“Solar Energy” WS 2014/2015

Lecture 5:
Part 1: Operation of Real Silicon Solar Cells
Part 2: Design of Silicon Solar Cells

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KIT Focus Optics & Photonics

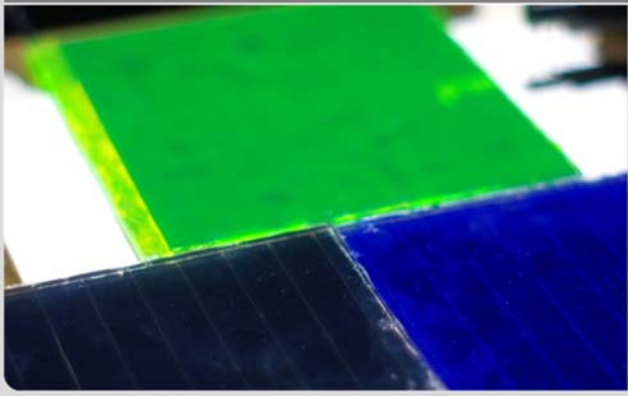
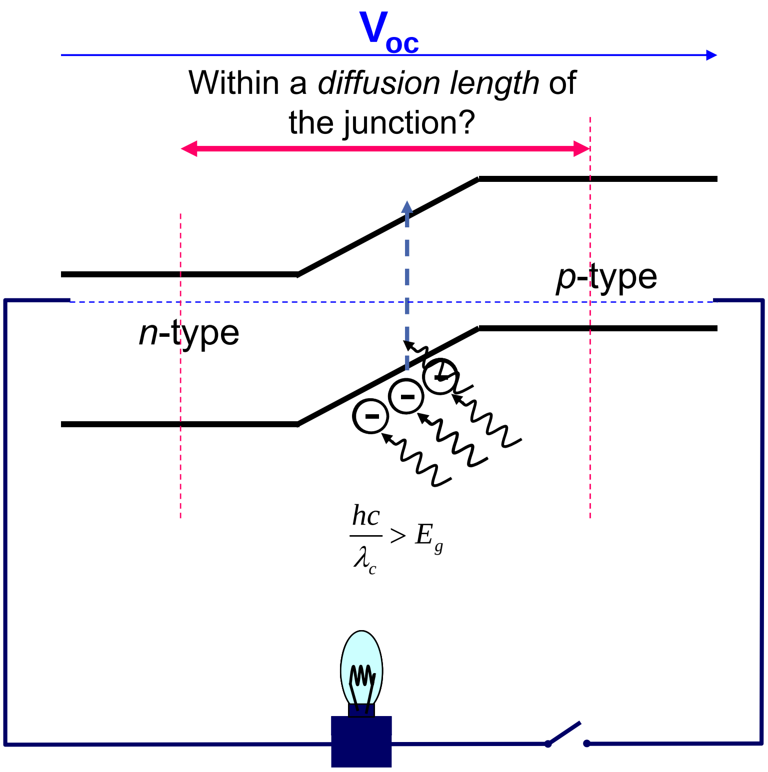


Photo-generated Current



1. *n*- and *p*-type semi’s form *pn*-junction ⇒ energy gradient ⇒ electric field
2. Electric field separates charge ⇒ current
3. Electric field gives rise to potential ⇒ voltage
4. Current at a voltage ⇒ power

OPEN CIRCUIT:

⇒ charge builds up on the contacts

⇒ charge build-up produces a potential voltage (V_{oc})

LOADED CIRCUIT

⇒ **photo current** will flow and voltage will drop

Diode Equation – Light vs Dark

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

Thermal voltage:
V_{th} = kT/q
= 25.7mV at 25°C

proportional to photon flux

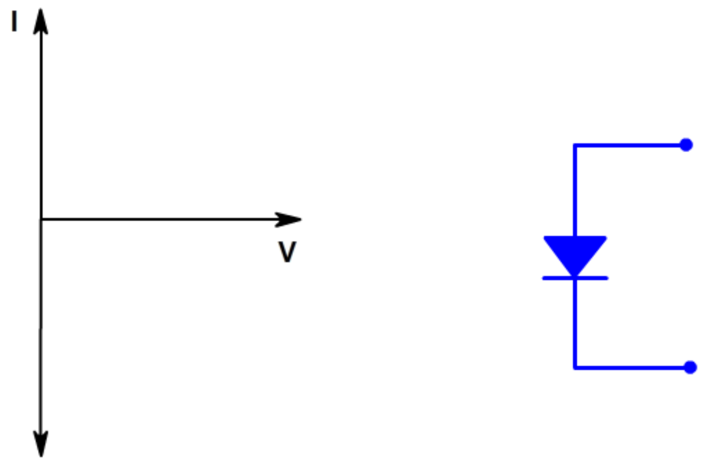
Where I_L is the photocurrent
I_0 is the diode saturation (dark) current
k is Boltzmann constant = 1.38×10^{-23} J/K
q is the electronic charge = 1.6×10^{-19} C

Typical numbers: $I_0 \cong$ 1nA – 1μA, $I_L \cong$ 3 – 4A

Short Circuit: $V = 0$, $I = I_L$
$= I_{sc}$ (under most conditions)

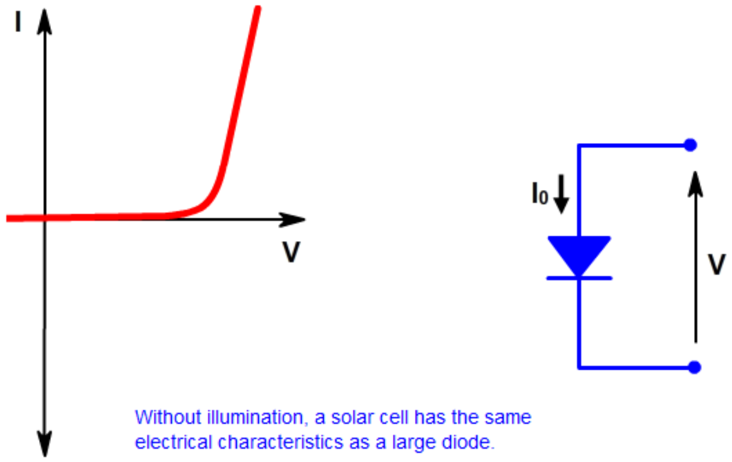
Open Circuit: $V = V_{oc}$, $I = 0$

Diode Equation – Light vs Dark



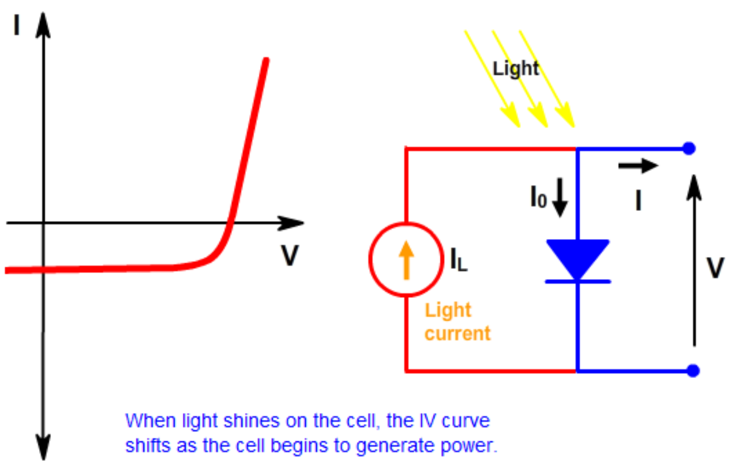
Source: adapted from Honsberg & Bowden “PVCDROM”

Diode Equation – Light vs Dark



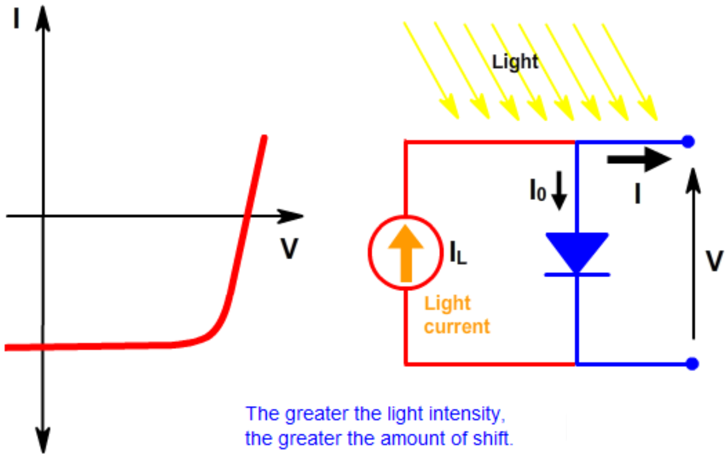
Source: adapted from Honsberg & Bowden "PVCDROM"

Diode Equation – Light vs Dark



Source: adapted from Honsberg & Bowden "PVCDROM"

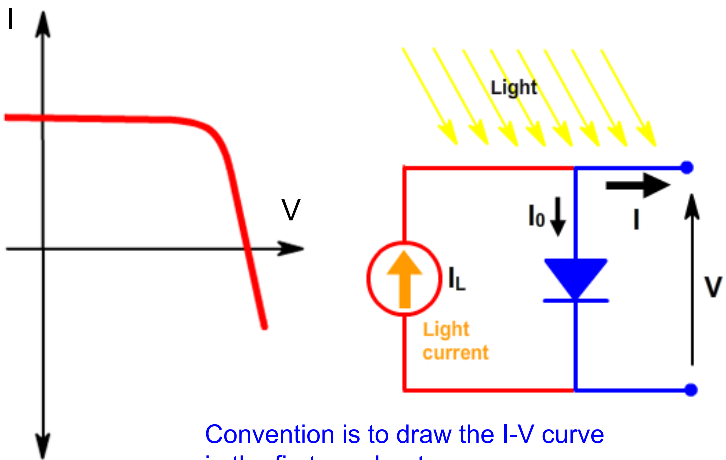
Diode Equation – Light vs Dark



The greater the light intensity, the greater the amount of shift.

