Lab #5
Current/Voltage Curves, Efficiency Measurements and Quantum Efficiency

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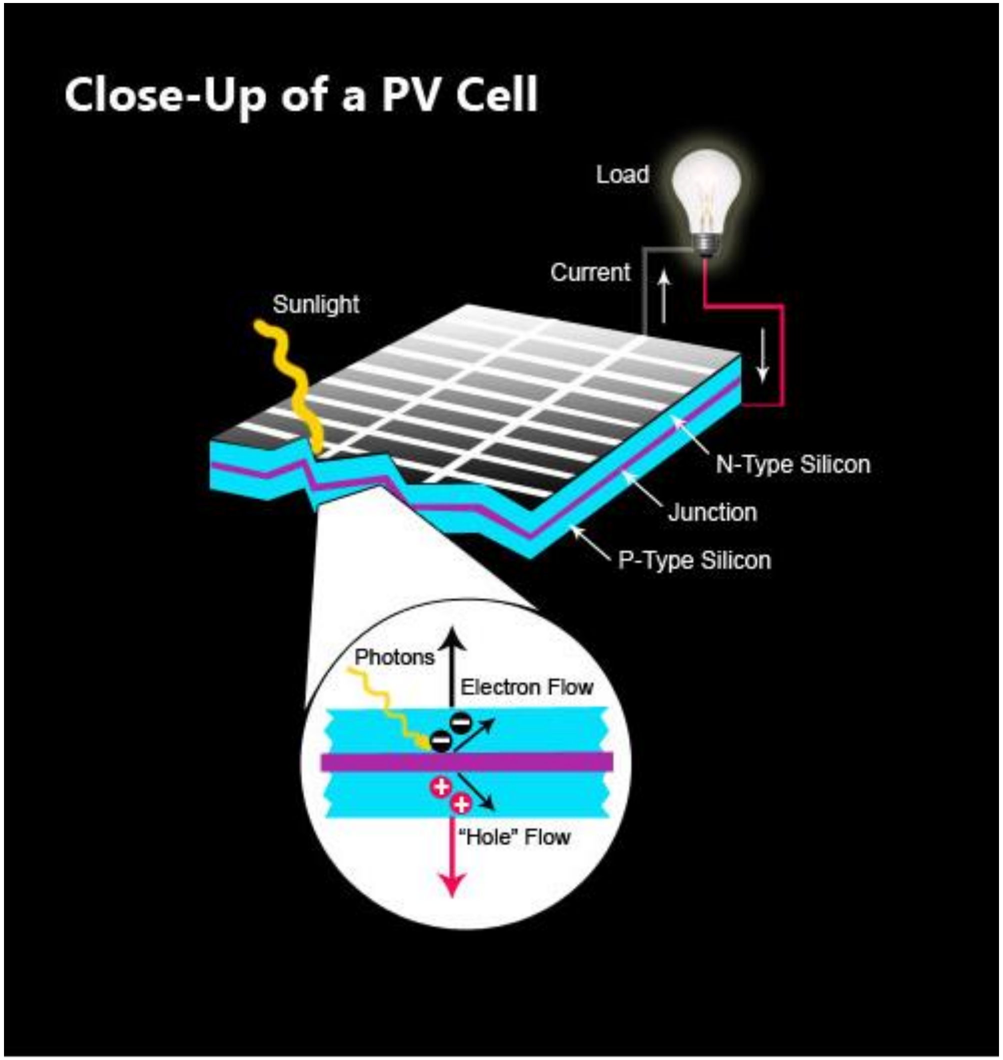
PHYS 4580, 6280, and 7280

