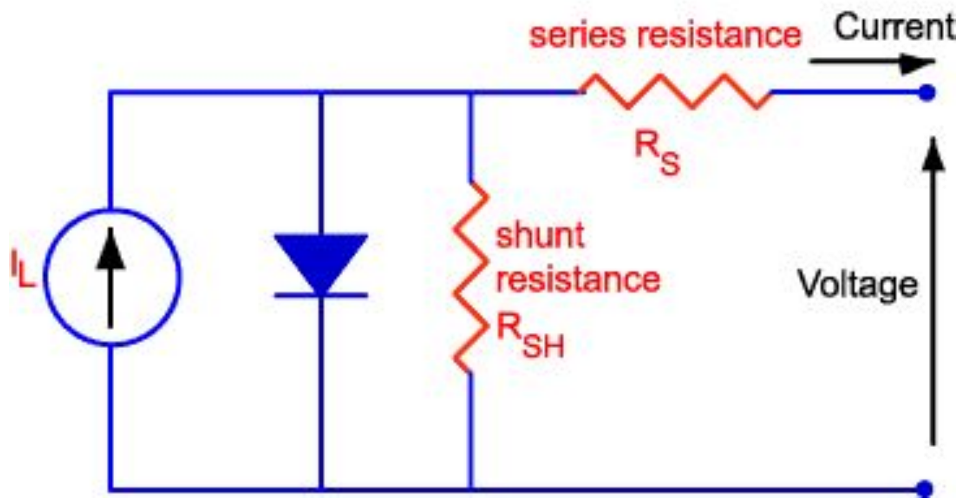
which is valid for $r_{sh} > 0.4$.

# Effect of shunt resistance on *I-V* curve

## With decreasing shunt resistance



# Impact of Both Series and Shunt Resistances




In the presence of both series and shunt resistances, the IV curve of the solar cell is given by;

$$I = I_{sc} - I_o[e^{q(V+IR_s)/nkT} - 1] - \frac{V + IR_s}{R_{sh}}$$

To combine the effect of both series and shunt resistances, the expression for $FF_{sh}$ can be used with $FF_0$ replaced by $FF_s$. The overall equation then becomes;

$$FF_{SH} = FF_0\left(1 - \frac{1}{r_{SH}}\right)$$

where $FF_s$ is given by;

$$FF_S = FF_0(1 - r_S)$$

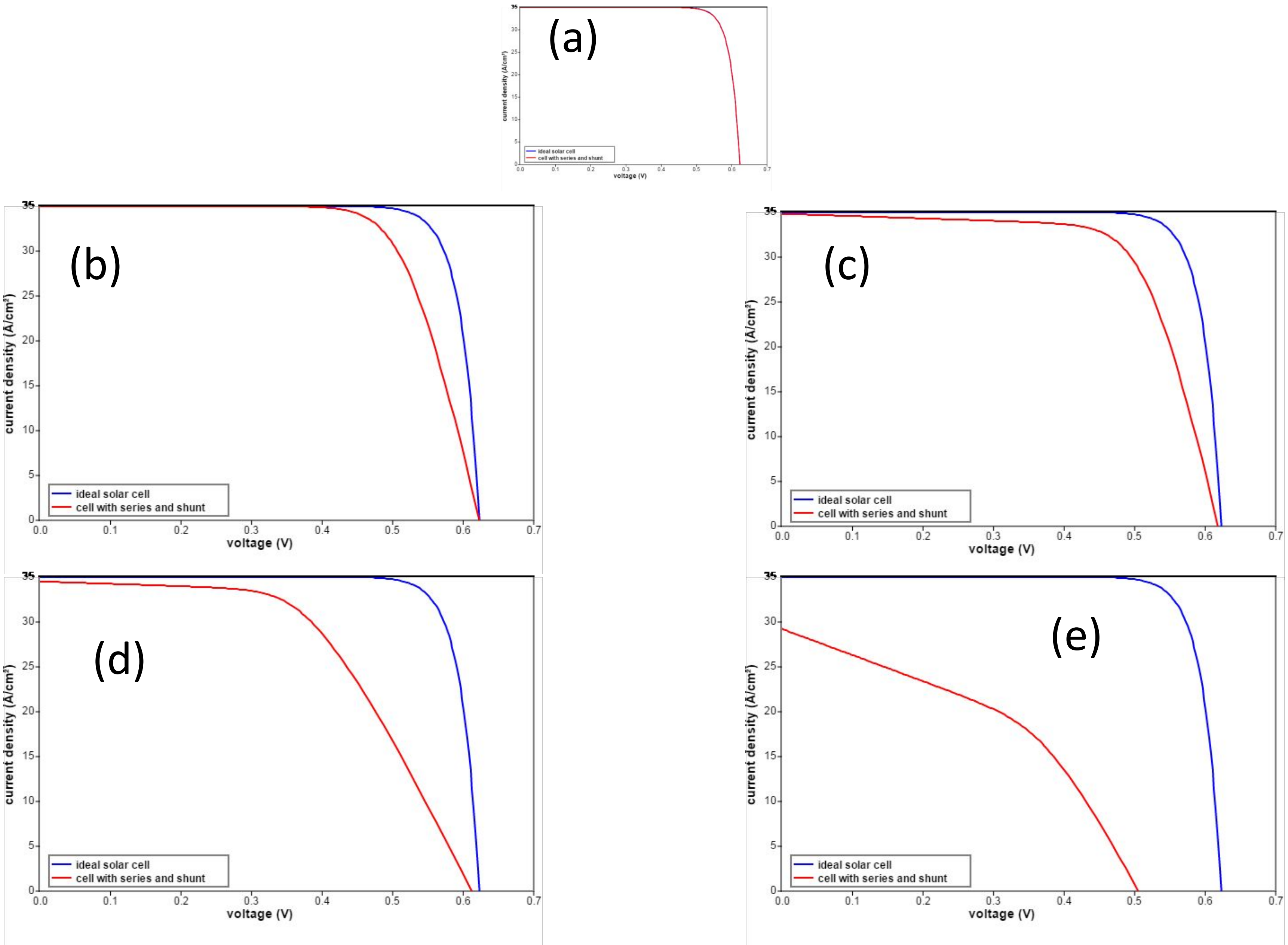
and by combining the above equations, the net equation for FF becomes;

$$FF_{SH} = FF_0(1 - r_S)\left(1 - \frac{1}{r_{SH}}\right)$$

$$FF = [FF_0(1 - 1.1r_s) + \frac{r_s^2}{5.4}][1 - \frac{V_{oc} + 0.7}{V_{oc}}\frac{1}{r_{sh}}FF_0(1 - 1.1r_s) + \frac{r_s^2}{5.4}]$$

# Effect of both series and shunt resistance on *I-V* curve

## With increasing series resistance and decreasing shunt resistance



# Effect of Temperature

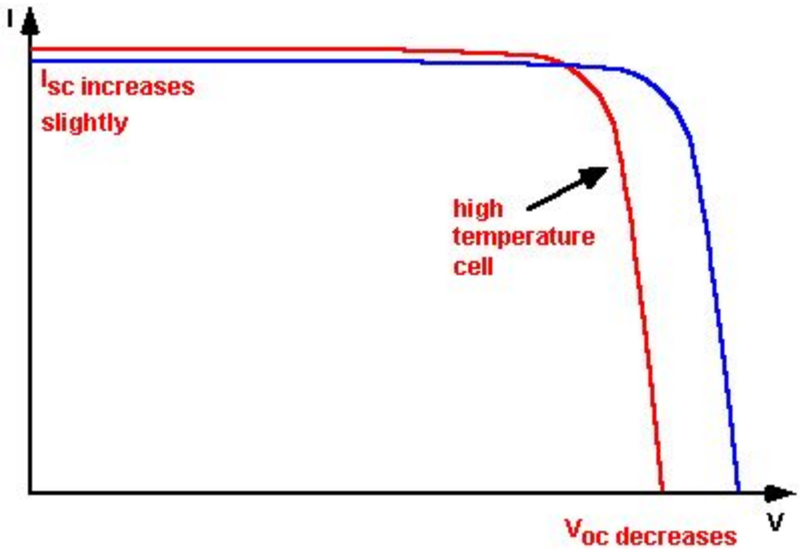
Like all other semiconductor devices, solar cells are sensitive to temperature.

Increase in temperature reduces the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters.

The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material.

Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap.

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage.



The open-circuit voltage decreases with temperature because of the temperature dependence of $I_0$. The equation for $I_0$ from one side of a *p-n* junction is given by;

$$I_0 = qA \frac{Dn_i^2}{LN_D}$$

where: q is the electronic charge; D is the diffusivity of the minority carrier; L is the diffusion length of the minority carrier; $N_D$ is the doping; and $n_i$ is the intrinsic carrier concentration

In the above equation, many of the parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, $n_i$.

The intrinsic carrier concentration depends on the band gap energy (with lower band gaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations).

The equation for the intrinsic carrier concentration is;

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{3/2} \exp\left(-\frac{E_{G0}}{kT}\right) = BT^3 \exp\left(-\frac{E_{G0}}{kT}\right)$$

where: T is the temperature; h and k are constants; $m_e$ and $m_h$ are the effective masses of electrons and holes respectively; $E_{GO}$ is the band gap linearly extrapolated to absolute zero; and B is a constant which is essentially independent of temperature.

Substituting these equations back into the expression for $I_0$, and assuming that the temperature dependencies of the other parameters can be neglected, gives;

$$I_0 = qA\frac{D}{LN_D} BT^3 \exp\left(-\frac{E_{G0}}{kT}\right) \approx B'T^{\gamma} \exp\left(-\frac{E_{G0}}{kT}\right)$$

where B' is a temperature independent constant. A constant , γ, is used instead of the number 3 to incorporate the possible temperature dependencies of the other material parameters. For silicon solar cells near room temperature, $I_0$ approximately doubles for every 10 °C increase in temperature.

The impact of $I_0$ on the open-circuit voltage can be calculated by substituting the equation for $I_0$ into the equation for $V_{oc}$ as shown below;

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0}\right) = \frac{kT}{q}\left[\ln I_{SC} - \ln I_0\right] = \frac{kT}{q}\ln I_{SC} - \frac{kT}{q}\ln\left[B'T^{\gamma}\,exp\left(-\frac{qV_{G0}}{kT}\right)\right]$$
$$= \frac{kT}{q}\left(\ln I_{SC} - \ln B' - \gamma\ln T + \frac{qV_{G0}}{kT}\right)$$

where $E_{G0} = qV_{G0}$. Assuming that $dV_{oc}/dT$ does not depend on $dI_{sc}/dT$, $dV_{oc}/dT$ can be found as;

$$\frac{dV_{OC}}{dT} = \frac{V_{OC} - V_{G0}}{T} - \gamma\frac{k}{q}$$

The above equation shows that the temperature sensitivity of a solar cell depends on the open circuit voltage of the solar cell, with higher voltage solar cells being less affected by temperature. For silicon, $E_{G0}$ is 1.2, and using γ as 3 gives a reduction in the open-circuit voltage of about 2.2 mV/°C;

$$\frac{dV_{OC}}{dT} = -\frac{V_{G0} - V_{OC} + \gamma\frac{kT}{q}}{T} \approx -2.2mV\ per\ {}^{o}C\ for\ Si$$

$$V_{oc} - V_{GO} = \frac{kT}{q}(\ln I_{sc} - \ln B' - \gamma \ln T)$$

$$Now, \quad \frac{dV_{oc}}{dT} = \frac{k}{q}(\ln I_{sc} - \ln B' - \gamma \ln T - \frac{k\gamma}{q})$$

$$\frac{dV_{oc}}{dT} = \frac{1}{T}\frac{kT}{q}(\ln I_{sc} - \ln B' - \gamma \ln T) - \gamma \frac{k}{q}$$

$$\frac{dV_{oc}}{dT} = \frac{V_{oc} - V_{GO}}{T} - \gamma \frac{k}{q}$$

$$\frac{dV_{oc}}{dT} = -\frac{V_{GO} - V_{oc} + \gamma \frac{kT}{q}}{T}$$

The short-circuit current, $I_{sc}$, increases slightly with temperature, since the band gap energy, $E_G$, decreases and more photons have enough energy to create e-h pairs. However, this is a small effect and the temperature dependence of the short-circuit current from a silicon solar cell is;

$$\frac{1}{I_{SC}}\frac{dI_{SC}}{dT} \approx 0.0006\, per\ \ ^oC\ for\ Si$$

The temperature dependency of FF for silicon is approximated by the following equation;

$$\frac{1}{FF}\frac{dFF}{dT} \approx \left(\frac{1}{V_{OC}}\frac{dV_{OC}}{dT} - \frac{1}{T}\right) \approx -0.0015\, per\ \ ^oC\ for\ Si$$

The effect of temperature on the maximum power output, $P_m$, is;

$$P_{Mvar} = \frac{1}{P_M}\frac{dP_M}{dT} = \frac{1}{V_{OC}}\frac{dV_{OC}}{dT} + \frac{1}{FF}\frac{dFF}{dT} + \frac{1}{I_{SC}}\frac{dI_{SC}}{dT}$$

$$\frac{1}{P_M}\frac{dP_M}{dT} \approx -(0.004\ to\ 0.005) per\ \ ^oC\ for\ Si$$

# 300 K or 25 °C ?

Most semiconductor modelling is done at 300 K since it is close to room temperature and a convenient number. However, solar cells are typically measured almost 2 degrees lower at 25 °C (298.15 K). In most cases the difference is insignificant (only 4 mV of $V_{oc}$) and both are referred to as room temperature.

# Questions

**Q 1)** Calculate the efficiency and peak power of a Si solar cell of area 100 $cm^2$ operating at $27^o$ C, with short circuit current of 2.2 A under standard illumination. Given: FF=0.75

**Q 2)** In above problem if the operating temperature of the solar cell increases to about $40^o$ C, calculate the efficiency.

**Q 3)** A p-n junction solar cell has $V_{oc}$ =0.5 V and $J_{sc}$ =20 mA/$cm^2$ .A second, of same area, has $V_{oc}$ =0.6 V and $J_{sc}$ =16 mA/$cm^2$. Assuming that both cells obey the ideal diode equation, find the values of $V_{oc}$ and $J_{sc}$ when the two cells are connected (a) in parallel and (b) in series.

**Q 4)** A solar cell has a short circuit current density of 30 mA/cm$^2$ and open circuit voltage of 0.6 V under one Sun illumination at room temperature. Use the ideal diode equation to calculate the open circuit voltage which is expected under illumination by 100 Suns, stating any assumption made. In practice an open-circuit voltage of 0.66 V is measured. Compare this with your result and suggest reasons for any discrepancy.

**Q 5)** A n-p homo-junction solar cell has emitter thickness of $x_n$ and a base thickness of $x_p$. If the front surface reflectivity is R and bulk absorption is α for photons of energy E,

(a) Find an expression for the photon flux density reaching the base when the incident flux density is $b_0(E)$.

(b) Find an expression for the flux density absorbed in the base.

(c) If each absorbed photon in base delivers exactly one electron to the contacts, what is the photocurrent density from the cell? You may ignore the emitter photocurrent, and assume that the space charge width is negligible.

(d) Now find an expression for the Quantum efficiency.

(e) A n-p solar cell has $x_n$=20 μm and R=0.1 for all photon energies. At 800 nm the absorption of the cell material is 1.0x10$^5$ m$^{-1}$. A student calculates that the QE is only 60%. What might be the reason for this.

**Q 6)** A semiconductor has an intrinsic carrier density $n_i$ of $2.0\times10^{12}$ $m^{-3}$ at 300 K. A thin slab of this material is exposed to a light pulse of photon energy 2.1 eV and intensity 1000 $W/m^2$ for an interval of 1 ns. If the absorption coefficient is $5\times10^{5}$ $m^{-1}$ at 2.1 eV, calculate the concentration of photogenerated electrons and holes immediately after the pulse. You may neglect recombination during the light pulse. Hence find new concentration of electrons (n) and holes (p) and the product (np) in the following cases:

(a) If the semiconductor is intrinsic (i.e., n=p in the dark)

(b) If the semiconductor is doped with a concentration of $1\times10^{22}$ $m^{-3}$ donor impurities, which may be considered to be fully ionized?

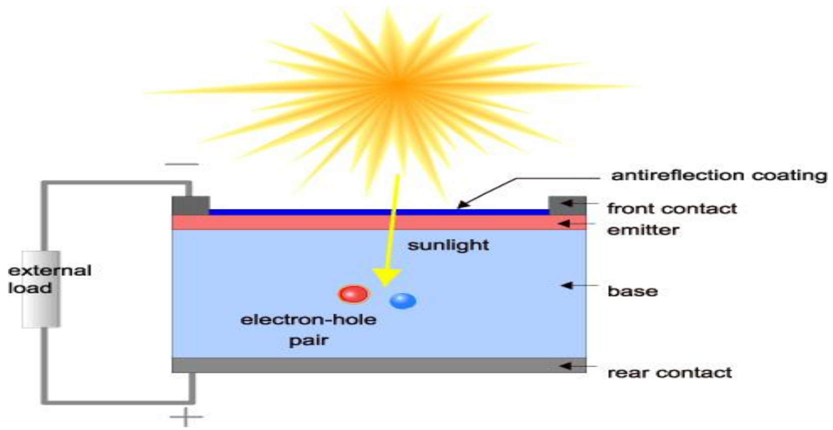
(c) In which case is the rate of radiative recombination faster?

