

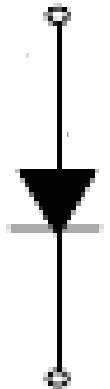
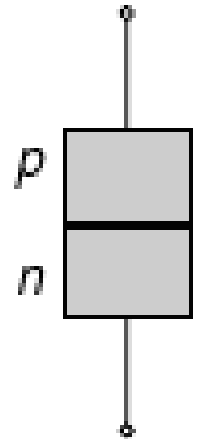
EE 446/646

Photovoltaic Devices II

Y. Baghzouz

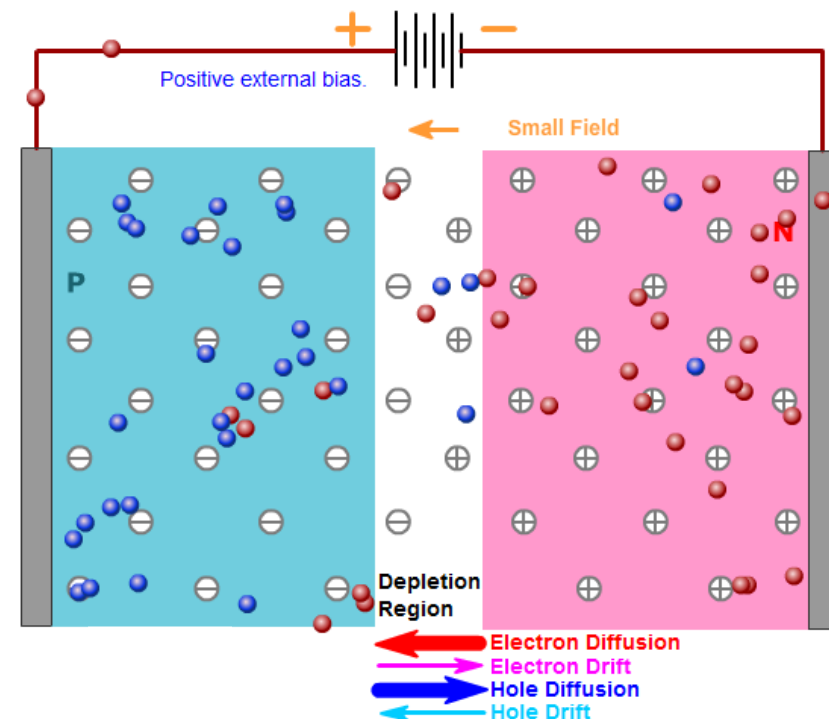
The p-n junction diode

- Before discussing the case when a p-n junction is exposed to sunlight, it is worth reviewing the p-n junction diode since it has some common electrical characteristics.
- A diode is an electronic component that consists of a p-n junction, just like a solar cell, except that it has a much smaller surface and the semiconductor material is not exposed as both sides are entirely covered with electrical contact material.
- With no external voltage, a diode is basically a p-n junction that is under equilibrium between diffusion and drift currents, as described earlier.



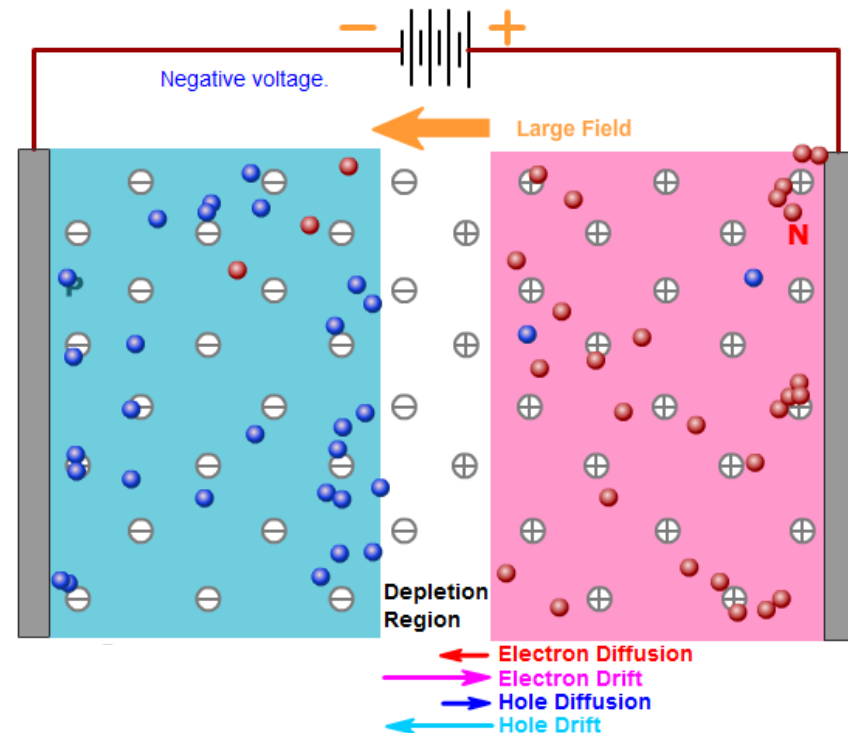
Diode Under Forward Bias

- When a voltage is applied across the terminals of a diode with the positive side connected to the p-type material and the negative side connected to the n-type material, the diode is said to be in the *forward bias* state.
- In forward bias, the applied electric field by the voltage source is in opposite direction of that of the built-in electric field in the depletion region. The net electric field is weakened, thus reducing the barrier to the diffusion of carriers from one side of the junction to the other. This results in an increase in the diffusion current
- The majority carriers are supplied from the external circuit, hence resulting in a net current flows under forward bias.