Simple solar cell structure



The Diode Equation

Ideal Diode Law

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

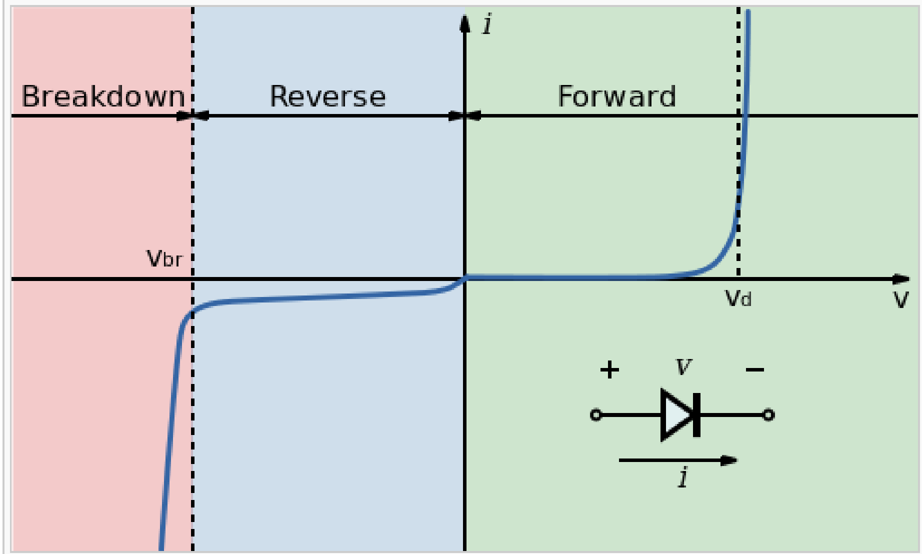


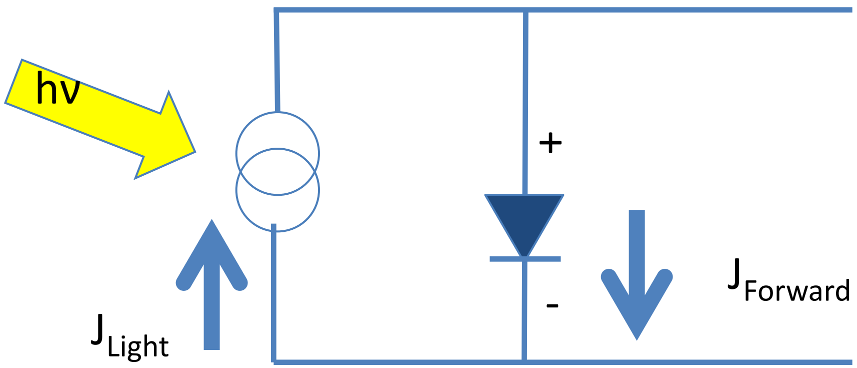
Figure 5: I–V characteristics of a p–n junction diode (not to scale—the current in the reverse region is magnified compared to the forward region, resulting in the apparent slope discontinuity at the origin; the actual I–V curve is smooth across the origin).

I = net current;
I_0 = "dark saturation current", aka diode leakage current, aka reverse saturation current;
V = applied voltage across the terminals of the diode;
q = electron charge;
k = Boltzmann's constant;
T = absolute temperature (K).

I_0 is a property of the junction interfaces and recombination in the device.