# Solar Cell Design Principles

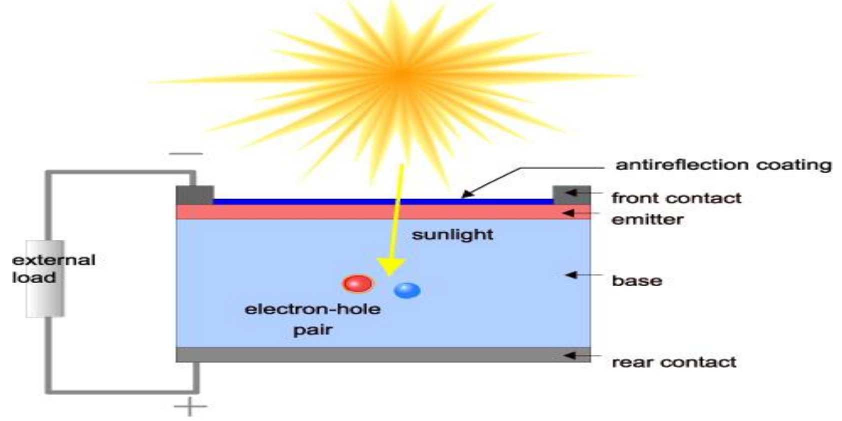
$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}} \qquad V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \qquad I = I_0 \left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L$$

Three factors for max efficiency....???

1. Absorption of light
2. Separation of light generated charge carriers
3. Transport of separated charge carriers to external load without resistive losses



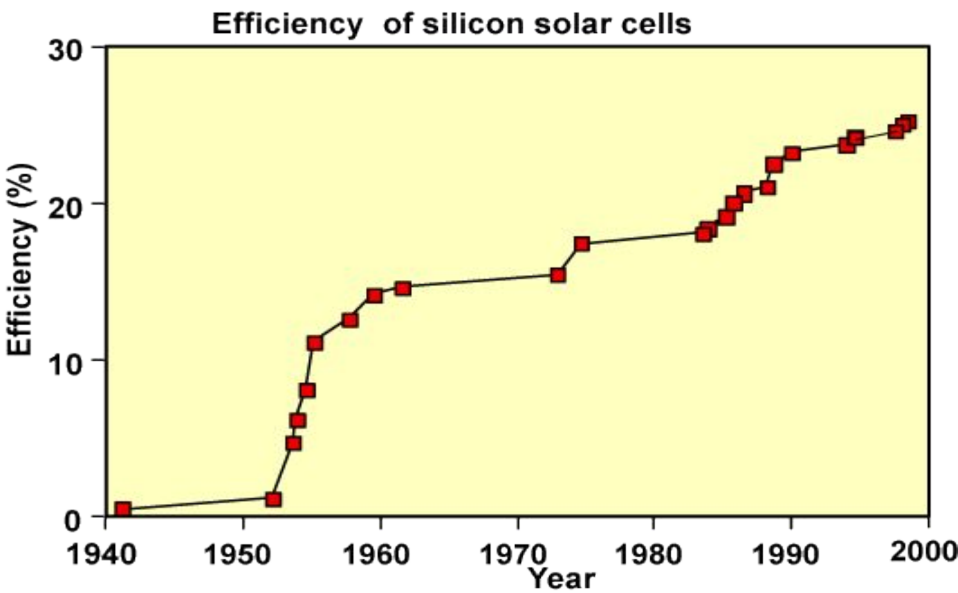
$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$




The theoretical efficiency for photovoltaic conversion is in excess of 86.8%.

For silicon solar cells η =about 29%. (AM1.5G)

Huge difference is mainly due to:




•theoretical maximum efficiency assume energy from each photon optimally used,

•no unabsorbed photons and that each photon is absorbed in a material which has a band gap equal to the photon energy

• temperature and resistive effects do not dominate

•high concentration ratio

•Voc & Isc increases with high concentration so FF

# Solar Cell Design Principles and requirements:

In designing such single junction solar cells, the principles for maximizing cell efficiency are:

- increasing the light collected by the cell so into carriers--increasing the collection of light-generated carriers by the *p-n* junction;

- minimising the dark current;

- extracting the current from the cell without resistive losses.

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

# Constraints/limitations:

- Solar cell design involves specifying the parameters of a solar cell structure in order to maximize efficiency, given a certain set of constraints.

- working environment in which solar cells are produced power.

- commercial environment: a competitively priced solar cell
  - the cost of solar cell structure must be taken into consideration.

- In a research environment where the objective is to produce a highly efficient laboratory-type cell, maximizing efficiency rather than cost, is the main consideration.

# Losses and reduction of losses:

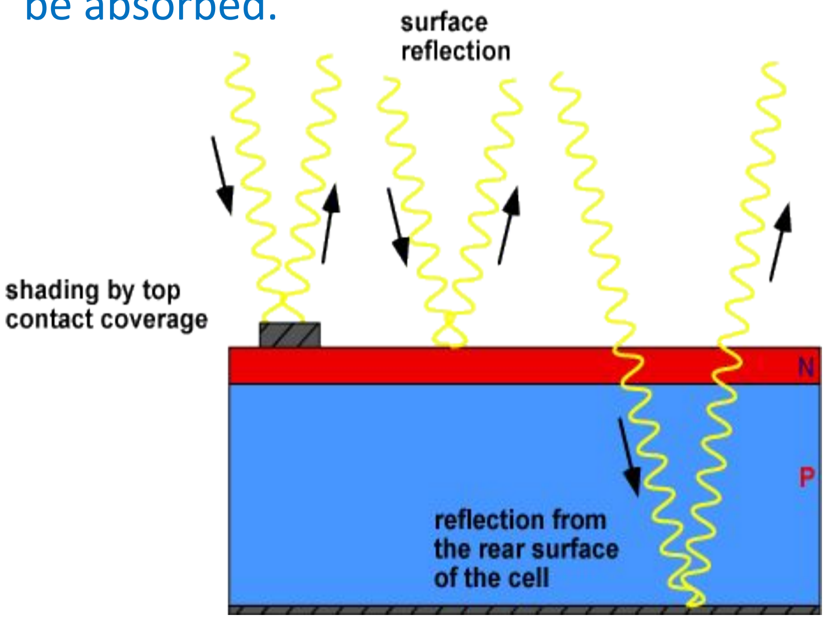
# Optical Losses

$$I_{sc} = qAG(L_n + W + L_p)$$

Optical losses mainly effect the power from a solar cell by lowering the short-circuit current.

Optical losses consist of light which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface, or because it is not absorbed in the solar cell.

For the most common semiconductor solar cells, the entire visible spectrum (350 - 780 nm) has enough energy to create electron-hole pairs and therefore all visible light would ideally be absorbed.




R> 30%

due to its high refractive index.

$$R = \left(\frac{n_0 - n_{Si}}{n_0 + n_{Si}}\right)^2$$

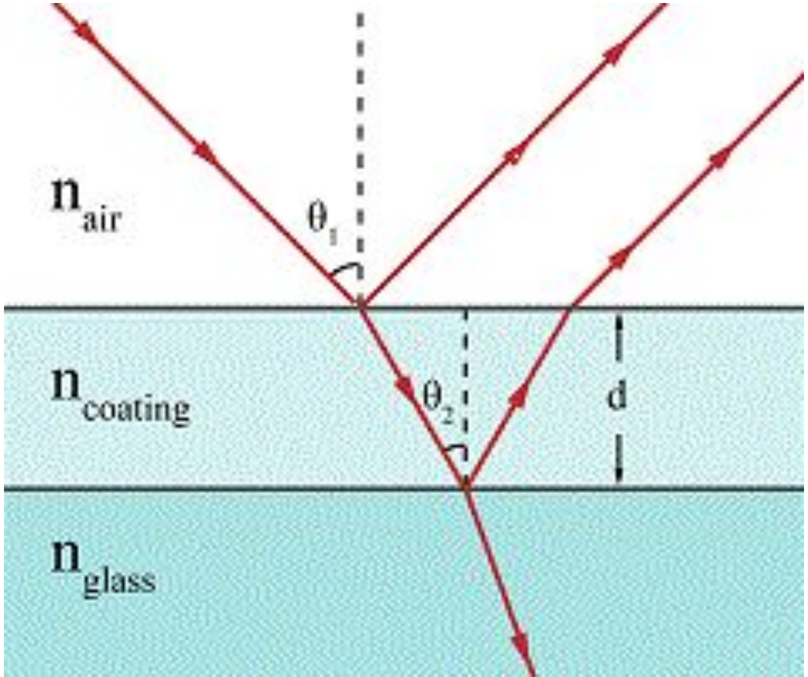
**How to reduce R???**

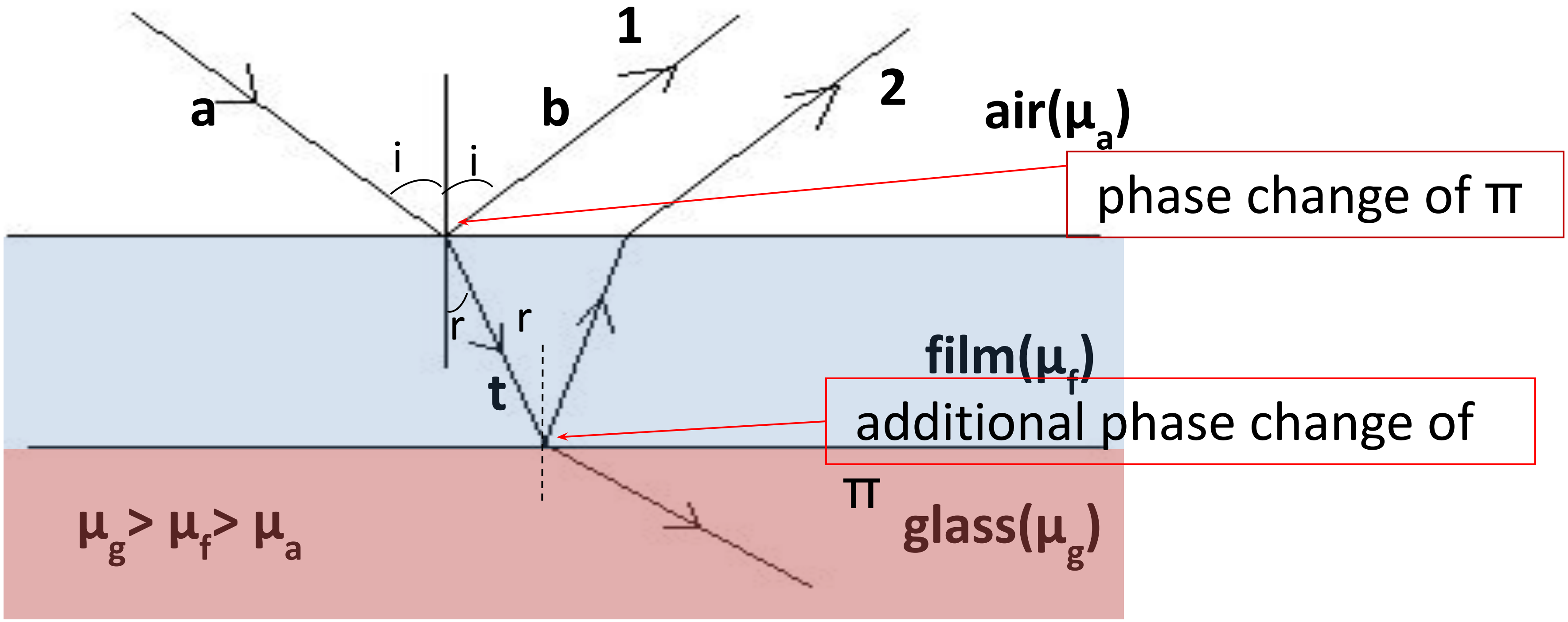
Sources of optical loss in a solar cell.

# Anti reflection films
# [Anti reflection coatings (AR)]

**Phase condition** -wave reflected from the top and bottom surfaces of the thin films are in opposite phase. Overlapping leads to destructive interference .

**Amplitude Condition** – Waves have equal amplitude






Phase of beams 1 and 2 reflected from the top and bottom surfaces of the thin films should be 180º out of phase.

Destructive interference b/w 1 & 2, **$\Delta = (2n+1)\lambda/2$**

$$\Delta = 2\mu_f t \cos r - \frac{\lambda}{2} - \frac{\lambda}{2}$$

Addition or subtraction of a full wave ($\lambda$) does not affect the phase.

$$\Delta = 2\mu_f t\cos r - \frac{\lambda}{2} - \frac{\lambda}{2} \approx 2\mu_f t\cos r$$

For normal incidence *cos r* =1 ;

$$\Delta = 2\mu_f t$$

Destructive interference b/w 1 & 2, **Δ= (2n+1)λ/2**

$$2\mu_f t = (2n+1)\frac{\lambda}{2}$$

for minimum thickness of nonreflecting film, n = 0 ,

$$\boxed{t = \frac{\lambda}{4\mu_f}}$$

$$\boxed{\text{where} \quad \mu_f = \sqrt{\mu_a \mu_g}}$$

If a film having thickness of **λ/4** $\mu_f$ and, $\mu_g > \mu_f > \mu_a$ , then waves reflected from the upper surface of the film destructively interfere with the waves reflected from the lower surface of the film. Such a film known as a non reflecting film.

As

$$\boxed{\mu_f = \sqrt{\mu_a \mu_g}}$$

This equation gives the estimate of refractive index of this film which should be coated on a surface to reduce its reflectivity. If $\mu_a$= 1 (for air) and $\mu_g$ = refractive index of glass then

$$\boxed{\mu_f = \sqrt{\mu_g}}$$

For glass, μ=1.5,

$$\boxed{\mu_f = 1.224}$$

No material is available with this μ for thin film coating.

$MgF_2$ (μ=1.38) and cryolite (μ=1.36) are used for anti reflecting coating on optical components.

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

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

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

- Reflection can be reduced by surface texturing.

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

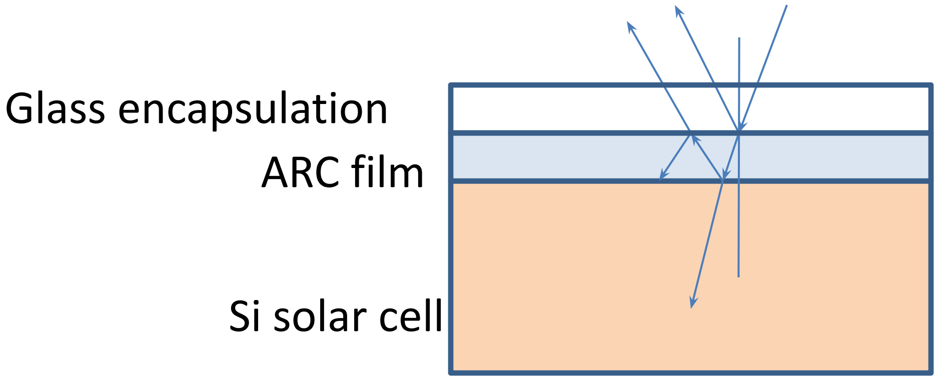
- The optical path length in the solar cell may be increased by a combination of surface texturing and light trapping.

The reflection of a silicon surface is over 30% due to its high refractive index. The reflectivity, R, between two materials of different refractive indices is determined by:

$$R = \left(\frac{n_0 - n_{Si}}{n_0 + n_{Si}}\right)^2$$

where $n_0$ is the refractive index of the surroundings and $n_{Si}$ is the complex refractive index of silicon. For an unencapsulated cell $n_0 = 1$. For an encapsulated cell $n_0 = 1.5$. The refractive index of silicon changes with wavelength.

$$n_f = \sqrt{n_g n_{Si}}$$



# Anti-Reflection Coatings

- Bare silicon has a high surface reflection of over 30%. The reflection is reduced by texturing and by applying anti-reflection coatings (ARC) to the surface.

- Anti-reflection coatings on solar cells are similar to those used on other optical equipment such as camera lenses.

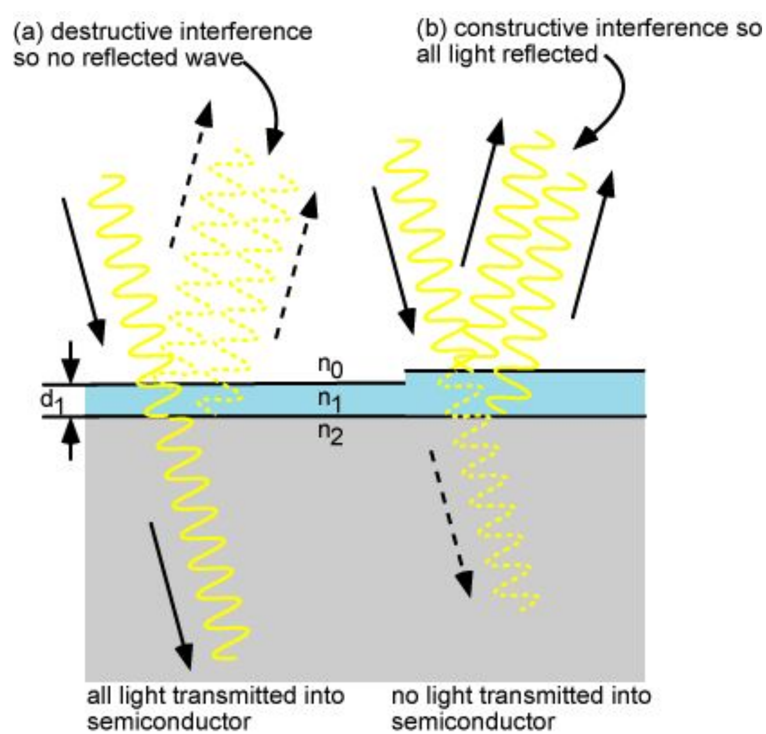
- They consist of a thin layer of dielectric material, with a specially chosen thickness

# Principle of ARC:

interference effects in the coating cause the wave reflected from the anti-reflection coating top surface to be out of phase with the wave reflected from the semiconductor surfaces.

