EE 446/646
Photovoltaic Devices II

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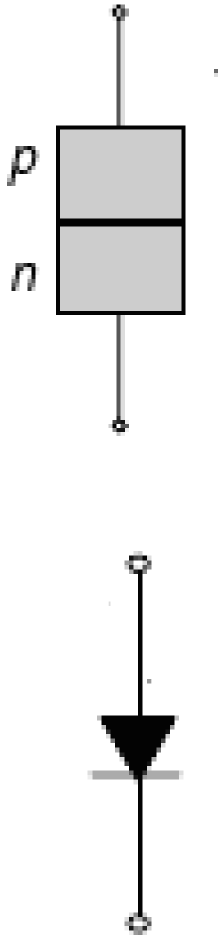
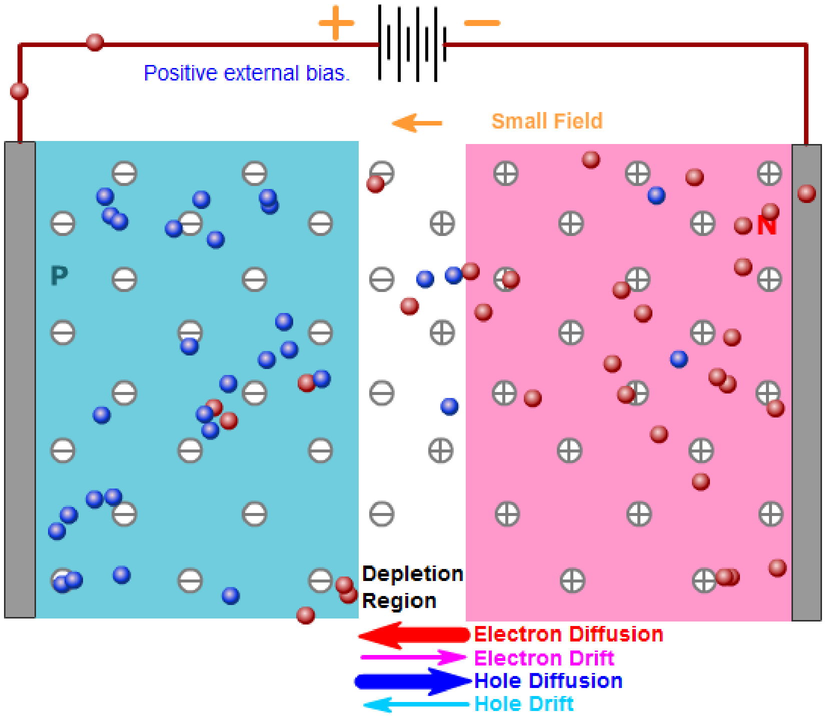
The p-n junction diode

- 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.



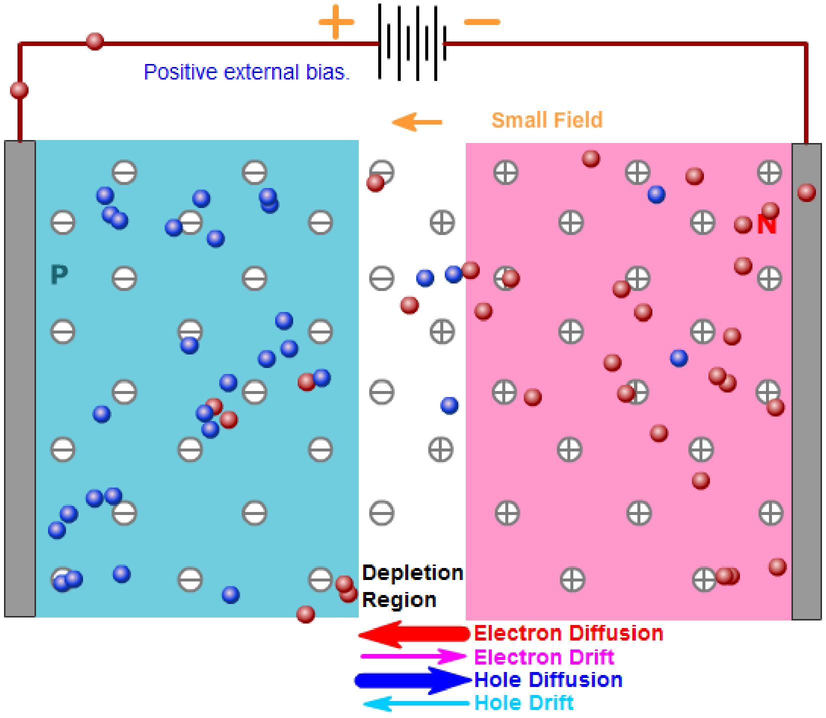
Diode Under Forward Bias

- 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.