http://en.wikipedia.org/wiki/Diode

Light Generated Current is Opposite Direction of *Forward Dark Current*

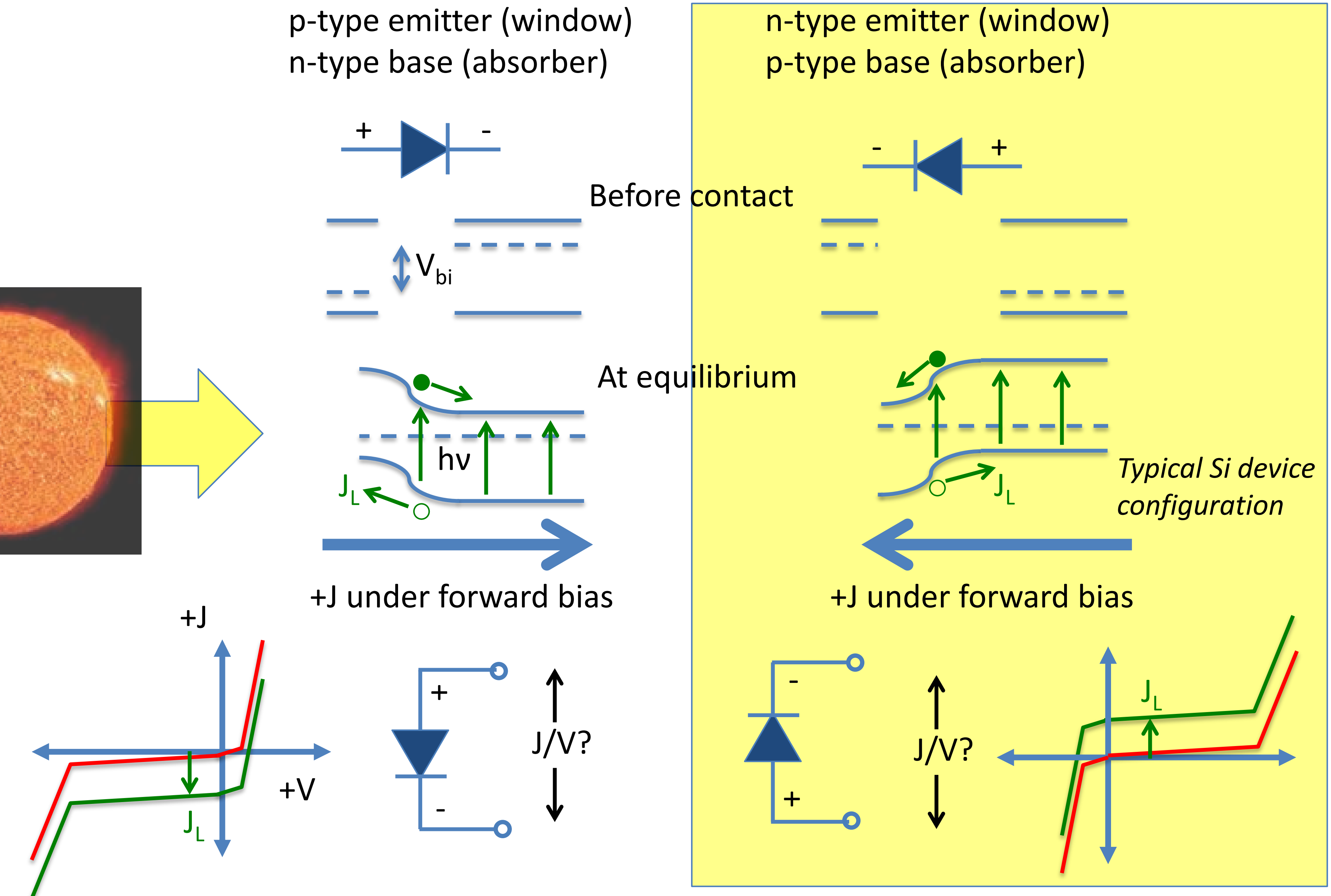


Principle of Superposition

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

Where n is the diode quality factor, reflects type of recombination in the device

Homojunction solar cell (e.g., Silicon)



Light Generated Current is Opposite Direction of *Forward Dark Current*

IV Curve

- The IV curve of a solar cell is the superposition of the IV curve in the dark with a constant light-generated current (I_L) .
- The light current shift the J/V curve down so V_{OC} occurs near the "turn-on knee" in the diode curve.

I_L = light generated current.