- These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy.

# Thickness of the film...?



The thickness of the anti-reflection coating is chosen so that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave.

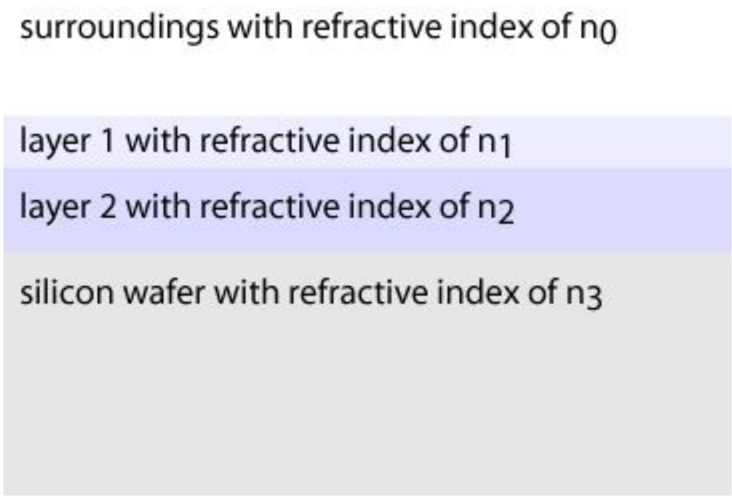
For a quarter wavelength anti-reflection coating of a transparent material with a refractive index $n_1$ and light incident on the coating with a free-space wavelength $\lambda_0$, the thickness $d_1$ which causes minimum reflection is calculated by:

$$d_1 = \frac{\lambda_0}{4n_1}$$

Four multicrystalline wafers covered with films of silicon nitride. The difference in color is solely due to the thickness of the film.

# Double Layer Anti Reflection Coatings

A further reduction in reflectivity is achieved through a *double layer anti-reflection coating* (DLARC). Popular DLARC coatings are zinc sulfide (ZnS) with magnesium flouride (MgF) or layers of silicon nitride with varying refractive index. However, this is usually too expensive for most commercial solar cells.

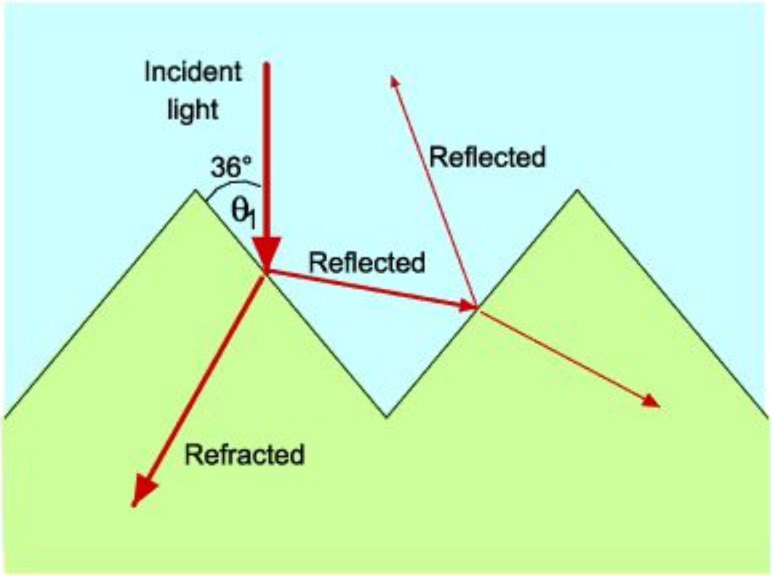



Double layer anti-reflection film on silicon wafer. The layers are usually deposited on a textured substrate to decrease the reflectivity further.

## Question

Calculate the thickness required of the ARC film if the green wavelength is to be lest reflected from the surface of the Si ($n_{Si}$=3.8) solar cell.

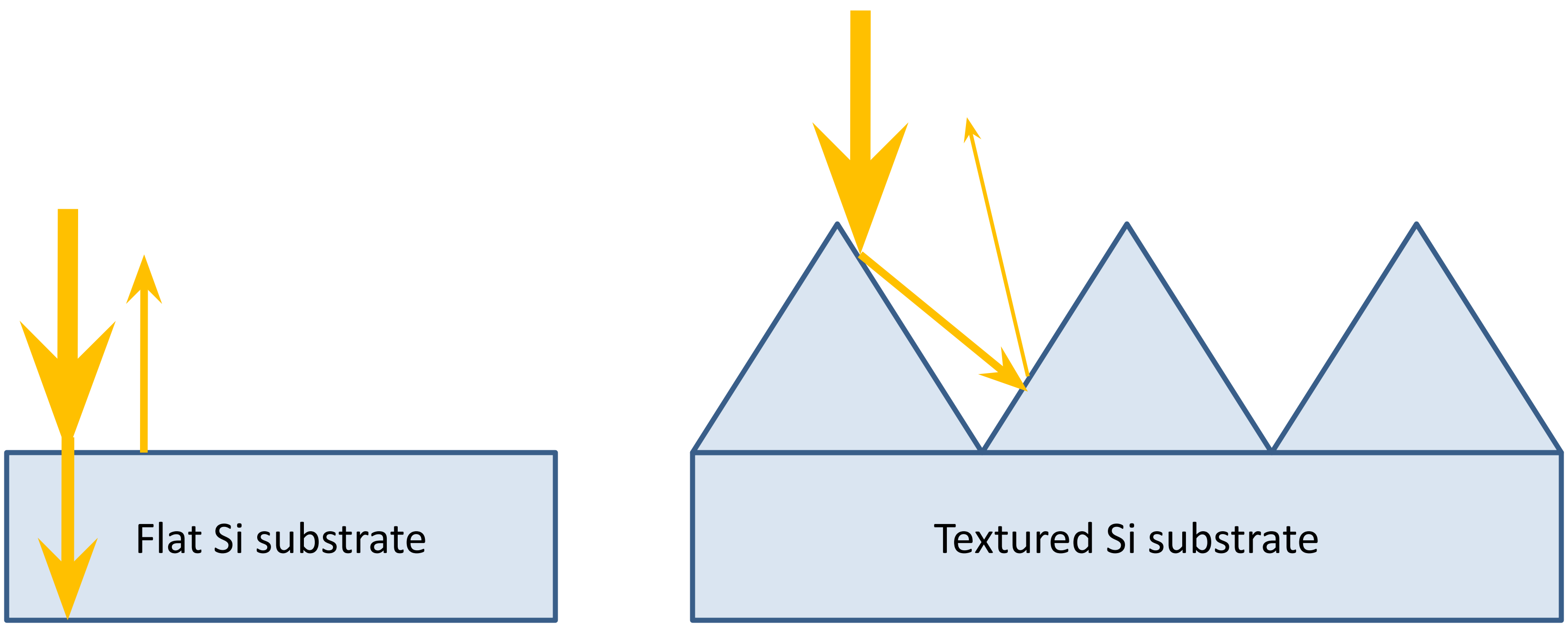
# Other ways to reduce reflection...???



# Surface Texturing

**Surface texturing, either in combination with an anti-reflection coating or by itself, can also be used to minimize reflection.**

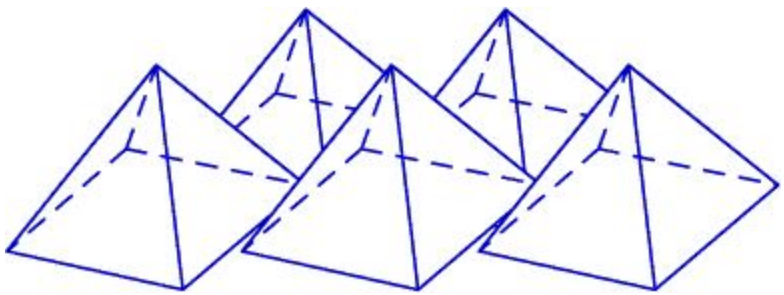
**Any "roughening" of the surface reduces reflection by increasing the chances of reflected light bouncing back onto the surface, rather than out to the surrounding air.**



**Surface texturing can be accomplished in a number of ways.**

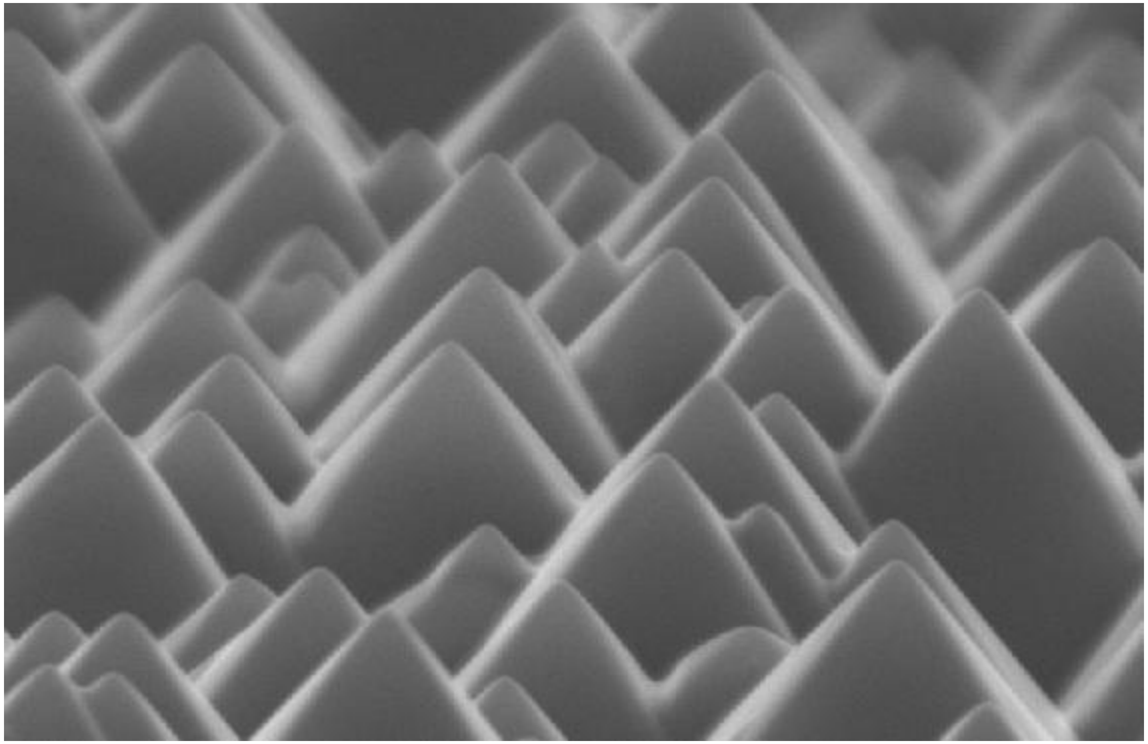
**A single crystalline substrate can be textured by etching along the faces of the crystal planes. The crystalline structure of silicon results in a surface made up of pyramids if the surface is appropriately aligned with respect to the internal atoms.**

**One such pyramid is illustrated in the drawing below.**



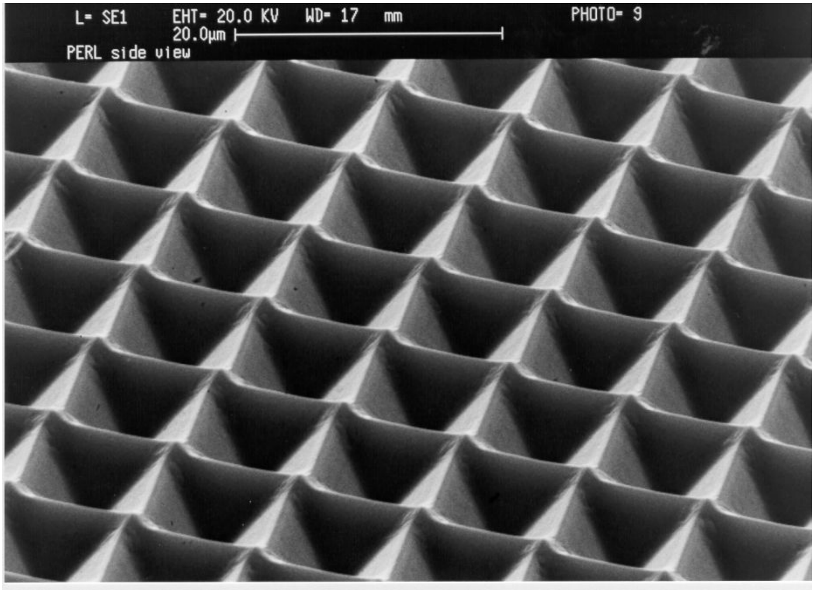
A square based pyramid which forms the surface of an appropriately textured crystalline silicon solar cell.

**An electron microscope photograph of a textured silicon surface is shown in the photograph below. This type of texturing is called "random pyramid" texture, and is commonly used in industry for single crystalline wafers.**



Scanning electron microscope photograph of a textured silicon surface. Image Courtesy of The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

Another type of surface texturing used is known as "inverted pyramid" texturing. Using this texturing scheme, the pyramids are etched down into the silicon surface rather than etched pointing upwards from the surface. A photograph of such a textured surface is shown below.




Scanning electron microscope photograph of a textured silicon surface. Image Courtesy of The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

# Light Trapping

- The optimum device thickness is not controlled solely by the need to absorb all the light.

- For example, if the light is not absorbed within a diffusion length of the junction, then the light-generated carriers are lost to recombination.

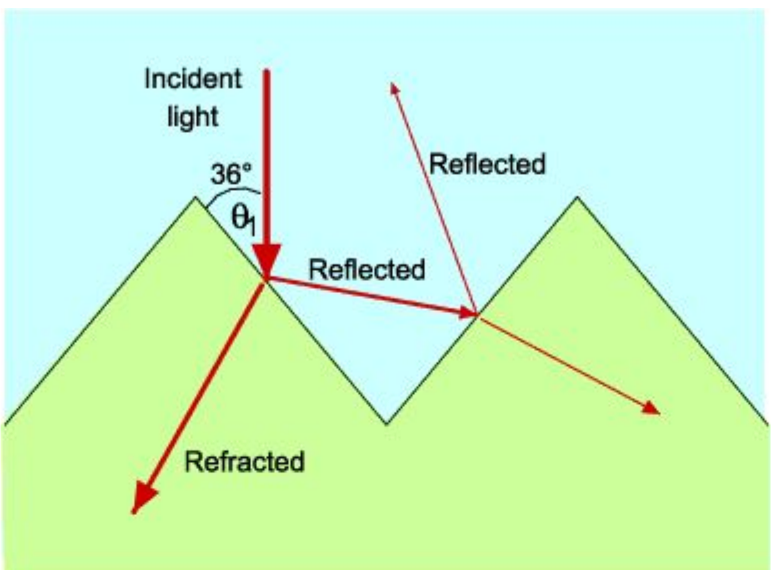
- In addition, as discussed in the Voltage Losses Due to Recombination, a thinner solar cell which retains the absorption of the thicker device may have a higher voltage. Consequently, an optimum solar cell structure will typically have "light trapping" in which the optical path length is several times the actual device thickness, where the optical path length of a device refers to the distance that an unabsorbed photon may travel within the device before it escapes out of the device. This is usually defined in terms of device thickness.

- For example, a solar cell with no light trapping features may have an optical path length of one device thickness, while a solar cell with good light trapping may have an optical path length of 50, indicating that light bounces back and forth within the cell many times.

Light trapping is usually achieved by changing the angle at which light travels in the solar cell by having it be incident on an angled surface. A textured surface will not only reduce reflection as previously described but will also couple light obliquely into the silicon, thus giving a longer optical path length than the physical device thickness. The angle at which light is refracted into the semiconductor material is, according to Snell's Law, as follows:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

In a textured single crystalline solar cell, the presence of crystallographic planes make the angle $\theta_1$ equal to 36° as shown below.



