ME4252 Nanomaterials for Energy Engineering

Solar Cells

Monocrystalline Si solar cells

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Solar Cell Parameters

- The important parameters which are used to characterize solar cells are the following :

1. Short-circuit current (I_{SC})
2. Open-circuit voltage (V_{OC})
3. Fill factor (FF) and
4. Efficiency (η)

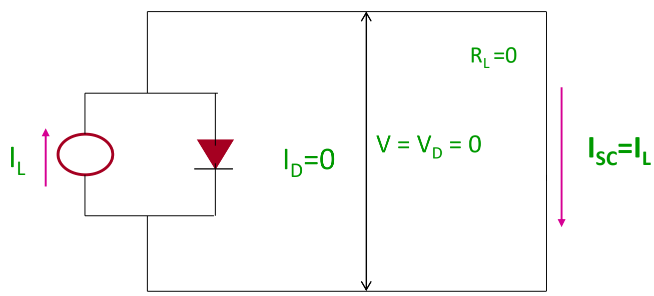
All the parameters can be determined from the I-V curve

Short-circuit current

- The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited)

For Short - circuited cell, $V = 0$ in eq.1, and

$$I_{sc} = I_L = qAg_{op}(L_h + L_e + W)$$

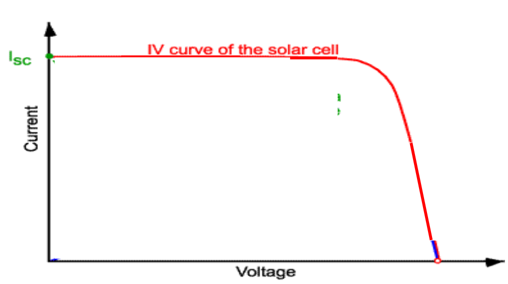


Ideal Solar Cell in short-circuit

3

Short-circuit current

- The short-circuit current is due to the generation and collection of light-generated carriers
- For an ideal solar cell, at negligible losses, short-circuit current and light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell

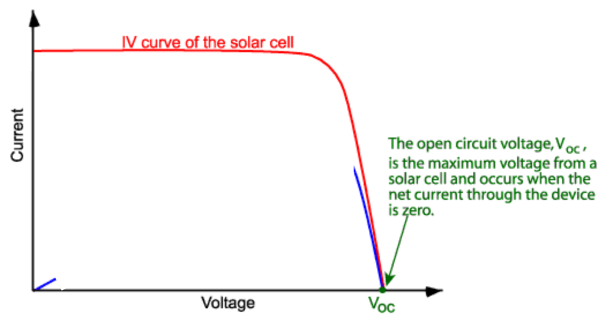


I-V curve of a solar cell showing I_{sc}

4

Open-Circuit Voltage

- The open-circuit voltage V_{oc} is the maximum voltage that can be drawn from a solar cell, and this occurs at zero current.
- The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.



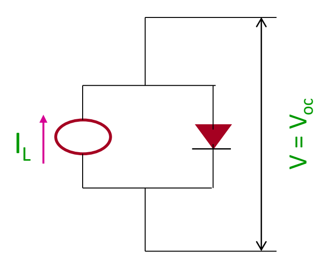
I-V curve of a solar cell showing the open-circuit voltage

Open-Circuit Voltage

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

$$\text{For } V = V_{oc},\ I = 0$$

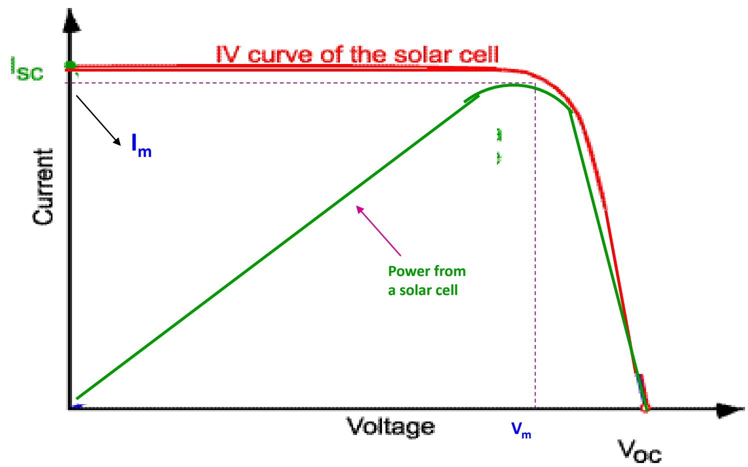
$$\boxed{V_{oc} = \frac{kT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)}$$