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

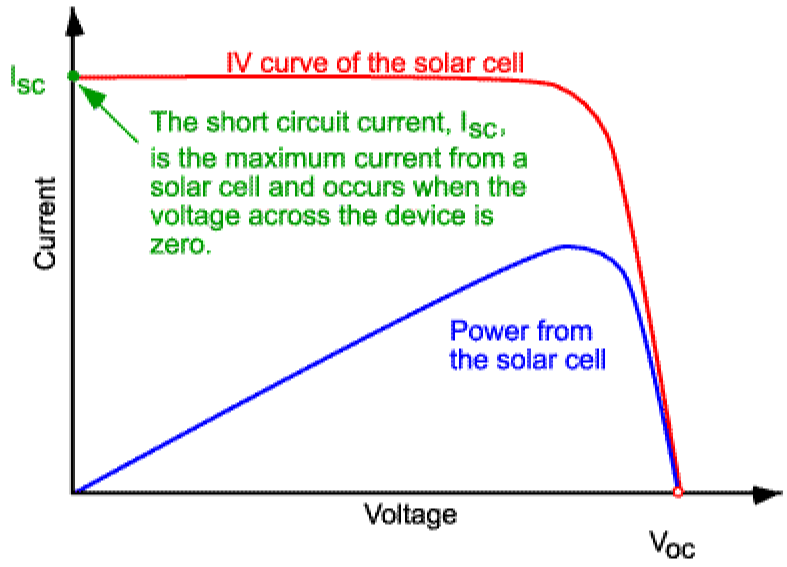
Go to Animation

PVEDUCATION.ORG

Lindholm, F. A., J. G. Fossum, and E. L. Burgess, "Application of the superposition principle to solar-cell analysis", *IEEE Transactions on Electron Devices*, vol. 26, no. 3, pp. 165–171, 1979.

Short circuit photocurrent

The short-circuit current (I_{SC}) is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the IV curve below.



I_{SC} is due to the generation and collection of light-generated carriers. For an ideal PV cell with moderate resistive loss, I_{SC} and the light-generated current are identical (I_{SC} is the largest current which may be drawn from the solar cell).

Short circuit (photo)current (I_{SC}) or current density (J_{SC})

I_{SC} (or J_{SC}) is the current (or current density) when the device leads are "shorted" (i.e., connected electrically to one another)

I_{SC} depends on a number of factors, as follows :

the area of the solar cell. To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{sc} in mA/cm^2) rather than the short-circuit current;

the number of photons (i.e., the power of the incident light source). Isc from a solar cell is directly dependant on the light intensity;

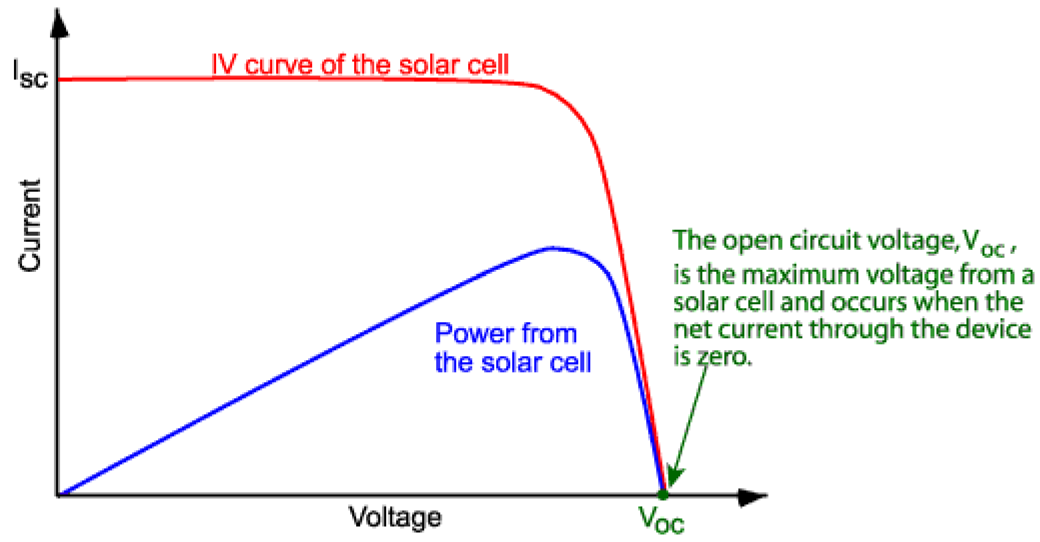
the spectrum of the incident light. For most solar cell measurement, the spectrum is standardised to the AM1.5 spectrum;

the optical properties (absorption and reflection) of the solar cell (discussed in Optical Losses); and

the collection probability of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the absorber.

Open circuit photovoltage (V_{OC})

The open-circuit voltage, V_{oc}, is the maximum voltage available from a solar cell, and this occurs at zero current.