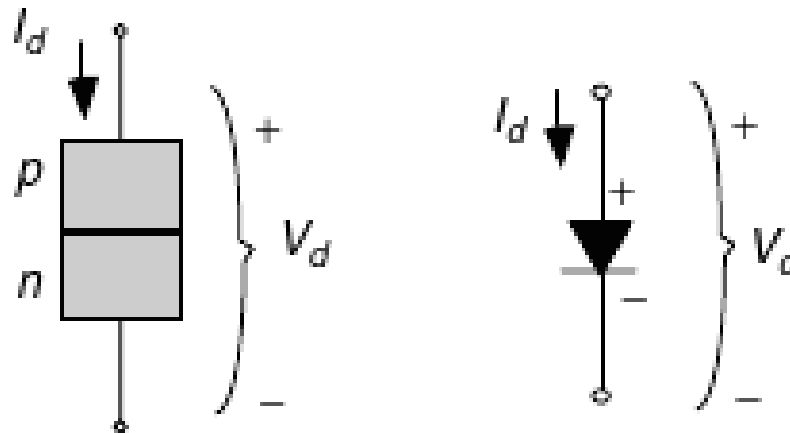
Diode Under Reverse Bias

- In a semiconductor, the minority carriers recombine → more carriers can diffuse across the junction.
- → The diffusion current is a recombination current. The higher the rate of recombination events, the greater the current flow.
- In reverse bias, a voltage is applied across the device such that the electric field at the junction increases.
- The higher electric field reduces the probability that carriers can diffuse across the junction, hence the diffusion current decreases.
- As in forward bias, the drift current is limited by the number of minority carriers on either side of the p-n junction, and is relatively unchanged by the increased electric field.



p-n junction diode

- When a forward voltage V_d is applied across the diode terminals, current would flow easily through the diode from the p-side to the n-side. The forward voltage across the diode is only a few tenths of a volt.
- If we try to send current in the reverse direction, only a very small (nA-pA) reverse saturation current I_0 will flow (result of thermally generated carriers with the holes being swept into the p-side and the electrons into the n-side). I_0 is often referred to as the “**dark saturation current**”.

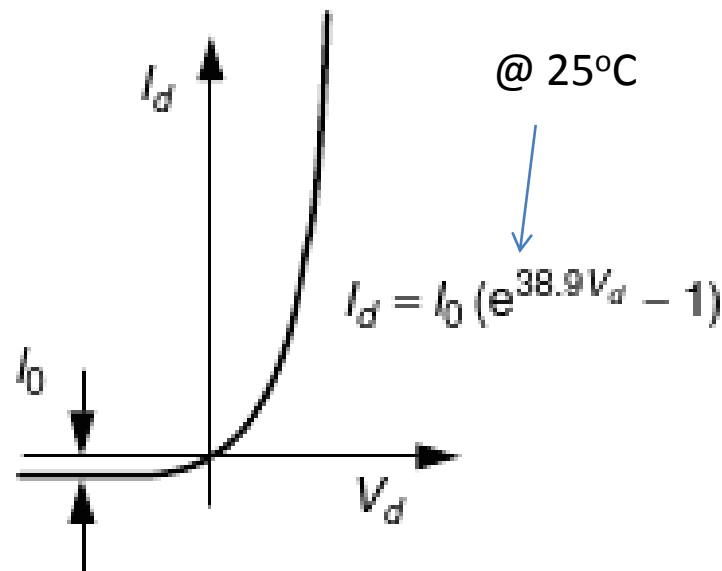


Diode voltage-current characteristic

- The voltage– current characteristic curve for the p –n junction diode is described by the following Shockley diode equation:

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

- where q is the electron charge (1.602×10^{-19} C), k is Boltzmann's constant (1.381×10^{-23} J/K), and T is the junction temperature (K), and I_0 is the dark saturation current.



Ideality Factor

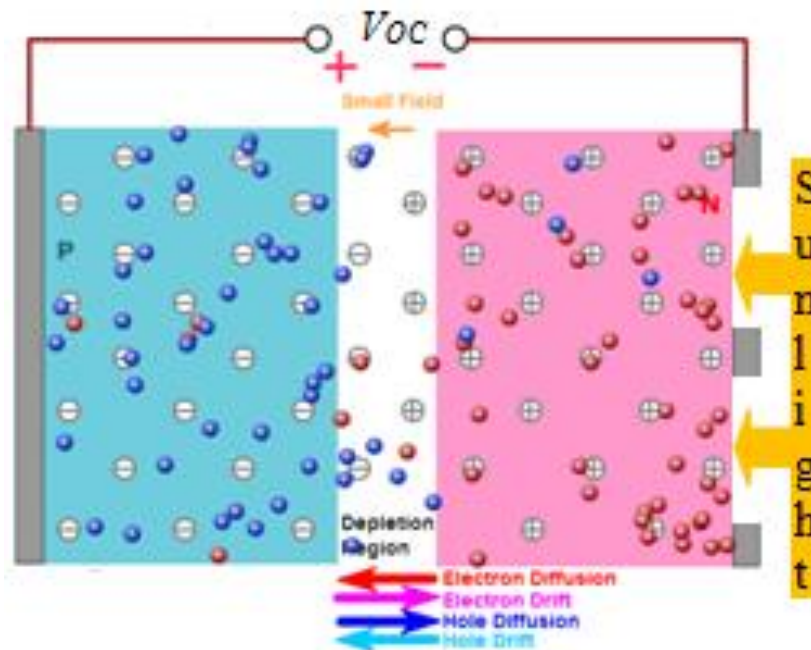
- In general,

$$I_d = I_0(e^{qV_d/AkT} - 1)$$

- where A is the ideality factor.
 - A = 1 if the transport process is purely diffusion,
 - A = 2 if the transport process is primarily recombination in the depletion region.