Source: *adapted from Honsberg & Bowden "PVCDROM"*

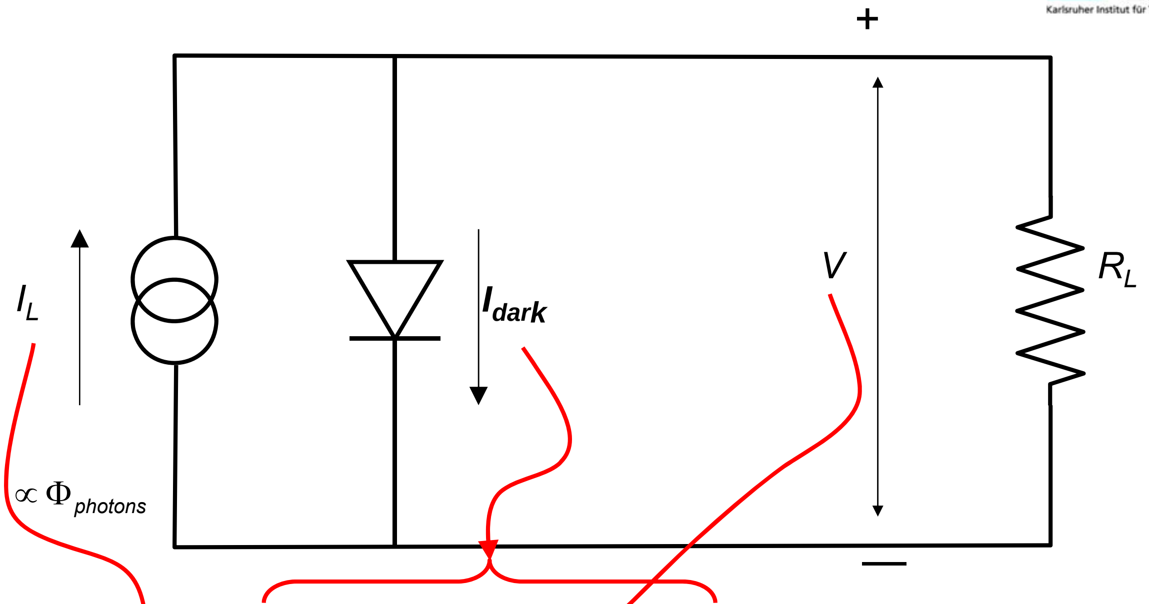
Diode Equation – Light vs Dark



Convention is to draw the I-V curve in the first quadrant

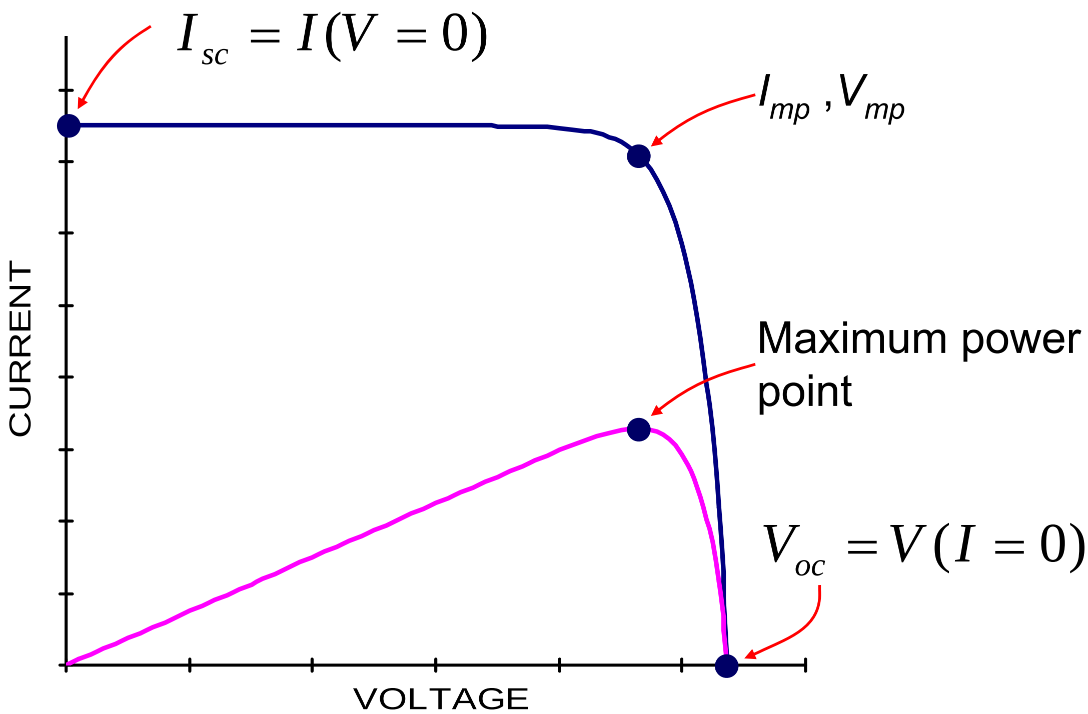
Source: *adapted from Honsberg & Bowden "PVCDROM"*

Equivalent Circuit



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

I–V Curve

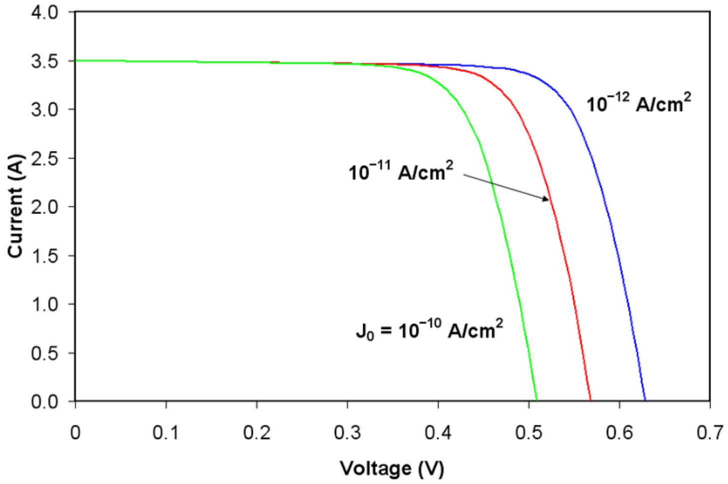


I–V Curve: Effect of I_0

Re-arranging previous equation for V_{oc} gives:

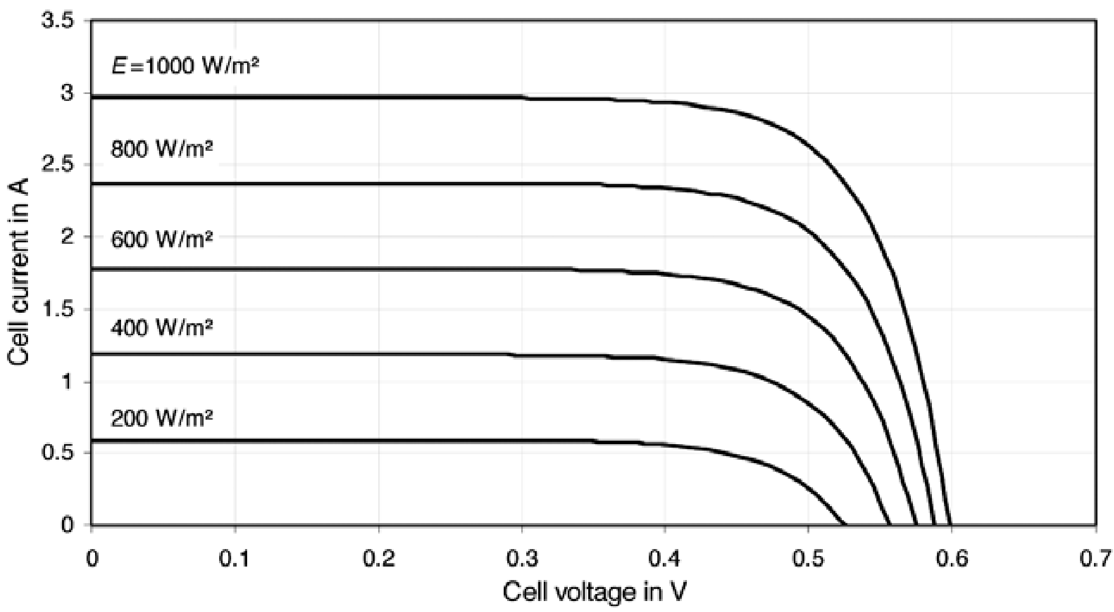
$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1 \right) \qquad (3)$$

Effect of I_0 (or J_0) in terms of current density shown for a Si solar cell:



Source: Wikipedia "Theory of Solar Cells"

I–V Curve: Effect of Illumination Intensity



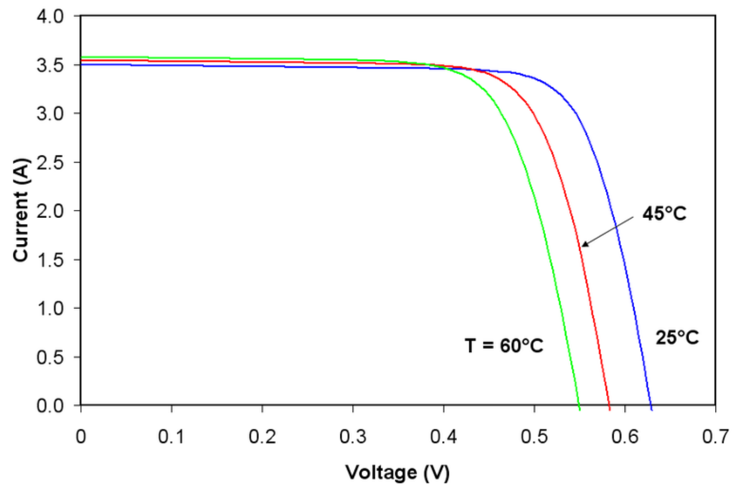
Source: Quaschning (2005) "Understanding Renewable Energy Systems"

I–V Curve: Effect of Temperature

Increasing *T* reduces bandgap of semiconductor and increases the energy of e^- in material

Lower additional energy required to bridge bandgap
→ V_{oc} reduced significantly
→ I_{sc} increased slightly

Standard test conditions (STC) are T = 25°C and 1000 W/m² but in reality T is much higher (at least >45 °C)



Source: Wikipedia "Theory of Solar Cells"

I–V Curve: Effect of Temperature

V_{oc} decreases with *T* due to *T*-dependence of I_0. Remembering (lecture 4, slide 28) the equation for I_0 from one side of a *p-n* junction is:

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

Many of these parameters have *some* *T*-dependance, but greatest effect is due to n_i ⇒ depends on the E_g (lower E_g having higher n_i) and on energy of carriers (so higher T gives higher n_i)

