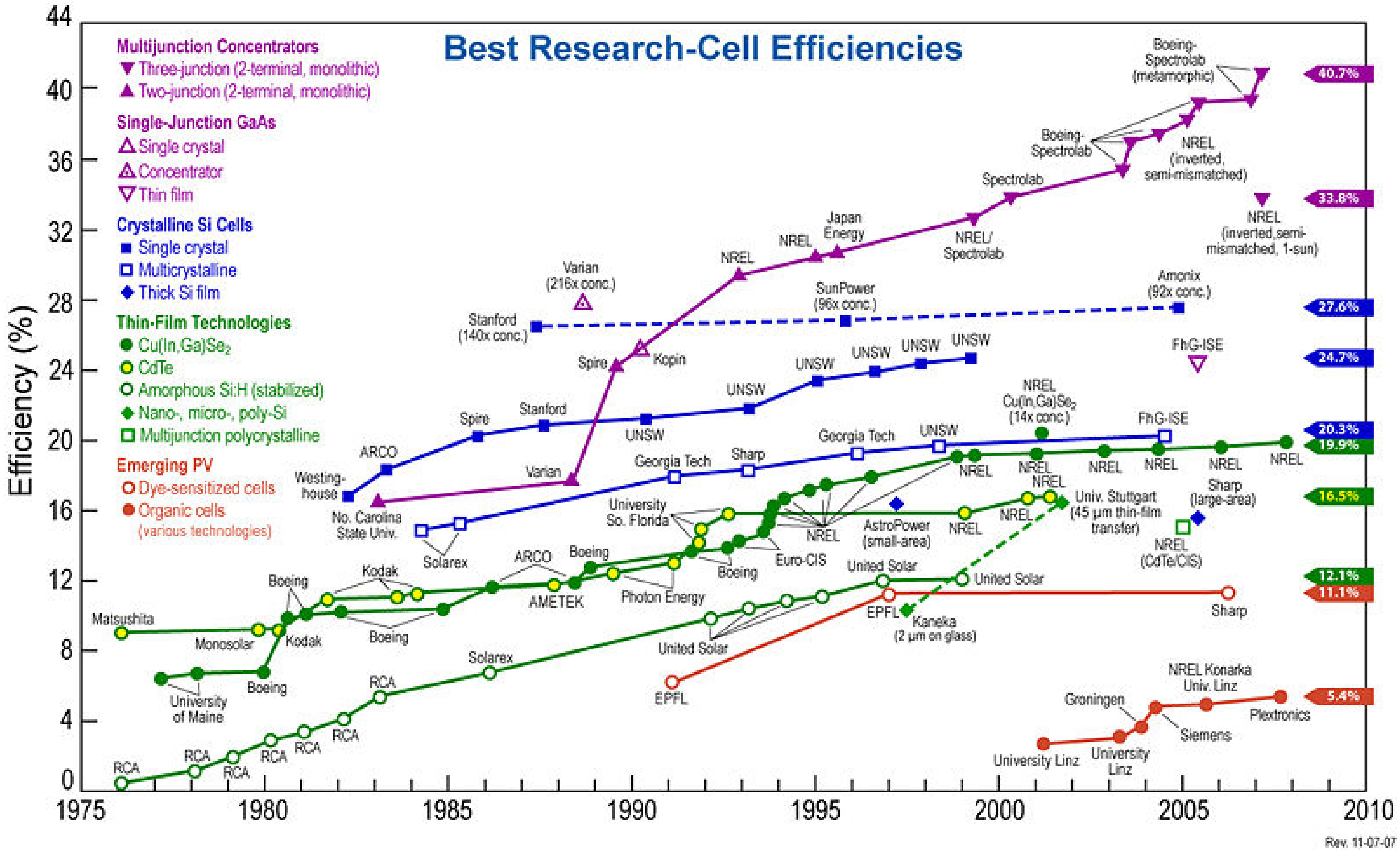
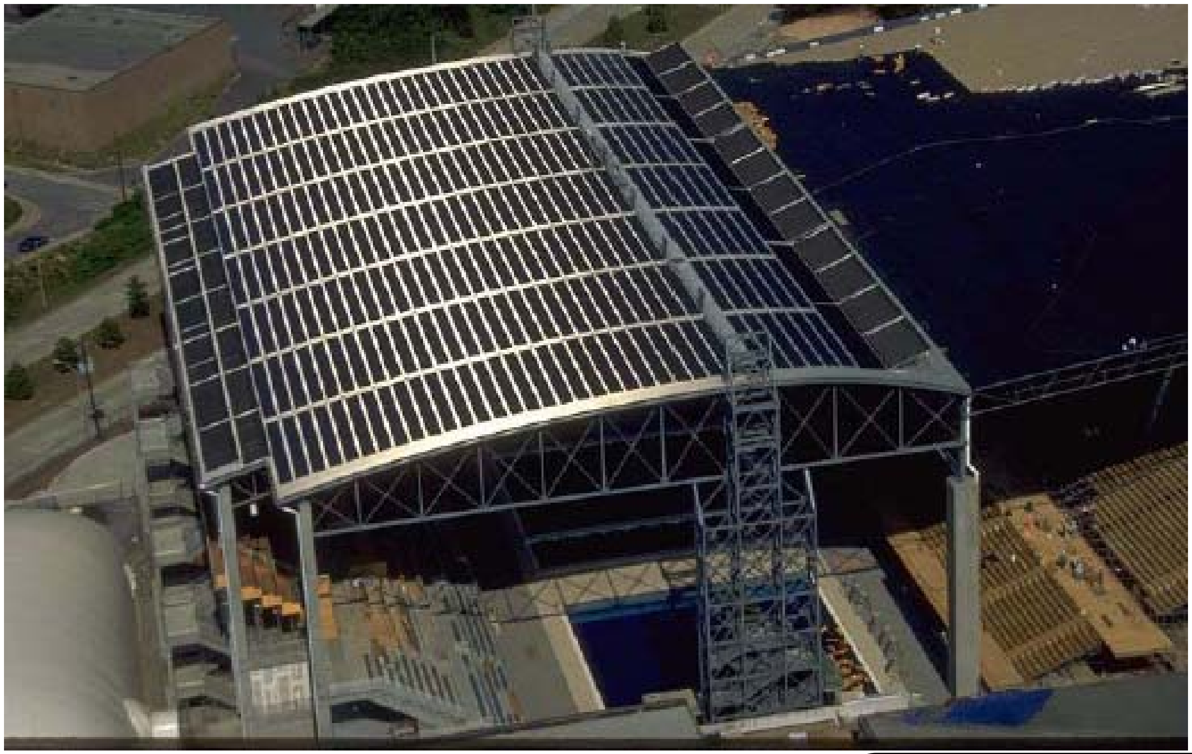
What is the highest efficiency Solar Cell?



