Tutorial 4

Exercise 1: Foundational Exercise

1. The maximum power generated by the solar cell occurs at the Maximum Power Point (MPP). It is calculated by multiplying the current at maximum power Imp by the voltage at maximum power Vmp:

   $$P_{max} = I_{mp} \times V_{mp} = 5.85\ \text{A} \times 0.52\ \text{V} = 3.042\ \text{W}$$

2. The Fill Factor FF measures the "squareness" of the solar cell's I-V characteristic. It is the ratio of the maximum power to the theoretical power (the product of open-circuit voltage Voc and short-circuit current Isc:

   $$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{3.042\ \text{W}}{0.61\ \text{V} \times 6.24\ \text{A}} \approx 0.7992$$

3. Efficiency ηis the ratio of the electrical power output Pmax to the incident solar power Pin. First, convert the cell area to square meters and calculate the total input power:

   Area in m^2:

   $$156\ \text{cm}^2 \times (1\ \text{m}/100\ \text{cm})^2 = 0.0156\ \text{m}^2$$

   Total Input Power:

   $$P_{in} = 1000\ \text{W/m}^2 \times 0.0156\ \text{m}^2 = 15.6\ \text{W}$$

   Now, calculate the efficiency:

   $$\eta = \frac{P_{max}}{P_{in}} \times 100\% = \frac{3.042\ \text{W}}{15.6\ \text{W}} \times 100\% = 19.5\%$$

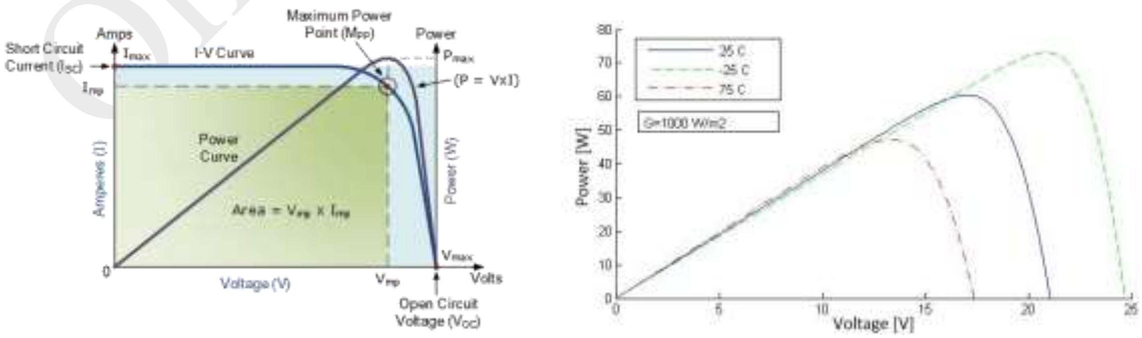
Exercise 2: Complex Synthesis Problem

1. To find the new open-circuit voltage Voc, new, we calculate the voltage drop caused by the increase in temperature from the Standard Test Condition (STC) of 25ºC to the operating temperature of 65ºC.

   Temperature Difference (ΔT): $65^\circ\text{C} - 25^\circ\text{C} = 40^\circ\text{C}$

   Voltage Coefficient in V/°C (β): $-0.3\%/^\circ\text{C}$ of $0.70\ \text{V} = -0.0021\ \text{V}/^\circ\text{C}$:

In the context of solar cells, the voltage coefficient (more formally the Temperature Coefficient of Voc is a metric that describes how the open-circuit voltage of a cell changes as its temperature deviates from the standard 25ºC reference

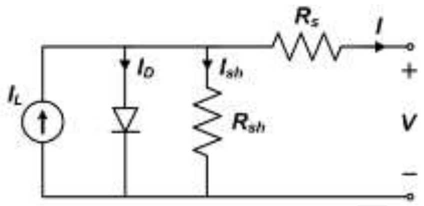


Voltage Drop: $\Delta V = \beta \times \Delta T = -0.0021\ \text{V}/^\circ\text{C} \times 40^\circ\text{C} = -0.084\ \text{V}$