I–V Curve: Effect of Temperature

Equation for n_i 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:

h = Planck' constant, 6.626×10^{-34} J·s

k = Boltzmann's constant, 1.3806×10^{-23} J/K

m_e and m_h = effective masses of electrons and holes, respectively

E_{G0} = bandgap linearly extrapolated to absolute zero

B = constant which is essentially independent of temperature

Substituting back into expression for I_0 (assuming that T-dependencies of 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 γ is used instead of 3 to incorporate possible T-dependencies of other materials. For Si solar cells near RT, I_0 approximately doubles for every 10 °C increase in temperature

I–V Curve: Effect of Temperature

Now substituting I_0 back into equation for V_{oc} (with $E_{G0} = qV_{G0}$)

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

$$= \frac{kT}{q}\left(\ln I_{SC} - \ln B' - \gamma \ln T + \frac{qV_{G0}}{kT}\right)$$

and assuming that dV_{oc}/dT does not depend on dI_{sc}/dT, then dV_{oc}/dT is

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

$\Rightarrow$ demonstrates that T sensitivity of solar cell depends on V_{oc}

For Si, E_{G0} = 1.2, and using γ = 3 gives a <u>reduction in V_{oc} of ~2.2 mV/°C</u>

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

I–V Curve: Effect of Temperature

I_{sc} increases slightly with T since the E_G decreases and more photons can create e^--h^+ pairs. But this is a small effect and the T dependence of I_{sc} from a silicon solar cell is

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

The T dependency of FF for silicon is approximated by

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

The effect of T on the maximum power output P_m is

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

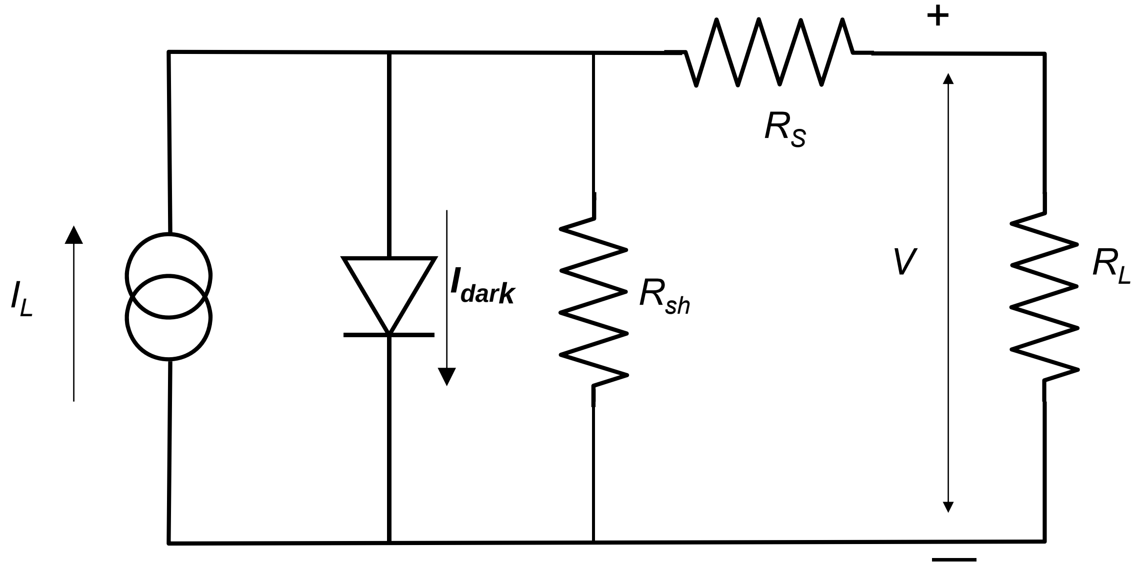
$$\frac{1}{P_M}\frac{dP_M}{dT} \approx -(0.004\ to\ 0.005)per\ \ ^{o}C\ for\ Si$$

Extended Equivalent Circuit

- Simple equivalent circuit sufficient for most applications (to within few % of measured cells)
- Extended model describes behaviour more exactly
- Charge carriers experience V drop going through the semiconductor junction to external contacts → expressed via a series resistance R_S

  (R_S also important when considering interconnection of solar cells to form PV modules)
- An additional parallel resistance R_S (or shunt, R_{sh}) describes the leakage currents (e.g. at cell edges)

Extended Equivalent Circuit



$$I = I_L - I_0\left(\exp\left(\frac{q(V+IR_s)}{kT}\right)-1\right)-\frac{V}{R_{sh}}$$

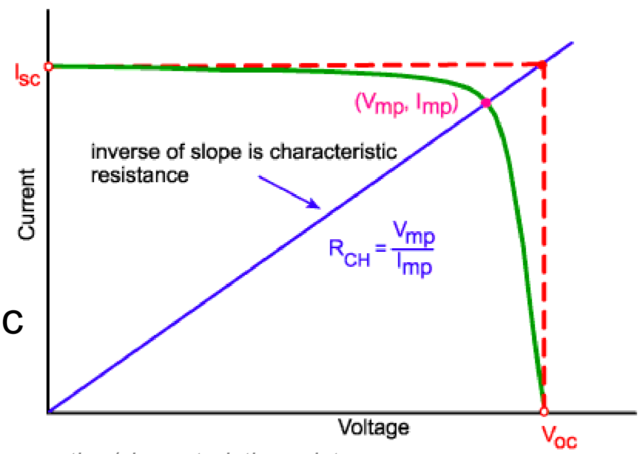
I–V Curve: Characteristic Resistance

Characteristic resistance R_{CH} of solar cell ≡ output resistance of solar cell at maximum power point.

If the resistance of the load R_L is equal to characteristic resistance ⇒ maximum power is transferred to the load (solar cell operates at MPP)

$$R_{CH} = \frac{V_{mp}}{I_{mp}} \approx \frac{V_{oc}}{I_{sc}}$$

Useful parameter in solar cell analysis, particularly when examining the impact of parasitic loss mechanisms



Source: http://www.pveducation.org/pvcdrom/solar-cell-operation/charecteristic-resistance

I–V Curve: Effect of Series Resistance

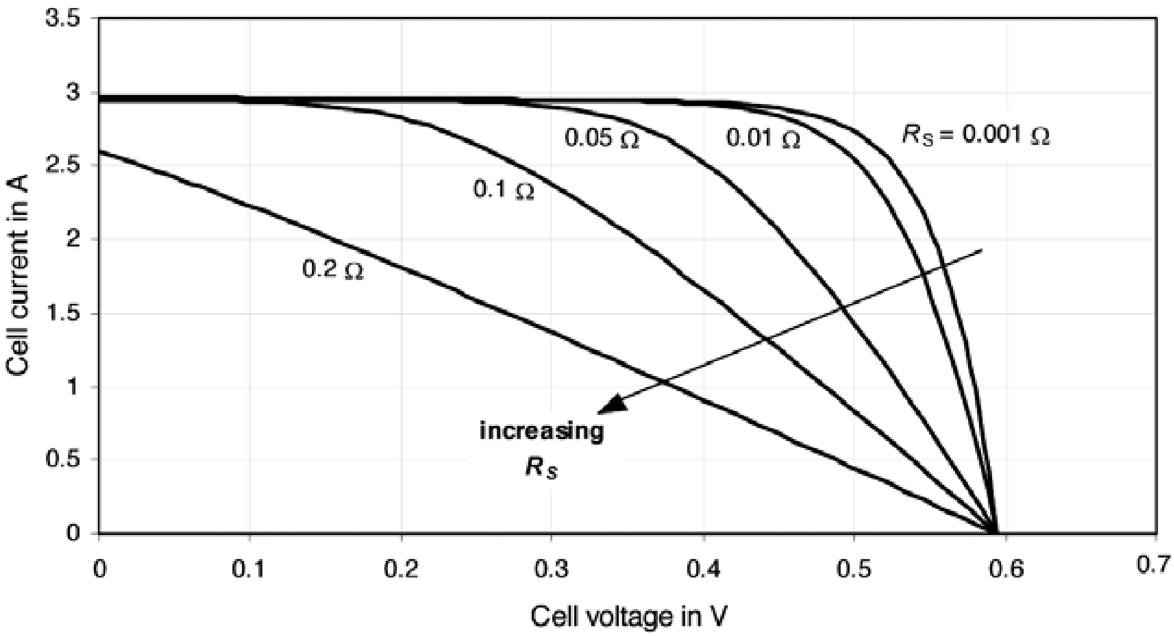
Series resistance in a solar cell has three causes:

1. movement of current through emitter and base of solar cell;
2. contact resistance between metal contact and silicon; and
3. resistance of front and rear metal contacts.

Main impact of series resistance is to reduce the FF, although excessively high values may also reduce I_{sc}

Series resistance does not affect the solar cell at V_{oc} since the overall current flow through the solar cell (and thus through R_S) is zero. But near V_{oc} ⇒ I-V curve is strongly effected by R_S

I–V Curve: Effect of Series Resistance



Source: Quaschning (2005) "Understanding Renewable Energy Systems"

I–V Curve: Effect of Series Resistance

Simple method to estimate R_S of solar cell ⇒ find slope of I-V curve at V_{oc}

Effect on FF: for moderate values of R_S ⇒ revised MPP approximated as power in the absence of R_S minus the power lost in R_S:

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

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

$$P'_{MP} = P_{MP}(1 - r_S)$$ defining normalised shunt resistance $$r_S = \frac{R_S}{R_{CH}}$$

and if we assume that V_{oc} and I_{sc} are not affected by R_S then:

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

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

Typical values for area-normalized R_S range from 0.5 Ωcm^2 (lab cells) up to 1.3 Ωcm^2 (commercial solar cells)