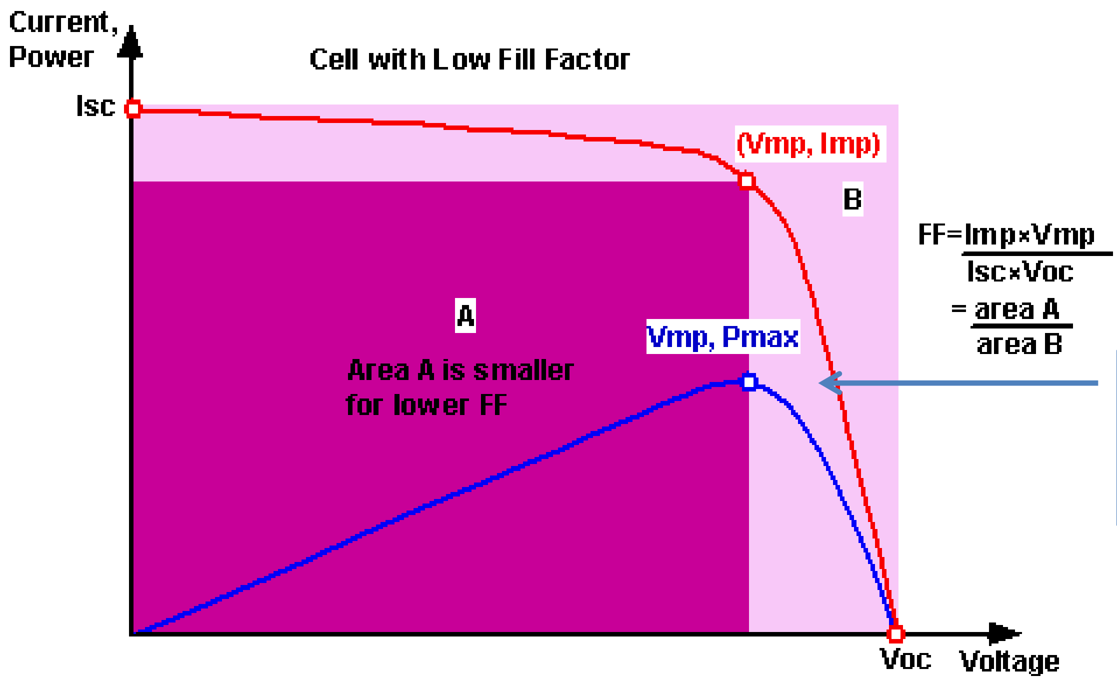


$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_L \quad \Rightarrow \quad V_{OC} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_o} + 1\right)$$

An equation for V_{oc} is found by setting the total current (I) to zero in the expression for the ideal solar cell.

Solar cell fill factor (FF) and Max Power Point (mpp)

- At I_{SC} and V_{OC}, the power from the solar cell is zero.
- The "fill factor“ (FF) is an important parameter for determining the maximum power from a solar cell.
- The FF is the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}.
- Graphically, the FF is a measure of the area of the largest rectangle which will fit in the IV curve.



$P_{out} = I * V$

$dP/dV = 0$

Solar cell efficiency

The efficiency of a solar cell (sometimes known as the power conversion efficiency, or PCE, and also often abbreviated η) represents the ratio where the output electrical power at the maximum power point on the IV curve is divided by the incident light power – typically using a standard AM1.5G simulated solar spectrum.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

