1. Temperature Effects

$V_{oc}$ decreases (approx 0.33% per °C for monocrystalline Si PV) as the temperature increases.

\[ \therefore \text{PV's have a negative temperature coefficient} \]

→ show Fig 2.12

$I_{sc}$ changes much less with temperature.

\[ \therefore \text{Power output decreases as temperature increases} \]

→ Winter in northern latitudes with snow reflecting light onto a PV array is a good application for PV

→ In hot climates, PV cells may reach 70°C → techniques for cooling them are important

2. Modelling Resistive Losses in the PV cell

a. More on the PV circuit model

\[
\begin{align*}
I &= I_0 - I_L = I_0 (e^{V_0/V_T} - 1) - I_L \\
\text{for } I_{sc} \rightarrow V_0 = 0 & \Rightarrow I_0 = 0 \\
\therefore I &= -I_L = -I_{sc} \\
\therefore I_L &= I_{sc} \\
\text{for } V_{oc} \rightarrow I &= 0 \\
\therefore I_{sc} &= I_0 = I_0 (e^{V_{oc}/V_T} - 1)
\end{align*}
\]
Figure 2.12 Effects of temperature on the $I-V$ characteristic.
or \[ V_{oc} = \frac{K}{Q} \ln\left( \frac{I_{sc}}{I_0} + 1 \right) \]

\[ I_{sc} = \text{"light current"} \]

\[ I_0 = \text{"dark current"} \]

\[ V_{oc} = \text{function of light and dark currents} \]

If we include the diode nonideality factor, \( n \)

\[ V_{oc} = nK \ln\left( \frac{I_{sc}}{I_0} + 1 \right), \text{ but } n \text{ is close to 1} \]

Note: \[ K = \frac{kT}{Q} \]

\[ V_{oc} = \frac{kT}{Q} \ln\left( \frac{I_{sc}}{I_0} + 1 \right) \]

This indicates \( V_{oc} \) increases with temperature!

It does NOT!

The dark current, \( I_0 \), increases with temperature, enough
to offset increasing \( T \), so that \( V_{oc} \) decreases as temperature increases

b. Modeling Losses

i. recombination and other "shorting losses"

\[ \rightarrow \text{can be modeled as a shunt resistor, } R_2, \text{ in parallel with the PV} \]

\[ R_2 \text{ effect: small decrease in } V_{oc}, \text{ larger decrease in the fill factor} \]
2 Solar cells

Figure 2.18 Texturisation by raised pyramids.
Figure 2.21 Equivalent circuits and I–V characteristics of a solar cell that includes: (a) series resistance; (b) shunt resistance.
(2) Resistive losses (resistance in contacts, bus bars, fingers and the bulk semiconductor material) can be modeled as a resistor in series with the PV, $R_1$

\[
\begin{align*}
I_L & \quad R_1 \quad I \quad V \\
\end{align*}
\]

$R_1$ effect: small decrease in $I_{sc}$, but a larger decrease in the fill factor

→ Show Fig 2.21

(3) Circuit model with $R_1$ and $R_2$

\[
\begin{align*}
I_1 &= I_L - I_D \\
I_0 &= I_0 \left( e^{\frac{V_0}{V_T}} - 1 \right) \\
V_0 &= V_{out} + I_{out} R_1 \\
I_{out} &= I_1 - I_2 \\
I_2 &= \frac{V_D}{R_2} = \frac{V_{out} + I_{out} R_1}{R_2} \\
\therefore I_{out} &= I_L - I_0 \left( e^{\frac{V_{out} + I_{out} R_1}{V_T}} - 1 \right) - \frac{V_{out} + I_{out} R_1}{R_2}
\end{align*}
\]
2. Poly- or Multicrystalline Si PV

- Similar to the single or mono-crystalline PV cells
- Different manufacturing process

Monocrystalline Si → 
Cz or Czochralski process → saw to wafer → finely polished

Single xtal ingot

Multicrystalline Si → 
cast multicrystalline block → cut to smaller block → wafurized

Poly Si PV are about 18% less efficient than single xtal Si PV

But: (a) Poly Si PV are lower cost
(b) are made rectangular, more densely packed than rounded single crystal Si PV

- Poly Si PV cells have a scaly, shimmering blue distinctive appearance
  anti-reflective coatings

Poly Si grain boundaries present unwelcome sites for e−-hole recombination, hence lower efficiency than single crystal PV
3. Amorphous Si (a-Si) PV
   - 1st "thin-film" PV technology.
   - Easy to manufacture and low-cost
   - a-Si PV has lower efficiency: 6-8% → about half the efficiency of single-crystal Si PV
   - But a-Si is better than single-crystal Si PV in weak or diffuse light (indoors like powering a calculator)
   - a-Si PV is less adversely affected by temp than Sc Si PV

a. a-Si
   - a better light absorber than Sc-Si
     - very thin films can be used for PV → 0.1μm
   - no regular lattice structure → random structure
   - incomplete bonds and many defects
   - results in energy stopping stones between valence and conduction bands → promotes recombination
   - low charge carrier mobility
   - Techniques have been developed to overcome these issues.