New V_{oc}: $0.70\ \text{V} - 0.084\ \text{V} = 0.616\ \text{V}$

2. In the equivalent circuit model, dust acts as a Shunt Resistance Rsh in parallel with the solar cell's diode. The interaction shifts the I-V curve "knee" in two ways:
   Shunt Effect Rsh: Dust creates alternative current paths (leaks), which lowers the slope of the I-V curve in the voltage region near Voc. This "rounds off" the knee because current is diverted through the dust layer instead of the external load.
   Temperature Effect Voc drop: High heat increases the reverse saturation current I_0 of the diode, which directly compresses the voltage axis.
   Combined Result: The lower Voc shifts the knee to the left, while the reduced Rsh flattens the top of the curve and rounds the corner. This significantly reduces the total area under the I-V curve (Maximum Power Point), leading to a much lower Fill Factor.
3. To mitigate these desert-specific losses, the following changes are recommended:
   Material Change (Wide Bandgap): Switch to a material with a higher bandgap (e.g., Gallium Arsenide or Wide-gap Perovskites). Higher bandgap materials have lower intrinsic carrier concentrations, making their Voc much less sensitive to thermal increases compared to standard silicon.
   Structural Change (Anti-Soiling Coating): Implement a hydrophobic or electrodynamic screen (EDS) on the glass surface. This structural modification reduces dust adhesion and allows for easier cleaning (self-cleaning), maintaining a high Rsh and preventing the Fill Factor degradation caused by dust accumulation.

Exercise 3: The "Real-World" Shunt & Series Loss



The shunt current flows through the parallel Shunt Resistance Rshunt. According to the equivalent circuit, the voltage across the shunt resistor is the sum of the output voltage V and the voltage drop across the series resistor I .Rs.

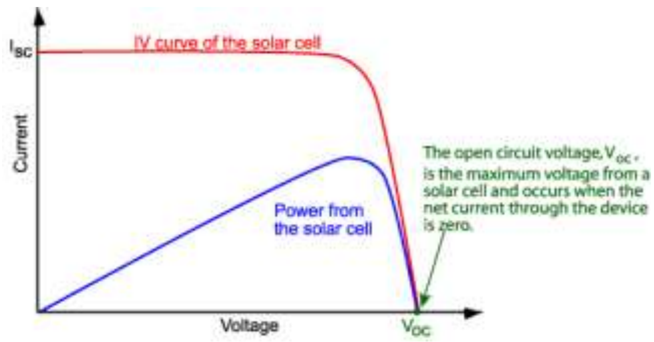
$$I_{sh} = \frac{V + I \cdot R_s}{R_{shunt}}$$

Substitute the known values into the Kirchhoff's current law equation. Since I_D is negligible, the equation becomes:

$$I = I_L - \frac{V + I \cdot R_s}{R_{shunt}} \text{ Then } 10.05I = 39.55 \text{ Though } I = \frac{39.55}{10.05} \approx 3.9353 \text{ A}$$

Exercise 4: Determining Dark Saturation Current (I_0)

The open-circuit voltage, V_{OC}, is the maximum voltage available 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. The open-circuit voltage is shown on the $I - V$ curve below.



$$V_{oc} = nV_t \ln\left(\frac{I_{sc}}{I_0} + 1\right) \text{ Then } I_0 = \frac{I_{sc}}{e^{\frac{V_{oc}}{nV_t}} - 1} \approx 3.3257 \times 10^{-10} \text{ A}$$

Exercise 5: LED Wavelength and Material

State the relevant equation: The energy of an emitted photon ($Ephoton$) is related to its wavelength:

$$E_{photon} = \frac{hc}{\lambda}$$

where h is Planck's constant (6.626×10^{-34} J·s or 4.136×10^{-15} eV·s) and c is the speed of light (3×10^8 m/s). In an LED, $E_{photon} = E_g$.

$$\lambda = \frac{hc}{E_g} \approx 3.65 \times 10^{-7} \text{ m}$$

Exercise 6: LED Circuit Design (Current Limiting)