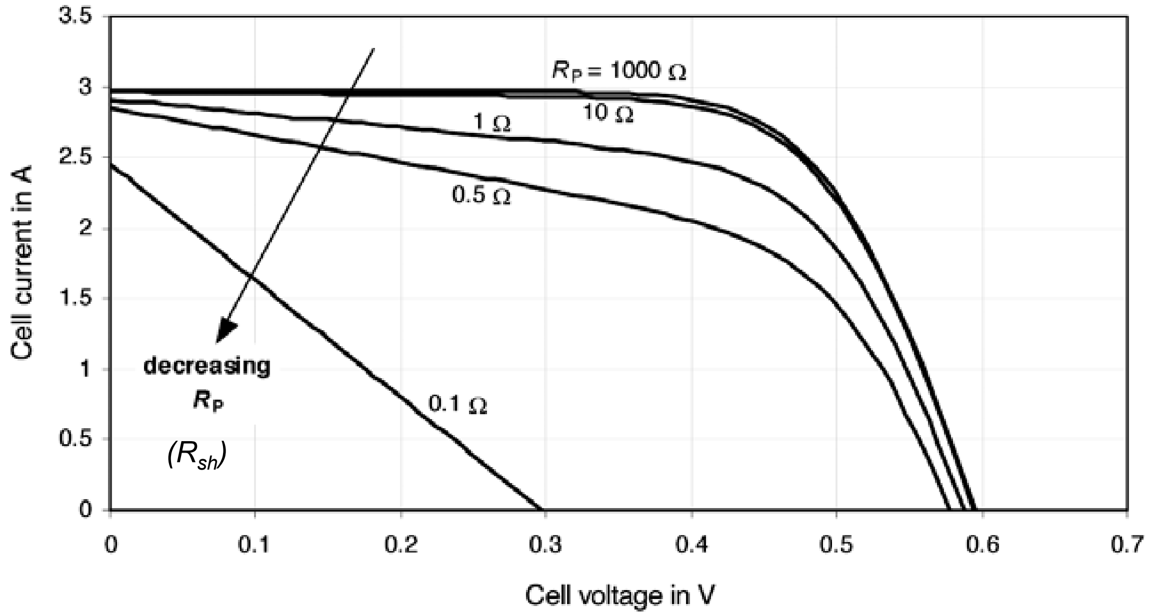
I–V Curve: Effect of Shunt Resistance

Significant power losses caused due to R_{SH} ⇒ typically due to manufacturing defects, rather than poor solar cell design

Low R_{SH} causes power loss by providing alternate current path for light-generated current ⇒ reduces amount of current flowing through *pn*-junction ⇒ reduces the voltage from the solar cell.

Effect of R_{SH} is particularly severe at low light levels, since there will be less light-generated current. In addition, at lower V (where the effective resistance R_{CH} of solar cell is high) ⇒ impact of R_{SH} is large

I–V Curve: Effect of Shunt Resistance



Source: Quaschning (2005) "Understanding Renewable Energy Systems"

I–V Curve: Effect of Shunt Resistance

Simple method to estimate R_{SH} of solar cell ⇒ find slope of I-V curve near I_{sc}

Maximum power approximated as power in the absence of R_{SH} minus the power lost in R_{SH}

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

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

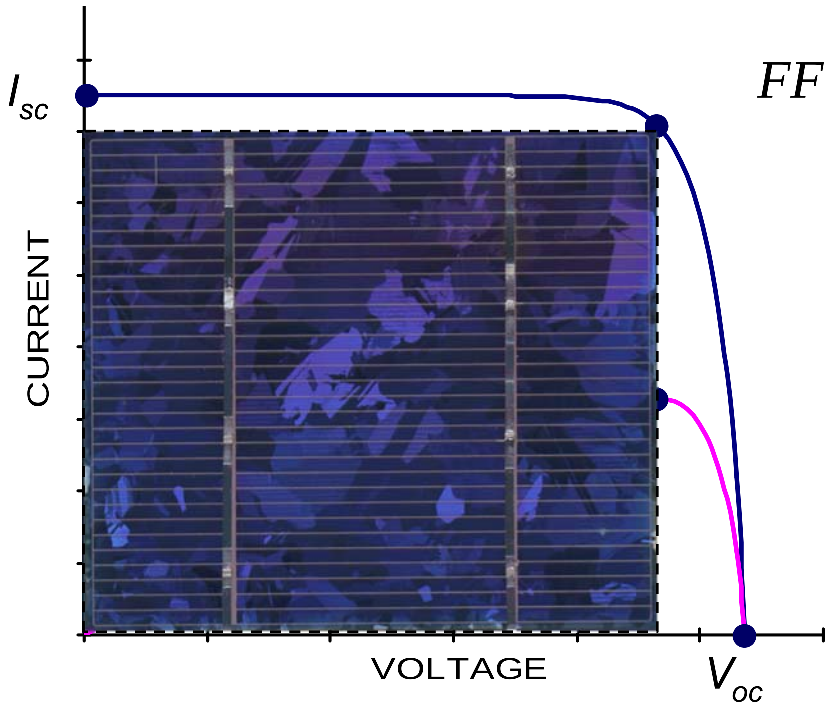
where we define the normalised shunt resistance as $r_{SH} = \frac{R_{SH}}{R_{CH}}$

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

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

Typical values for area-normalized R_S range MΩcm^2 (lab cells) down to ~1000 Ωcm^2 (commercial solar cells)

I–V Curve: Effect of Fill Factor



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

$\approx 65\%$ thin-film

≈ 75-80% silicon

If $R_S << R_{CH}$ or $R_{SH} >> R_{CH}$ $\Rightarrow$ little effect on the FF

I–V Curve: Effect of Illumination Intensity (revisited)

Changing light intensity on a solar cell changes all parameters, including I_{sc}, V_{oc}, FF, η, and impact of R_S and R_{SH}

The light intensity on a solar cell $\Rightarrow$ called the number of "suns", where 1 sun = standard illumination (AM1.5, 1 kW/m^2)

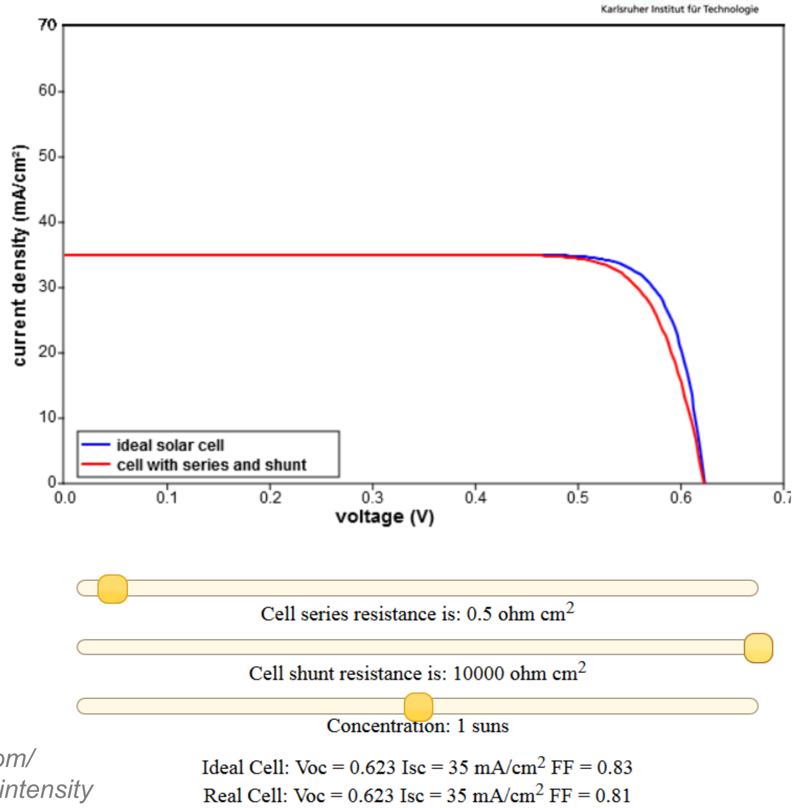
E.g.

- a system with 10 kW/m^2 incident on the solar cell would be operating at 10 suns, or at 10X
- The common PV modules which are designed to operate under 1 sun conditions are called a "flat plate" modules, while those relying on concentrated sunlight are called "concentrators"