# Lambertian Rear Reflectors

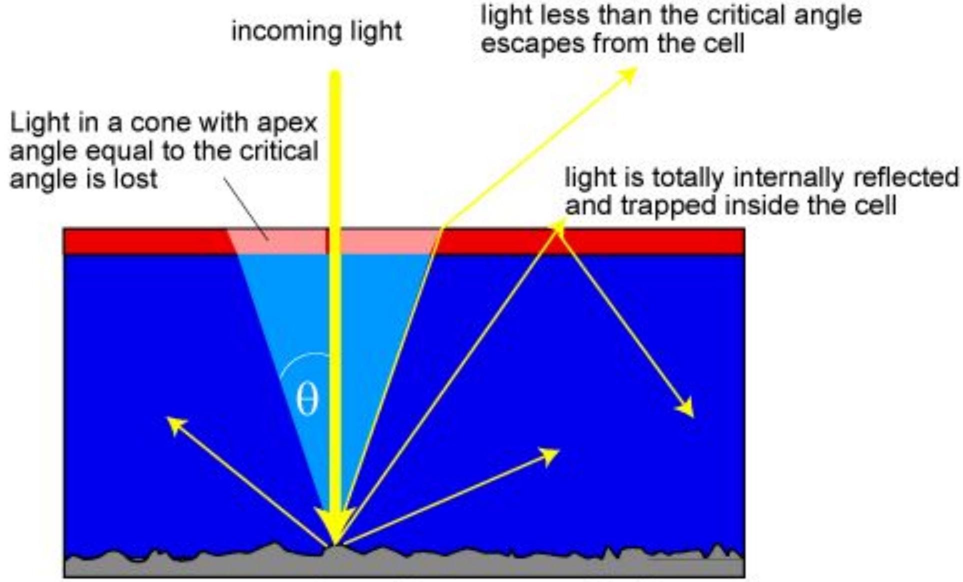
- A Lambertian back reflector is a special type of rear reflector which randomizes the direction of the reflected light.

- High reflection off the rear cell surface reduces absorption in the rear cell contacts or transmission from the rear, allowing the light to bounce back into the cell for possible absorption.

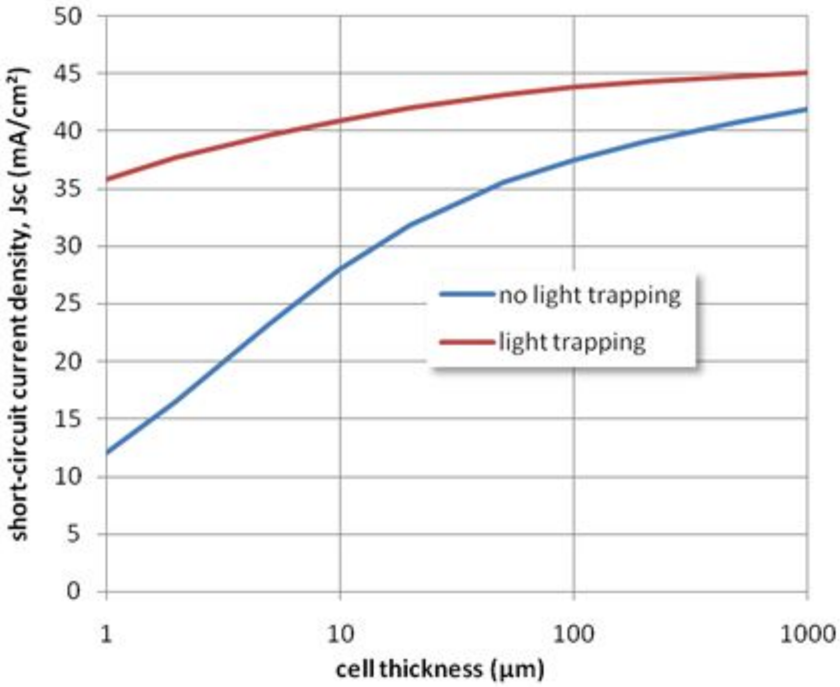
- Randomising the direction of light allows much of the reflected light to be totally internally reflected. Light reaching the top surface at an angle greater than the critical angle for total internal reflection is reflected again towards the back surface.

- Light absorption can be dramatically increased in this way, since the pathlength of the incident light can be enhanced by a factor up to $4n^2$ where n is the index of refraction for the semiconductor.

This allows an optical path length of approximately 50 ($4 \times 3.5^2 \approx 50$) times the physical devices thickness and thus is an effective light trapping scheme. A Lambertian rear surface is illustrated in the figure below.




Light trapping using a randomised reflector on the rear of the cell. Light less than the critical angle escapes the cell but light greater than the critical angle is totally internally reflected inside the cell. In actual devices, the front surface is also textured using schemes such as the random pyramids mentioned earlier.




Light trapping increases the short-circuit current ($J_{SC}$) of the solar cell - particularly for thin devices.

# Recombination Losses

Recombination losses effect both the current collection (and therefore the short-circuit current) as well as the forward bias injection current (and therefore the open-circuit voltage).

Recombination is frequently classified according to the region of the cell in which it occurs.

Typically, recombination at the surface (surface recombination) or in the bulk of the solar cell (bulk recombination) are the main areas of recombination. The depletion region is another area in which recombination can occur (depletion region recombination).

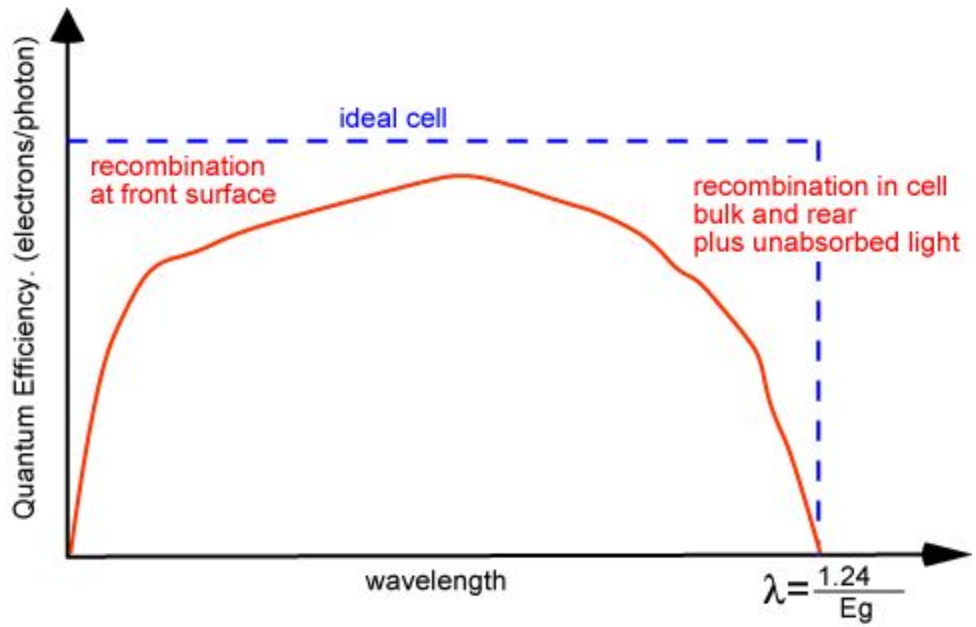
http://www.pveducation.org/pvcdrom/design/surface-recombination

# Current Losses Due to Recombination

In order for the *p-n* junction to be able to collect all of the light-generated carriers, both surface and bulk recombination must be minimised. In silicon solar cells, the two conditions commonly required for such current collection are:

- the carrier must be generated within a diffusion length of the junction, so that it will be able to diffuse to the junction before recombining; and

- in the case of a localized high recombination site (such as at an unpassivated surface or at a grain boundary in multicrystalline devices), the carrier must be generated closer to the junction than to the recombination site. For less severe localised recombination sites, (such as a passivated surface), carriers can be generated closer to the recombination site while still being able to diffuse to the junction and be collected without recombining.




Typical quantum efficiency in an ideal and actual solar cell, illustrating the impact of optical and recombination losses.

# Voltage Losses due to Recombination

The open-circuit voltage is the voltage at which the forward bias diffusion current is exactly equal to the short circuit current. The forward bias diffusion current is dependent on the amount recombination in a *p-n* junction and increasing the recombination increases the forward bias current. Consequently, high recombination increases the forward bias diffusion current, which in turn reduces the open-circuit voltage. The material parameter which gives the recombination in forward bias is the diode saturation current. The recombination is controlled by the number of minority carriers at the junction edge, how fast they move away from the junction and how quickly they recombine. Consequently, the dark forward bias current, an hence the open-circuit voltage is affected by the following parameters:

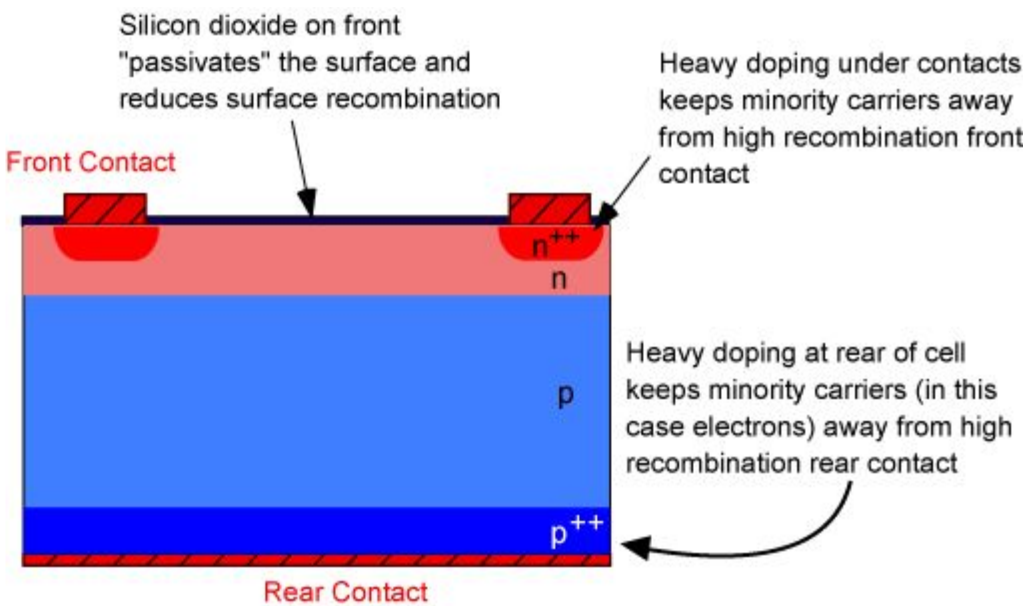
- the number of minority carriers at the junction edge. The number of minority carriers injected from the other side is simply the number of minority carriers in equilibrium multiplied by an exponential factor which depends on the voltage and the temperature. Therefore, minimising the equilibrium minority carrier concentration reduces recombination. Minimizing the equilibrium carrier concentration is achieved by **increasing the doping**;

- the diffusion length in the material. A low diffusion length means that minority carriers disappear from the junction edge quickly due to recombination, thus allowing more carriers to cross and increasing the forward bias current. Consequently, to minimise recombination and achieve a high voltage, a **high diffusion length is required.** The diffusion length depends on the types of material, the processing history of the wafer and the doping in the wafer. High doping reduces the diffusion length, thus introducing a trade-off between maintaining a high diffusion length (which affects both the current and voltage) and achieving a high voltage;

- the presence of localised recombination sources within a diffusion length of the junction. A high recombination source close to the junction (usually a surface or a grain boundary) will allow carriers to move to this recombination source very quickly and recombine, thus dramatically increasing the recombination current. The impact of surface recombination is reduced by **passivating the surfaces**.

# Surface Recombination

Surface recombination can have a major impact both on the short-circuit current and on the open-circuit voltage. High recombination rates at the top surface have a particularly detrimental impact on the short-circuit current since top surface also corresponds to the highest generation region of carriers in the solar cell. Lowering the high top surface recombination is typically accomplished by reducing the number of dangling silicon bonds at the top surface by using "passivating" layer on the top surface. The majority of the electronics industry relies on the use of a thermally grown silicon dioxide layer to passivate the surface due to the low defect states at the interface[1]. For commercial solar cells, dielectric layers such as silicon nitride are commonly used.




Techniques for reducing the impact of surface recombination.

Since the passivating layer for silicon solar cells is usually an insulator, any region which has an ohmic metal contact cannot be passivated using silicon dioxide. Instead, under the top contacts the effect of the surface recombination can be minimised by increasing the doping. While typically such a high doping severely degrades the diffusion length, the contact regions do not participate in carrier generation and hence the impact on carrier collection is unimportant. In addition, in cases where a high recombination surface is close to the junction, the lowest recombination option is to increase the doping as high as possible.

# Design for High $V_{oc}$:

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}} \qquad V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \qquad I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L$$

Voc: Voltage at which Isc is equal and opposite to forward bias diffusion current.

Depends upon recombination rate

Any increase in recombination rate: increase in I0: decrease in Voc

Low recombination rate:

passivated surface to reduce surface recombination

large diffusion length

high doping reduces the diffusion length: optimized doping

cell volume should be small: if large thickness then carriers generated near to base may recombine

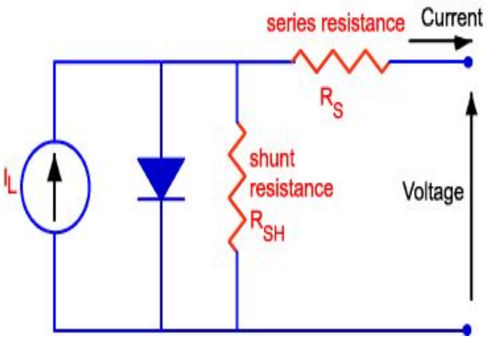
# Design for High FF:

Maximum absorption:
High $I_L$

Minimum recombination:
High $I_L$ & $V_{oc}$

Minimum resistive losses

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$




Series Resistance
as low as possible

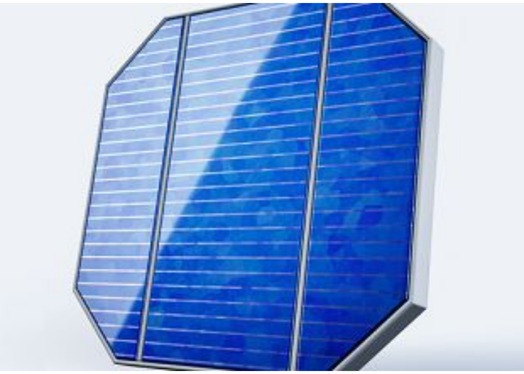
Shunt resistance
as high as possible

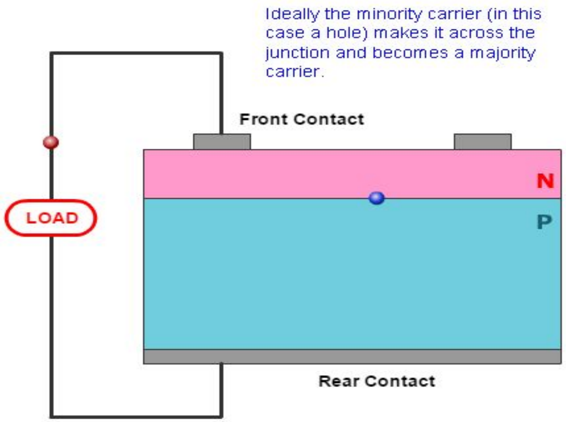
Design parameter

Processing parameter
faulty solar cell processing
Decreases Rsh

# Contact Design

To collect the current:

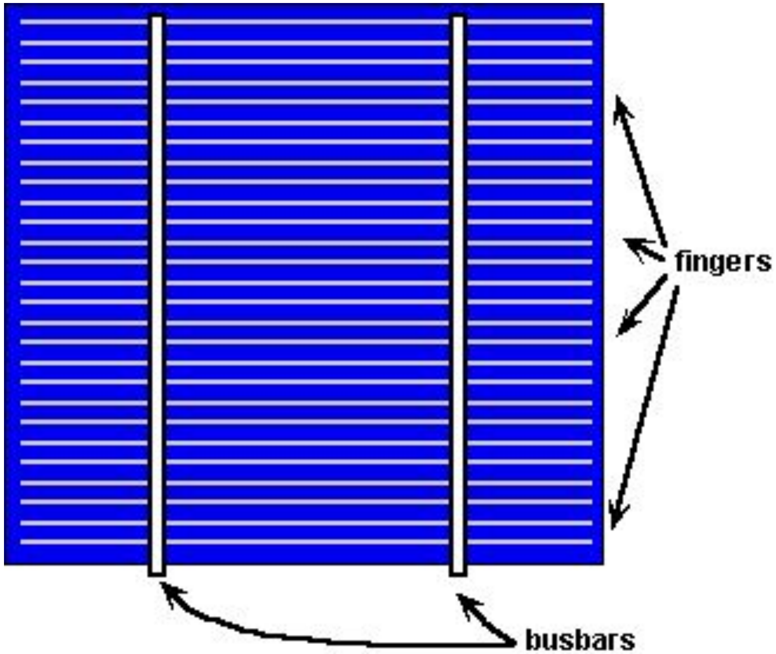


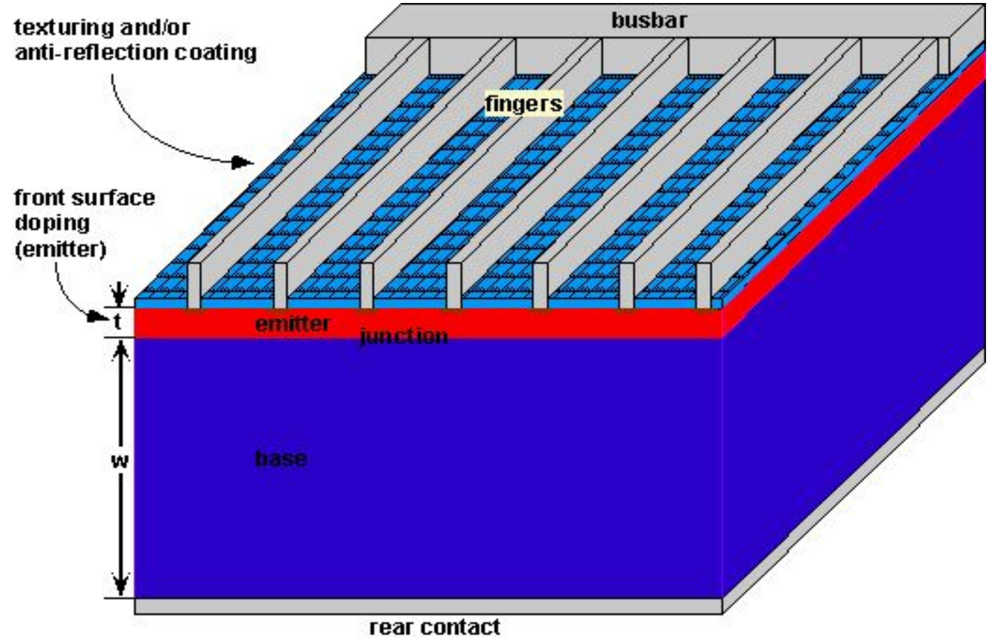


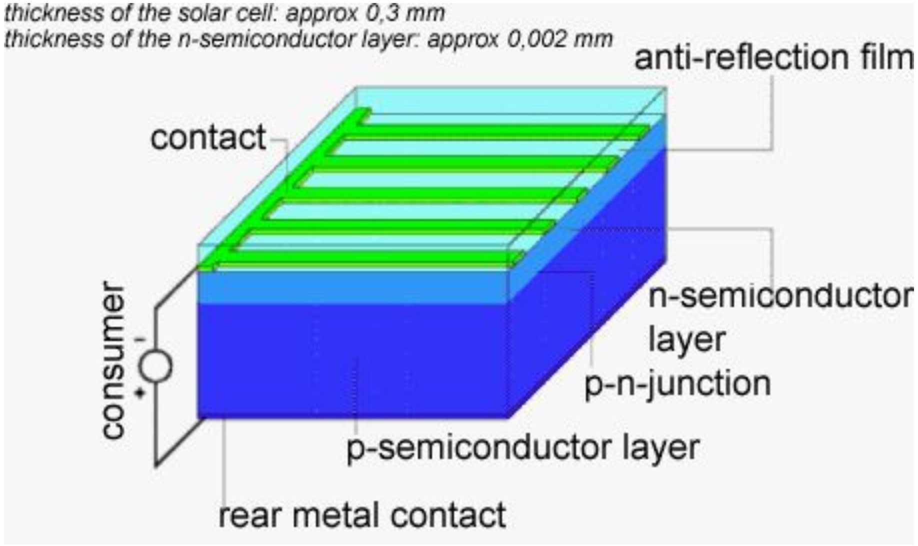
# Series Resistance

In addition to maximizing absorption and minimizing recombination, the final condition necessary to design a high efficiency solar cell is to minimise parasitic resistive losses. Both shunt and series resistance losses decrease the fill factor and efficiency of a solar cell. A detrimentally low shunt resistance is a processing defect rather than a design parameter. However, the series resistance, controlled by the top contact design and emitter resistance, needs to be carefully designed for each type and size of solar cell structure in order to optimise solar cell efficiency.

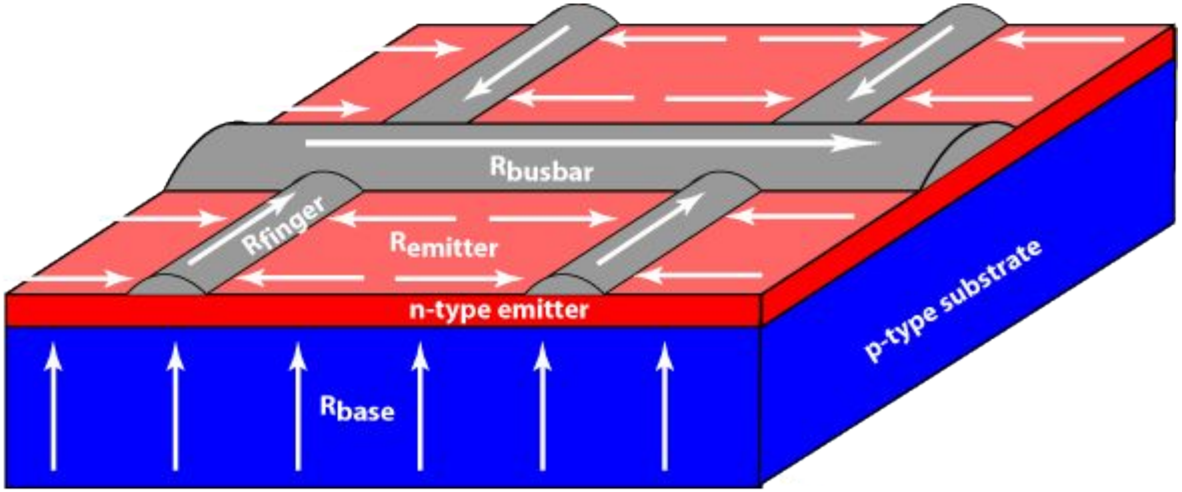
The series resistance of a solar cell consists of several components as shown in the diagram. Of these components, the emitter and top grid (consisting of the finger and busbar resistance) dominate the overall series resistance and are therefore most heavily optimised in solar cell design.




Why not single contact to ????

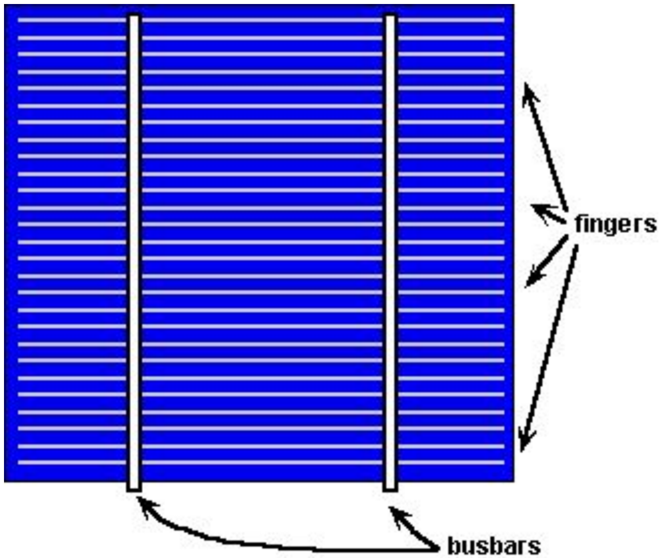



Resistive components and current flows in a solar cell.

Metallic contact: necessary to collect generated current

Fingers:
collect the current from all over emitter

Busbar:
Collect the current from all fingers & deliver to eternal circuit




Top contact design in a solar cell. The busbars connect the fingers together and pass the generated current to the external electrical contacts.

# Resistance Rs...???

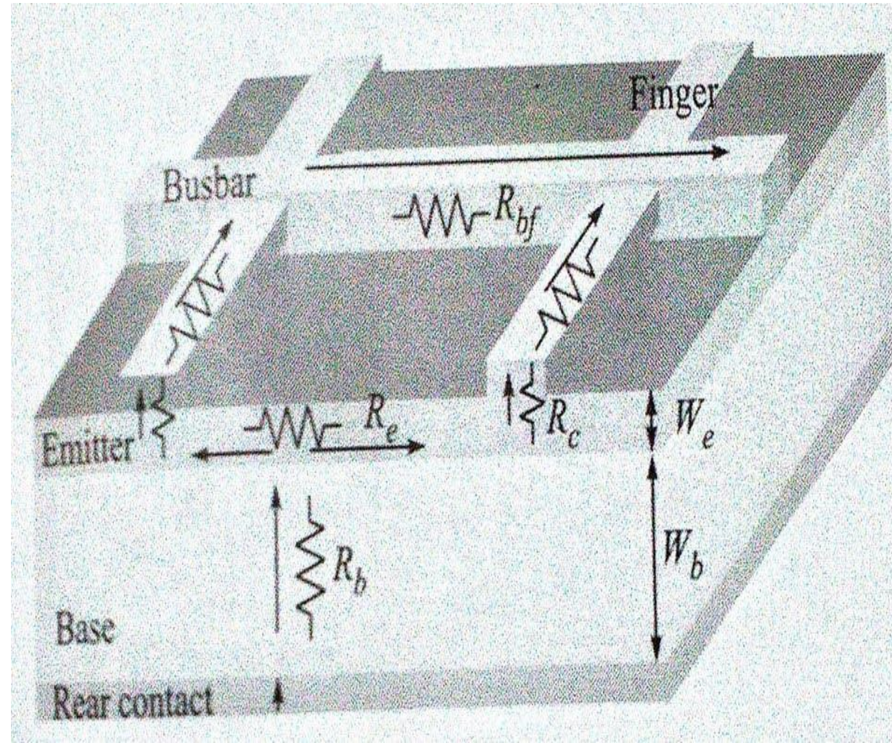
Resultant..??

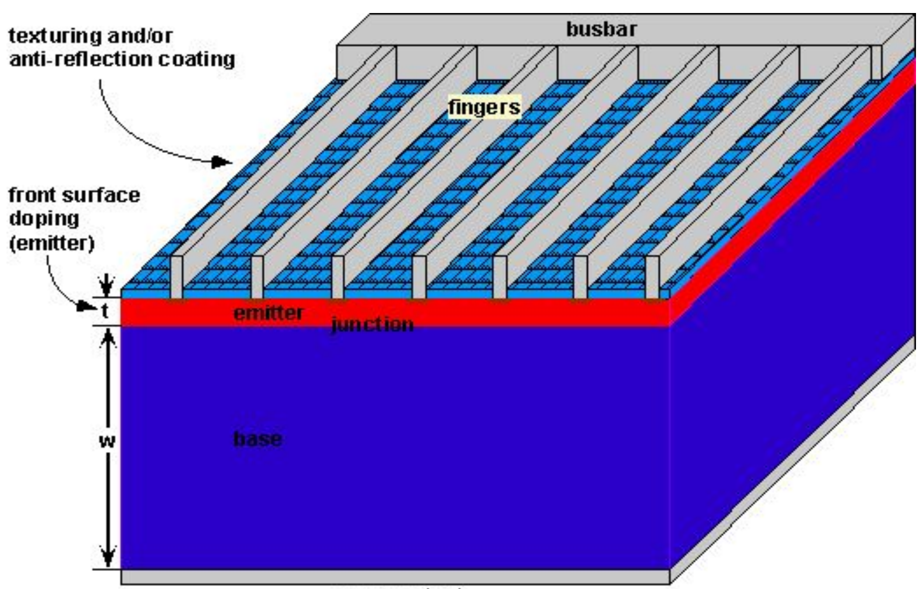
Series :

- Base resistance Rb
- Emitter resistance Re
- Resistance of metal contact at front and back Rbf
- Resistance of semicond-metal Interface Rc

Rs = Rb + Re + Rc + Rbf

Re and Rbf most dominating resistance.



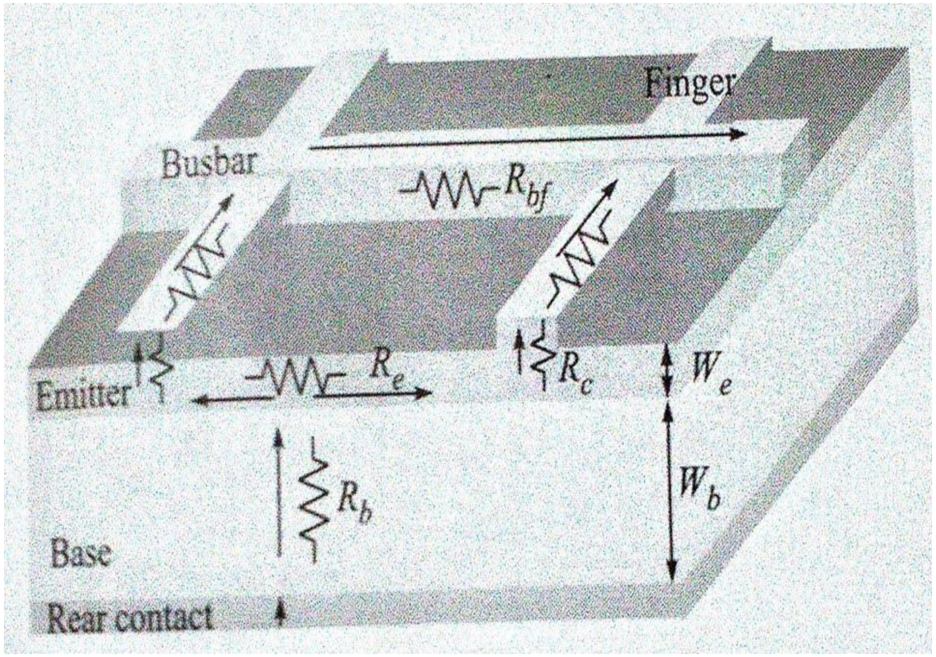

The key design trade-off in top contact design:

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.

# Base Resistance

Base is uniformly doped

current typically flows perpendicular to the cell surface from the bulk of the cell and then laterally through the top doped layer until it is collected at a top surface contact




$$R_b = \frac{\rho_b W_b}{A} \qquad = \frac{\rho_b W}{A}$$

We<<Wb
Wb=W

taking into account the thickness of the material. Where:
l = length of conducting (resistive) path
$\rho_b$= "bulk resistivity" (inverse of conductivity) of the bulk cell material (0.5 - 5.0 Ω cm for a typical silicon solar cell)
*A* = cell area, and
w = width of bulk region of cell.

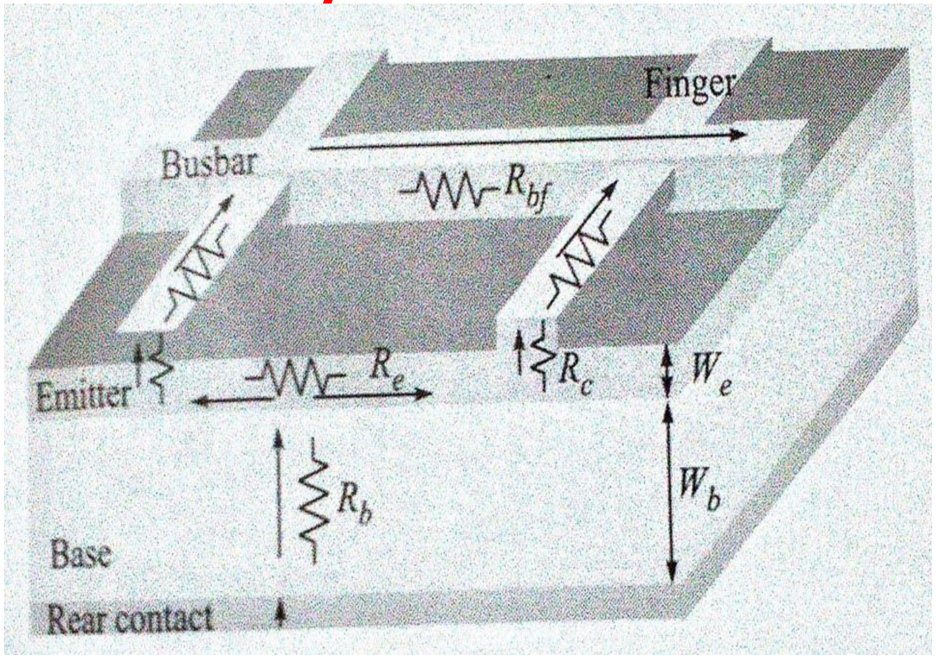
# Emitter/Sheet Resistivity

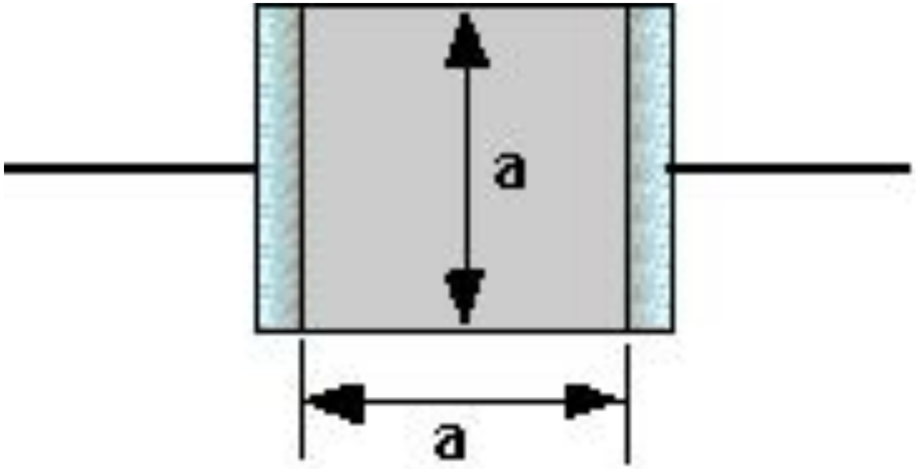
current in emitter is in lateral direction.

Emitter formed by diffusion process at high T, doping of emitter not uniform
And no accurate We.

Difficult to get accurate Re

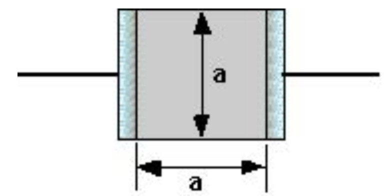
sheet resistivity:
depends on both the resistivity and the thickness, can be readily measured for the top surface *n*-type layer.