Ideal solar cell in open circuit

- V_{oc} depends on the saturation current of the solar cell and the light-generated current
- Silicon solar cells on high quality single crystalline material have open-circuit voltages of up to 730 mV under one sun and AM1.5 conditions, while commercial devices on multicrystalline silicon typically have open-circuit voltages around 600 mV

Output Power of a solar cell



I-V curve of a solar cell showing maximum power points

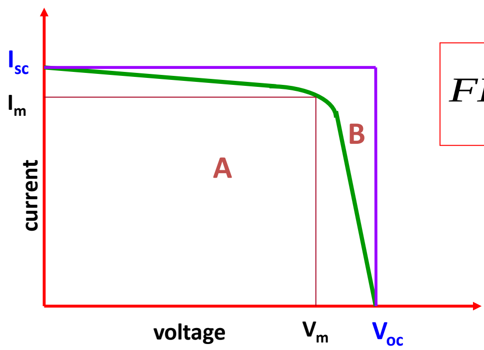
Fill Factor

- The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell.
- The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}.

$$\boxed{FF = \frac{V_m I_m}{V_{oc} I_{Sc}}}$$

- For cells of reasonable efficiency, FF is in between 0.7 to 0.85

Fill Factor



$$FF = \frac{\text{area } A}{\text{area } B} = \frac{V_m I_m}{V_{oc} I_{Sc}}$$

Graphical representation of fill factor

- Graphically, the *FF* is a measure of the "squareness" of the I-V curve and is also the area of the largest rectangle which will fit in the I-V curve

Efficiency

- Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun
- The efficiency is the most commonly used parameter to compare the performance of one solar cell to another
- The efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another
- Terrestrial solar cells are measured under AM1.5 conditions (1000 W/m^2) and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions (1367 W/m^2)

Efficiency

- The conversion efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{V_m I_m}{P_{in}} \times 100\% = \frac{V_{oc} I_{sc} FF}{P_{in}} \times 100\%$$

Solar cell parameters

$$\text{Short-circuit Current}: I_{sc} = I_L = qAg_{op}(L_h + L_e + W)$$

$$\text{Open circuit Voltage}: \; V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

$$\text{Fill factor}: \qquad FF = \frac{V_m I_m}{V_{oc} I_{Sc}}$$

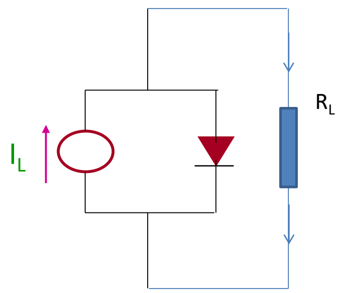
Emperically the ideal fill factor can be expressed as,

$$FF_o = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \qquad (\text{for } v_{oc} > 10)$$

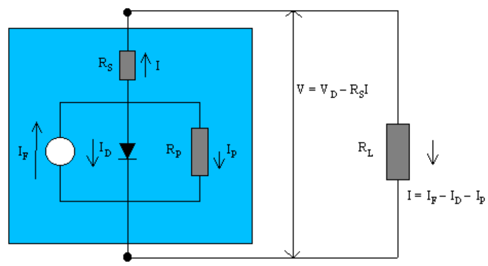
Where, $v_{oc} = \dfrac{V_{OC}}{(kT/q)}$, known as normalized voltage

$$\text{Efficiency}, \quad \eta = \frac{P_m}{P_{in}} = \frac{V_m I_m}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

Ideal Solar Cell



Real Solar Cell

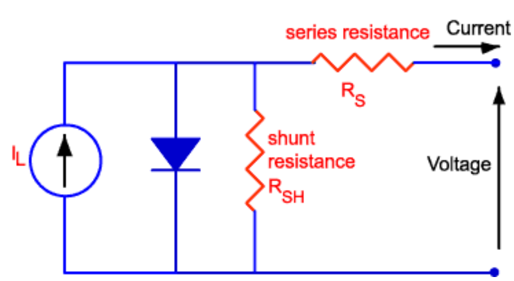


The current flowing through the load resistor R_L of a real solar cell:

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

Resistive effects

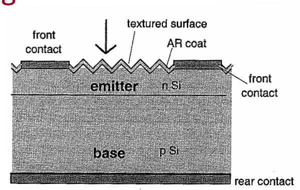
- In real cell, power is dissipated due to resistive effects which are known as parasitic resistances – *series resistance (R_s) and shunt resistance (R_{sh})*
- Series and shunt resistances reduce the fill factor



Equivalent circuit including series and shunt resistances

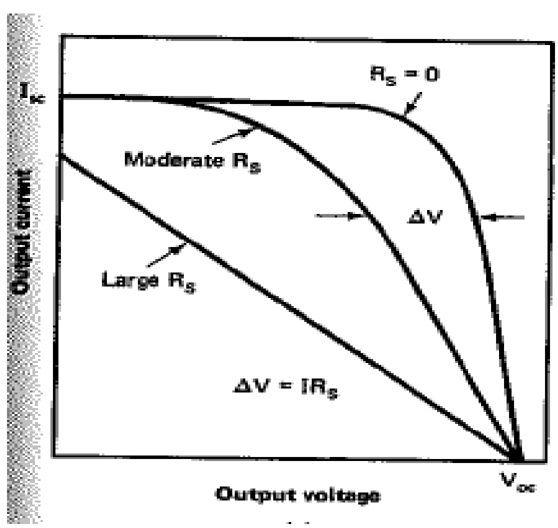
Effects of series resistance

- Series resistance arises from-
  1. resistance of the cell material to current flow
  2. resistive contacts of front surface and the metallic and
  3. bulk resistance of material of the metallic contacts
- The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current
- Series resistance does not affect the solar cell open-circuit voltage since the overall current flowing through the solar cell, and therefore through the series resistance is zero



15

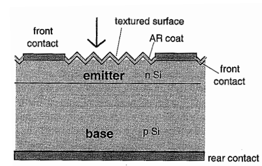
Effect of Series resistance



Effect of series resistance on I-V characteristics (or shunt) of a solar cell

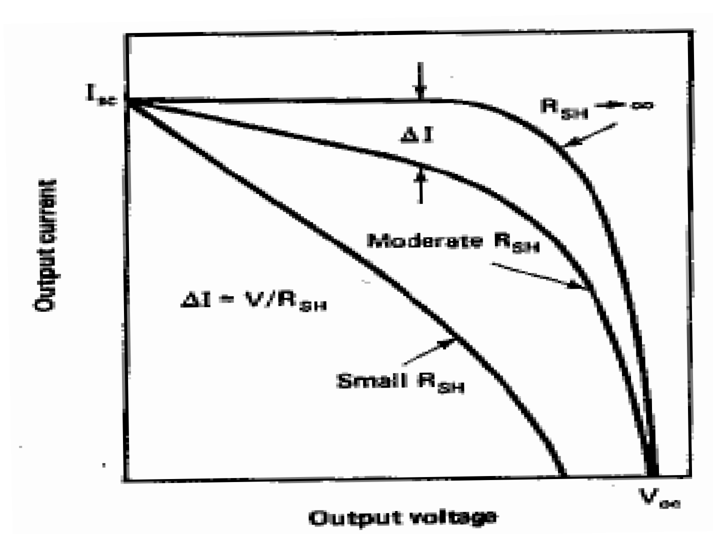
16

Effect of Shunt resistance



- The parallel or shunt resistance arises from the leakage of current through the cell- around the edges of the device and in the junction due to the presence of crystal defects, impurities
- 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 main impact of shunt resistance is to **decrease** the fill factor, although low values might reduce the open-circuit voltage

Effect of Shunt resistance



Effect of shunt resistance on I-V characteristics (or Fill factor) of a solar cell