I–V Curve: Effect of Illumination Intensity

Good quality lab cell

- low R_S
- high R_{SH}
- 1 sun

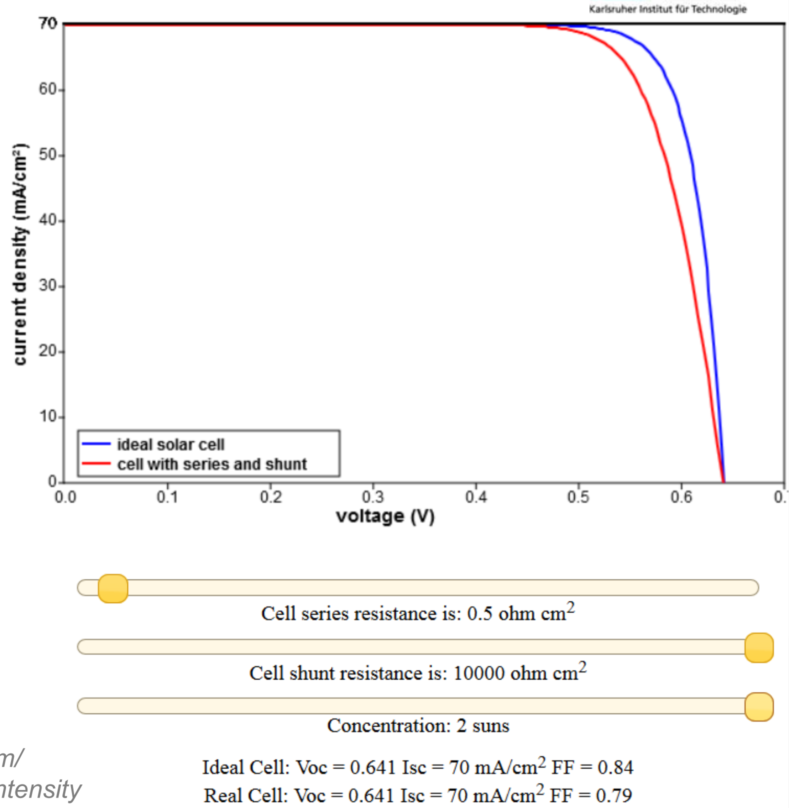


Source: http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity

I–V Curve: Effect of Illumination Intensity

Good quality lab cell

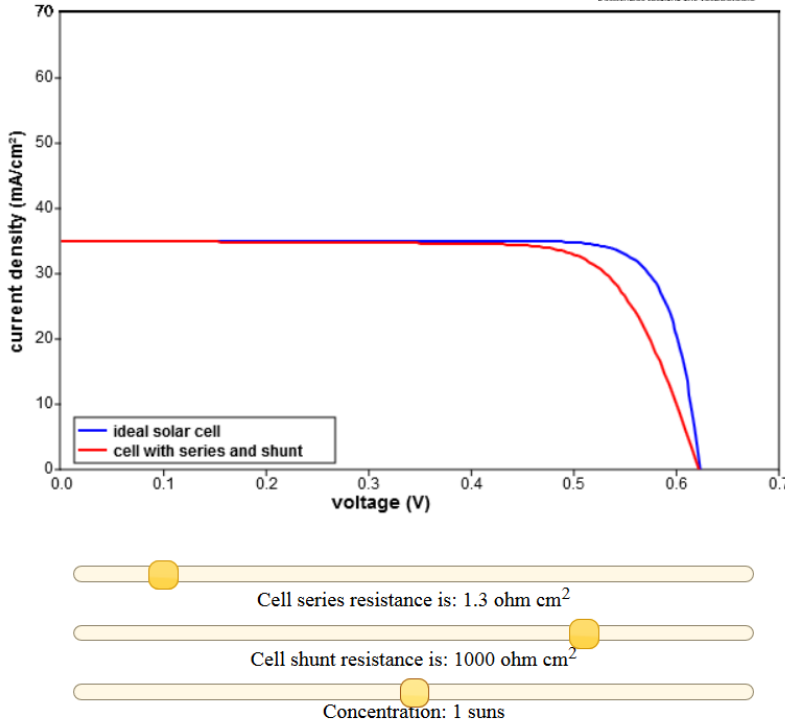
- low R_S
- high R_{SH}
- 2 suns



Source: http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity

I–V Curve: Effect of Illumination Intensity

Commercial solar cell
- poorer R_S
- poorer R_{SH}
- 1 sun

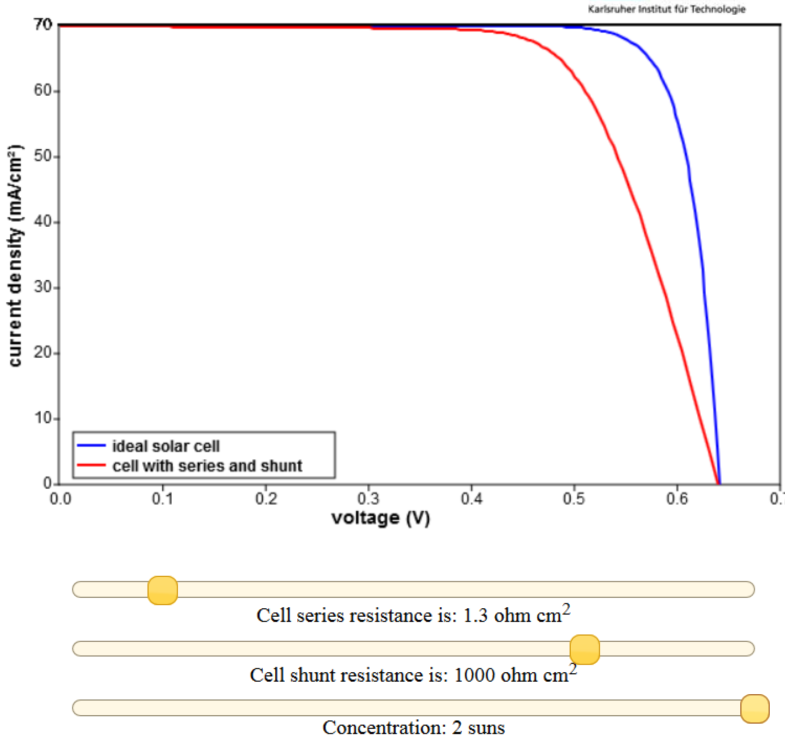


Ideal Cell: Voc = 0.623 Isc = 35 mA/cm^2 FF = 0.83
Real Cell: Voc = 0.622 Isc = 35 mA/cm^2 FF = 0.76

Source: *http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity*

I–V Curve: Effect of Illumination Intensity

Commercial solar cell
- poorer R_S
- poorer R_{SH}
- 2 suns



Ideal Cell: Voc = 0.641 Isc = 70 mA/cm^2 FF = 0.84
Real Cell: Voc = 0.64 Isc = 69.9 mA/cm^2 FF = 0.7

Source: *http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity*

I–V Curve: Effect of Illumination Intensity

Solar cell I_{sc} depends linearly on light intensity ⇒ device operating under 10 suns would have 10x times the I_{sc} as same device under 1-sun operation
⇒ does not provide an efficiency increase, since the incident power also increases linearly with concentration.

Instead, the efficiency benefits arise from the logarithmic dependence of the V_{oc} on I_{sc}

$$V'_{OC} = \frac{nkT}{q}\ln\left(\frac{XI_{SC}}{I_0}\right) = \frac{nkT}{q}\left[\ln\left(\frac{I_{SC}}{I_0}\right) + \ln X\right] = V_{OC} + \frac{nkT}{q}\ln X$$

So, doubling of light intensity (X=2) causes a 18 mV rise in V_{oc}.

I–V Curve: Effect of Illumination Intensity

Concentrators have several potential advantages, including
- higher efficiency potential than a 1-sun solar cell
- possibility of lower cost

The cost of a concentrating PV system may be lower than a corresponding flat-plate PV system since only a small area of solar cells is needed

But efficiency benefits of concentration may be reduced by increased losses in R_S as the I_{sc} increases and also the increased T operation of solar cell. Power loss due to series resistance increases as the square of the concentration

I–V Curve: Effect of Illumination Intensity

Solar cells experience daily variations in light intensity
⇒ incident power from sun varying between 0 and 1 kW/m^2

At low light levels, the effect of R_{SH} becomes increasingly important. As the light intensity decreases, the bias point and current through the solar cell also decreases, and the characterstic resistance of the solar cell begins to approach R_{SH}. When these two resistances are similar, the fraction of the total current flowing through the R_{SH} increases, thereby increasing the fractional power loss due to R_{SH}.

Consequently, under cloudy conditions, a solar cell with a high R_{SH} retains a greater fraction of its original power than a solar cell with a low R_{SH}

Diode Ideality Factor

Ideality factor of a diode *n* ⇒ measure of how closely the diode follows the ideal diode equation

or

There are effects that result in our diode not following simple diode equation ⇒ ideality factor *n* is a way of describing this

Recombination mechanisms

Ideal diode equation assumes that all recombination occurs via band to band or recombination via traps in the bulk areas from the device (i.e. not in the junction). Via that assumption, the derivation gives the ideal diode equation below and the ideality factor, *n*, is equal to one

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

Diode Ideality Factor

However, recombination does occur in other ways / areas of the device
⇒ these recombinations produce ideality factors different from ideal

The values for *n* in the following table reflect the number of carriers the need to come together during the recombination process

Recombination Type	Ideality factor	Description
SRH, band to band (low level injection)	1	Recombination limited by minority carrier.
SRH, band to band (high level injection)	2	Recombination limited by both carrier types.
Auger	2/3	Two majority and one minority carriers required for recombination.
Depletion region (junction)	2	two carriers limit recombination.

Diode Ideality Factor

Most solar cells usually exhibit near-ideal behaviour under Standard Test Conditions (so n ≈ 1)

Under certain operating conditions, however, device operation may be dominated by recombination in the space-charge (depletion) region
⇒ characterized by a significant increase in I_0 as well as an increase in ideality factor to n ≈ 2.

Higher *n* value increases the solar cell output voltage but the higher I_0 value decreases it. Typically, I_0 is the more significant factor ⇒ result is a reduction in voltage

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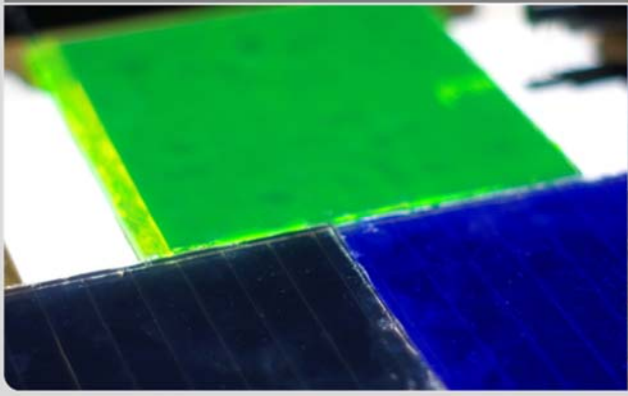
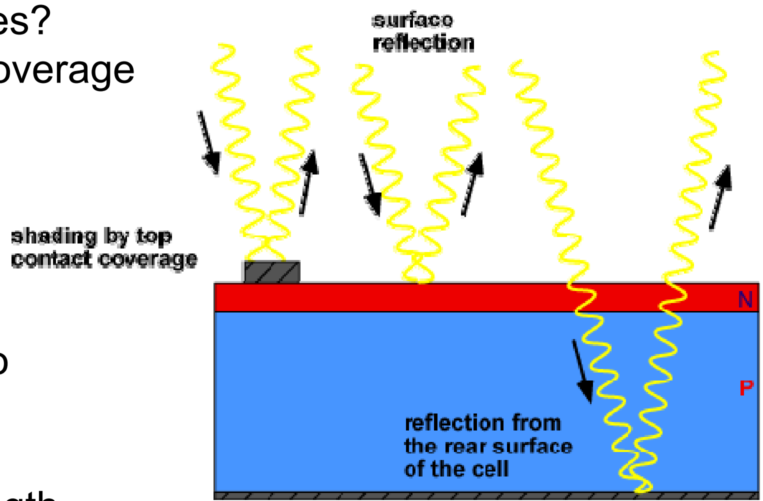


Optical Losses

Optical losses chiefly effect the power from a solar cell by lowering I_{sc}, e.g. light that had enough energy to generate an e^{-}-h^{+} pair but does not due to reflection or not being absorbed in solar cell

How to reduce optical losses?

