PV Concept and a Limit on Collection Efficiency

- When a **photon is absorbed** in a block of a semiconducting material such as silicon, it can **excite an electron** from the **valence band** to the **conduction band**.
- Once this has occurred, the **electron can move freely** in the conduction band. Likewise, the hole created in the valence band can **propagate like a positively charged electron**.
- The aim of the ***photovoltaic cell*** is to use these **electron and hole excitations** to drive an external circuit.

Collection efficiency in the context of photovoltaic (PV) cells refers to the **fraction of photo-generated charge carriers (electrons and holes)** that are successfully **collected at the electrodes** and contribute to the **external current**, rather than being lost to recombination.

$$Collection\ Efficiency = \frac{Number\ of\ carriers\ collected\ (electrons\ and\ holes)}{Number\ of\ carriers\ generated\ by\ absorbed\ photons}$$

Why collection efficiency matters: Even if a material absorbs light well (high absorption coefficient), **poor collection efficiency** means much of that energy is **wasted**. So, both **optical absorption** and **carrier collection** must be optimized for high-efficiency solar cells.

- When a photon of energy $E = \hbar\omega$ is incident on a material with a band gap E_{gap} between its (filled) valence band and (empty) conduction band, it can only lead to a conduction electron if $E > E_{gap}$.
- Thus, for example, only photons with an energy $\hbar\omega > 1.1\ eV$ can excite an electron from the valence band to the conduction band of a silicon crystal.
- Knowing the energy spectrum of the photons in solar radiation – we can immediately determine an upper bound on the collection efficiency of a solar cell with gap E_{gap}. The **limit on collection efficiency** using the Planck radiation spectrum relation

$$\frac{dP}{dA d\omega} = \frac{\hbar}{4\pi^2 c^2} \frac{\omega^3}{e^{\frac{\hbar\omega}{k_B T}} - 1}.$$

- Then the total incident power per unit area from sun:

$$P_{total} = CA \int_0^\infty dE\ \frac{E^3}{e^{\frac{E}{k_B T}} - 1}$$

- where C is an overall proportionality constant not relevant here, $E = \hbar\omega$ is the energy of a single photon of angular frequency ω, and A is the area exposed to the solar radiation.

- A solar cell with band gap E_{gap} can only absorb photons with energy $E > E_{gap}$. However, **each absorbed photon contributes only** E_{gap}, to electrical power (the rest is lost as heat).
- So, the maximum power the cell can extract is: $P_{max}(E_{gap}) = n.(E_{gap})E_{gap}$
- Where, $n.(E_{gap})$ is the number of photons with $E > E_{gap}$, given by:

$$n.(E_{gap}) = CA \int_{E_{gap}}^{\infty} dE \, \frac{E^2}{e^{\frac{E}{k_B T}} - 1}$$

- So,

$$P_{max}(E_{gap}) = n.(E_{gap})E_{gap} = CAE_{gap} \int_{E_{gap}}^{\infty} dE \, \frac{E^2}{e^{\frac{E}{k_B T}} - 1}$$

- Let $x = \frac{E}{k_B T}$, so $dE = k_B T \, dx$. Then $E = x.k_B T$ and $E_{gap} = x_{gap}.k_B T$

  So, the integrals become

$$P_{total} = CA \int_{0}^{\infty} dE \, \frac{E^3}{e^{\frac{E}{k_B T}} - 1} = CA(k_B T)^4 \int_{0}^{\infty} \frac{x^3}{e^x - 1} \, dx$$

$$P_{max} = CAE_{gap} \int_{E_{gap}}^{\infty} dE \, \frac{E^2}{e^{\frac{E}{k_B T}} - 1} = CA(k_B T)^4 x_{gap} \int_{x_{gap}}^{\infty} \frac{x^2}{e^x - 1} \, dx$$

- **Collection efficiency**, $\eta_{collection}^{max} = \frac{P_{max}}{P_{total}} = \frac{CA(k_B T)^4 x_{gap} \int_{x_{gap}}^{\infty} \frac{x^2}{e^x - 1} dx}{CA(k_B T)^4 \int_0^{\infty} \frac{x^3}{e^x - 1} dx} = x_{gap} . \frac{\int_{x_{gap}}^{\infty} \frac{x^2}{e^x - 1} dx}{\int_0^{\infty} \frac{x^3}{e^x - 1} dx}$

- **Collection efficiency**, $\boldsymbol{\eta_{collection}^{max} = x_{gap} . \frac{\int_{x_{gap}}^{\infty} \frac{x^2}{e^x - 1} dx}{\int_0^{\infty} \frac{x^3}{e^x - 1} dx}}$

- Then, **for the case of Silicon**, where $E_{gap} \cong 1.1\ eV$. The usable fraction of energy can then be computed as the ratio of the two integrals. Changing variables to $x = \frac{E}{k_B T}$ with T=6000 K and $k_B = 8.617 \times 10^{-5}$ eV/K gives $x_{gap} = \frac{E_{gap}}{k_B T} = \frac{(1.124\ eV)}{\left(8.617\times10^{-5}\frac{\text{eV}}{\text{K}}\right).(6000\text{ K})} \cong 2.1739$

$$\eta_{collection}^{max} = \frac{P_{max}^{(Si)}}{P_{total}} = 2.1739\,\frac{\int_{2.17}^{\infty} \frac{x^2}{e^x - 1}\,dx}{\int_0^{\infty} \frac{x^3}{e^x - 1}\,dx} \cong 0.439$$

- Thus, a silicon photovoltaic solar cell can extract at most **43.9%** of the energy in 6000 K blackbody radiation.

- An **upper bound on the collection efficiency of a solar cell** can be derived in this way for any material for which $\boldsymbol{E_{gap}}$ **is known**; the 1.124 eV gap of silicon is very close to optimal for collecting energy from a 6000 K blackbody spectrum.

- From the Figure, it is clear that Silicon solar cells can only absorb photons with energy **greater than or equal to the bandgap energy** (1.1 eV).

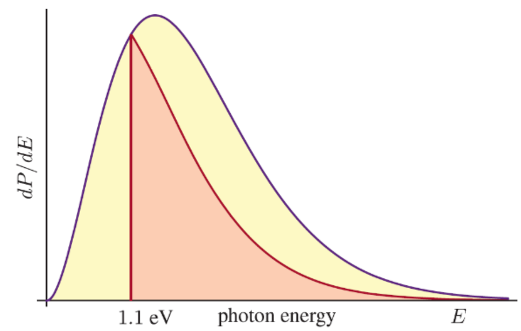

Figure 25.12 The solar power that can be collected by a silicon solar cell with $E_{gap} = 1.1$ V is shown in orange. The total (yellow + orange) area indicates the total power available in a thermal spectrum at 6000 K. The collection efficiency is the ratio of the orange and total areas.

- Photons with energy **less than 1.1 eV do not have enough energy** to excite electrons across the bandgap. Therefore, **cannot generate electricity** in a silicon solar cell.