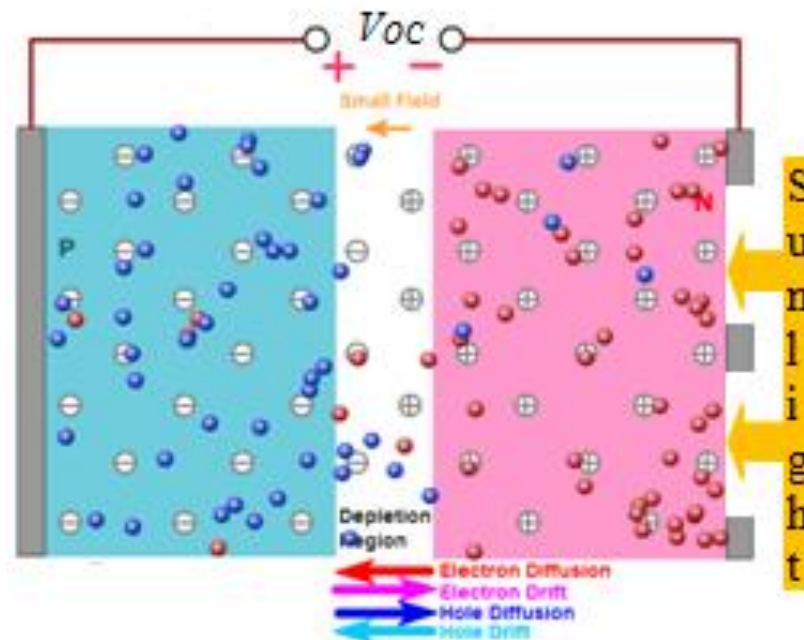
p-n junction cell exposed to sunlight

- When placed in the dark, a photovoltaic cell behaves like a p-n junction diode under no voltage excitation. Consider what happens in a p-n junction when it is exposed to sunlight.
 - Photons with sufficient energy are absorbed by the semiconductor and form hole-electron pairs (to be revisited after few slides).
 - If these mobile charge carriers reach the vicinity of the junction before they recombine, the electric field in the depletion region will push the holes into the p-side and push the electrons into the n-side. Hence, the p-side accumulates more holes and the n-side accumulates more electrons.



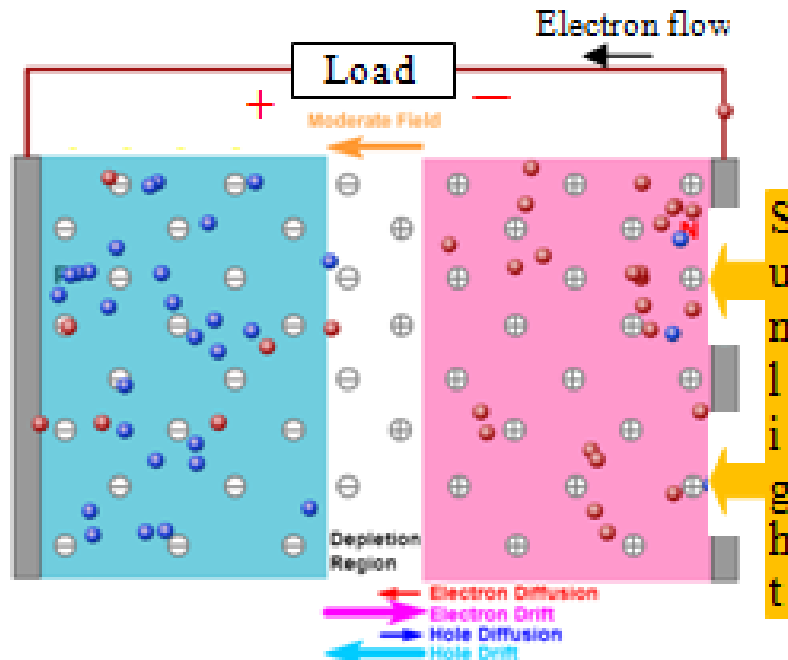
p-n junction cell exposed to sunlight

- This separation of charge creates an electric field at the junction which is in opposition to that already existing at the junction, hence a weaker net electric field which increases the diffusion current.
- If the light-generated carriers are prevented from leaving the solar cell, the forward bias of the junction increases to a point where the light-generated current is exactly balanced by the forward bias diffusion current, and the net current is zero. The resulting voltage at the cell terminals under this condition is called the *open-circuit voltage*.



p-n junction cell exposed to sunlight

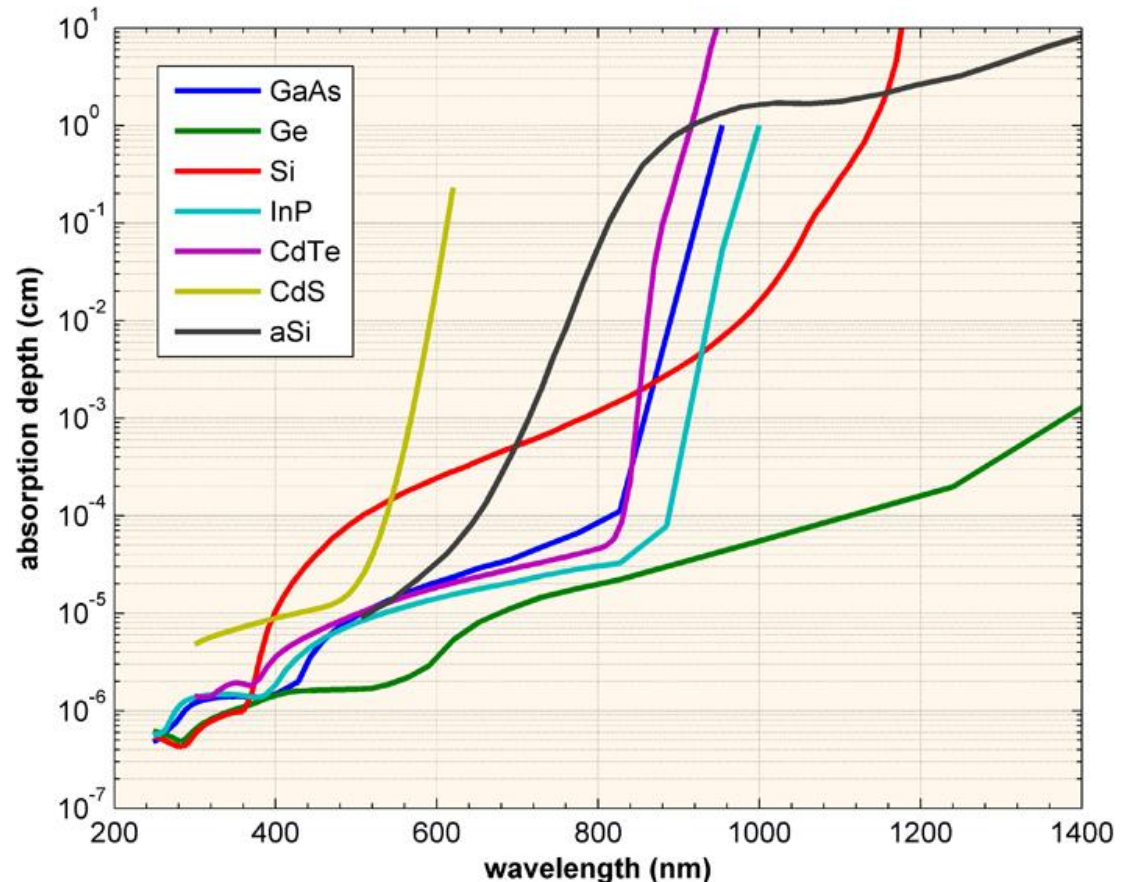
- when the cell terminals are connected to an external circuit, the light-generated electrons are provided an external path, while the holes remain stuck in the p-type semiconductor.
- Herein, the electrons will flow out of the n-side through the connecting wire to the load, and then recombine with holes that are waiting on the p-side to complete the circuit.
- In this case, the forward bias of the junction decreases to a point where the light-generated current is equal to the current supplied to the load (which is equal to electron drift minus electron diffusion). The result is a decrease in diffusion current due to an increase in the net electric field across the junction.