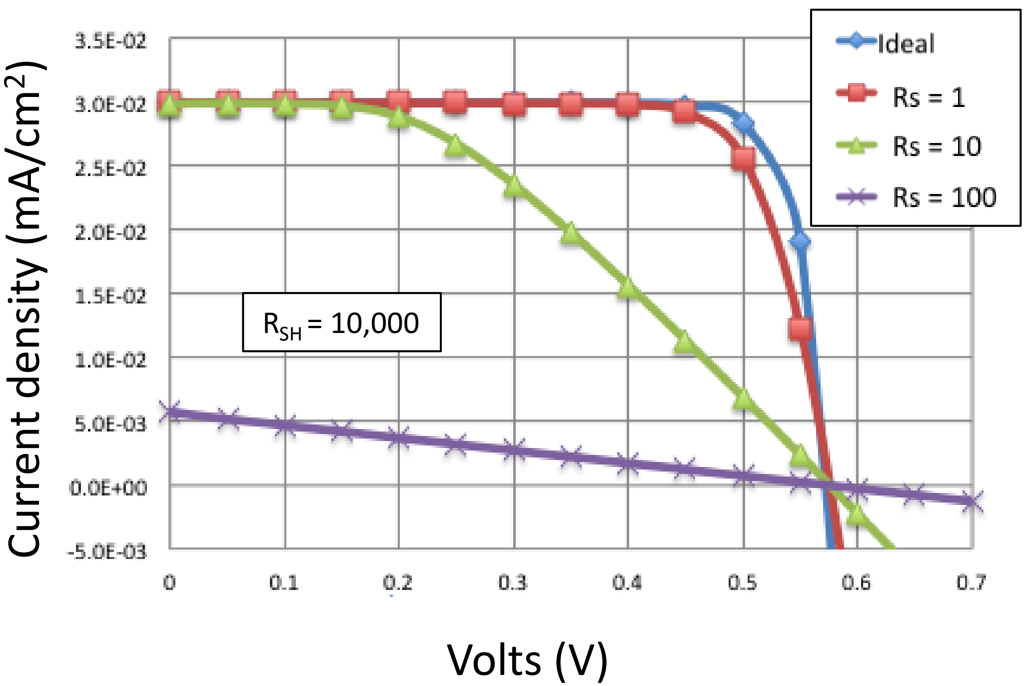
$$P_{\max} = V_{OC} I_{SC} FF \qquad \eta = \frac{V_{OC} I_{SC} FF}{P_{inc}}$$

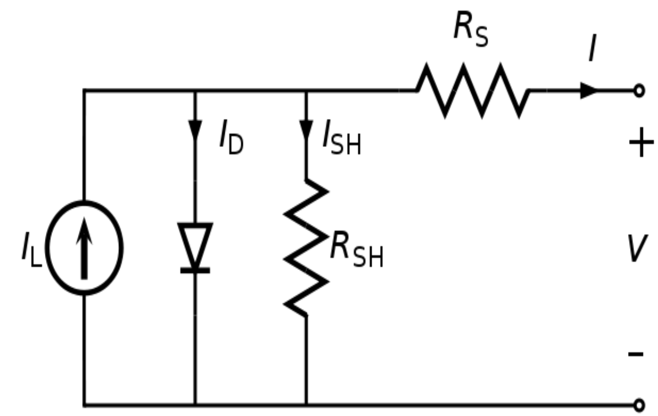
where V_{oc} is the open-circuit voltage;
where I_{sc} is the short-circuit current; and
where FF is the fill factor
where η is the efficiency.

Power in AM1.5G spectrum is 1kW/m^2 , or 100 mW/cm^2

For a 10 x 10 cm^2 cell, the input power (AM1.5G) is 100 mW/cm^2 x 100 cm^2 = 10 W.