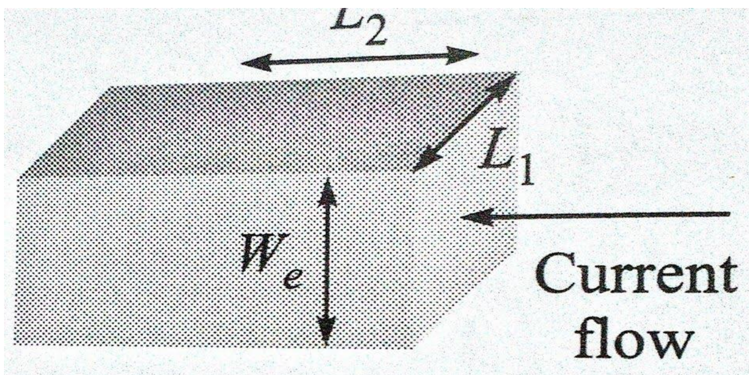



# Emitter/Sheet Resistivity

$$\rho_{\square} = \rho_{sh} = \frac{\rho}{W_e} = \frac{1}{q\mu_n(x)N_d(x)W_e}$$




$$R_e = \frac{\rho l}{A} = \frac{\rho l_2}{W_e l_1} = \frac{\rho_{sh} a}{a} = \rho_{sh} \quad for \;\; square \;\; sheet$$



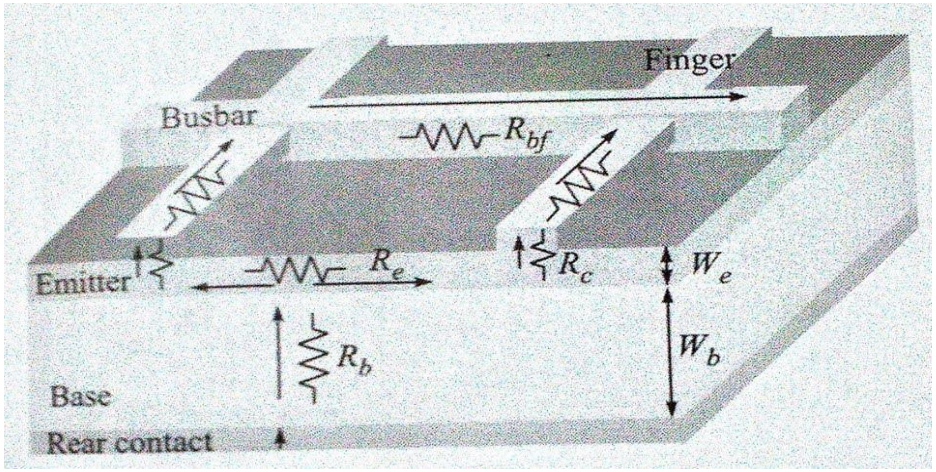

Where ρ is the resistivity of the layer; and $W_e$ is the thickness of the layer. The sheet resistivity is normally expressed as ohms/square or Ω/□.

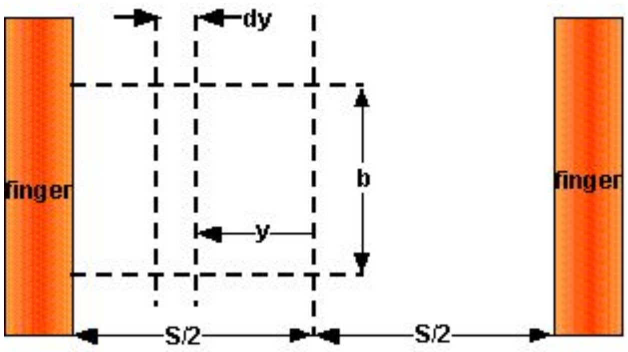
The resistance of a square conductive sheet is the same no matter what size it is so long as it remains a square.

# Power Loss in Emitter

sheet resistivity gives info about the power loss due to the emitter resistance as a function of finger spacing in the top contact.

the distance that current flows in the emitter is not constant. Current can be collected from the base close to the finger and therefore has only a short distance to flow to the finger or, alternatively, if the current enters the emitter between the fingers, then the length of the resistive path seen by such a carrier is half the grid spacing.



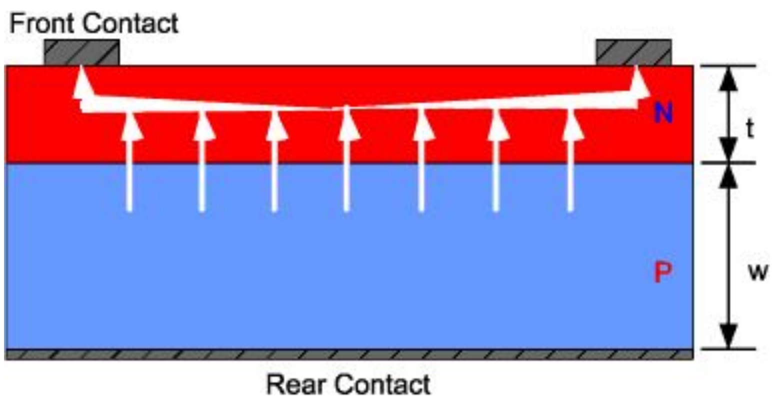




Current density in emitter is not uniform

Idealised current flow from point of generation to external contact in a solar cell. The emitter is typically much thinner than shown in the diagram.

# Emitter Resistance

Based on the sheet resistivity, the power loss due to the emitter resistance can be calculated as a function of finger spacing in the top contact. However, the distance that current flows in the emitter is not constant. Current can be collected from the base close to the finger and therefore has only a short distance to flow to the finger or, alternatively, if the current enters the emitter between the fingers, then the length of the resistive path seen by such a carrier is half the grid spacing.




Idealised current flow from point of generation to external contact in a solar cell. The emitter is typically much thinner than shown in the diagram.

The incremental power loss in the section *dy* is given by:

$$dP_{loss} = I^2 dR$$

The differential resistance is given by: $= \frac{\rho_{sh}}{b} dy$ ??????

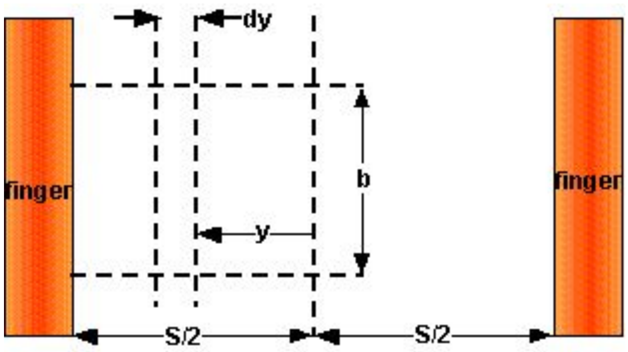
$$dR = \frac{\rho}{A} dy \quad = \frac{\rho}{W_e b} dy \quad = \frac{\rho_{sh}}{b} dy$$

where

ρ is the sheet resistivity in Ω/sqr

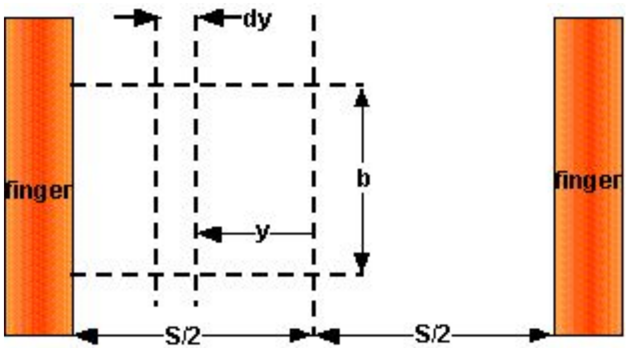
b is the distance along the finger; and

y the distance between two grid fingers as shown below.




Dimensions needed for calculating power loss due to the lateral resistance of the top layer.

The current also depends on y and I(y) is the lateral current flow, which is zero at the midpoint between grating lines and increases linearly to its maximum at the grating line, under uniform illumination. The equation for the current is:




$$I(y) = Jby$$

where

J is the current density;

b is the distance along the finger; and

y the distance between two grid fingers as shown in fig.

The total power loss is therefore:

*S* is the spacing between grid lines.

$$P_{loss} = \int I(y)^2 dR = \int_0^{S/2} \frac{J^2 b^2 y^2 \rho_\square dy}{b} = \frac{J^2 b \rho_\square S^3}{24}$$

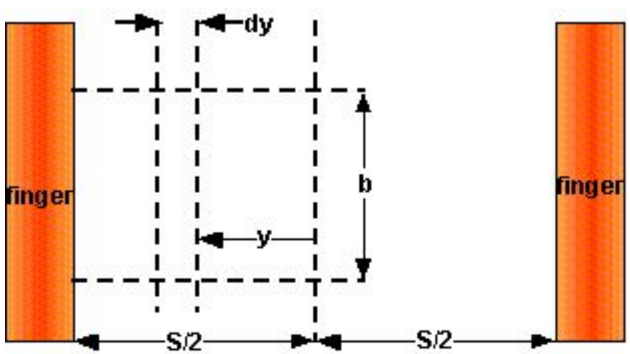
At the maximum power point, the generated power is:

$$P_{gen} = J_{MP}\, b\, \frac{S}{2} V_{MP}$$

$$P_{loss} = \frac{J^2 b \rho_{\square} S^3}{24}$$

The fractional power loss is given by:

$$P_{\% lost} = \frac{P_{loss}}{P_{gen}} = \frac{\rho_{\square} S^2 J_{MP}}{12 V_{MP}}$$



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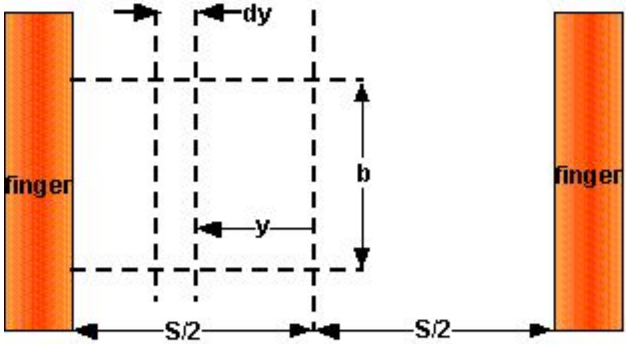


The fractional power loss is given by:

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Claculate finger spacing for a typical silicon solar cell where $\rho$= 40 Ω/sq, $J_{mp}$ = 30 mA/cm$^2$, $V_{mp}$ = 450 mV, to have a power loss in the emitter of less than 4%.

Hence, the minimum spacing for the top contact grid can be calculated.

to have a power loss in the emitter of less than 4% the finger spacing should be less than 4 mm.

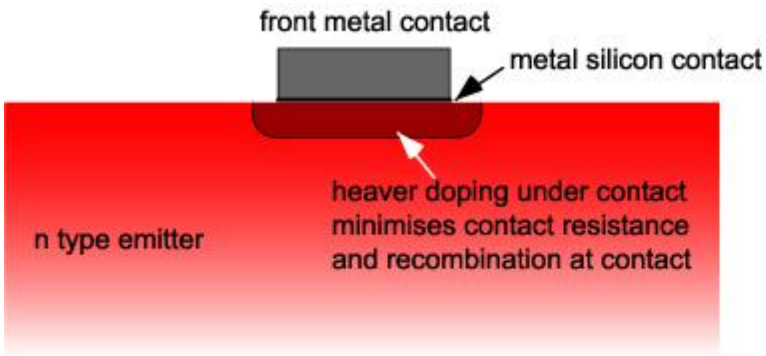
# Contact resistance

Contact resistance losses occur at the interface between the silicon solar cell and the metal contact.

To keep top contact losses low, the top $N^+$ layer must be as heavily doped as possible. However, a high doping level creates other problems.

If a high level of phosphorus is diffused into silicon, the excess phosphorus lies at the surface of the cell, creating a "dead layer", where light generated carriers have little chance of being collected.

Many commercial cells have a poor "blue" response due to this "dead layer". Therefore, the region under the contacts should be heavily doped, while the doping of the emitter is controlled by the trade-offs between achieving a low saturation current in the emitter and maintaining a high emitter diffusion length.

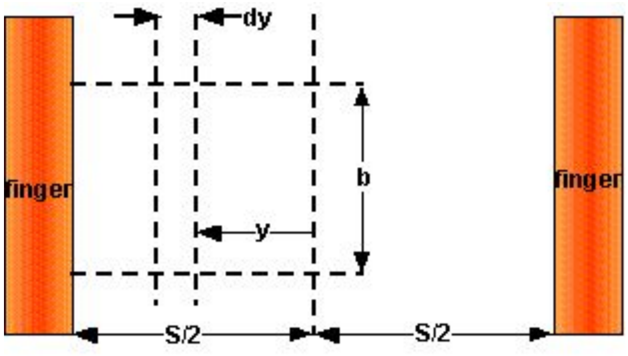



Points of contact resistance losses at interface between grid lines and semiconductor.

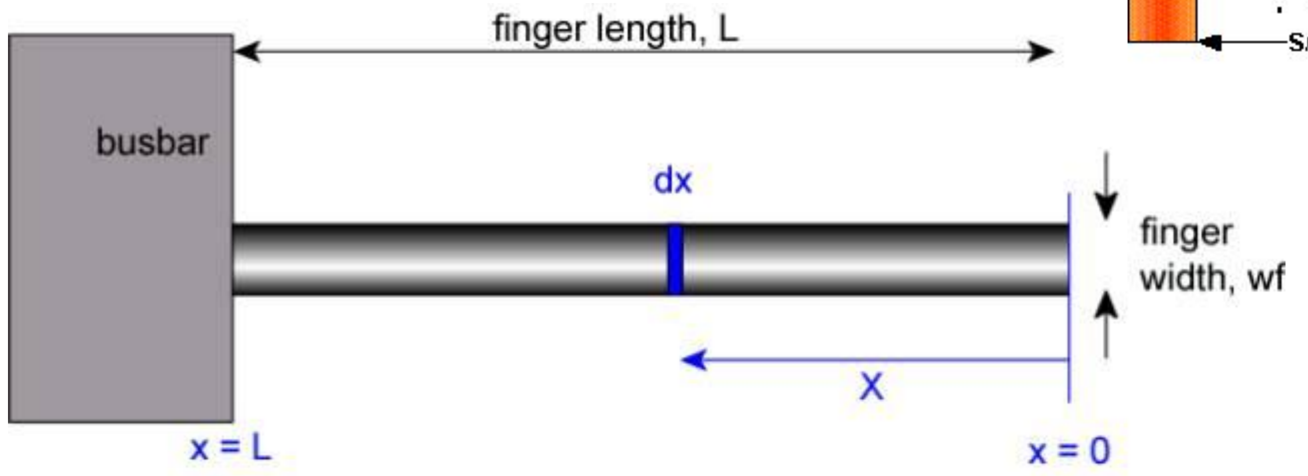
In commercial screen printed solar cells the contact resistance varies across the wafer. The physics of silver paste firing are quite complicated so small differences in surface topology and local heating cause large variations in the quality of the silver-silicon bond.

# Finger Resistance

To provide higher conductivity, the top of a cell has a series of regularly spaced finger. While tapered fingers theoretically provide lower losses technology limitations mean that fingers are usually uniform in width. The resistive loss in a finger is calculated as below.



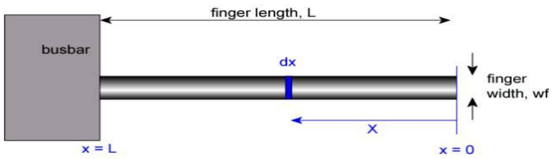

**Calculation of Power Loss in the Fingers**




Calculation of the power loss in a single finger. The width is assumed constant and it is assumed that the current is uniformly generated and that it flows perpendicularly into the finger, i.e., no current flow directly into the busbar.

Consider an element dx at a distance x from the end of the finger.

The current through the element dx is: $xJ_{MP}S_f$




where $J_{mp}$ is the current at maximum power point and $S_f$ is the finger spacing.

The resistance of the element dx is: $$\frac{dx\rho_f}{w_f d_f}$$

where $w_f$ is the finger width, $d_f$ is the finger depth (or height) and $\rho_f$ is the effective resistivity of the metal.

The power loss in the element dx is: $$I^2R = \frac{dx\rho_f}{w_f d_f}\left(xJ_{MP}S_f\right)^2$$

Integrating x from 0 to L gives the power loss in the finger:

$$\int_0^L \frac{\left(xJ_{MP}S_f\right)^2\rho_f}{w_f d_f}dx = \frac{1}{3}L^3J_{MP}^2S_f^2\frac{\rho_f}{w_f d_f}$$

Q1. Claculate finger spacing for a typical silicon solar cell where $\rho$= 40 Ω/sq, $J_{mp}$ = 30 mA/cm$^2$, $V_{mp}$ = 450 mV, to have a power loss in the emitter of less than 4%.