- Minimise front contact coverage (trade-off with R_S)
- Anti-reflection coatings (ARC) on front surface
- Reflection reduced via surface texturing
- Make solar cell thicker to increase absorption (but be mindful of *L!*)
- Increase optical path length in solar cell via light trapping



Source: http://www.pveducation.org/pvcdrom/design/optical-losses

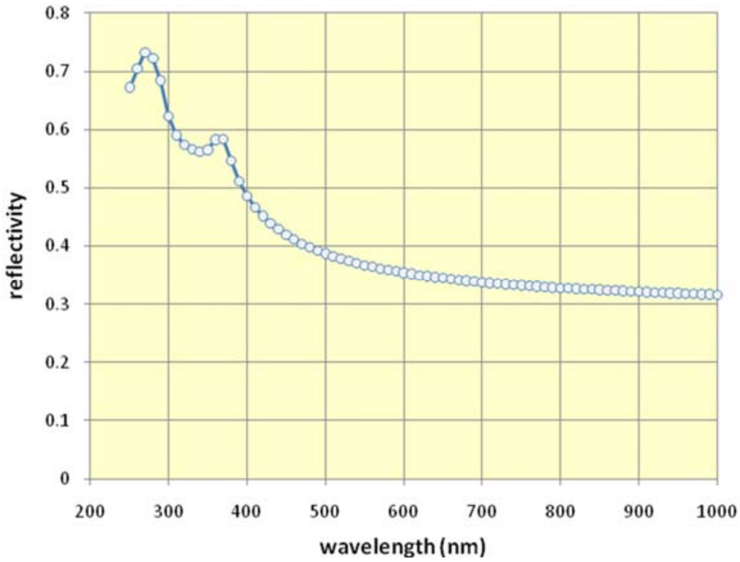
Optical Losses

Reflectivity R between two materials of different refractive index:

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

where n_0 is the refractive index of the surroundings and n_{Si} is the complex refractive index of Si. For a solar cell in air, $n_0 = 1$ (shown in graph):

For an encapsulated cell $n_0 = 1.5$

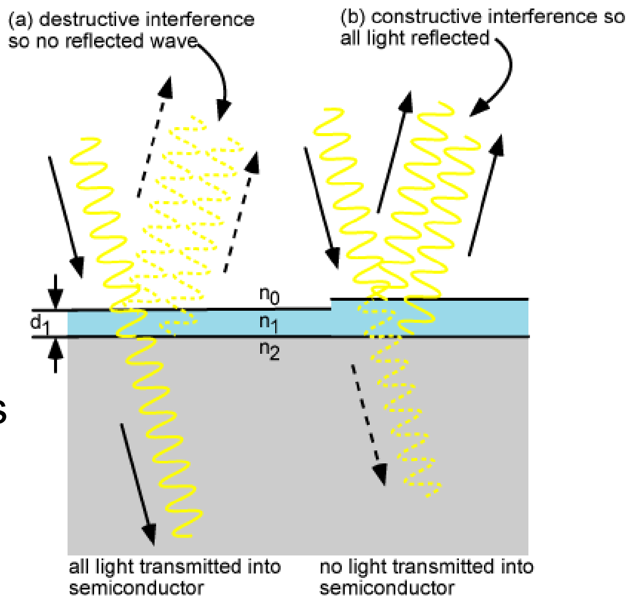


Source: http://pveducation.org/pvcdrom/materials/optical-properties-of-silicon

Optical Losses

Anti-reflection coatings on solar cells ⇒ similar to ARC's used on other optical equipment, e.g. camera lenses.

ARC's consist of thin layer of dielectric material, with specially chosen thickness so that interference effects in coating cause the wave reflected from ARC top surface to be out of phase with the wave reflected from the semiconductor surfaces ⇒ out-of-phase reflected waves interfere destructively with one another, resulting in zero net reflected energy



Source: http://pveducation.org/pvcdrom/materials/optical-properties-of-silicon

Optical Losses

ARC thickness chosen so that the λ in the dielectric material is ¼ of the λ of the incoming wave. For a ¼ λ ARC made of a dielectric material with refractive index n_1 and light of incident wavelength λ_0, the thickness d_1 which results in the minimum reflection is calculated by:

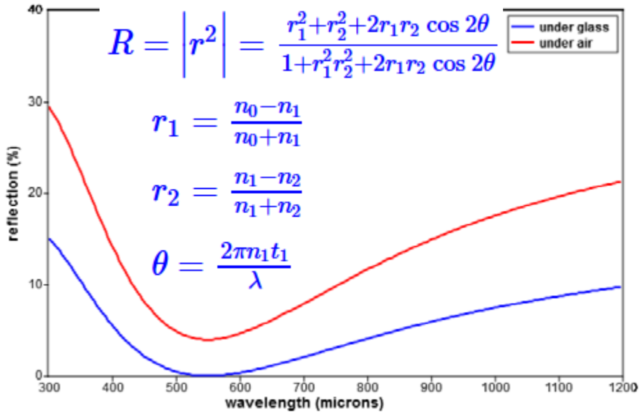
$$d_1 = \frac{\lambda_0}{4n_1}$$

Reflection is further minimized if n_1 is the geometric mean of that of the materials on either side (e.g. n_0 = glass or air and n_2 = semiconductor):

$$n_1 = \sqrt{n_0 n_2}$$

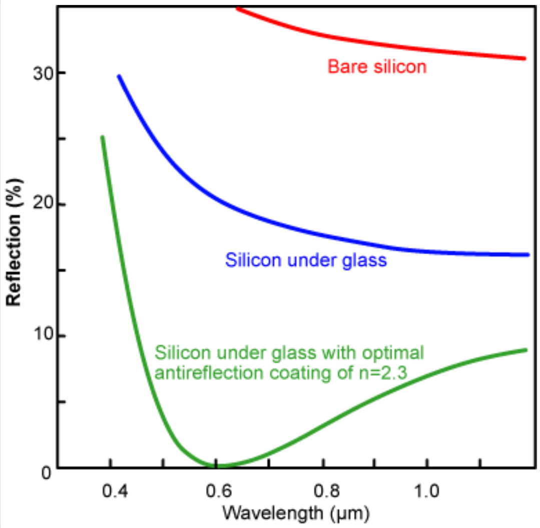
⇒ improved optical coupling

e.g. shown for n_1 = 2.29 and d_1 = 60nm (optimized for under glass)

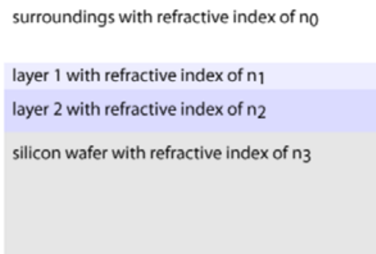


Source: http://www.pveducation.org/pvcdrom/design/anti-reflection-coatings

Optical Losses



Four multicrystalline silicon (mc-Si) wafers covered with silicon nitride ARC

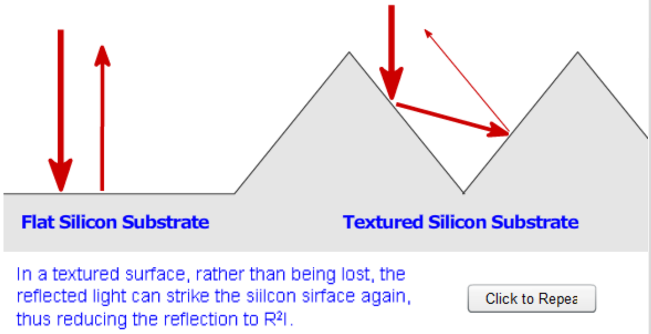


N.B. extension to double-layer ARCs also possible ($n_2 > n_1$)

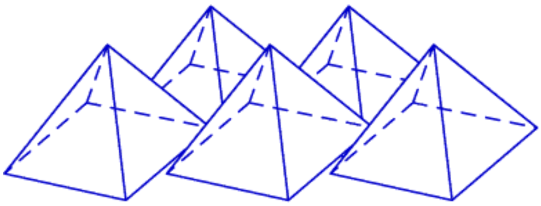
Source: http://www.pveducation.org/pvcdrom/design/anti-reflection-coatings

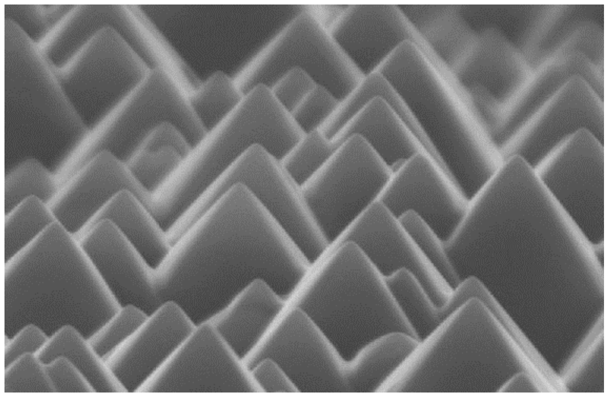
Optical Losses

Surface texturing can also minimize reflection ⇒ "roughening" surface reduces reflection by increasing the chances of reflected light bouncing back onto the surface



Crystalline silicon (c-Si) wafers are textured by etching along the faces of certain crystal planes
⇒ results in “pyramid” texture





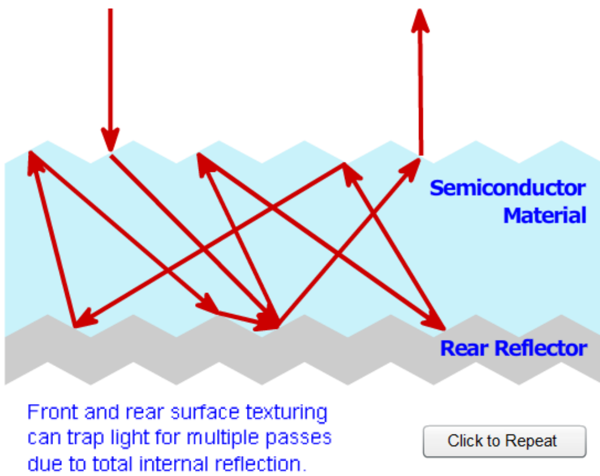
Source: http://www.pveducation.org/pvcdrom/design/surface-texturing

Optical Losses

Remember, that if the light is not absorbed within diffusion length *L* of junction ⇒ light-generated carriers are lost to recombination

Thus, a good solar cell structure will have "light trapping" ⇒ optical path length is several times the actual device thickness, e.g. solar cell with no light trapping features may have optical path length of one device thickness, but good light trapping may result in an optical path length of 50
⇒ light bounces back and forth within the cell many times

Achieved via changing angle that light enters the solar cell, e.g. pyramid texturing



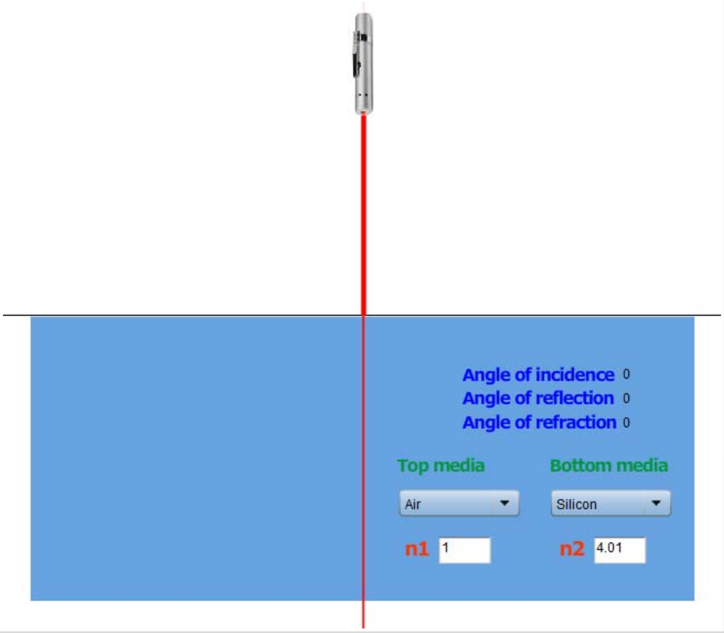
Source: http://www.pveducation.org/pvcdrom/design/light-trapping

Optical Losses

Angle at which light is refracted into the semiconductor material is given by Snell's Law:

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

where θ_1 and θ_2 are the angles for the light incident on the interface relative to the normal plane of the interface within the mediums with refractive indices n_1 and n_2, respectively.