GT CRC Roof-Mounted PV System

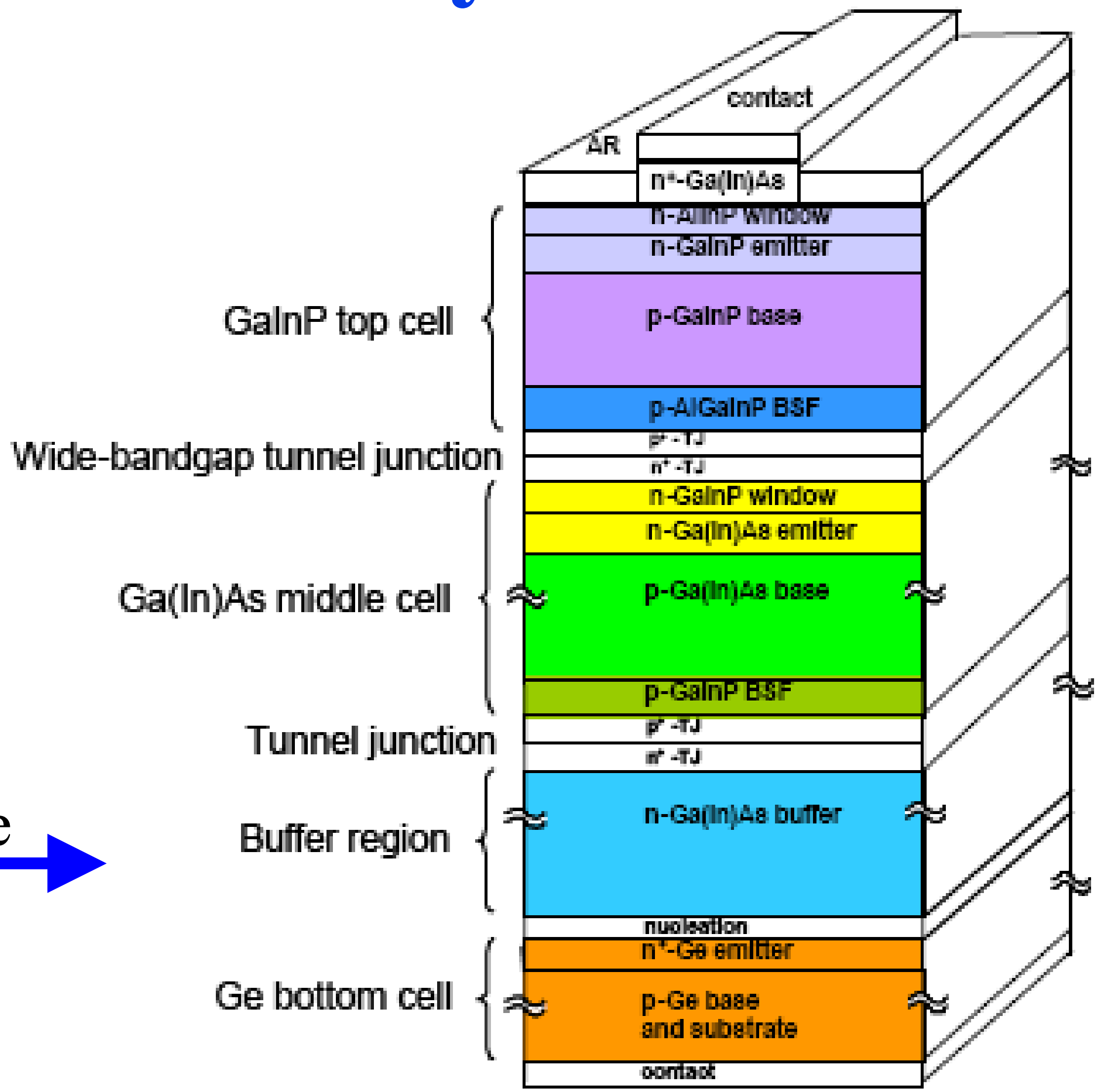
- Largest single PV structure at the time of it’s construction for the 1996 Olympic games
- Produced more than 1 billion watt hrs. of electrical energy that has been fed into the GT power grid