Conversion Efficiency Limits

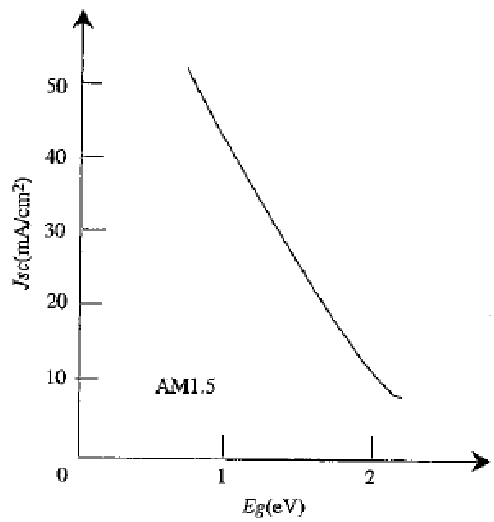
- The performance of a *p-n* junction solar cell is determined by the *open-circuit voltage* (V_{oc}), the *short-circuited current* (I_{sc}), and *the fill factor (FF)*

- *Since the fill factor is ideally only a function of* V_{oc} *the maximum efficiency depends firstly on the limiting values of open-circuit voltage* (V_{oc}) *and* then on *short-circuited current*

Short-circuited Current and Efficiency

- For an ideal p-n junction cell, I_{sc} is equal to the light generated current which is a function of the carrier generation rate
- For a given wavelength the probability of generation of carriers depends on the band gap of the material making up the cell
- Thus, maximum of I_{sc} will depend on band gap of the semiconductor material
- The maximum of I_{sc} increases with decreasing band gap since more photons have the sufficient energy required to create EHPs.

Short-circuited Current and Efficiency



I_{sc} ***versus*** *band gap of solar cell material*

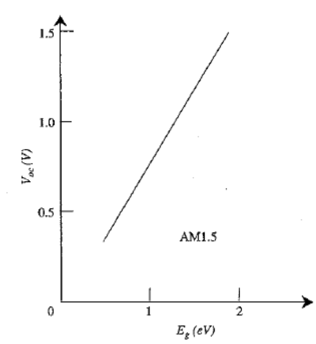
Open-circuit Voltage and Efficiency

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

$$But\ I_0 = B'T^{\gamma} \exp\left(-\frac{E_g}{kT}\right)$$

At a given temperature,

$$I_0 \alpha \exp\left(-\frac{E_g}{kT}\right)$$

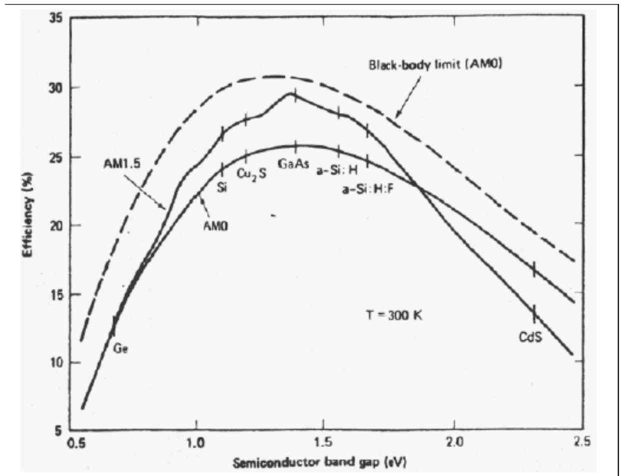


V_{oc} of p-n junction solar cell as a function of band gap

Hence, lower the band gap, larger I_0 and smaller the V_{oc}

Therefore, V_{oc} decreases with decreasing band gap of the material of the cell

- Net effect:
  For highest efficiency the band gap of semiconductor should be optimum



Solar conversion efficiency limits as a function of the band gap of the cell material at T=300K

Efficiency losses

Much of the energy from sunlight reaching a PV cell is lost before it can be converted into electricity