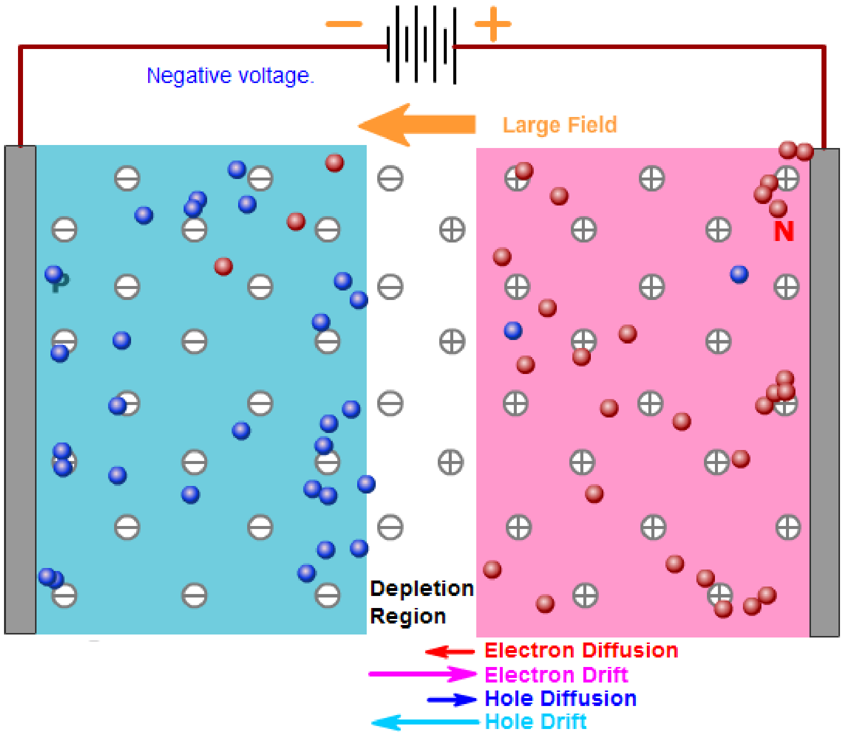
Diode Under Forward Bias

- The majority carriers are supplied from the external circuit, hence resulting in a net current flows under forward bias.
- In a semiconductor, the minority carriers recombine and thus more carriers can diffuse across the junction.
- Consequently, the diffusion current which flows in forward bias is a recombination current. The higher the rate of recombination events, the greater the current flow.



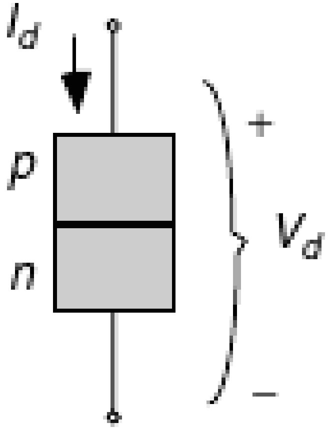
Diode Under Reverse Bias

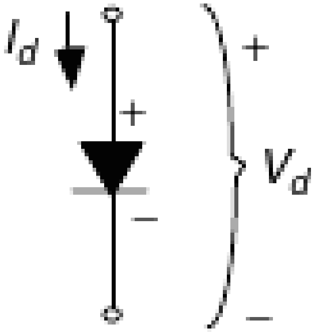
- In reverse bias, a voltage is applied across the device is such that the electric field at the junction increases.
- The higher electric field in the depletion region decreases the probability that carriers can diffuse from one side of the junction to the other, hence the diffusion current decreases.
- 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 - recap

- 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**".



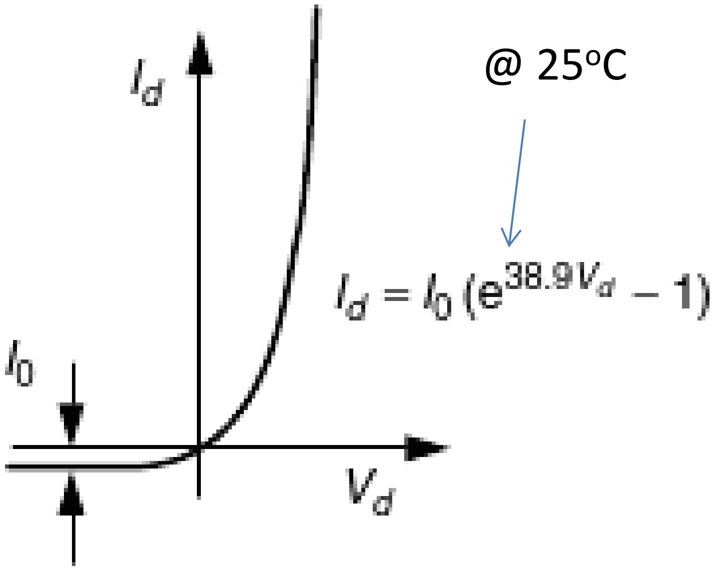


Diode voltage-current characteristic

- 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_o is the dark saturation current.



@ 25°C

Ideality Factor

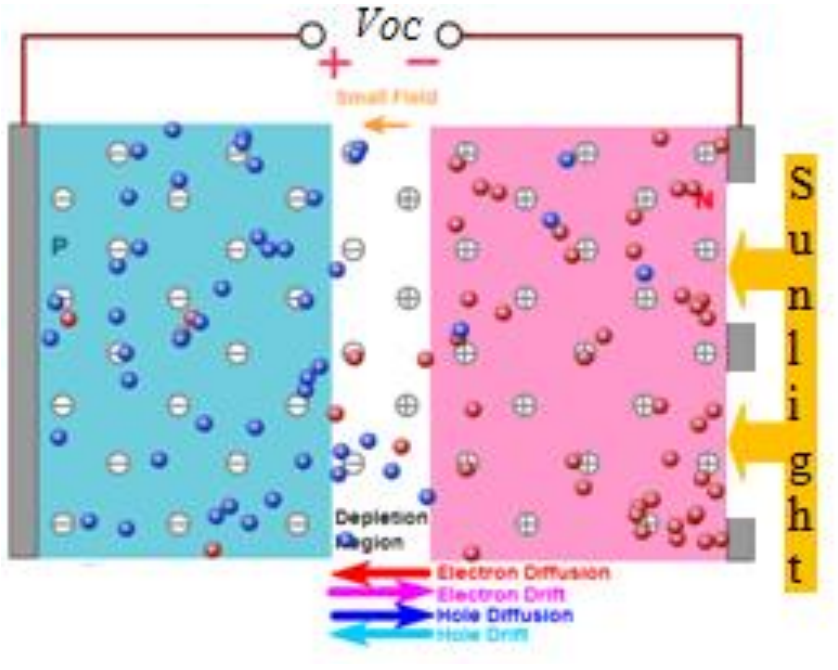
- In general,

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

- 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.