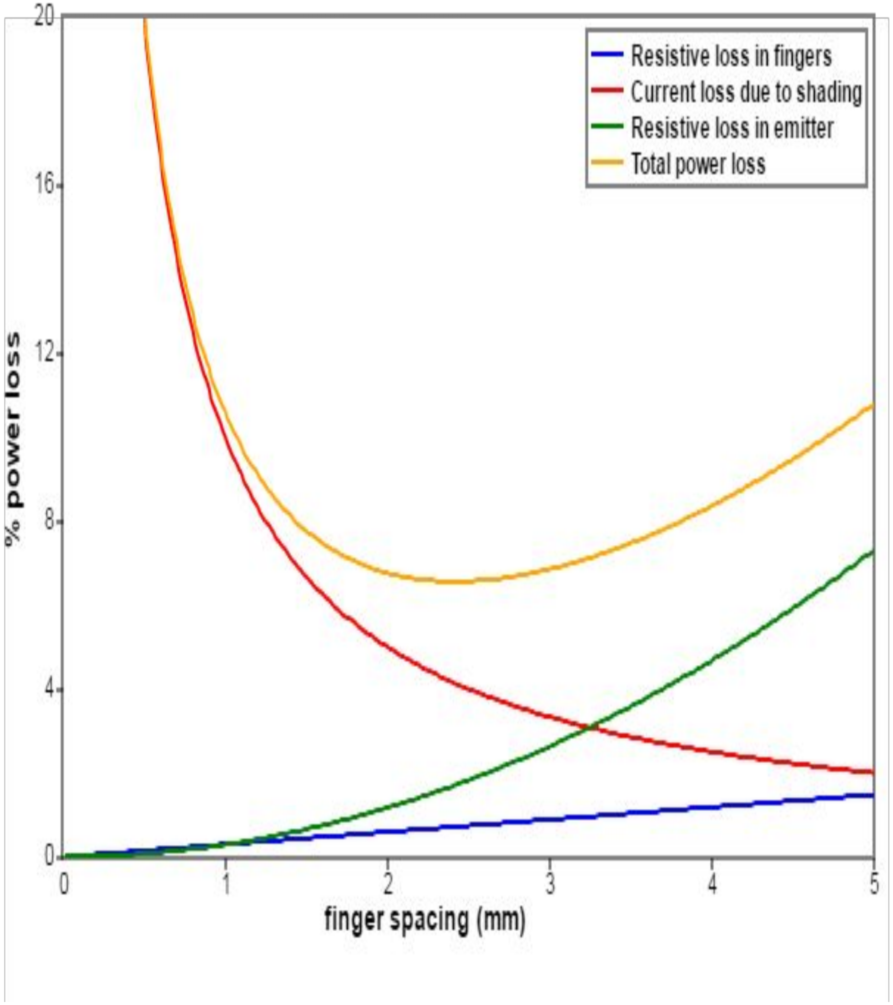
Hence, the minimum spacing for the top contact grid can be calculated.

to have a power loss in the emitter of less than 4% the finger spacing should be less than 4 mm.

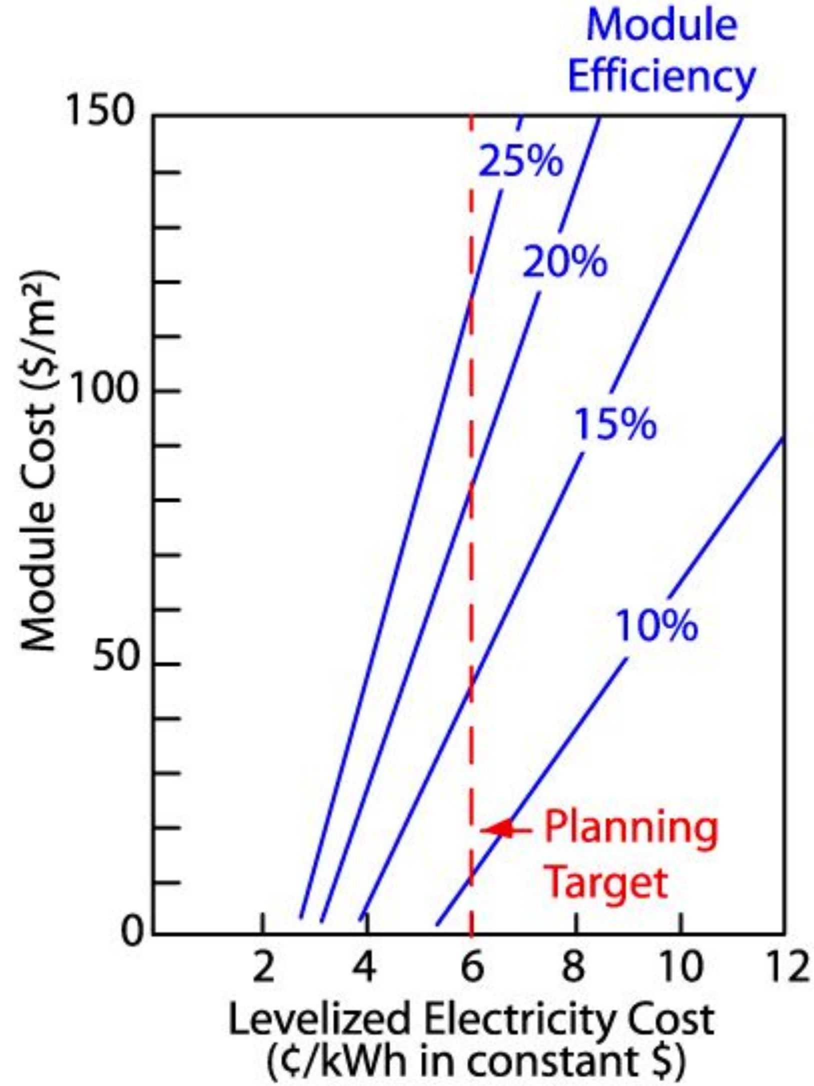
Q2. Calculate the total emitter power loss in solar cell of are 100 cm2, L is 10 cm, W is 10 cm, sheet resistance Rs of solar cell is 45Ω/•, peak current is 2.1 A, spacing b/w fingers is 2.5 mm and width of fingers is 0.1 mm and width of busbar is 2.5 mm.

Q3. A cell is realized in a material of ref index 4.2. what would be the refractive index and thickness of ARC coating for minimum reflective loss (I) when the cell is exposed to air (II) when the cell is encapsulated with glass cover?

# Solar Cell Design Principles



Resistive loss in fingers
Current loss due to shading
Resistive loss in emitter
Total power loss
% power loss
finger spacing (mm)
0
4
8
12
16
20
1
2
3
5

Module Efficiency
25%
20%
15%
10%
Planning Target
Module Cost ($/m²)
150
100
50
0
2
4
6
8
10
12
Levelized Electricity Cost
(¢/kWh in constant $)

# Types of Solar cell

## Based on the type of crystal:

1. The Monocrystalline silicon cell:

   produced from *pure silicon (single crystal).* Since the Monocrystalline silicon is pure and defect free, the efficiency of cell will be higher.

2. polycrystalline solar cell, *liquid silicon*

   is used as raw material and polycrystalline silicon was obtained followed by *solidification process*. The materials contain various crystalline sizes. Hence, the efficiency of this type of cell is less than Monocrystalline cell.

3. Amorphous silicon/Thin Film:

   *depositing silicon film on the substrate like glass plate.*

- The efficiency of amorphous cells is much lower than that of the other two

  As a result, they are used mainly in low power equipment,

## Comparison of Types of solar cell

| Material | Efficiency (%) |
|---|---|
| Monocrystalline silicon | 14-17 |
| Polycrystalline silicon | 13-15 |
| Amorphous silicon | 5-7 |

# Monocrystalline Solar Cells

# Evolution of Silicon solar cell design

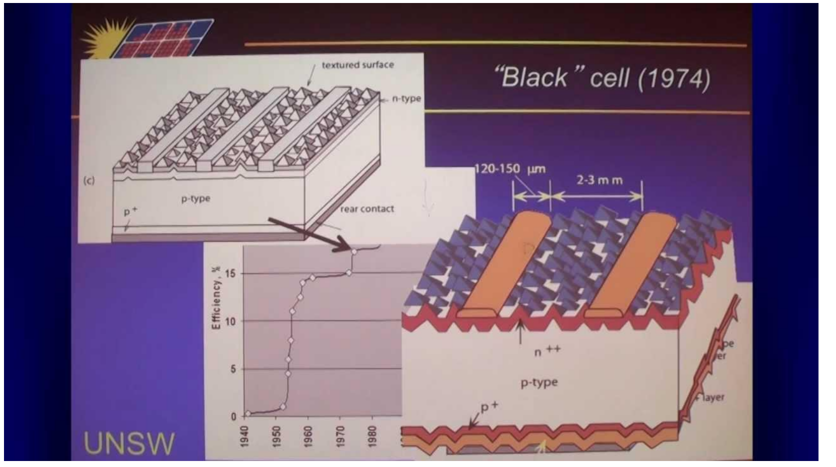
Let us look at how the strategies discussed previously have been incorporated into the design of silicon solar cell.

## Black Cells

Typical black cell designs were developed in early 1980s and exhibited efficiencies up to 17%.

They are called “black cells” because of their almost zero reflectivity.

Black cells are incorporated the innovation of the surface texturing as well as the features of the basic cell discussed earlier.



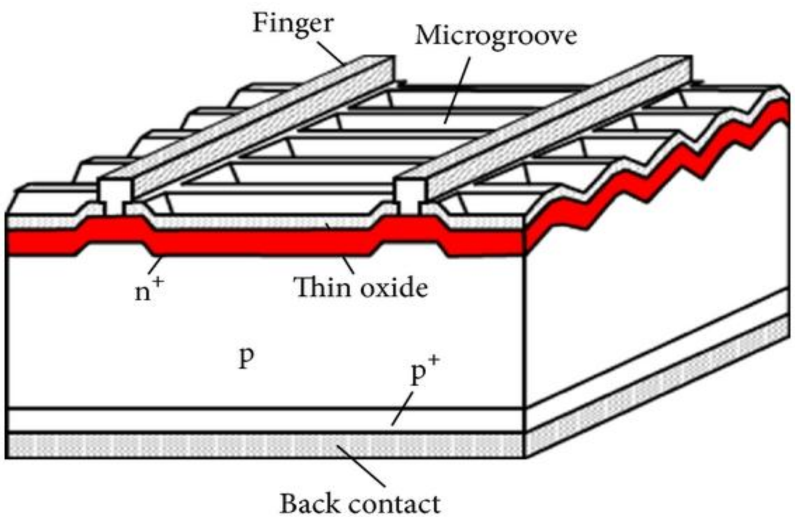
# Passivated emitter cells

- Passivated emitter solar cells (PESC) are so called because of the innovation of the passivation of the non-contacted front surface with a thin layer of silicon dioxide.

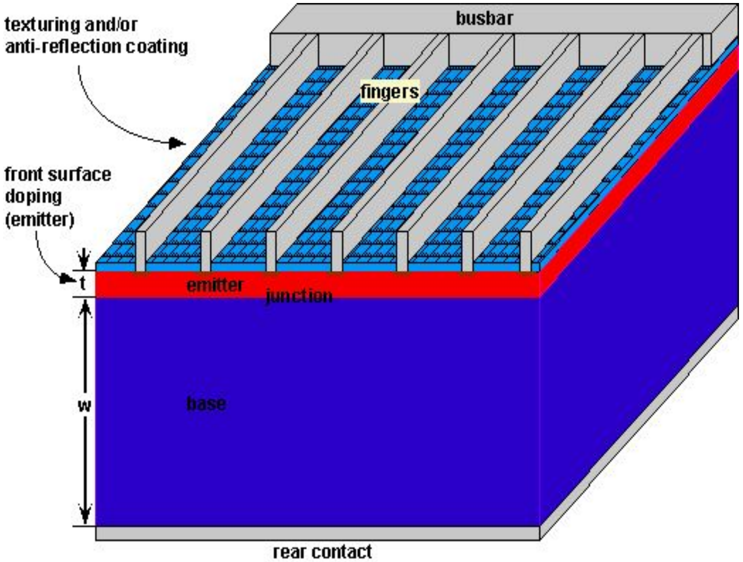
- Improvements such as these make it worthwhile using more expensive float zone produced silicon, which is better quality than CZ (Czochralski) method and has a longer diffusion length.

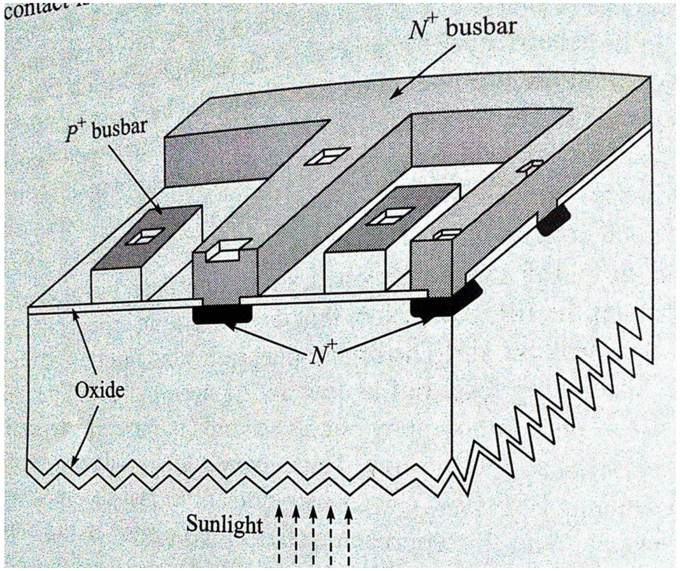
- THE PESC was designed at the University of New South Wales and achieved an efficiency of 20% in 1985.

Front surfave passivation: Sio2
Back surface field passivation: High level doping



# Rear point contact cell




No metal contact at front surface

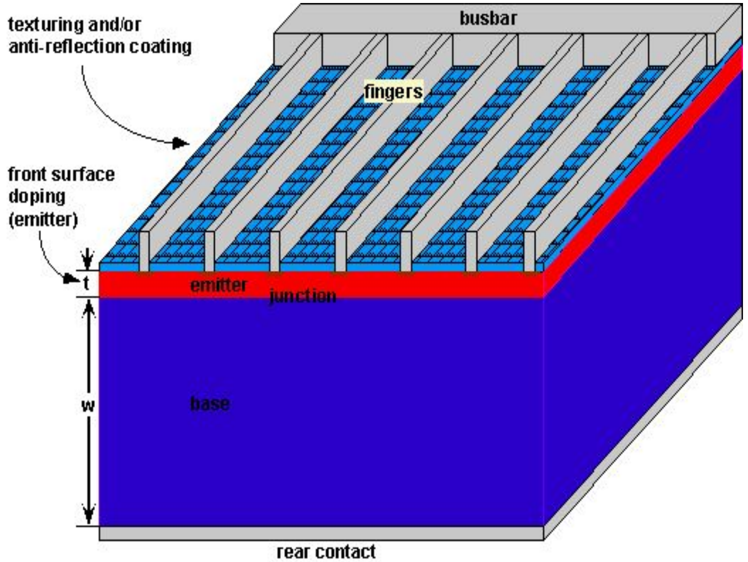
By replacing both the n and p contacts on the rear of the cell,

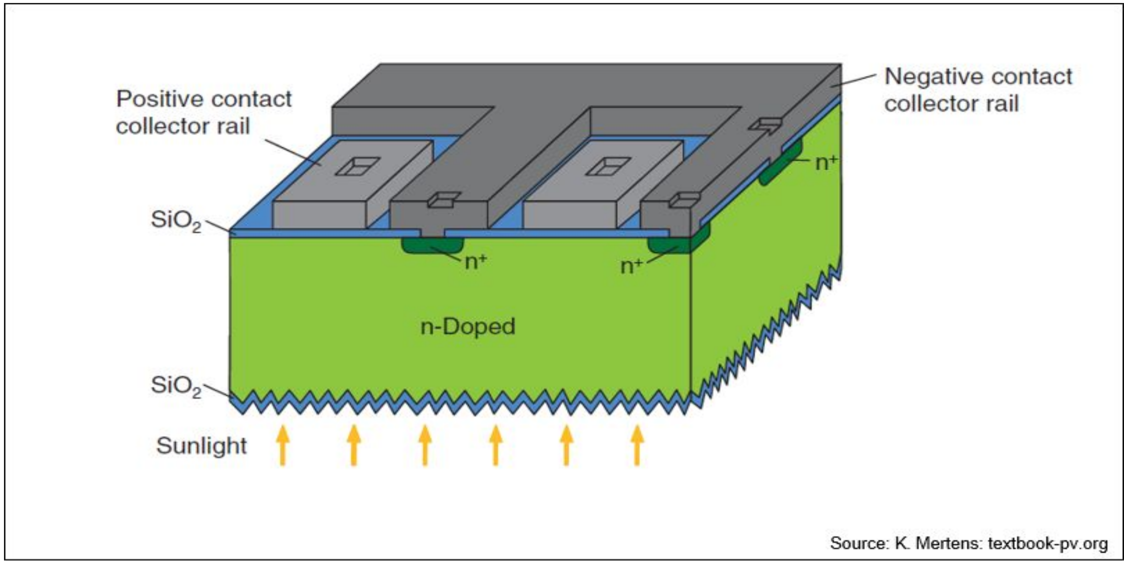
-  eliminates shading losses entirely.
- N+ diffused through local lethography
- Thermal oxide layer for both surface  (batter passivation than BSE)

- Whole back surface for contact: low resistive material can be used so high FF
- Blue light is absorbed away from junction so no need to optimize junction depth

- Efficiency increases upto 22% due to no shadowing loss and batter passivation and diffusion length

# Rear point contact cell

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# Rear point contact cell

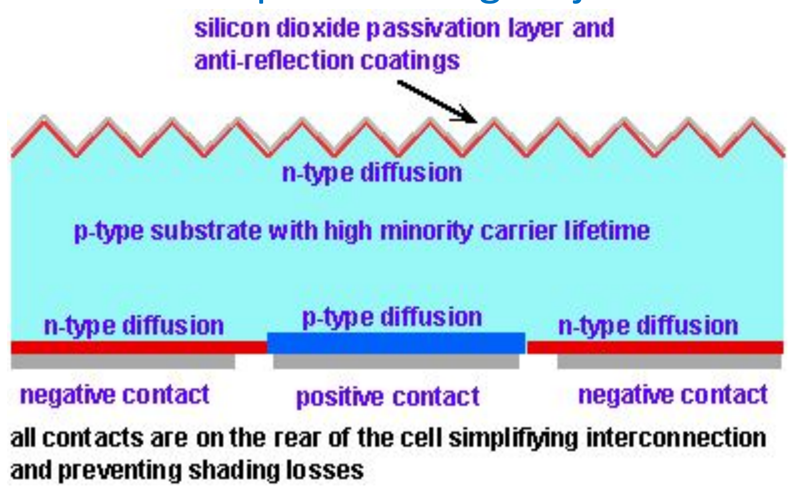
-  Extremely high purity material is needed
    - Diffuse to the rear of the cell. Large diffusion length
    - Trapping of light b/w two surface

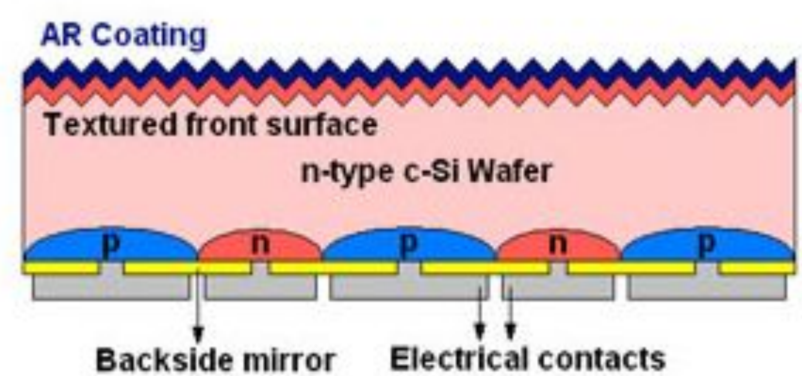
- Small space charge regions will develop at the rear of the cell between contacts of opposite polarity rather than at the front.