Light Absorption Depth

- Light absorption depth is how far into a material light of a particular wavelength can penetrate before it is absorbed. This depends on the material and also on the wavelength of light which is being absorbed.
- The absorption depth is a useful parameter which gives the distance into the material at which the light drops to about 36% (or $1/e$) of its original intensity.

Absorption depth of common semiconductor materials (@ 300° K)



High energy light (blue) is absorbed within a few microns.

Low energy (red) is absorbed after a few hundred microns.

Light Intensity & Generation Rate

- The intensity of light at any point in the device can be calculated by

$$I = I_o e^{-(x/\alpha)}$$

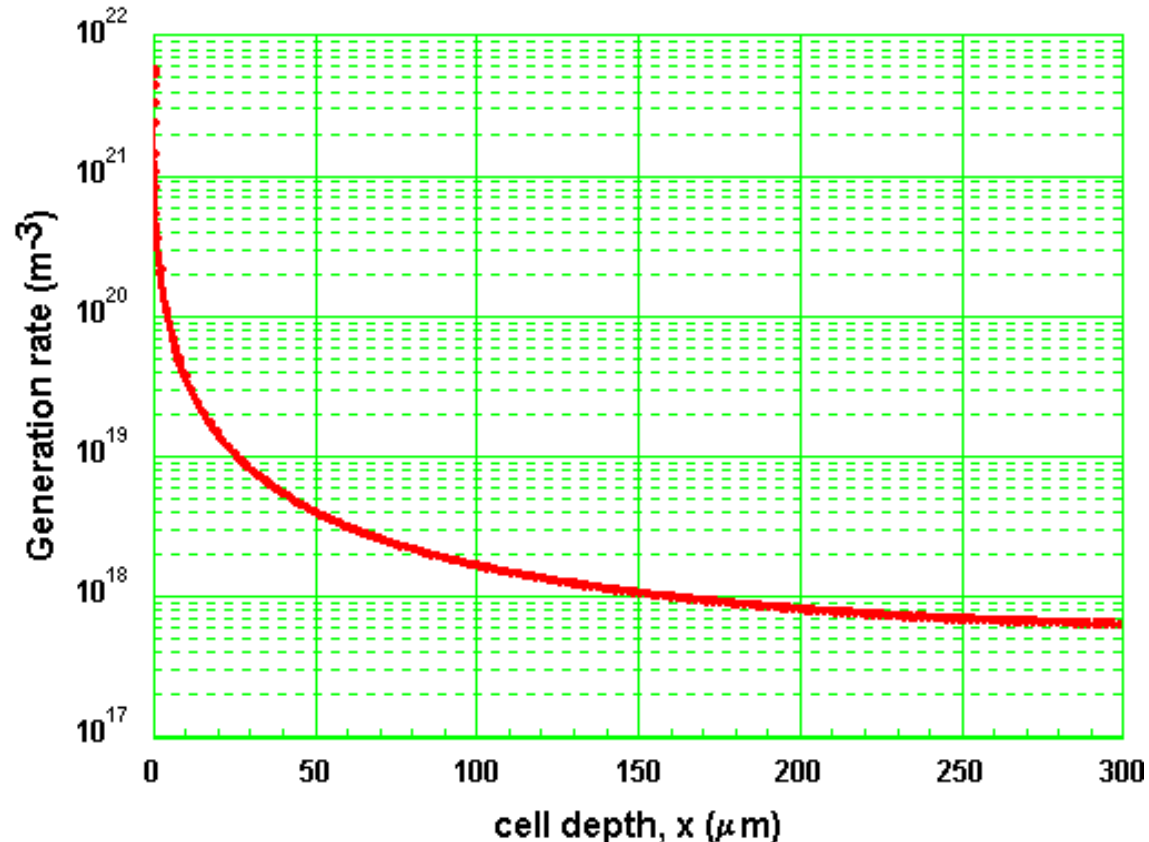
where α is the absorption depth (in cm), x is the distance (in cm) into the material at which the light intensity is being calculated; and I_o is the light intensity at the top surface.