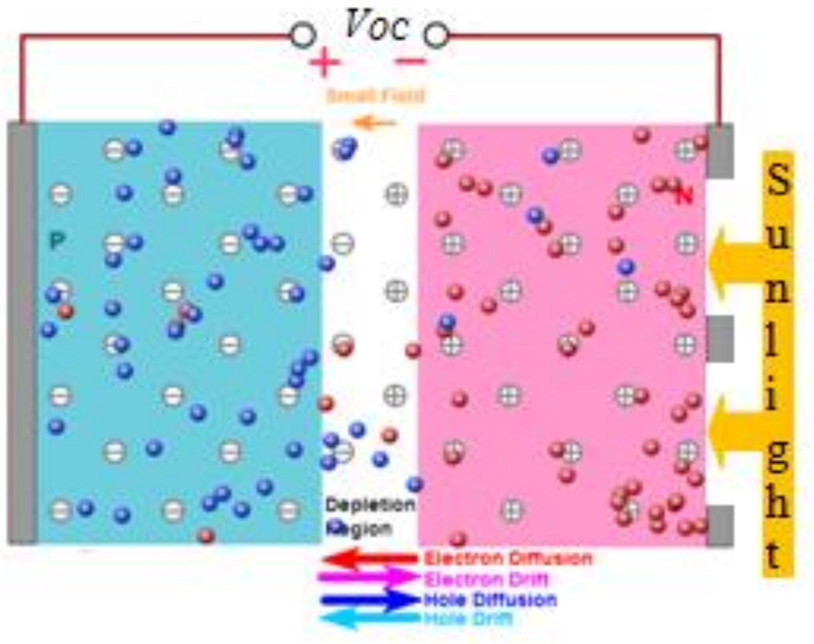
p-n junction cell exposed to sunlight

- When placed in the dark, a photovoltaic cell behaves like a p-n junction diode. When it is exposed to sunlight.
  - Photons with sufficient energy are absorbed by the semiconductor and form hole-electron pairs.
  - 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.



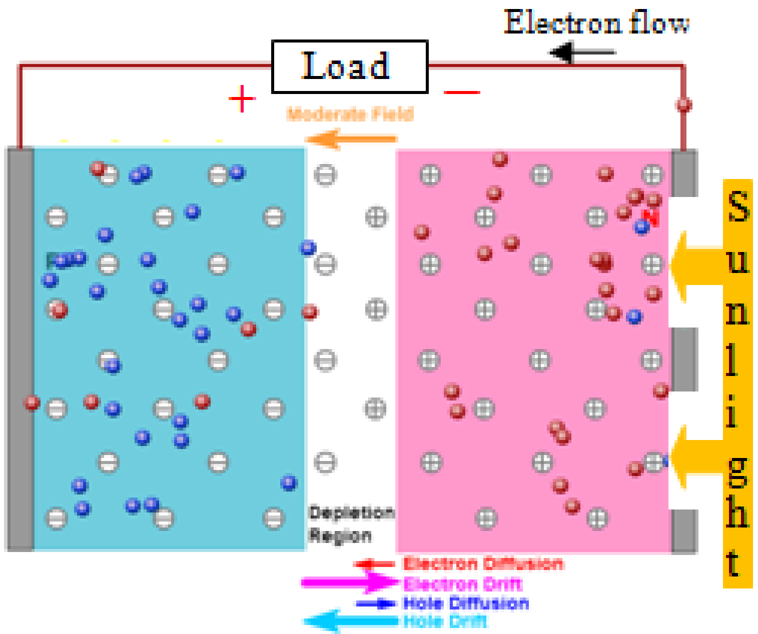
p-n junction cell exposed to sunlight

- 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.*



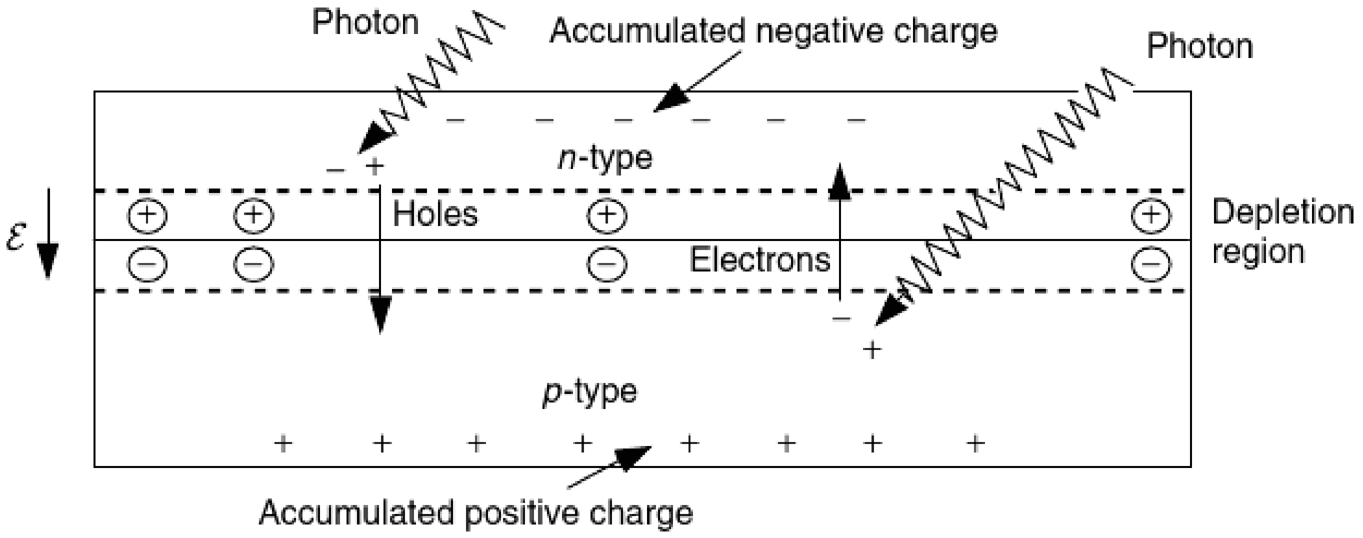
p-n junction cell exposed to sunlight

- 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 since they cannot flow through wire.
- 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.
- 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.