PV - Photovoltaic

Highest Efficiency Device

- GaInP/GaInAs/Ge by Spectrolab (A Boeing Company) achieved 40.7% efficiency in 2007.
- Current devices employed on satellites have efficiencies ~28.3%
- An approximate device structure

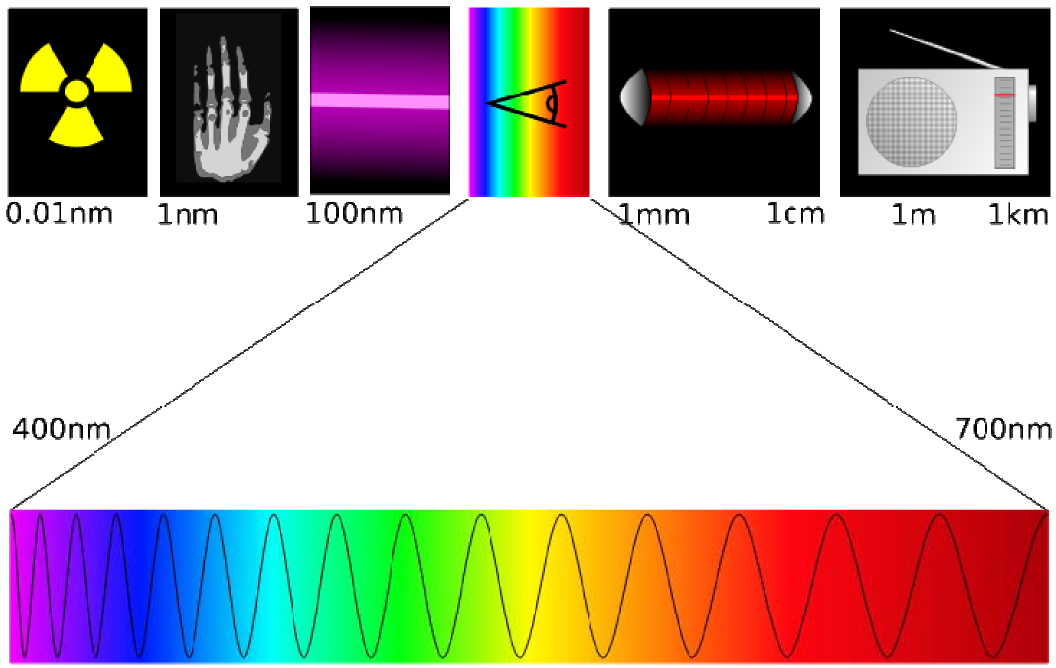


Law et. al, Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, pp. 1879.

Energy of a Photon

$$E\,[\text{eV}] = \frac{hc}{\lambda} = \frac{1.24}{\lambda[\mu\text{m}]}$$

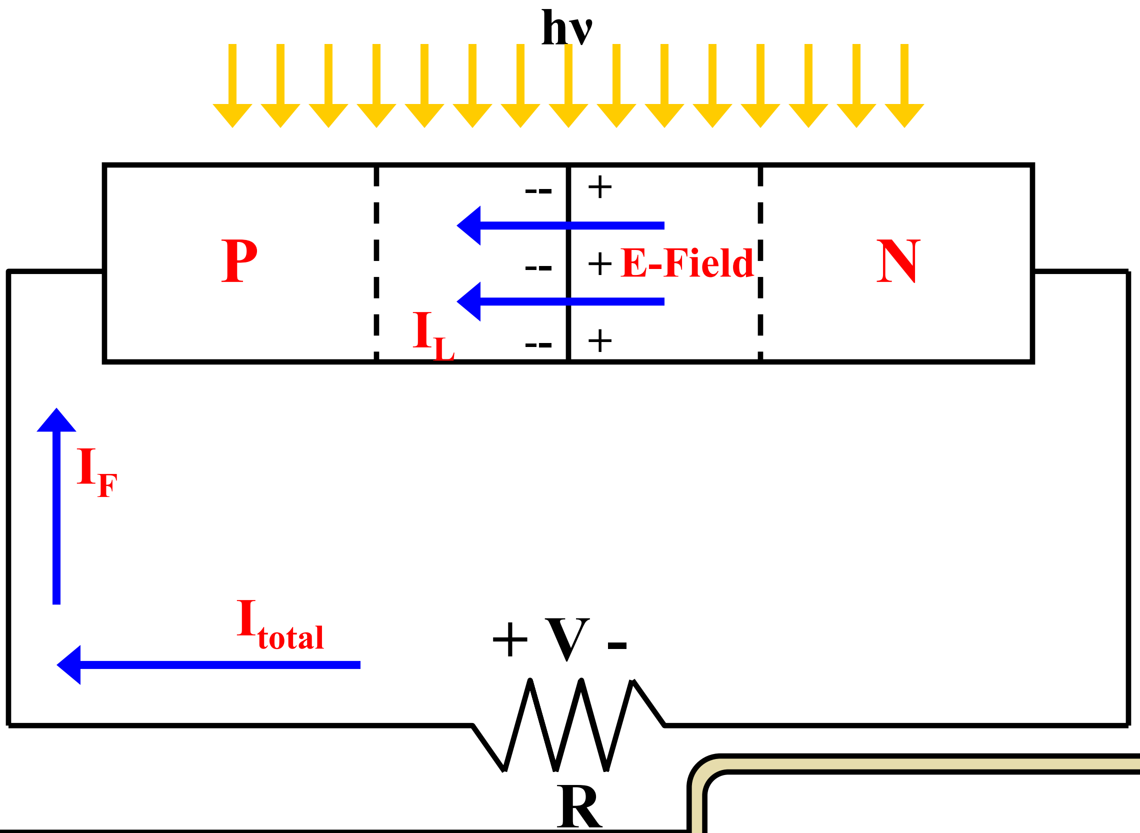
$h = 6.626\times10^{-34}$ [J·s]
$c = 3\times10^{8}$ [m/s]
$J = 1.602\times10^{-19}$ [eV]
λis the wavelength of light in meters