- The generation rate gives the number of electrons generated at each point in the device due to the absorption of photons. Assuming that the loss in light intensity (i.e., the absorption of photons) directly causes the generation of an electron-hole pair, then the generation rate is given by:

$$G = (1/\alpha) I_o e^{-(x/\alpha)}$$

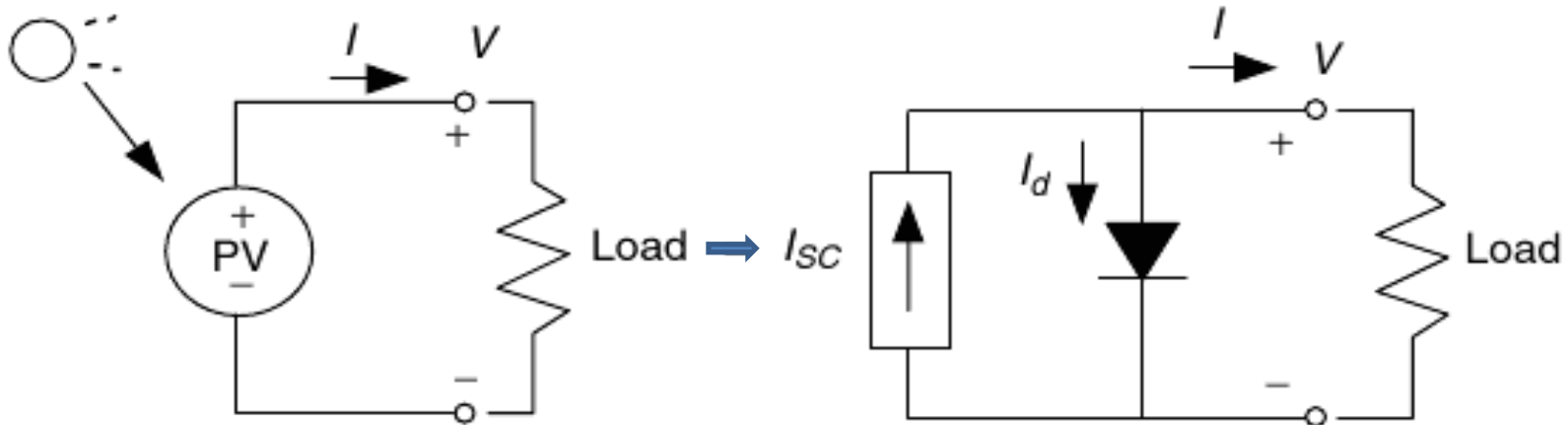
Generation Rate

- The generation as a function of distance for a standard solar spectrum (AM 1.5) incident on a piece of silicon is shown below.
- **Note:** there is an enormously greater generation of electron-hole pairs near the front surface of the cell, while further into the solar cell the generation rate becomes nearly constant.



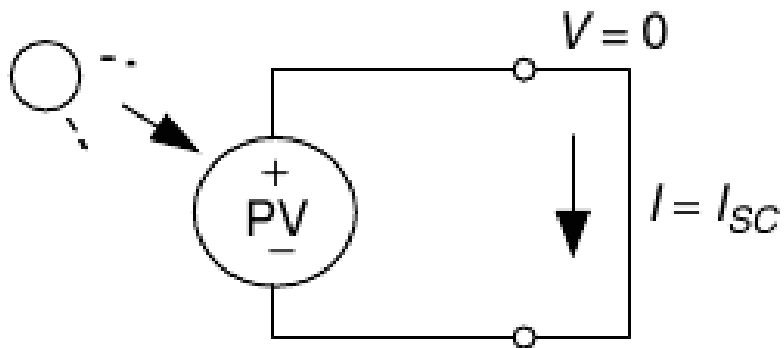
Simple Equivalent Circuit

- A simple equivalent circuit model for a photovoltaic cell consists of a real diode in parallel with an ideal current source.
- The ideal current source delivers current in proportion to the solar flux to which it is exposed.

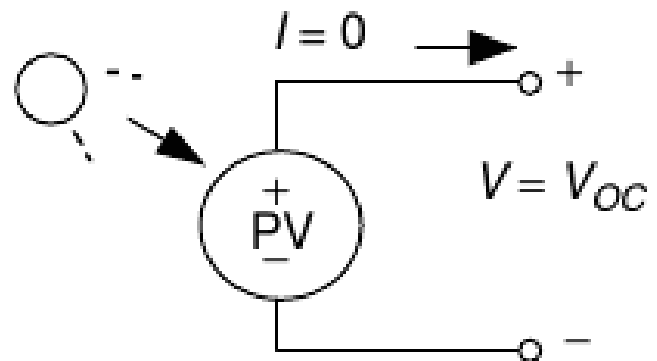


Short-circuit current and open-circuit voltage

- The short-circuit current I_{SC} is defined as the current that flows when the terminals are shorted together. This is equal to the magnitude of the ideal current source.
- The open-circuit voltage V_{OC} is defined as the voltage across the terminals when the leads are left open.

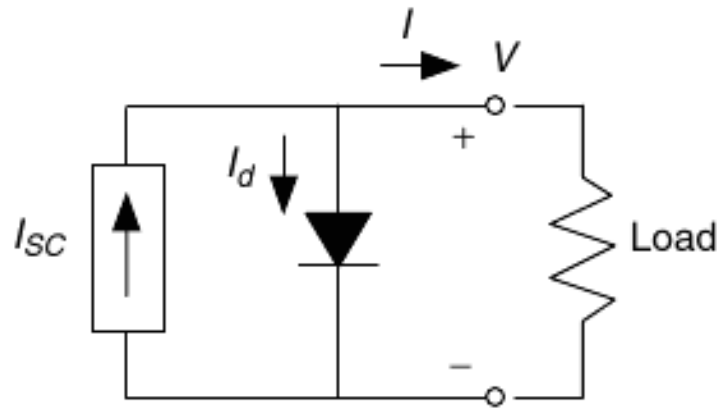


(a) Short-circuit current



(b) Open-circuit voltage

Current-voltage relation



- Relation between the short-circuit, diode, and load currents:

$$I = I_{sc} - I_d$$

- Substituting the diode current equation:

$$I = I_{sc} - I_0 (e^{qV/kT} - 1)$$

- At 25°C, $I = I_{sc} - I_0 (e^{38.9 V} - 1)$

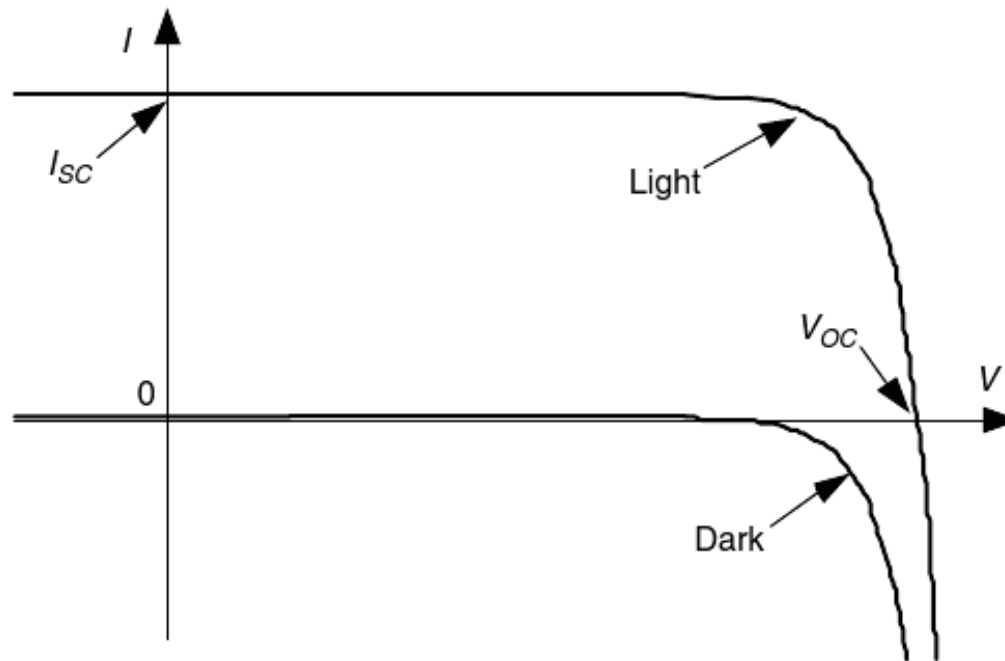
I-V Curve

- The open-circuit voltage can be found by setting the load current to zero:

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{I_{SC}}{I_0} + 1 \right)$$

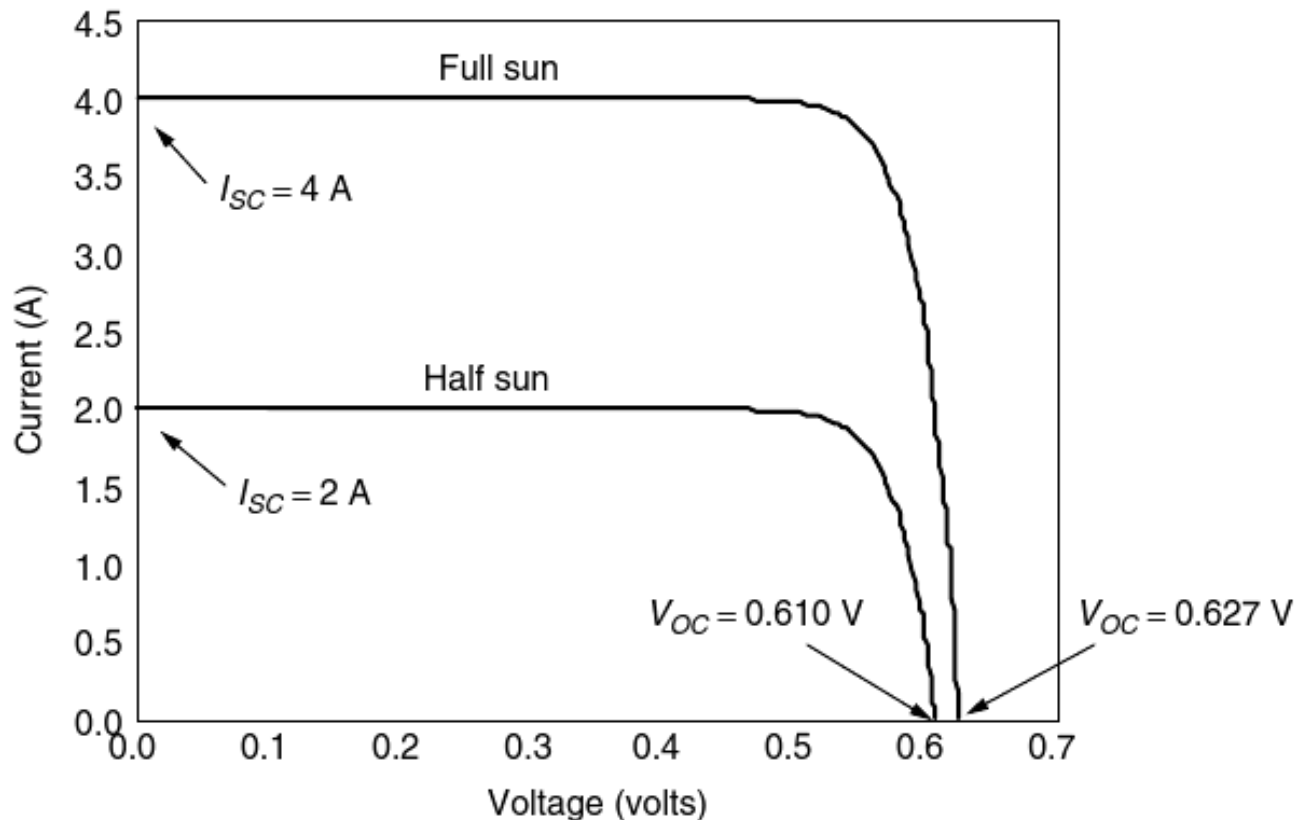
- At 25°C,

$$V_{OC} = 0.0257 \ln \left(\frac{I_{SC}}{I_0} + 1 \right)$$



Example

- Consider a 100-cm^2 photovoltaic cell with reverse saturation current $I_0 = 10^{-12} \text{ A/cm}^2$. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C . Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