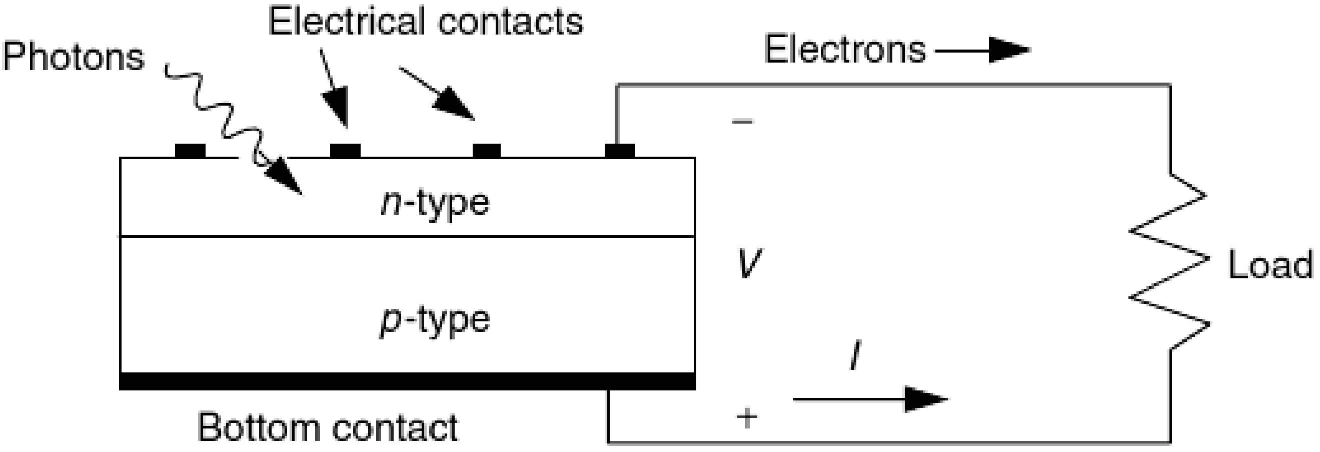
Generic PV cell

- When a p –n junction is exposed to sunlight,
  - As photons are absorbed, hole-electron pairs may be formed.
  - If these mobile charge carriers reach the vicinity of the junction, the electric field in the depletion region will push the holes into the p-side and push the electrons into the n-side.
  - The p-side accumulates holes and the n-side accumulates electrons, This creates a stronger electric field, and hence stronger voltage.



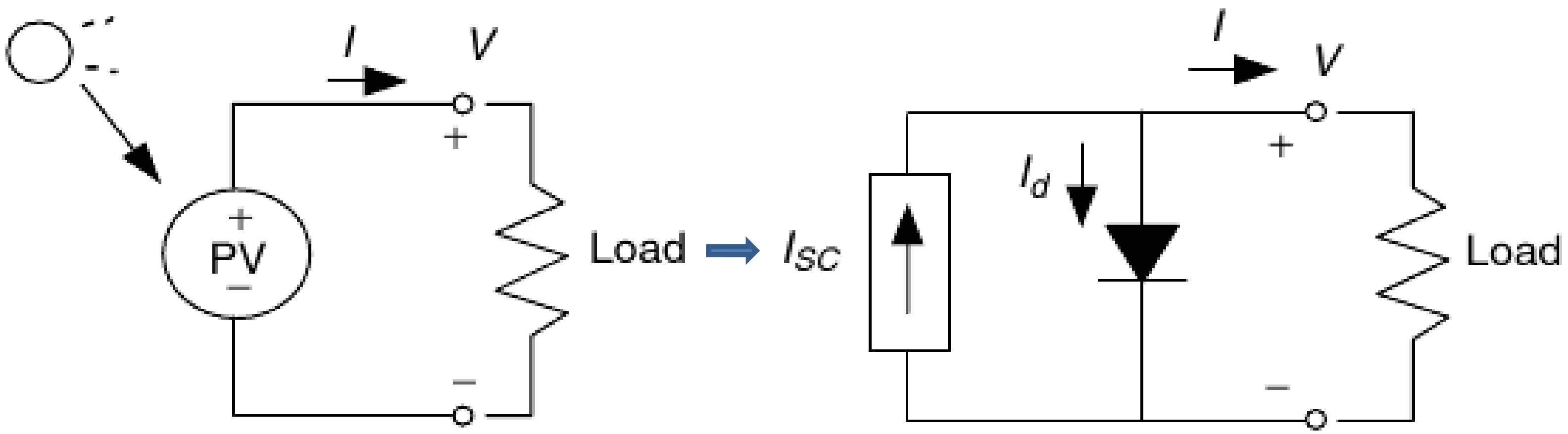
External current flow

- If electrical contacts are attached to the top and bottom of the cell, electrons will flow out of the n-side into the connecting wire, through the load and back to the p-side (a wire cannot conduct holes).
- When they reach the p-side, they recombine with holes completing the circuit.
- By convention, positive current flows in the direction opposite to electron flow.