Source: http://www.pveducation.org/pvcdrom/design/light-trapping

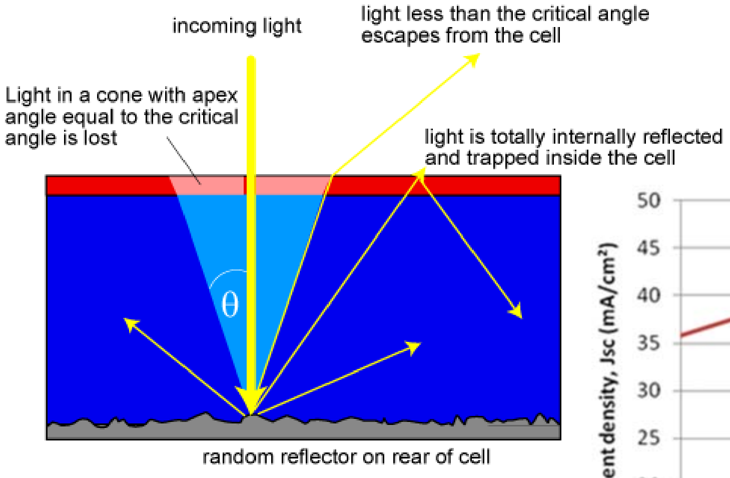
Optical Losses

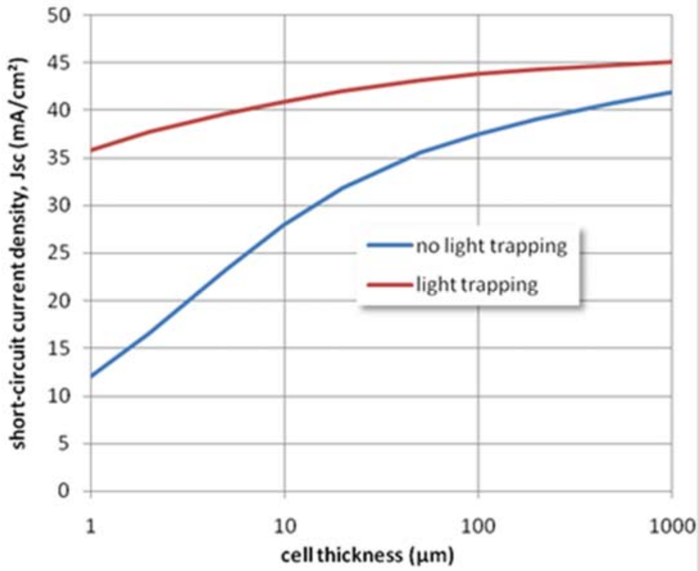
Lambertian back reflector ⇒ special type of rear reflector that randomises direction of reflected light (useful for thin-film solar cells).

Randomising the direction of light allows much of the reflected light to be totally internally reflected (TIR) ⇒ can occurs when light passes from high *n* to low *n* medium ⇒ the “critical angle” where this occurs found by setting θ_2 in Snell’s law to 0

Light absorption can be dramatically increased in this way, since the pathlength of the incident light can be enhanced by a factor up to $4n^2$
⇒ optical path length of ~50 times the physical devices thickness possible

Optical Losses





Source: http://www.pveducation.org/pvcdrom/design/lambertian-rear-reclectors

Recombination Losses

Recombination losses effect both the current collection (I_{sc}) as well as the forward bias injection current (and therefore V_{oc})

Recombination classified according to region of cell where it occurs:

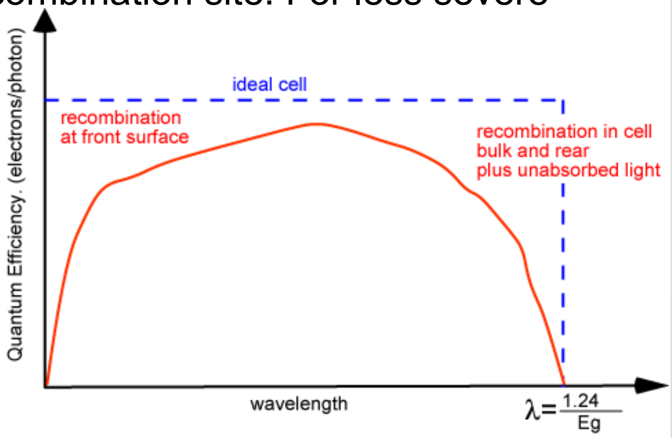
- Main places for recombination are at surfaces (surface recombination) or in the bulk of the solar cell (bulk recombination)
- Recombination can also occur in the depletion region

Recombination Losses: Current

For *p-n* junction to collect all light-generated carriers ⇒ minimise both surface and bulk recombination. In Si solar cells, two conditions are:

1. carrier must be generated within *L* of junction ⇒ can diffuse to junction before recombining
2. for localised sites of high recombination site (e.g. at unpassivated surface, or grain boundaries in mc-Si) ⇒ carrier must be generated closer to the junction than to recombination site. For less severe localised recombination sites (e.g. passivated surfaces), carriers can be generated closer to recombination site while still being able to diffuse to junction and be collected

⇒ photons of different energy have different collection probabilities



Source: http://www.pveducation.org/pvcdrom/design/current-losses-due-to-recombination

Recombination Losses: Voltage

V_{oc} is voltage at which the forward bias diffusion current exactly equals I_{sc} . Forward bias diffusion current depends on amount of recombination in *p-n* junction ⇒ recombination increases the forward bias current

Thus, high recombination increases the forward bias diffusion current, which in turn reduces the V_{oc}.

Material parameter which gives the recombination in forward bias is I_0.

Recombination is controlled by number of minority carriers at junction edge, how fast they move away from junction and how quickly they recombine

Consequently, I_0 and hence V_{oc} are affected by three following parameters:

1. no. of minority carriers at junction edge. The no. of minority carriers injected from the other side is simply the no. of minority carriers in equilibrium multiplied by an exponential factor (depends on *V* and *T*). Therefore, minimising the equilibrium minority carrier concentration reduces recombination. Minimizing the equilibrium carrier concentration is achieved by **increasing the doping**;

Source: http://www.pveducation.org/pvcdrom/design/current-losses-due-to-recombination

Recombination Losses: Voltage

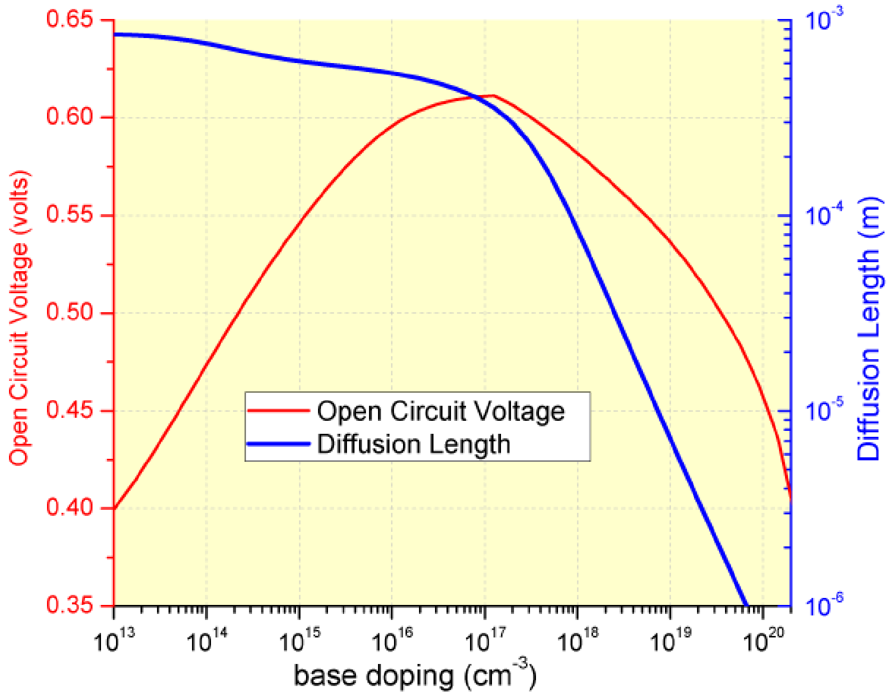
2. Diffusion length – a low L means minority carriers disappear from junction edge quickly due to recombination ⇒ allowing more carriers to cross and increasing I_0. Thus, to minimise recombination and achieve a high voltage, a **high diffusion length is required.**

   L depends on types of material, the processing history of the wafer and the doping in the wafer. High doping reduces L ⇒ trade-off between maintaining a high L (affects both the current and voltage) and achieving a high V_{oc}

3. A high recombination source close to the junction (e.g. front surface or a grain boundary) ⇒ allows carriers to move to this recombination site very quickly ⇒ dramatically increasing I_0. The impact of surface recombination is reduced by **passivating the surfaces**

Recombination Losses: Voltage

Net effect of increasing doping (N_D) on L and V_{oc} (assuming well passivated surfaces):