- Another difficulty is the risk of shorting out between contacts of opposite polarity on a single surface.

- The cell is made from lightly doped $n^-$ type silicon with heavily doped $n^+$ and $p^+$ type regions close to point contacts on the rear surface.

- The front surface is Passivated and textured as usual. The cell is thin (100 µm) and is intended to operate at high injection levels, so light trapping is important.



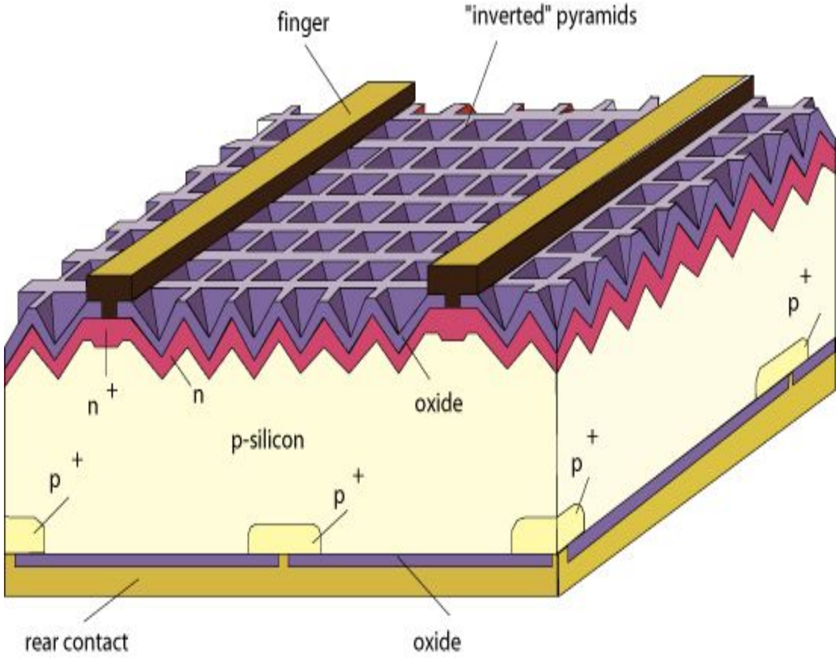
# Passivated emitter rear locally (PERL) diffused cell

- The passivated emitter rear locally diffused solar cell was developed at UNSW with an efficiency of 24% in 1994.

- The design exploits the advantage of point contacts in reducing recombination at the rear surface.

  It has the following features:

- Rear point contacts reduce the rear of the semiconductor-metal interface, where recombination is high, so that most of the rear surface may be contacted with oxide.



# Basic Si solar cell design

- A typical Si solar cell is an n-p junction made in a wafer of p type Si a few hundred µm thick and around 100 $cm^2$ in area.

- The p type wafer forms the base of the cell and is thick (300-500 µm) in order to absorb as much light as possible

- Base is lightly doped (~$10^{16}$ $cm^{-3}$) to improve diffusion lengths.

- The emitter is created by dopant diffusion and is heavily doped (~$10^{19}$ $cm^{-3}$) to reduce sheet resistance.

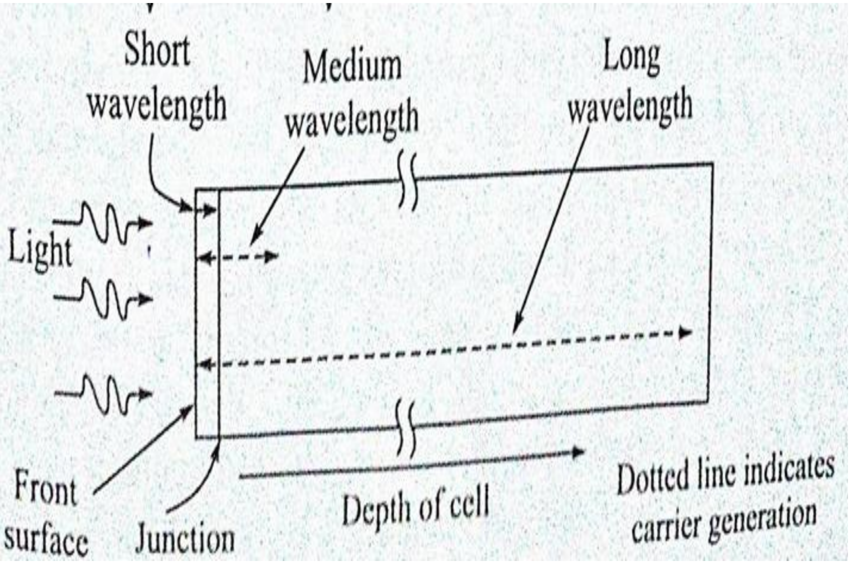
- The emitter layer should be thin (~1-5 µm) to allow as much light as possible to pass through to the base, but thick enough to keep series resistance reasonably low.

- The carrier collection front surface is negligible because of high recombination in this heavily doped layer.

- The front surface is anti-reflection coated and both front and back surfaces are connected before encapsulation in a glass covering.

# Quantum Efficiency

Probability of a incident photon resulting in generation and collection of an electron




$$QE(E) = EQE = \frac{current\ density\ collected}{q\ x\ incident\ photon\ flux\ density}$$

$$EQE = \frac{\Delta J_{sc}}{q\Delta\Phi_{\lambda}}$$

$$IQE = \frac{EQE}{1 - R(\lambda) - T(\lambda)}$$

## Quantum Efficiency Measurement parameters

- Solar cell performance for diff λ
- Material quality
  ( diffusion length and carrier life time), surface recombination
- Quality of cell fabrication/texture/passivation

.If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the QE is unity or 100%.

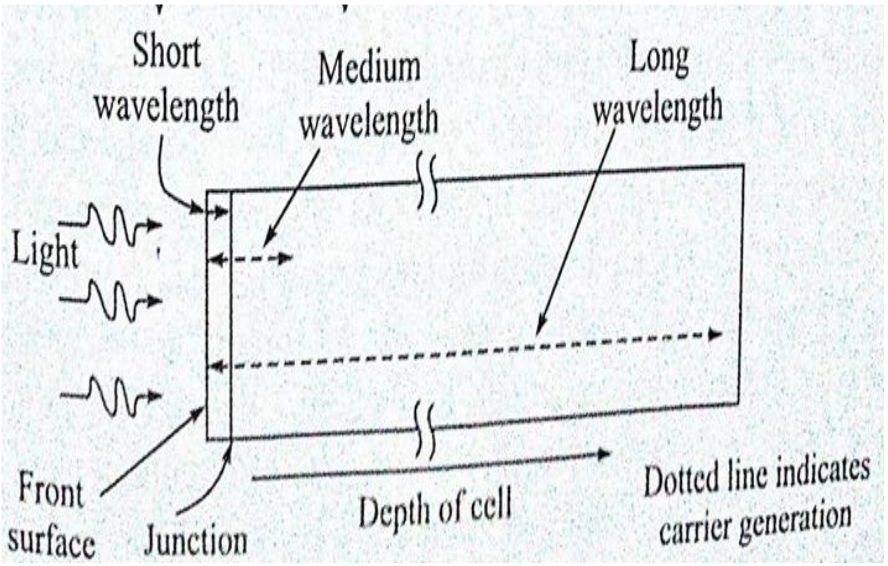
The quantum efficiency for photons with energy below the band gap is zero

Photon of different λ absorbed at different depth

Generation and collection of charge career before recombination in QE curve

High energy blue photon absorbed near to surface (100nm)

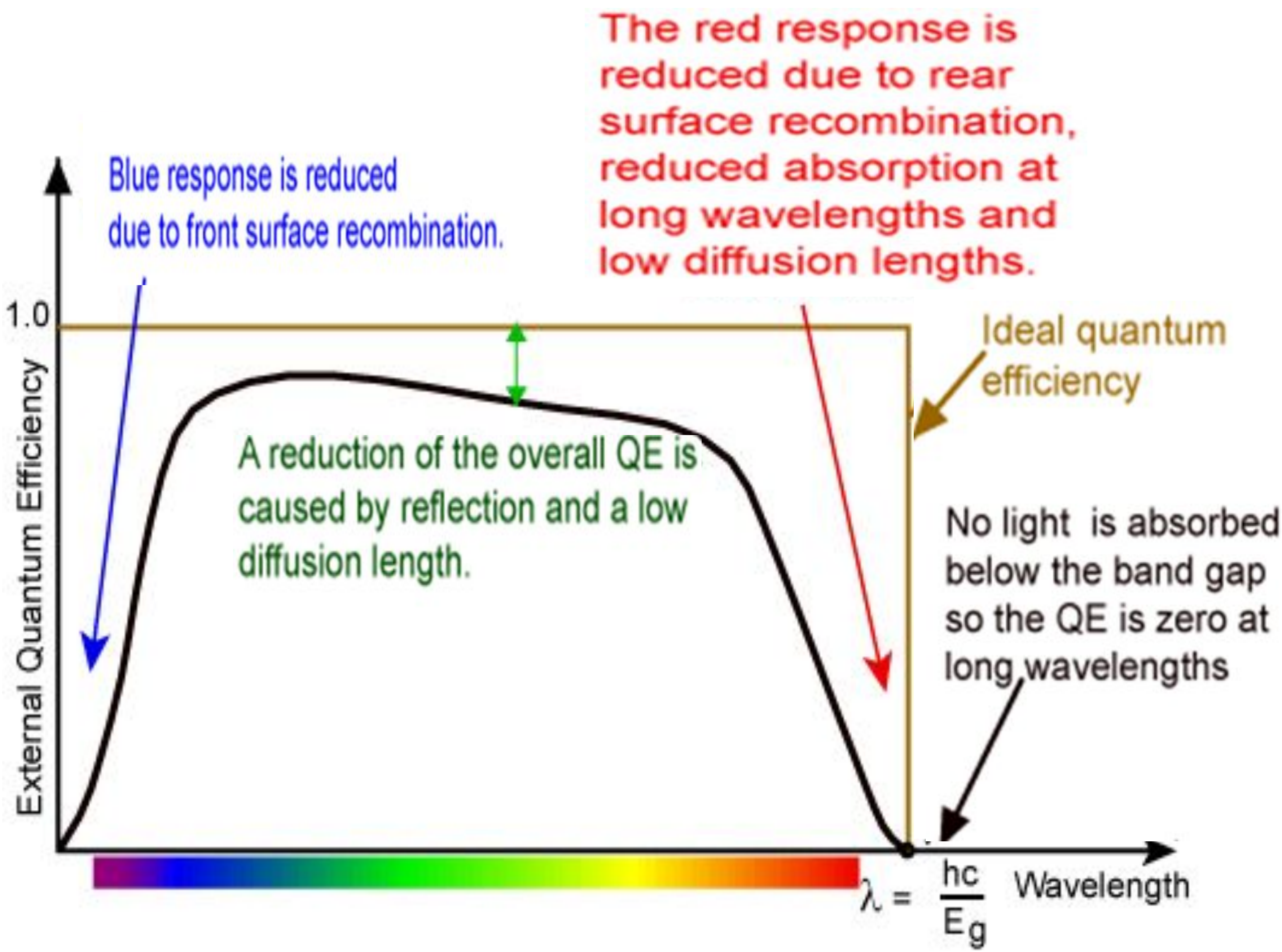
Mid λ green need few micron and Long wavelength red photon need few hundred micrometer.




QE for different λ gives info about different region

High QE for blue show high generation and collection of electron due to blue photon near the junction

Low QE for red shows, electron generated away from junction and high recombination


The red response is reduced due to rear surface recombination, reduced absorption at long wavelengths and low diffusion lengths.
Blue response is reduced due to front surface recombination.
1.0
Ideal quantum efficiency
External Quantum Efficiency
A reduction of the overall QE is caused by reflection and a low diffusion length.
No light is absorbed below the band gap so the QE is zero at long wavelengths
$\lambda = \frac{hc}{E_g}$
Wavelength

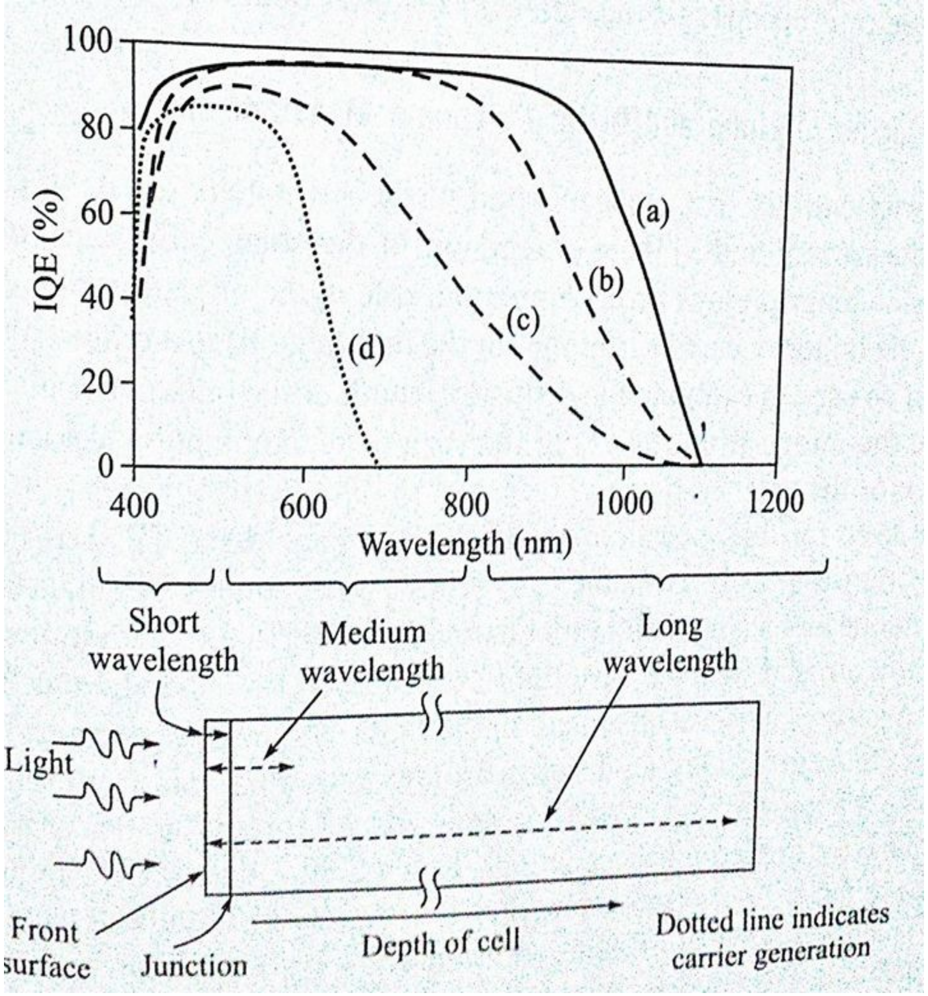
Cell a:

High QE for blue: front surface well passivated

High QE for green and red:

Junction is good , back surface recombination is low, High diffusion length,

QE is zero at 1100nm gives band gap




Cell b:

Material quality is good

Low QE in blue and red region : passivation is not good at front/back

Cell c:

Neither material nor passivation is good

Cell d:

High band gap (1.75ev) as QE is zero at 700nm