EELE408 Photovoltaics
Lecture 12: Solar Cell Sensitivities

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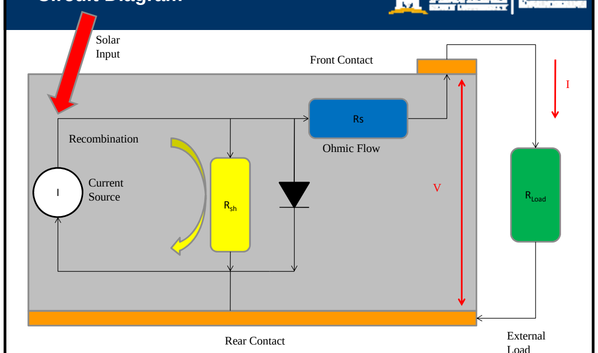
Effect of Parasitic Resistance

- Resistance effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances.
- The resistances are included in the circuit model by adding a resistor in parallel with the diode called the **shunt resistance** and a resistor in series with the diode called the **series resistance**
- The key impact of parasitic resistance is to reduce the fill factor

Circuit Diagram



Series Resistance

- Series resistance caused by the movement of current through
  - The semiconducting layers forming the emitter and base
  - The contact resistance between the metal and silicon
  - The resistance of the top and rear metal layer
- Excessively high series resistance can reduce the short circuit current as well as reduce the fill factor
- Particular problem at high current densities under concentrated light

Series Resistance

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

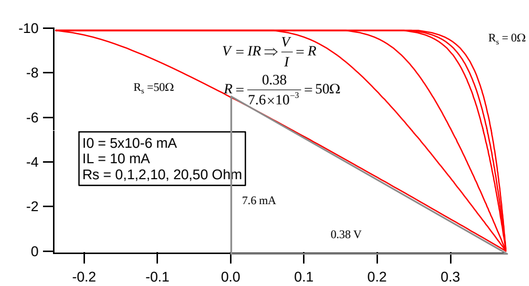
Add voltage drop across series resistor

$$= I_0\left[\exp\left(\frac{q(V-IR_s)}{kT}\right)-1\right]-I_L$$

$$\frac{I+I_L}{I_0} = \exp\left(\frac{q(V-IR_s)}{kT}\right)-1 \Rightarrow \ln\left[\frac{I+I_L}{I_0}\right] = \frac{q(V-IR_s)}{kT}$$

$$V = V_t \ln\left[\frac{I+I_L}{I_0}\right]+IR_s$$

Effect of Series Resistance



Series Resistance Impact on Fill Factor

Max power – power lost in resistor

$$P'_{mp} \approx P_{mp} - I_{mp}^2 R_s = V_{mp} I_{mp} - I_{mp}^2 R_s$$

$$\approx V_{mp} I_{mp}\left(1 - \frac{I_{mp}}{V_{mp}} R_s\right) = P_{mp}\left(1 - \frac{1}{R_{ch}} R_s\right)$$

$$P'_{mp} \approx P_{mp}(1 - r_s) \qquad r_s = \frac{R_s}{R_{ch}}$$

Normalized series Resistance

$$V'_{oc} I'_{sc} FF' \approx V_{oc} I_{sc} FF (1 - r_s)$$

Assume the open circuit voltage and short circuit current are not perturbed significantly

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

Second Order Empirical Equation
$r_s < 0.4$

$$FF' = FF(1 - 1.1 r_s) + \frac{r_s^2}{5.4}$$

Shunt Resistance

- Significant power losses due to shunt resistance are typically due to manufacturing defects rather than poor cell design
- Creates an alternative current path
  - Recombination
  - Junction shorting
- Reduces current flow through solar cell that reduces voltage of solar cell
- Severe at low light levels since less photogenerated current
- At low voltages shunt resistance has larger effect

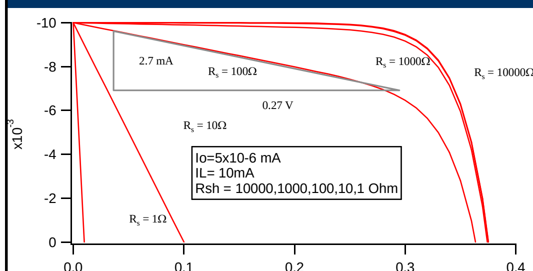
Shunt Resistance

$$I + I_L - I_d - \frac{V}{R_{sh}} = 0$$

Add current through shunt resistor

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

Effect of Shunt Resistance



$$V = IR \Rightarrow \frac{V}{I} = R$$

$$R = \frac{0.28}{2.7\times10^{-3}} = 100\Omega$$

Shunt Resistance Impact on Fill Factor

Max power – power lost in resistor

$$P'_{mp} \approx P_{mp} - \frac{V_{mp}^2}{R_{sh}} = V_{mp} I_{mp} - \frac{V_{mp}^2}{R_{sh}}$$

$$\approx V_{mp} I_{mp}\left(1 - \frac{V_{mp}}{I_{mp}} \frac{1}{R_{sh}}\right) = P_{mp}\left(1 - \frac{R_{ch}}{R_{sh}}\right)$$

$$P'_{mp} \approx P_{mp}(1 - r_{sh}) \qquad r_{sh} = \frac{R_{sh}}{R_{ch}}$$

Normalized shunt Resistance

$$V'_{oc} I'_{sc} FF' \approx V_{oc} I_{sc} FF\left(1 - \frac{1}{r_{sh}}\right)$$

Assume the open circuit voltage and short circuit current are not perturbed significantly

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

Empirical Equation
$r_{sh} > 0.4$

$$FF' = FF\left\{1 - \frac{v_{oc} + 0.7}{v_{oc}} \frac{FF}{r_{sh}}\right\}$$

Impact of Both Parasitic Resistances

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

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

$$FF' = FF\left\{1 - \frac{v_{oc} + 0.7}{v_{oc}} \frac{FF}{r_{sh}}\right\} \qquad FF' = FF(1 - 1.1 r_s) + \frac{r_s^2}{5.4}$$

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

Temperature Dependence ?