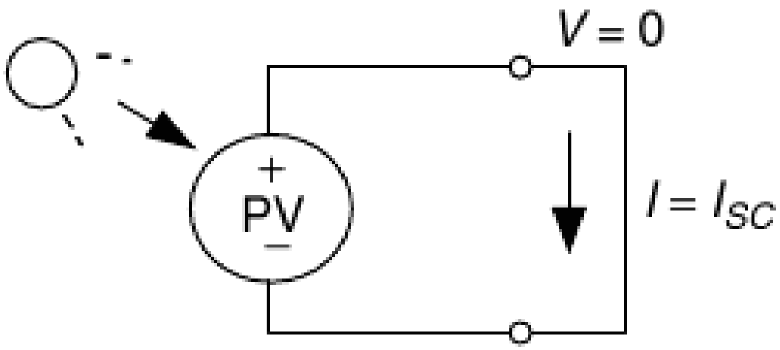
Simple Equivalent Circuit

- 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.

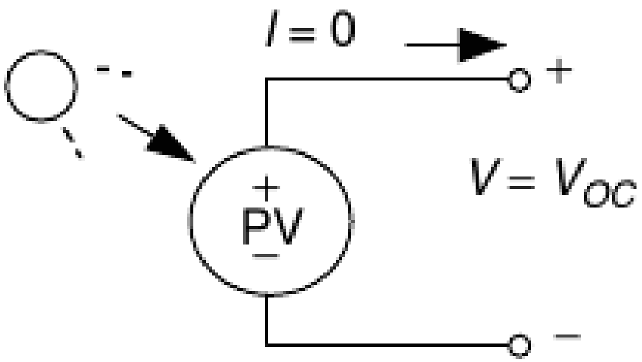


Short-circuit current and open-circuit voltage

- 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.

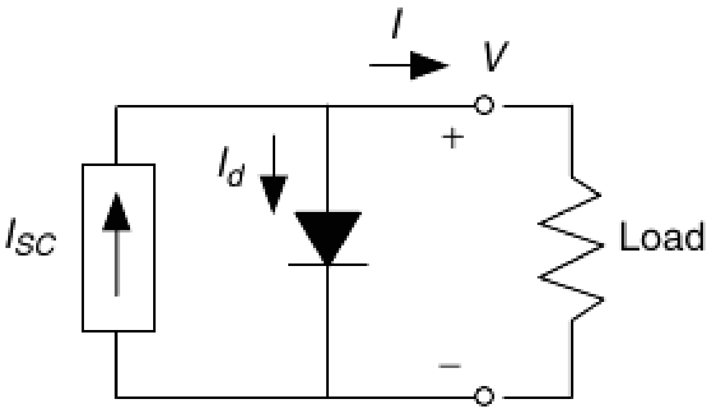


(a) Short-circuit current



(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:

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

- At 25ºC, $$I = I_{SC} - I_0 (e^{38.9\ \mathrm{V}} - 1)$$

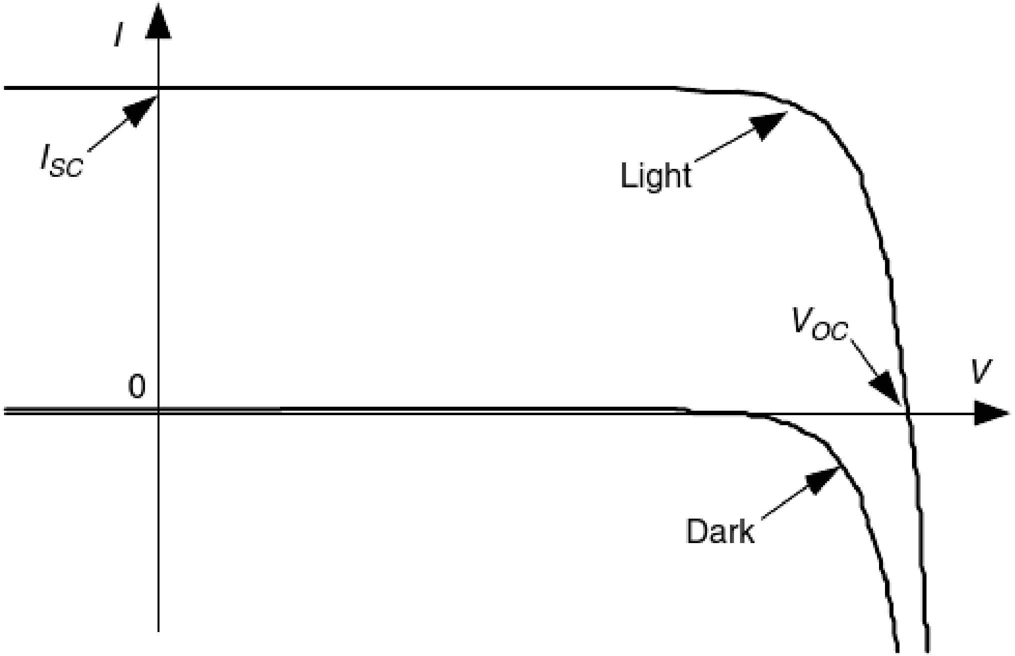
I-V Curve

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

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

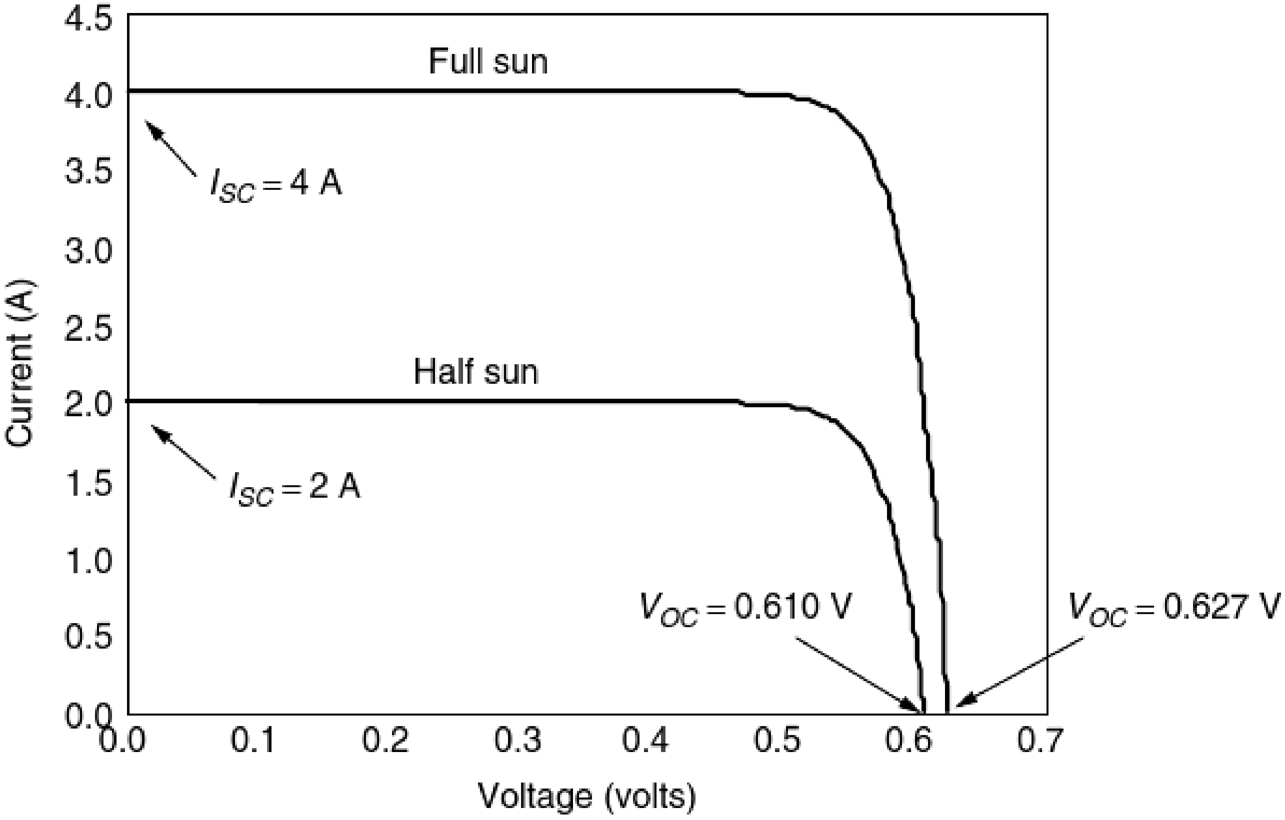
- At 25^{o}C,

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



Example

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

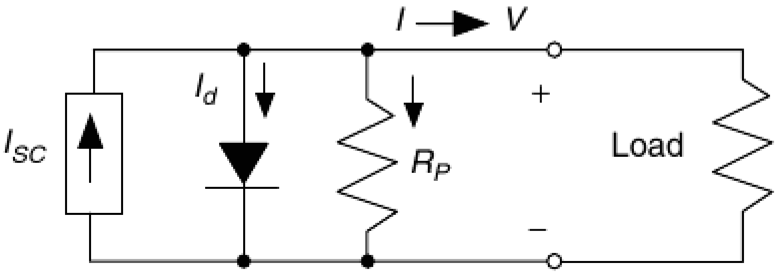


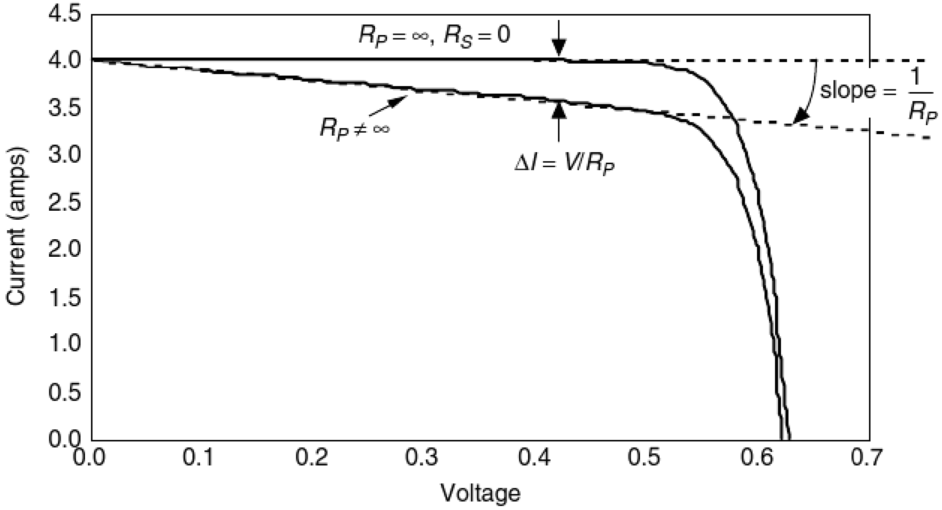
A more accurate equivalent circuit

- 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 $100V_{OC}/I_{SC}$.