	Bandgap [eV]	Wavelength [μm]
Ge	0.67	1.85
Si	1.12	1.107
GaAs	1.42	0.873
GaN	3.4	0.365

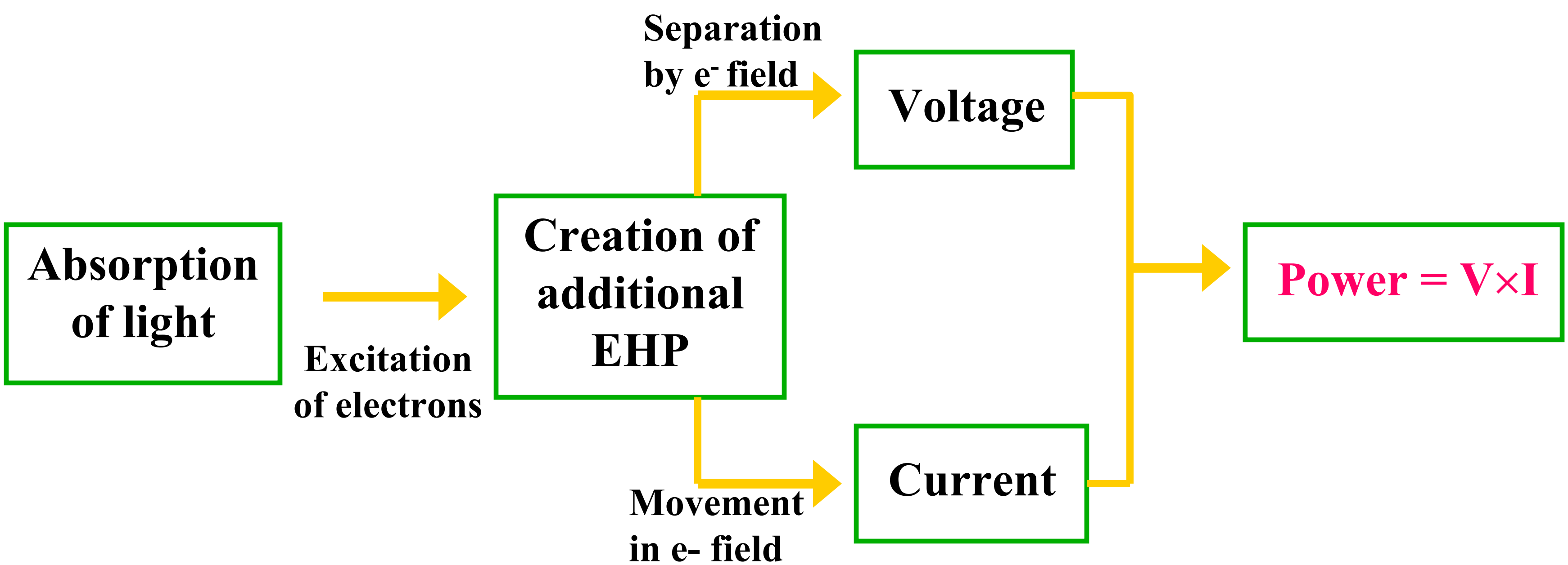
Photovoltaic Effect

- Solar cells are:
  - p-n junctions
  - Minority carrier devices
  - Voltage is not directly applied
- The photocurrent produces a voltage drop across the resistive load, which forward biases the pn junction.



Photovoltaic Effect

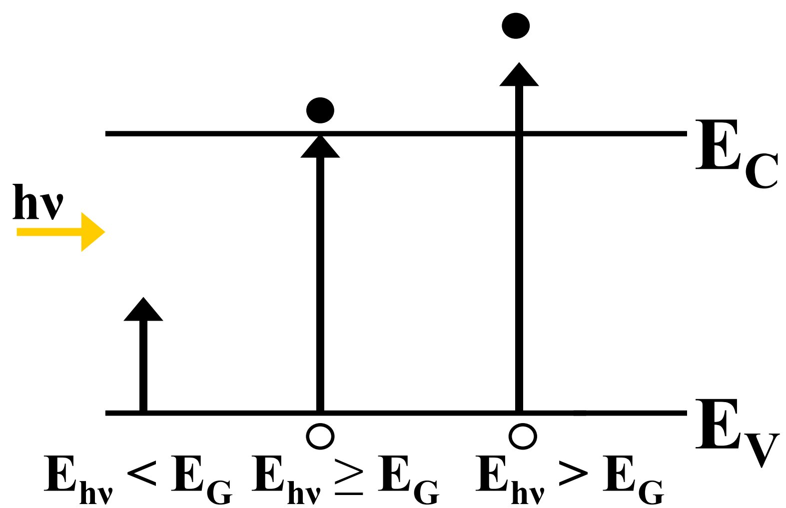
- Fundamental absorption is from:
  - annihilation or absorption of photons by the excitation of an electron from the valence band to the conduction band
  - leaves a hole in the valence band
- Ideally, each incident photon with $E_{h\nu} > E_G$ will create one electron flowing in the external device