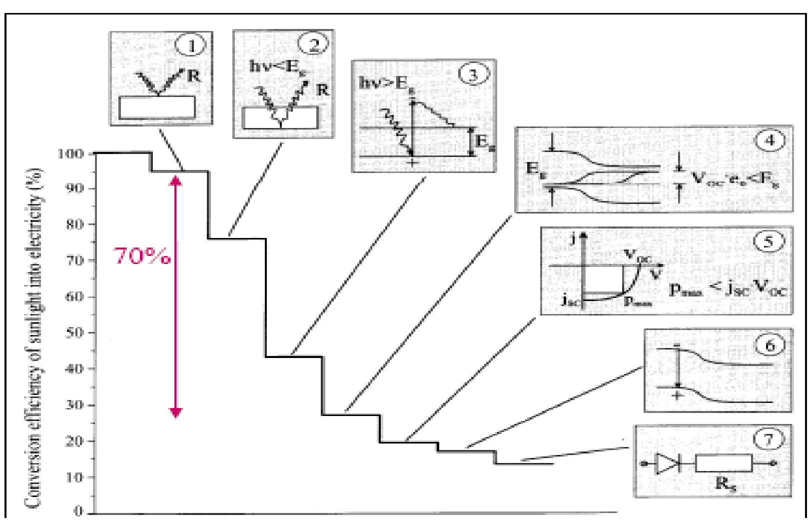
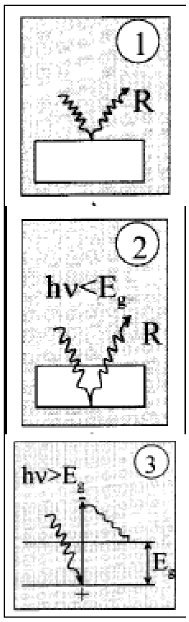


Illustration of many physical and technological mechanisms resulting in a low conversion efficiency

Efficiency losses



1. Due to reflection of the front surface, a part of incoming light is lost

   To reduce reflection losses at the top, surface can have antireflection coatings or texturing of the surface is employed

2. The photons with the energy less than the band gap energy ($h\nu<E_g$) are not absorbed in the semiconductor even if the thickness is sufficiently high

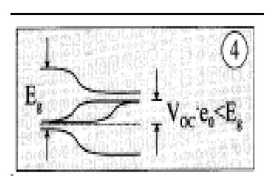
   This mechanism causes an efficiency loss of 23%

3. Although the photons with an energy, $h\nu>E_g$ generate *EHPs*; the excess energy ($h\nu-E_g$) is wasted in the form of heat

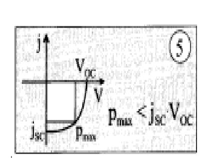
25

Efficiency losses

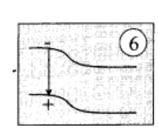
4. V_{oc} is always smaller that the E_g even though the electrons and holes are created at the bottom of the CB and at the top of the VB respectively because the E_F is located inside the energy band gap



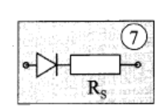
5. This loss is caused because Fill factor is smaller than unity. When the maximum power is extracted from a solar cell with optimal load, the operation voltage is smaller than the V_{oc}



6. Recombination losses due to photo generated carriers not reaching the electrical contacts give rise to a loss.



7. The electrical series resistance in the cell itself, its contacts and the external circuitry lead, contributes to the loss