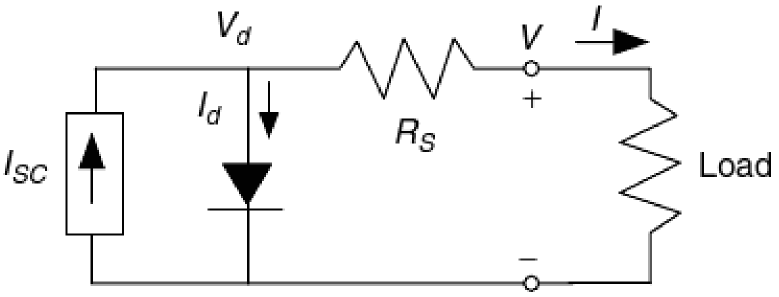


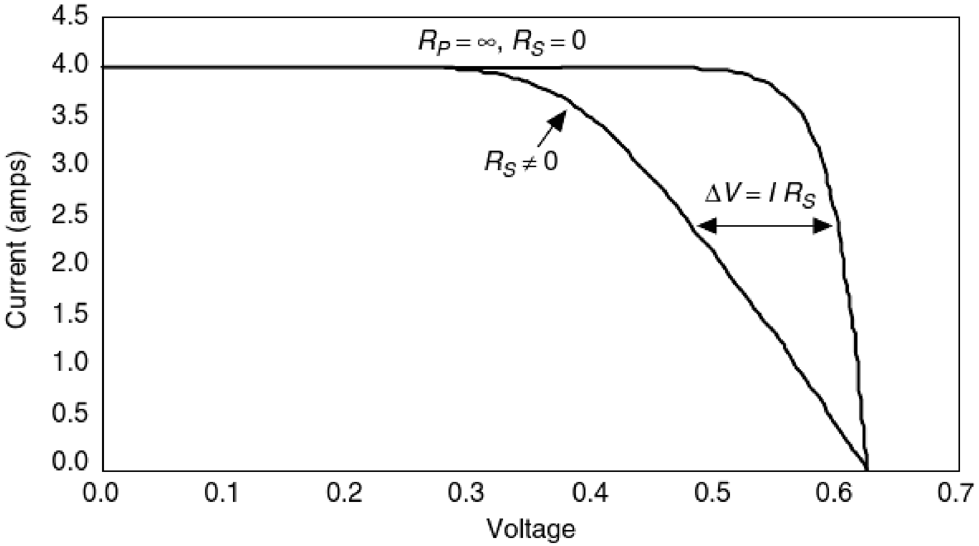
A more accurate equivalent circuit

- 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 $0.01V_{OC}/I_{SC}$.





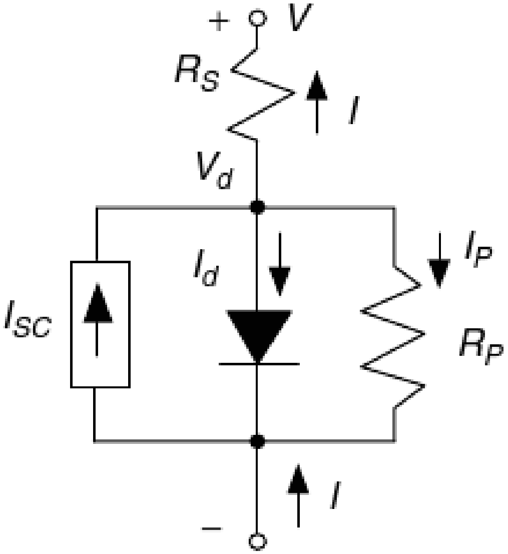
Final accurate equivalent circuit

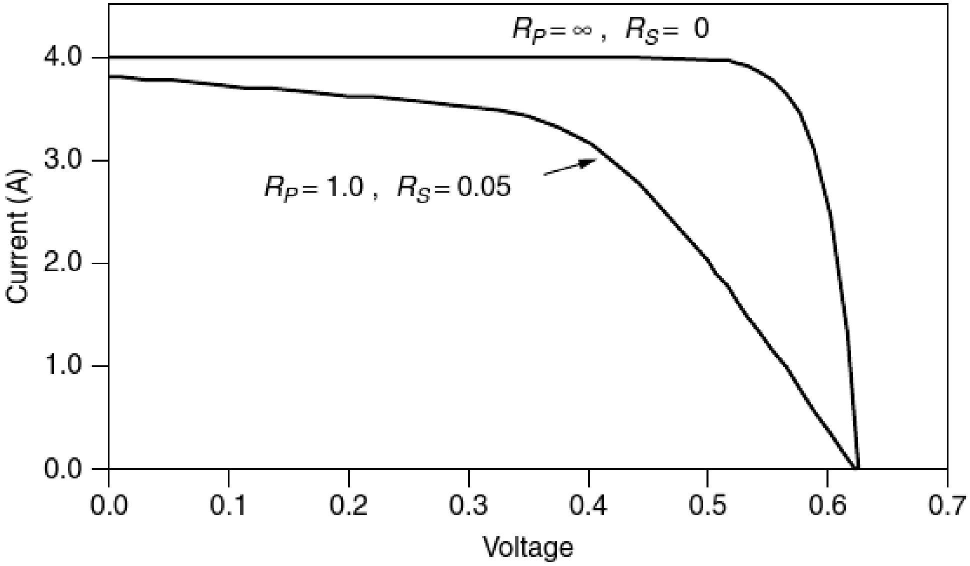
- Addition of both series resistance R_S and parallel resistance R_P.
- The current –voltage equation becomes (non explicit)

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

- At 25°C,

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





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

$$I = I_{SC} - \mathrm{I}_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

- Relation between load voltage and diode voltage

$$V = V_d - I R_S$$

Problems

8.1 For the following materials, determine the maximum wavelength of solar energy capable of creating hole-electron pairs:

a. Gallium arsenide, GaAs, band gap 1.42 eV.

b. Copper indium diselenide, $CuInSe_2$, band gap 1.01 eV

c. Cadmium sulfide, CdS, band gap 2.42 eV.

$E = h\nu = hc/\lambda$

8.2 A p-n junction diode at 25°C carries a current of 100 mA when the diode voltage is 0.5 V. What is the reverse saturation current, I_0?