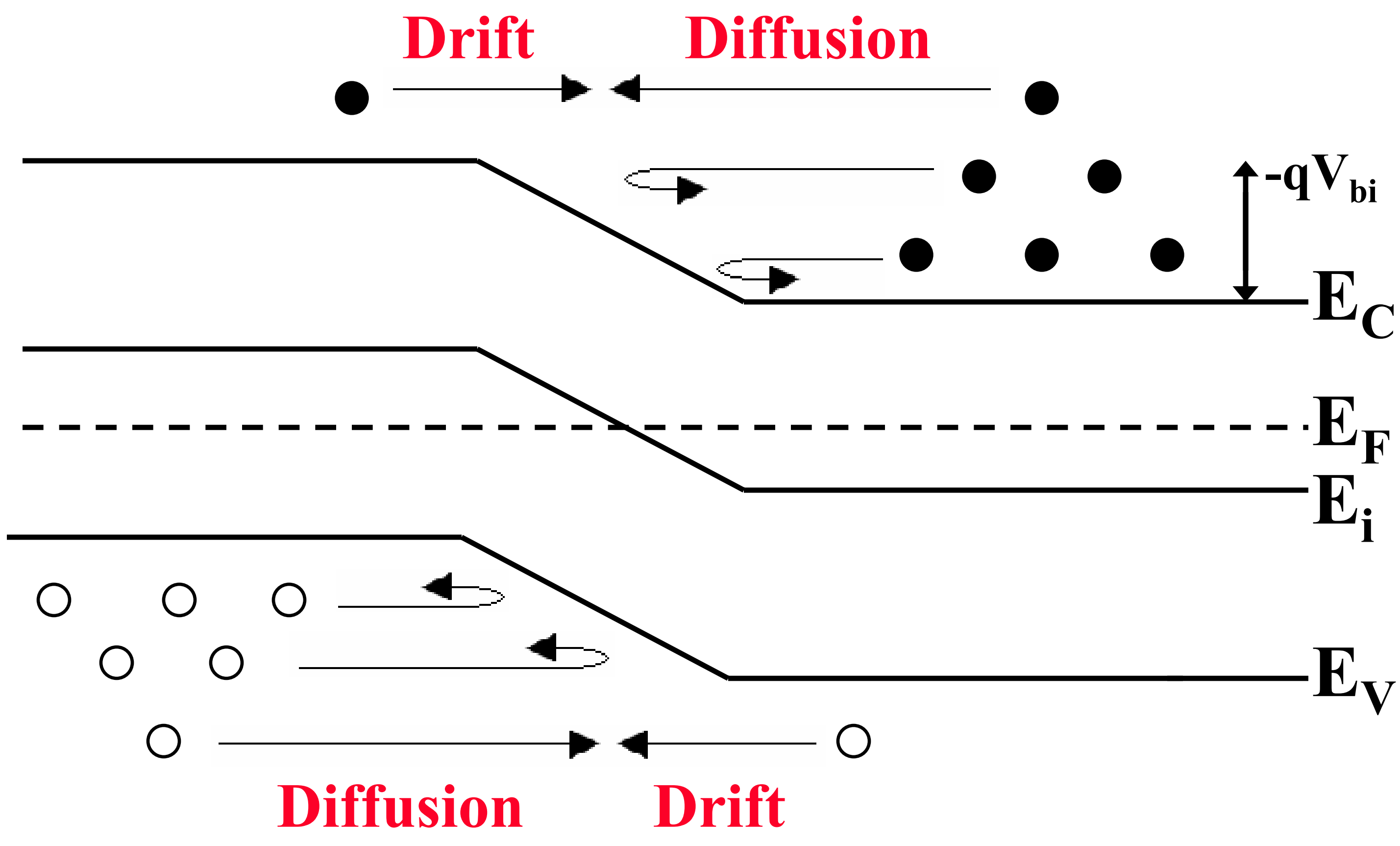
- $E_{h\nu} < E_G$: semiconductor is transparent to light

llumination and Generation

- Incident light on a solar cell causes an electron to be excited from the valence band into the conduction band (creating electron-hole pairs) everywhere in the device.
- $E_{h\nu} < E_G$: the device is transparent to the incident light.
- $E_{h\nu} \geq E_G$: photons are absorbed and EHP are photogenerated in the device.
- $E_{h\nu} > E_G$: energy generated is lost as heat to the device.