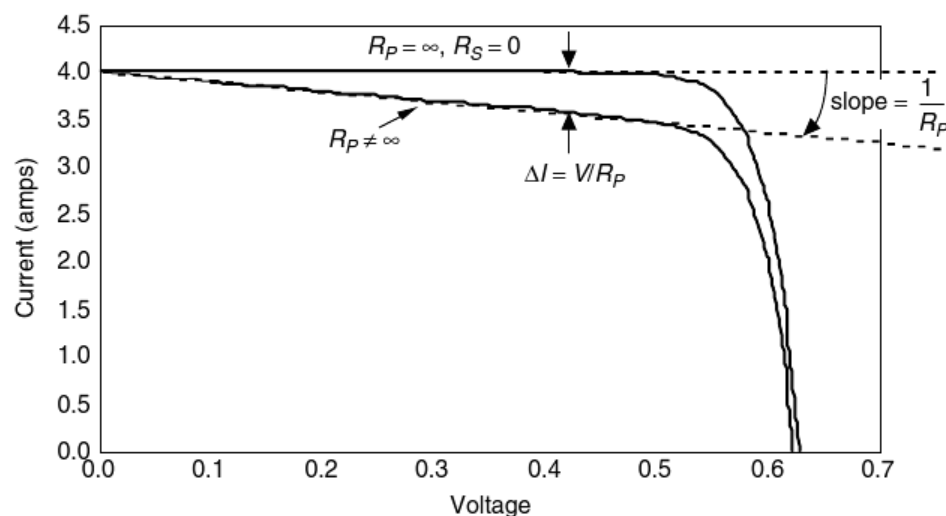
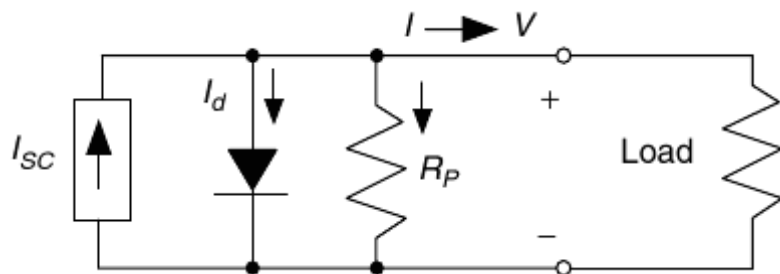


A more accurate equivalent circuit

- Addition of parallel leakage resistance R_p to account for manufacturing defects
- The ideal current source I_{SC} in this case delivers current to the diode, the parallel resistance, and the load:

$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$

- For a cell to have losses of less than 1% due to its parallel resistance, R_p should be greater than $100V_{OC}/I_{SC}$.

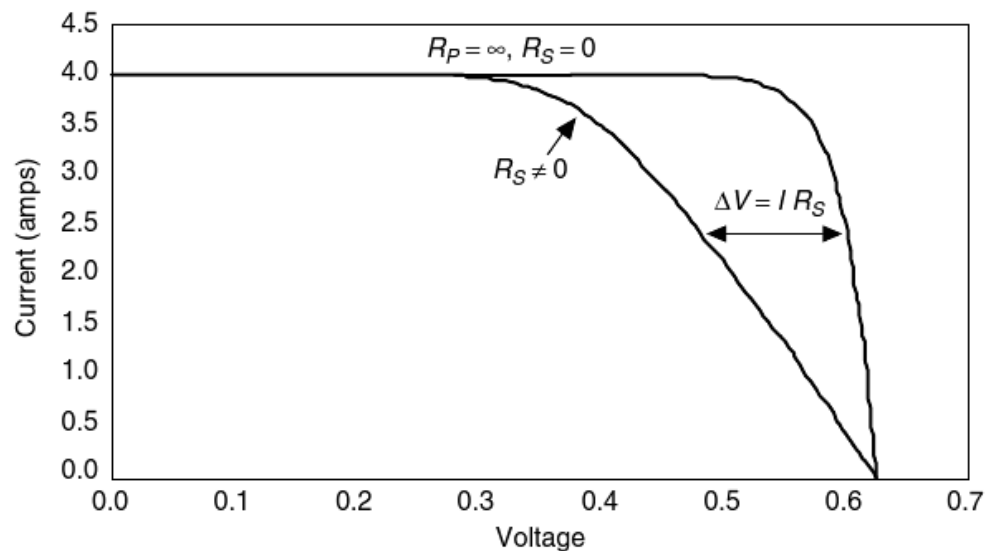
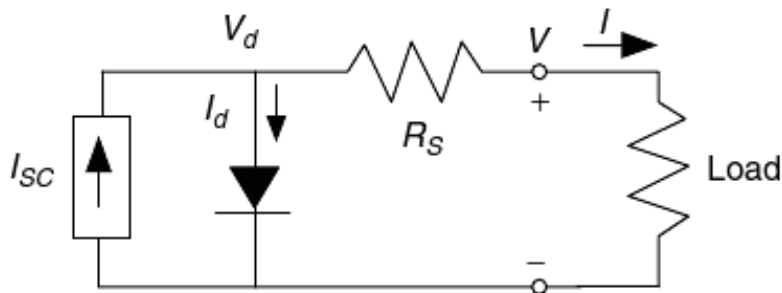


A more accurate equivalent circuit

- Addition of series resistance R_S to account for the resistance to the movement of current through the p-n materials; the contact resistance between metal and silicon; the resistance of the top and rear metal contacts.
- The diode voltage and load voltage are related by

$$V_d = V + I \cdot R_S$$

- For a cell to have losses of less than 1% due to its series resistance, R_S should be greater than $0.01V_{OC}/I_{SC}$.