Impact of Electrical Loss Due to High Series Resistance (R_S) PV cells

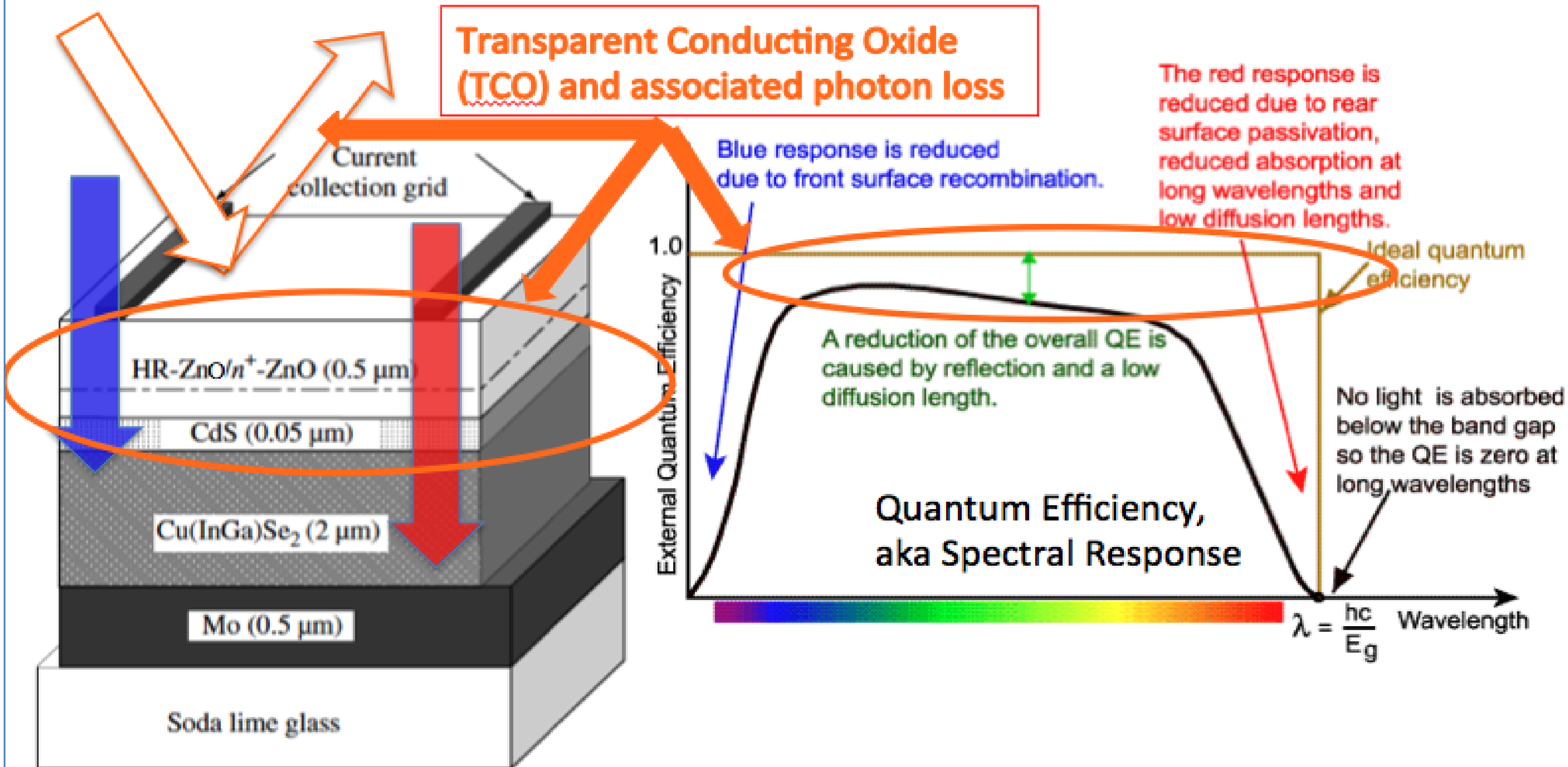




Diode equation with R_S and R_{SH}:

$$I = I_L - I_0 \exp\left[\frac{q(V + IR_S)}{nkT}\right] - \frac{V + IR_S}{R_{SH}}$$

Quantum Efficiency



Schematic cross section of a typical $Cu(InGa)Se_2$ solar cell

After "$Cu(InGa)Se_2$ Solar Cells", by Shafarman and Stolt, and *PVEducation.org*

Quantum Efficiency (also known as the *Spectral Response*)

- Determined as a function of wavelength
- Is the ratio of incident # of photons to the numbers of electron-hole pairs that flow in the external circuit.

- There are two versions of QE;
  - External QE (EQE) - considers all photons incident on the device.
  - Internal QE (IQE) – considers only photons that are absorbed in the active region of the device

- Clearly, it is much more straightforward to measure EQE than IQE

- The QE cannot never exceed 1 (or 100%)

- QE measurements are generally done at short circuit where the electric field within the device is large, but can also be done at any bias voltage and can reveal information about recombination in the PV device.