Solar Cells loose efficiency with the increase in temperature
Colder is better

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Temperature effect

- Increased temperature increase electron energy in material
- Less energy is needed to break bonds
- Less bond energy implies smaller band gap
- Therefore increased temperature reduces the band gap
- The open circuit voltage is impacted the most reducing it

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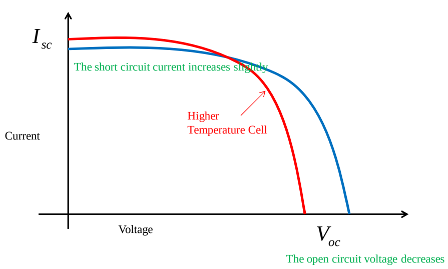
Effect of Temperature



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Temperature Sensitivity

- The open circuit voltage decreases with temperature because of the temperature dependence on I_0
- Look at one side of a p-n junction:
- Most significant effect is the intrinsic concentration (squared)

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{\frac{3}{2}} e^{-\frac{E_g}{kT}} \Rightarrow BT^3 e^{-\frac{E_g}{kT}}$$

$$I \propto n_i^2 \Rightarrow BT^{\gamma} e^{-\frac{E_g}{kT}}$$

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

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Temperature Dependence of Voc

- For silicon solar cells I_0 doubles for every 10°C increase in temperature

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_{sc}}{I_0}\right) = \frac{kT}{q}\left[\ln(I_{sc}) - \ln(I_0)\right] = \frac{kT}{q}\ln(I_{sc}) - \frac{kT}{q}\ln\left[BT^{\gamma} e^{-\frac{E_g}{kT}}\right]$$

$$= \frac{kT}{q}\left[\ln(I_{sc}) - \ln(B) - \gamma\ln(T) + \frac{qV_0}{kT}\right]$$

$$\frac{dV_{oc}}{dT} = \frac{V_{oc} - V_g}{T} - \gamma\left(\frac{k}{q}\right) \Rightarrow -2mV/^\circ C \Rightarrow \frac{1}{V_{oc}}\frac{dV_{oc}}{dT} = -0.003/^\circ C$$

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Temperature Dependence of Silicon Solar Cells

$$\frac{1}{V_{oc}}\frac{dV_{oc}}{dT} = -0.003/^\circ C$$

$$\frac{1}{I_{sc}}\frac{dI_{sc}}{dT} = +0.0006/^\circ C$$

$$\frac{1}{FF}\frac{d(FF)}{dT} \approx \frac{1}{6}\left[\frac{1}{V_{oc}}\frac{dV_{oc}}{dT} - \frac{1}{T}\right] \approx -0.0015/^\circ C$$

$$\frac{1}{P_m}\frac{dP_m}{dT} = \frac{1}{P_m}\frac{d(V_{oc}I_{sc}FF)}{dT} = \frac{1}{V_{oc}}\frac{dV_{oc}}{dT} + \frac{1}{I_{sc}}\frac{dI_{sc}}{dT} + \frac{1}{FF}\frac{d(FF)}{dT}$$

$$= -(0.004 - 0.005)/^\circ C$$

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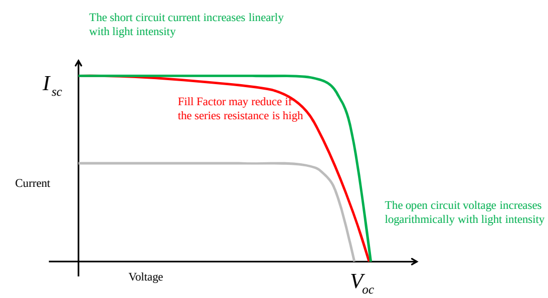
Effects of Light Intensity

- Light intensity impacts all solar cell parameters
- The light intensity on the solar cell is called the number of suns
- 1 sun corresponds to AM1.5 or 1kW/m^2
- $10\ \text{kW/m}^2$ would be 10 suns or 10X
- Solar cells design to use concentrated sunlight are called **concentrators**

Effect of Light Intensity



Concentrator

- Designed to operate at greater than 1 sun
- Sun light is focused or guided by optical elements
- Efficiency benefits stem from the logarithmic dependence of the open circuit voltage
- Can be offset by increases in series resistance and increased operation of temperature

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

Low Intensity Light

- Light intensities varies with time of day from $0\text{-}1\text{kW/m}^2$
- At low levels the shunt resistance value becomes more important
- As light intensity decreases, bias point and current decreases and equivalent resistance approaches shunt resistance
- Fraction of current through shunt resistance increases ➔ fractional power loss increases
- A solar cell with a high shunt resistance retains a greater fraction of its original power under cloudy or low intensity conditions