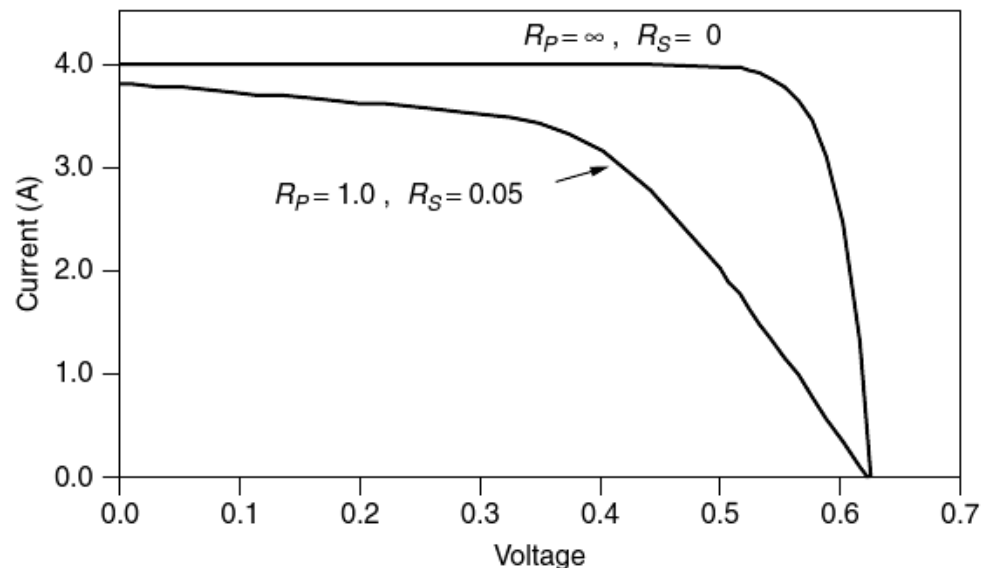
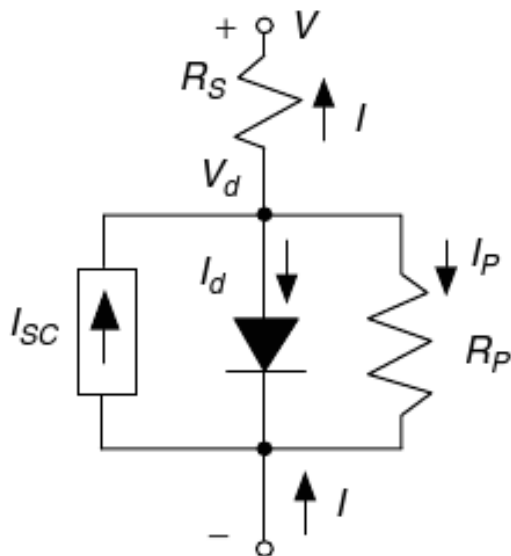
Final accurate equivalent circuit

- Addition of both series resistance R_S and parallel resistance R_P .
- The current –voltage equation becomes (non explicit)

$$I = I_{SC} - I_0 \left\{ \exp \left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left(\frac{V + I \cdot R_S}{R_P} \right)$$

- At 25°C,

$$I = I_{SC} - I_0 \left[e^{38.9(V + IR_S)} - 1 \right] - \frac{1}{R_P} (V + IR_S)$$



Useful current-voltage relationships

- Short circuit current in terms of load current, diode current, and parallel resistor current

$$I_{SC} = I + I_d + I_P$$

- Load current in terms of diode current, short-circuit current and diode voltage

$$I = I_{SC} - I_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

- Relation between load voltage and diode voltage

$$V = V_d - I R_S$$

Problem 5.2

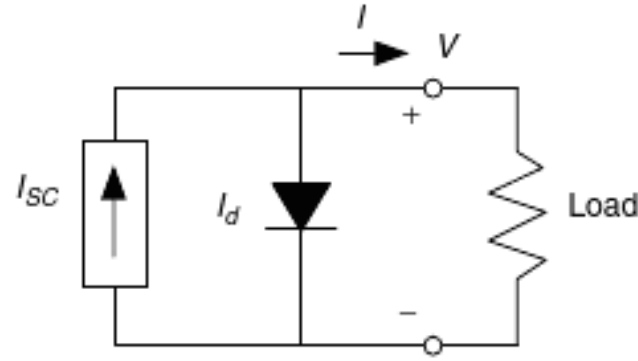
Cell area: 0.017 m^2

Reverse saturation current: $4 \times 10^{-11} \text{ A}$

Solar Insolation: 1 sun ($1,000 \text{ W/m}^2$)

Short-circuit current: 6.4 A

Temperature: 25 deg. C



Determine the following:

- Open-circuit voltage (Ans. 0.663 V)
- Load current and output power when $V = 0.55 \text{ V}$ (Ans. 6.32 A , 3.48 W)
- Efficiency of the cell under the load condition above (Ans. 20.45%)

Problem 5.3

Cell area: 0.017 m^2

Reverse saturation current: $4 \times 10^{-11} \text{ A}$

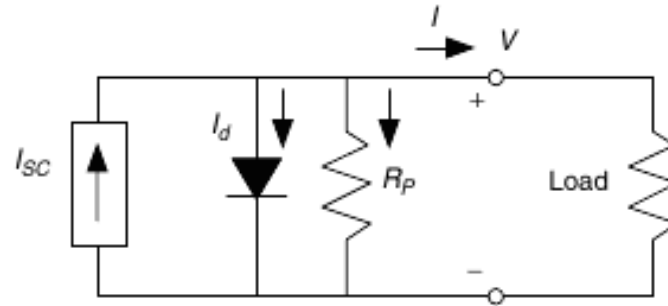
Solar Insolation: 1 sun ($1,000 \text{ W/m}^2$)

Short-circuit current: 6.4 A

Temperature: 25 deg. C

Parallel resistance: 10Ω

Voltage: 0.57 V



Find

- Load current and power delivered to the load ($I_d = 0.17 \text{ A}$, $I = 6.17 \text{ A}$, $P = 3.52 \text{ W}$)
- Efficiency of the cell (eff. = 20.7%)