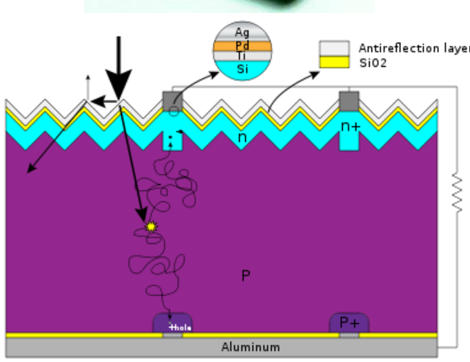
26

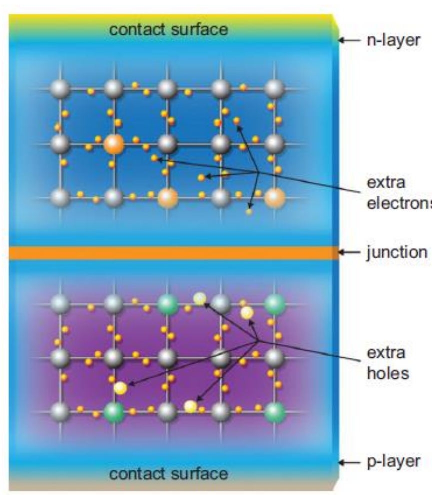
Solar Cells

(a) Crystalline Si-solar cells

http://www.appropedia.org/images/9/91/Solar1.ppt

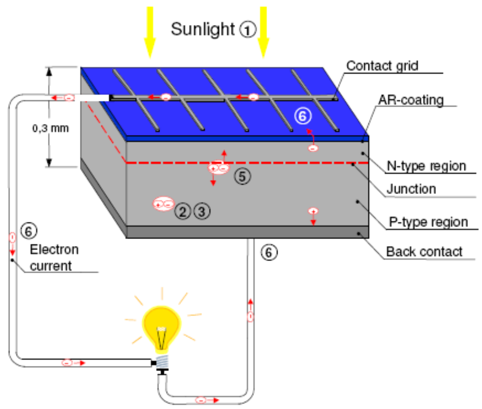
Si-solar cells





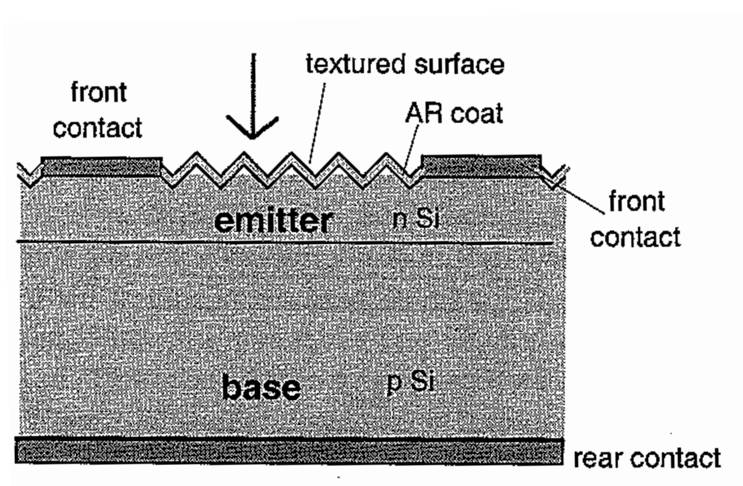
28

Principle of operation



- Absorption of light (hν > ΔE_g)
- Release of positive and negative charge-carriers
- Separation of carriers
- External current

Layer structure of basic silicon solar cell



Silicon solar cells design

Basic silicon solar cells

- n-p junction made using a p-type silicon wafer of few hundreds micron thick & around 100 cm^2 – area.
- p-type: 300 – 500 μm thick; absorbing light as much as possible; lightly doped (10^{16} cm^{-3}) to improve diffusion length
- n-type created by dopant diffusion – heavily doped (10^{18} cm^{-3}) to reduce series resistance
- n-layer: thin to allow as much as light to pass through to p-layer but thick enough to keep series resistance low.
- Carrier collection from emitter (n-type) is rather low because of high recombination due to heavy doping
- Front surface is anti-reflection coated;
- Contacts made for charge collection prior to encapsulation

Recombination

- Nearly all the volume of a typical crystalline Si-solar cell is provided by p-type.
- Effect of recombination in the depletion region and emitter layer (n-type) rather low, because of low level of photo generation in those thin layers - usually neglected.
- Dominated volume recombination in p-region includes radiative, Auger and trap-assisted mechanisms.

Recombination

- Net recombination rate:

$$U = U_{rad} + U_{Aug} + U_{SRH}$$

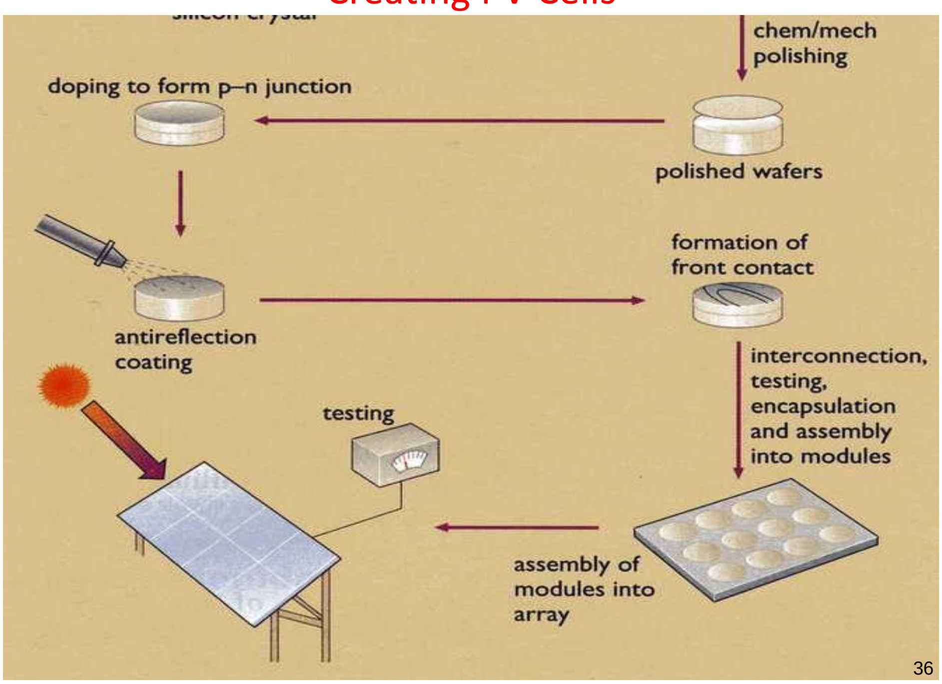
- Si being an indirect band gap material, radiative recombination is slow, $\tau_{n,\ rad}$ is typically of the order of milliseconds, this contribution is negligible

Silicon Ingots & Wafers (recall)

Cell fabrication

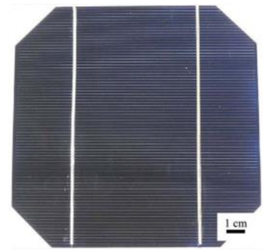
- Junction is made by doping: forming n-type layer using phosphorous on to the p-type wafer
- Front surface is textured to reduce reflectivity and an antireflection (AR) coating is deposited using liquid or vapor phase added.
- For Si, AR coating should have a refractive index of 2 (in the range 1.5 to 2.4) and thickness 80-100 nm.
- Suitable materials for AR coating:
  - Tantalum oxide (Ta_2O_5), titania (TiO_2) and silicon nitride (**Si_3N_4**).
  - Front and back contacts: Earlier version – Al used as rear contact; in large production – AR coating, front and back contacts are deposited by screen printing and then fired
  - Screen printing of contacts-relatively cheaper, but blocks a relatively large area of the cell and degrades conductivity

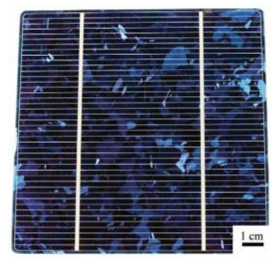
Creating PV Cells



Solar PV Materials:
Crystalline & Polycrystalline Silicon

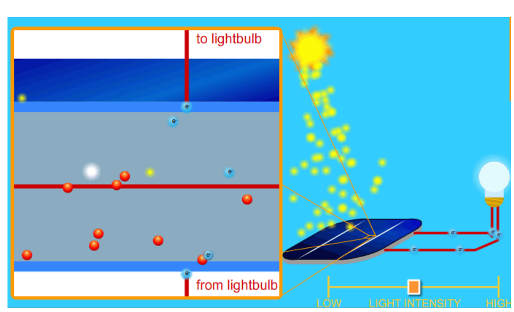
- **Advantages:**
  - High Efficiency (18-26%)
  - Established technology (The leader)
  - Stable
- **Disadvantages:**
  - Expensive production
  - Low absorption coefficient
  - Large amount of highly purified feedstock





How a Silicon-Based Solar Cell Works?

- Light with energy ≥ the band gap energy of Si is absorbed
- Energy is given to an electron in the crystal lattice
- This absorbed energy excites the electron; it is free to move
- A positive "hole" is left in the electron's place
- This separation of electrons and holes creates a voltage and a current



Source: http://www.compadre.org/portal/items/detail.cfm?ID=12726

Solar Photovoltaics

Building Integrated Photo-Voltaics

Photovoltaic solar panels on the roof of a house near Boston, Credit: Wikipedia

39