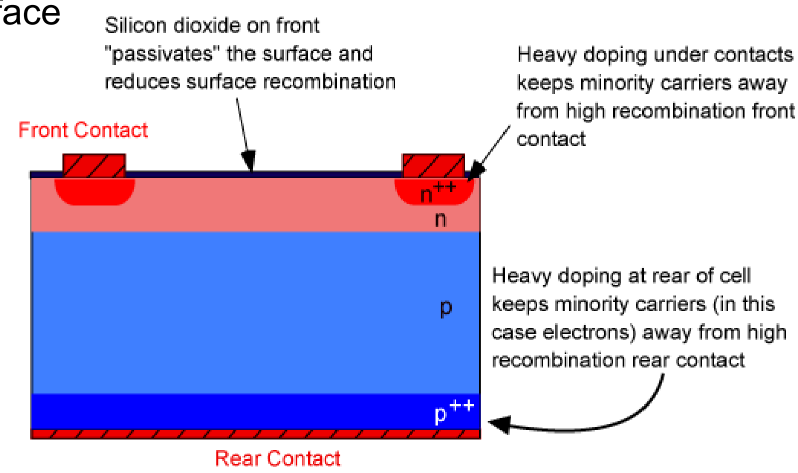
Source: *http://www.pveducation.org/pvcdrom/design/voltage-losses-due-to-recombination*

Surface Recombination

High recombination rates at top surface have particularly detrimental impact on I_{sc} since highest generation region of carriers occurs at top surface

Reducing high front surface recombination is typically accomplished by reducing the number of dangling silicon bonds at the top surface by using "passivating" layer, e.g. thermally grown silicon dioxide (SiO_2) or hydrogenated silicon nitride (a-SiN:H) layers to passivate the surface and reduce defect states at interface

Does not work under an ohmic metal contact. Instead, recombination effect minimised by increasing doping ⇒ high doping severely degrades *L*, but no carrier generation under the contacts

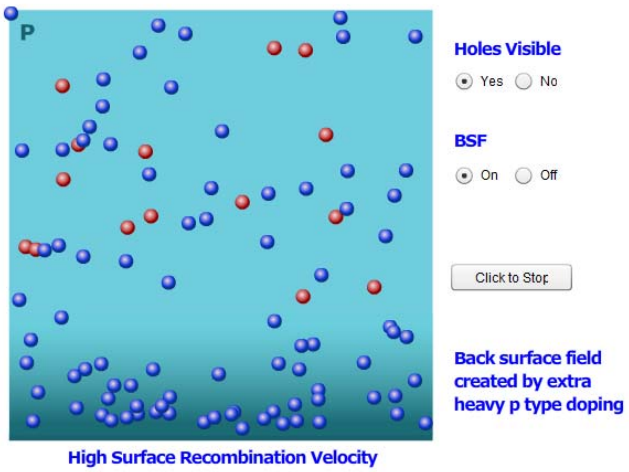


Source: *http://www.pveducation.org/pvcdrom/design/current-losses-due-to-recombination*

Surface Recombination

Similar effect employed at rear surface ⇒ "back surface field" (BSF) consists of a higher doped region at rear surface of solar cell. Interface between high- and low-doped region behaves like a *p-n* junction ⇒ forms electric field at interface ⇒ introduces a barrier to minority carrier flow to rear surface.

Thus, minority carrier concentration is maintained at higher levels in the bulk of the device ⇒ BSF has net effect of passivating rear surface

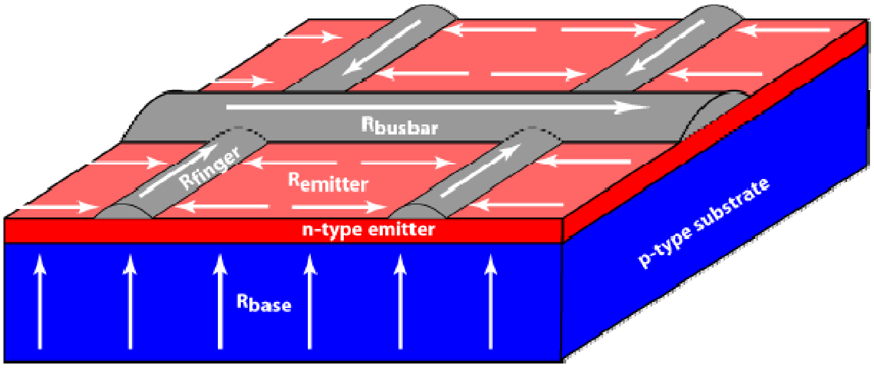


Source: *http://www.pveducation.org/pvcdrom/design/surface-recombination*

Top Contact Design

Finally, to design a high-efficiency solar cell we need to minimise parasitic resistive losses. Very low shunt resistance is a processing defect rather than design parameter. However, 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 to achieve the best efficiency

R_S of solar cell consists of several components, but the emitter and top grid (consisting of the finger and busbar resistance) dominate the overall series resistance ⇒ therefore most heavily optimised in solar cell design



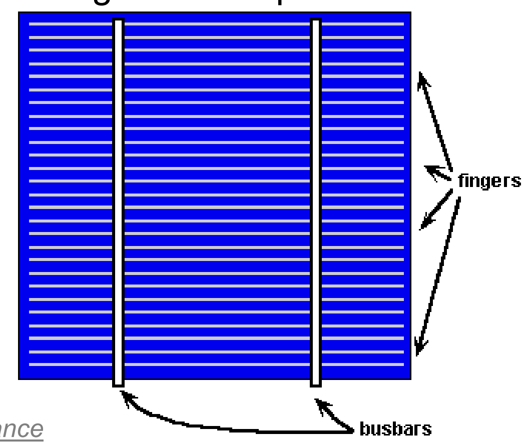
Source: *http://www.pveducation.org/pvcdrom/design/series-resistance*

Top Contact Design

Metallic top contacts necessary to collect current generated by solar cell

- “busbars" are connected directly to the external leads,
- "fingers" are finer areas of metallisation that collect current for delivery to the busbars

Key design trade-off in top contact design is balance between 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



Source: *http://www.pveducation.org/pvcdrom/design/series-resistance*

Top Contact Design

Photo-generated current typically flows perpendicular to 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.

Base Resistance:

The "bulk resistance" R_b to current flow through the bulk of the solar cell is defined as:

$$R_b = \frac{\rho l}{A} = \frac{\rho_b W}{A}$$

where:

l = length of conducting (resistive) path
ρ_b = resistivity of the bulk cell material (0.5 - 5.0 Ω cm for typical silicon solar cell)
A = cell area, and
W = width of bulk region of cell (typically ~300 μm thick)

Top Contact Design

For emitter layer, the resistivity and thickness are often unknown ⇒ difficult to calculate $R_{emitter}$ from the resistivity and thickness of this layer

Instead, we use a value known as the "sheet resistivity", which depends on both the resistivity and the thickness, that is easily readily measured for the top surface (typically *n*-type) layer. For a uniformly doped layer, the sheet resistivity $\rho_\square$ is defined as:

$$\rho_\square = \frac{\rho}{t}$$

where
ρ = resistivity of the emitter layer
t = the thickness of the layer

$\rho_\square$ is normally expressed as ohms/square or Ω/□ and measured using a four-point probe.

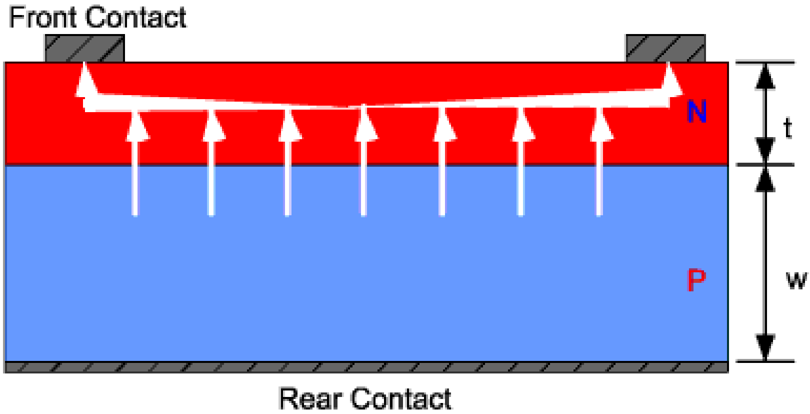
For non-uniformly doped *n*-type layers, $\rho_\square$ becomes:

$$\rho_\square = \frac{1}{\int_0^t \frac{1}{\rho(x)}\,dx}$$

Top Contact Design

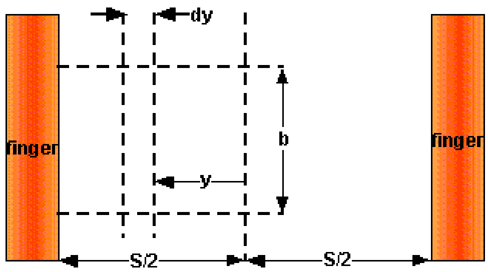
Based on $\rho_\square$, the power loss due to $R_{emitter}$ can be calculated as a function of finger spacing of the front contact.

But, the distance that current flows in the emitter is not constant $\Rightarrow$ current collected from the base close to the finger has only a short distance to flow to the finger, whereas if current enters the emitter between the fingers then the length of the resistive path is half the grid spacing



Source: *http://www.pveducation.org/pvcdrom/design/emitter-resistance*

Top Contact Design



So, now defining the following dimensions, the incremental power loss in section *dy* is:

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

The differential resistance *dR* is given by:

$$dR = \frac{\rho_\square}{b} dy$$

where

$\rho_\square$ = sheet resistivity in $\Omega/\square$

b = distance along the finger; and

y = distance between two grid fingers as shown above

Source: *http://www.pveducation.org/pvcdrom/design/emitter-resistance*

Top Contact Design

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. Given by:

$$I(y) = Jby$$

where
J = current density

The total power loss is therefore:

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

where
S = spacing between the grid lines

Source: http://www.pveducation.org/pvcdrom/design/emitter-resistance

Next Week

Lecture 6: High-efficiency silicon solar cells

Dr. Jan Christoph Goldschmidt
Head of Team "Novel Solar Cell Concepts"
Fraunhofer Institute for Solar Energy Systems

Lecture 7: Fabrication of Silicon Solar Cells + Thin-Film PV (a-Si)

N.B. Likely exam date is 17th March