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

8.3 For the simple equivalent circuit for a 0.005 m^2 photovoltaic cell shown below, the reverse saturation current is $I_0 = 10^{-9}$ A and at an insolation of 1-sun the short-circuit current is $I_{SC} = 1$ A,. At 25°C, find the following:

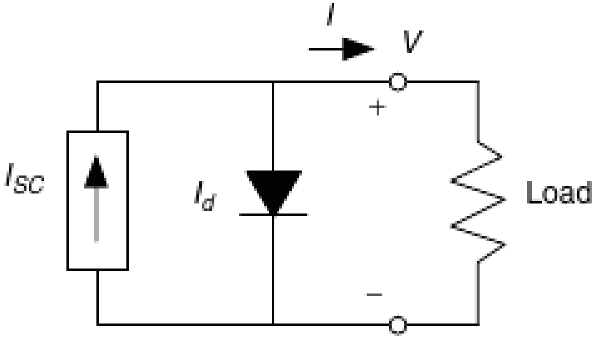


Figure P8.3

a. The open-circuit voltage.

b. The load current when the output voltage is $V = 0.5$ V.

c. The power delivered to the load when the output voltage is 0.5 V.

d. The efficiency of the cell at $V = 0.5$ V.

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

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

Pout = VI

η = Pout/Pin

Problems

8.4 The equivalent circuit for a PV cell includes a parallel resistance of $R_P = 10\ \Omega$. The cell has area 0.005 m^2, reverse saturation current of $I_0 = 10^{-9}$ A and at an insolation of 1-sun the short-circuit current is $I_{SC} = 1$ A, At 25°C, with an output voltage of 0.5 V, find the following:

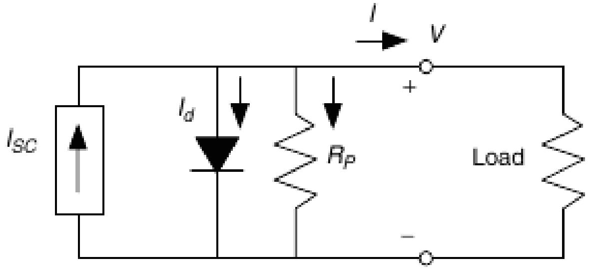
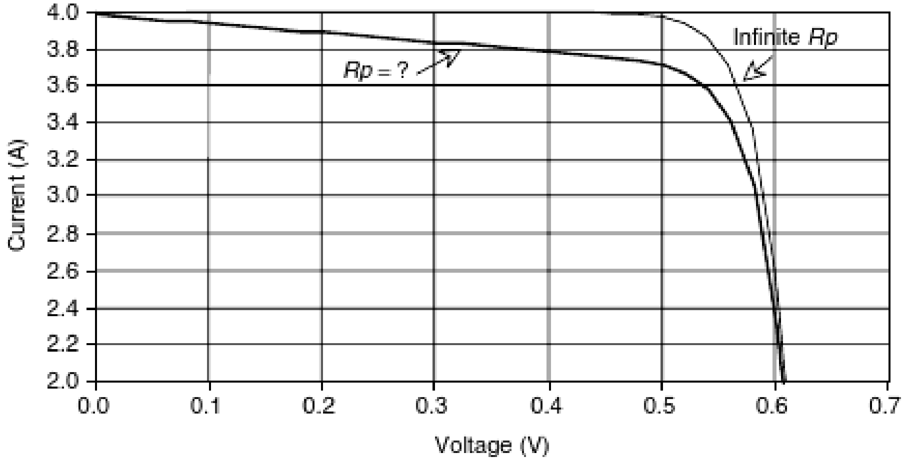


Figure P8.4

- **a.** The load current.
- **b.** The power delivered to the load.
- **c.** The efficiency of the cell.

8.5 The following figure shows two I-V curves. One is for a PV cell with an equivalent circuit having an infinite parallel resistance (and no series resistance). What is the parallel resistance in the equivalent circuit of the other cell?



$$I_d = I_0\left(e^{38.9V_d} - 1\right)$$

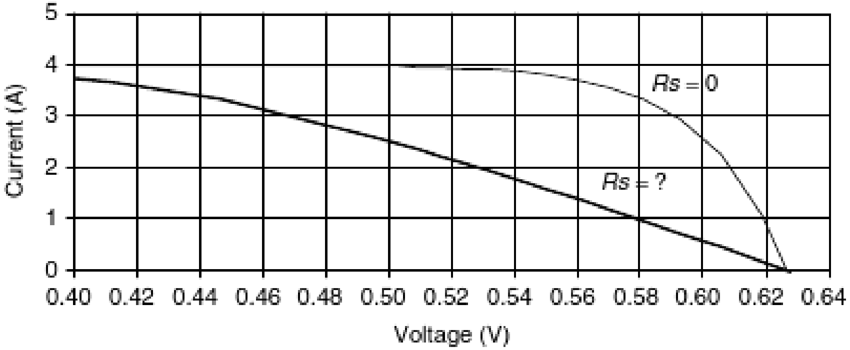
$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$

- P = VI
- η = Pout/Pin

- Rp = V/ΔI = 0.4/0.2 = 2Ω

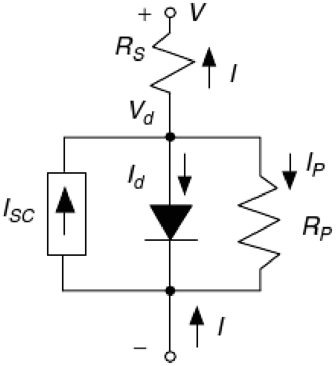
Problems

8.6 The following figure shows two I-V curves. One is for a PV cell with an equivalent circuit having no series resistance (and infinite parallel resistance). What is the series resistance in the equivalent circuit of the other cell?



- $R_s = \Delta V/I = 0.04/1 = 0.04\ \Omega$

Consider the cell equivalent circuit below. The following Parameters are known: Isc, Io, Cell temp, Rp, Rs and Vd.
1) Compute the power supplied by the cell.



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

$$V = V_d - I R_S$$

- P = VI