According to Kirchhoff's Voltage Law (KVL) in a simple series circuit with a voltage source (V_S), a resistor (R_S), and an LED, the supply voltage is the sum of the voltage drop across the resistor and the LED's forward voltage (V_D):

$$V_S = I_F R_S + V_D$$

$$V_R = V_{CC} - V_D = 9\text{V} - 2.1\text{V} = 6.9\text{V}$$

Where   is the forward current. The required resistance is:

$$R_S = \frac{V_R}{I_F} = \frac{6.9\text{V}}{0.020\text{A}} = 345\ \Omega$$

Exercise 7: LED Luminous Efficacy Calculation

Luminous efficacy η is defined as the ratio of the total luminous flux Φ_v produced by a light source to the total electrical power P it consumes. The formula is:

$$\eta = \frac{\Phi_v}{P} = \frac{1500 \text{ lm}}{12 \text{ W}} = 125 \text{ lm/W}$$

Exercise 8. Emission Wavelength Calculation

The energy of the emitted light from a laser diode is approximately equal to the bandgap energy Eg of the semiconductor material. Use the relationship between photon energy and wavelength:

$$\lambda = \frac{hc}{E_g} = \frac{1240 \text{ eV} \cdot \text{nm}}{1.43 \text{ eV}} \approx 867.13 \text{ nm}$$

Visible light ranges from roughly 400nm to 700nm. Because 867nm is longer than the visible red limit, it falls into the infrared region. Specifically, this is in the near-infrared spectrum.

Exercise 9. Threshold and Output Power

1. The output power Po of a laser diode is determined by the current supplied above the threshold current I_{th}. The formula is:

   $$P_o = \eta_{slope} \times (I - I_{th}) = 0.5 \text{ mW/mA} \times (60 \text{ mA} - 25 \text{ mA}) = 17.5 \text{ mW}$$

2. To find the efficiency, we first need the total electrical power consumption Pin at the operating point.

   $$P_{in} = V \times I = 2.0 \text{ V} \times 60 \text{ mA} = 120 \text{ mW}$$

   The Wall-Plug Efficiency is the ratio of optical output power to electrical input power:

   $$WPE = \left(\frac{P_o}{P_{in}}\right) \times 100\% = \left(\frac{17.5 \text{ mW}}{120 \text{ mW}}\right) \times 100\% \approx 14.58\%$$

Exercise 10: Complex Multi-Part Problem: Thermal Effects and Internal Losses

1. The mirror loss depends on the cavity length L and the facet reflectivity R.

   $$\alpha_m = \frac{1}{L} \ln\left(\frac{1}{R}\right) = \frac{1}{0.05 \text{ cm}} \ln\left(\frac{1}{0.32}\right) \approx 22.79 \text{ cm}^{-1}$$

   This represents the fraction of internally generated photons that actually escape the cavity:

   $$\eta_d = \eta_{int}\left(\frac{\alpha_m}{\alpha_m + \alpha_s}\right) = 0.85\left(\frac{22.79}{22.79 + 15}\right) \approx 0.5126 \text{ (or } 51.26\%)$$

   $$\eta_{slope} = \frac{E_p}{q} \cdot \eta_d \approx 0.947 \cdot 0.5126 \approx 0.485 \text{ W/A}$$

2. Using the initial threshold current 30mA and the operating current 100mA:

   $$P_o = \eta_{slope} \times (I - I_{th}) = 0.46 \text{ W/A} \times (0.100 \text{ A} - 0.030 \text{ A}) = 0.46 \times 0.07 \approx 0.0322 \text{ W} = 32.2 \text{ mW}$$

   $$\Delta T = P_{in} \times R_{th} = 0.2 \text{ W} \times 60 \text{ K/W} = 12 \text{ K}$$

   $$I_{th,new} = I_{th} \cdot e^{\frac{\Delta T}{T_0}} = 30 \text{ mA} \cdot e^{\frac{12}{60}} = 30 \cdot e^{0.2} \approx 30 \cdot 1.2214 \approx 36.64 \text{ mA}$$