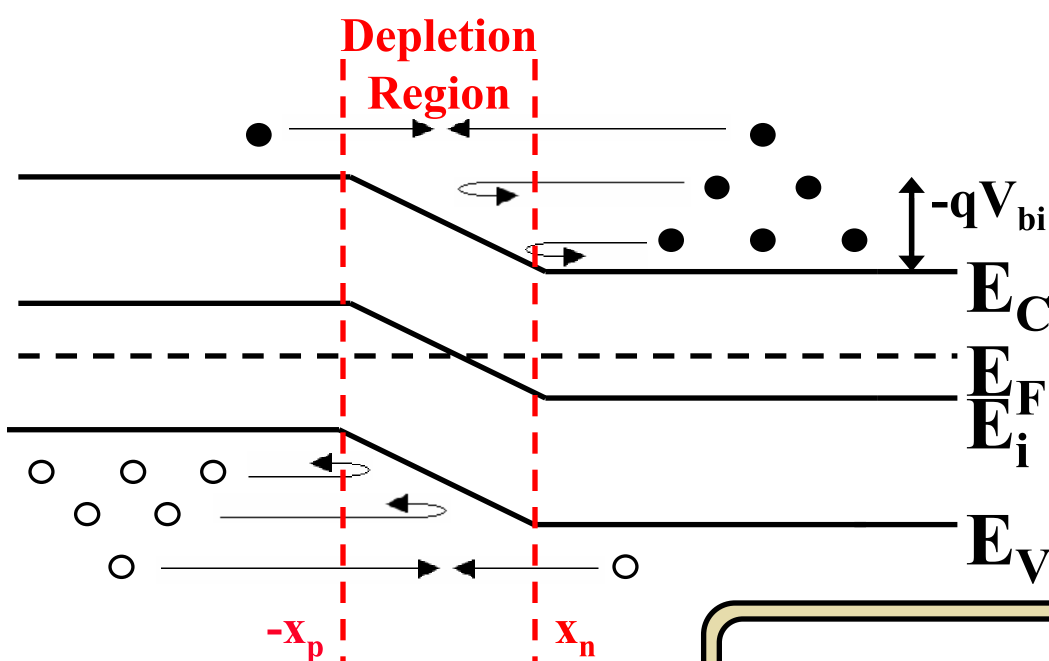


Diode at Equilibrium

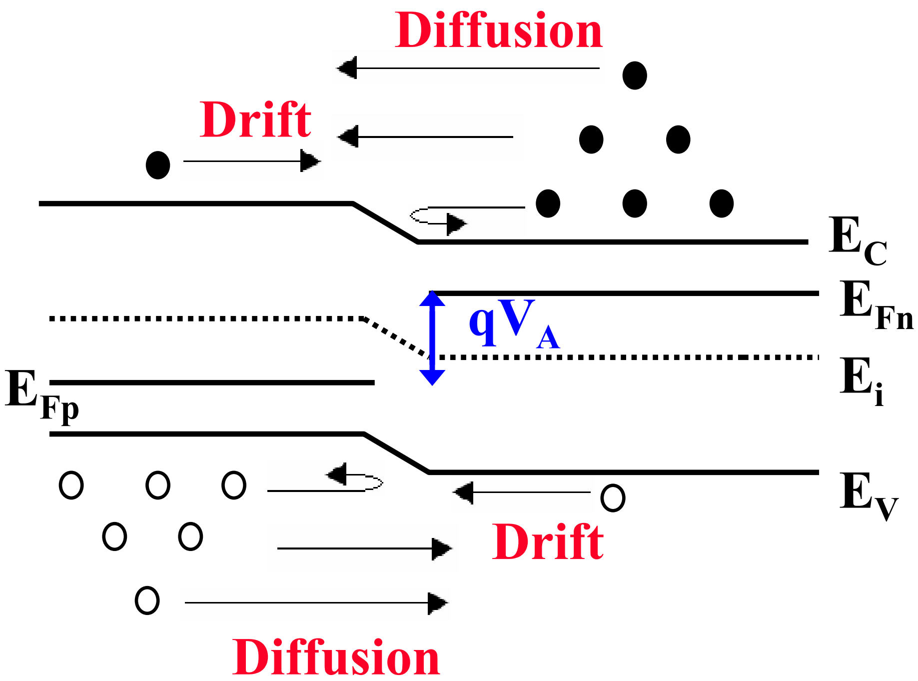


Depletion Region

- Every EHP generated in the:
  - Depletion region
  - Within a diffusion length ($\mathbf{L = \sqrt{D\tau}}$) away from the depletion region are:
    - Swept across the junction by an electric field.
- Referred to as **photocurrent** and is in the "reverse bias" direction. All other EHP recombine before they can be collected.
- **Photocurrent** is always in the "reverse bias" direction, therefore the net solar cell current is also in the "reverse bias" direction.



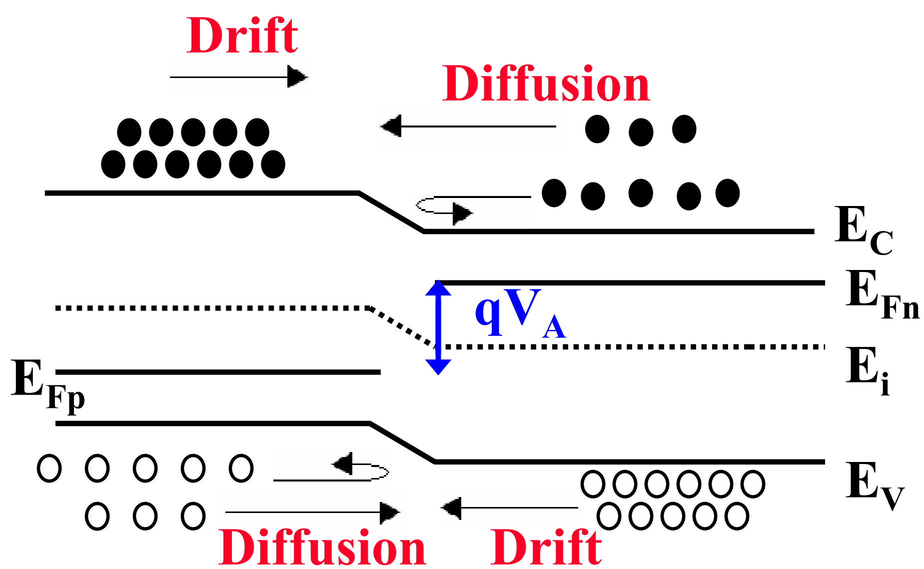
Forward Bias



- Voltage applied externally.
- Current is dominated by Diffusion.

Photogeneration

- Voltage is generated internally from EHP being swept across the junction by an electric field.
- Current is dominated by Drift.



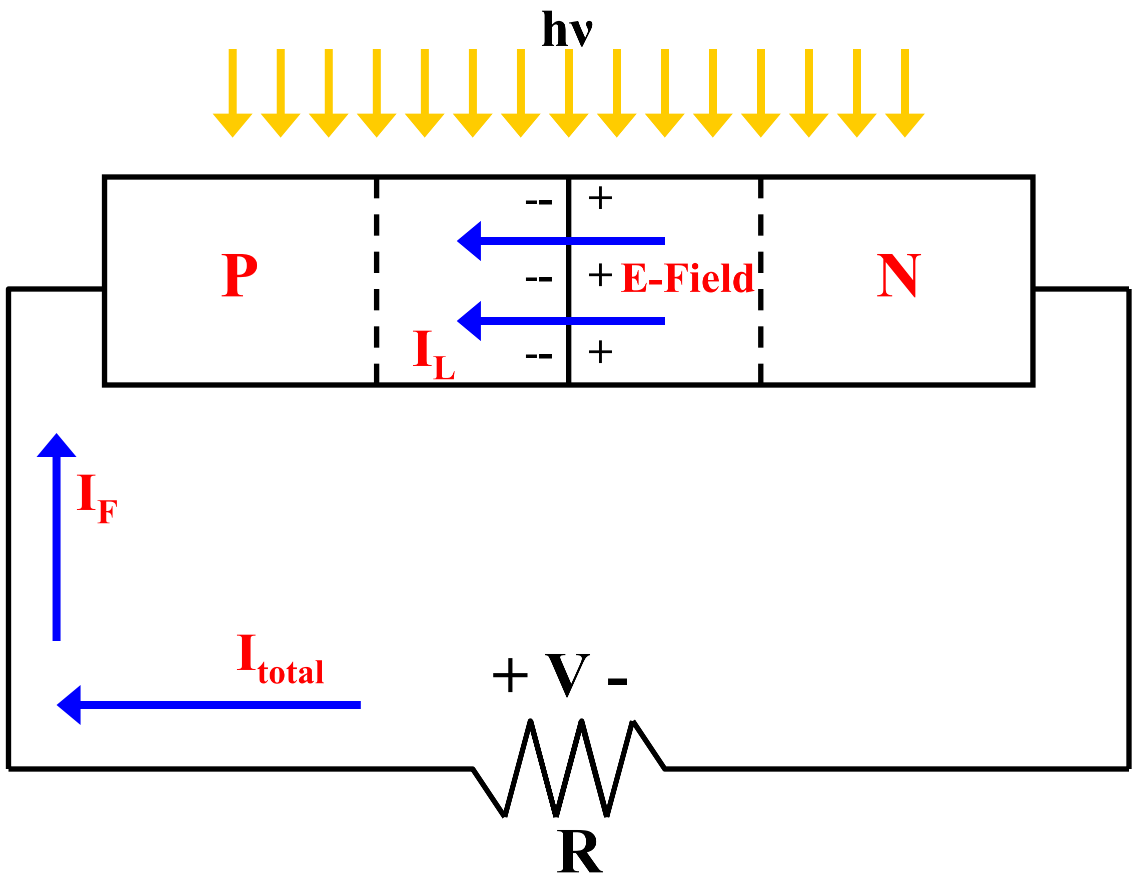
Law of the Junction

- V_A is the difference between Fermi level on the n-side and the p-side when a voltage is applied to a pn junction.

$$V_A = (kT/q)\ln\{(n_{p(x=-x_p)} \times p_{n(x=x_n)}/n_i^2\}$$

- It is related to the minority carriers in each region.
- V_A will be the same in the forward bias case and in the photogenerated case.

Current Collection



$$I_{total} = I_F - I_L$$

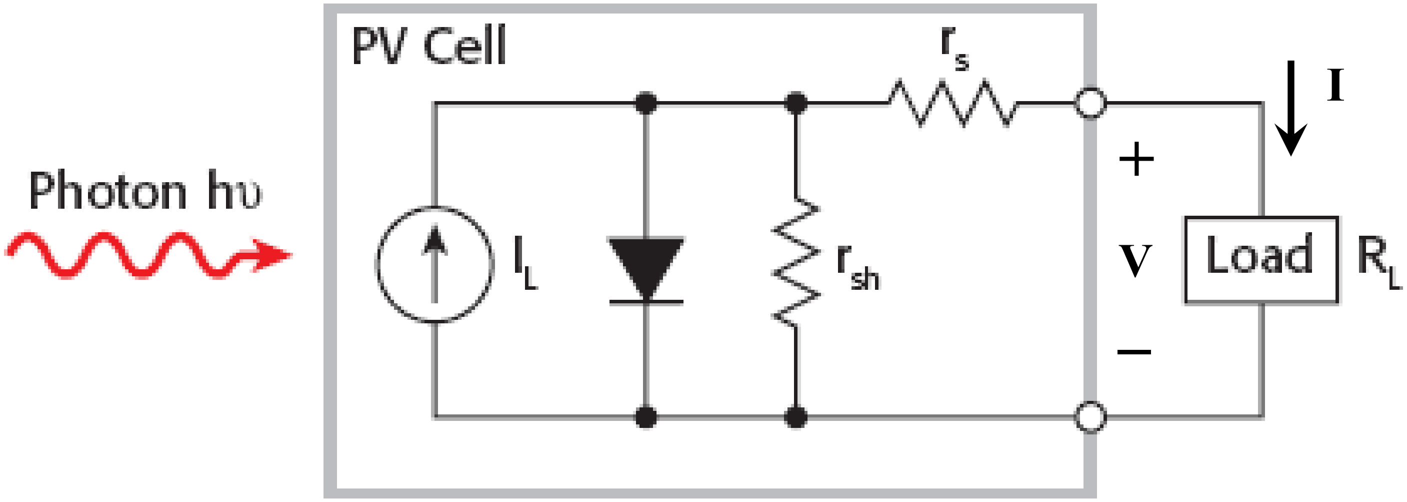
$$= I_s\{\exp(qV/kT) - 1\} - I_L$$

I_F = Forward-bias current

I_L = Photocurrent

I_s = Ideal reverse saturation current

Solar Cell Equivalent Circuit



- Using the Ideal diode law: $\mathbf{I = I_O(e^{\{qV/kT\}} - 1)}$
- $\mathbf{I = I_L - I_O(e^{\{[V+Ir_S]/nV_T\}} - 1) - (\{V + Ir_S\}/r_{shunt})}$
- $\mathbf{I_L}$ is the light induced current or short circuit current $\mathbf{(I_{SC})}$
- $\mathbf{V_{OC} = kT/q\ (ln\ \{[I_L/I_{OC}] + 1\})}$
- $\mathbf{r_S}$ is the series resistance due to bulk material resistance and metal contact resistances.
- $\mathbf{r_{Sh}}$ is the shunt resistance due to lattice defects in the depletion region and leakage current on the edges of the cell.
- $\mathbf{V_T = kT/q}$
- ***n*** **–** non ideality factor, = 1 for an ideal diode

IV Curves

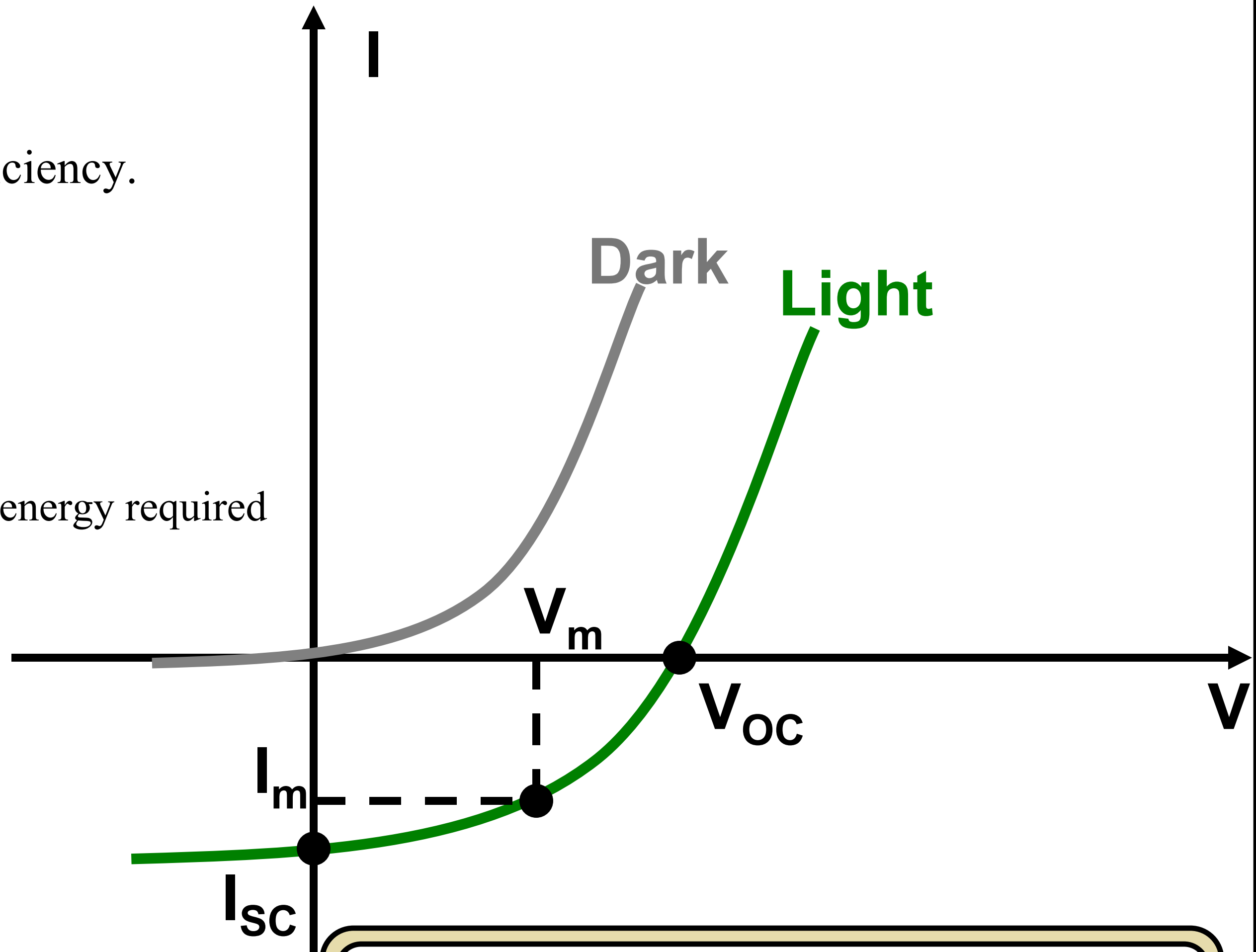
- **V_m and I_m** – the operating point yielding the maximum power output
- FF – fill factor – measure of how "square" the output characteristics are and used to determine efficiency.

  $$\mathbf{FF = V_m I_m / V_{OC} I_{SC}}$$

- η - power conversion efficiency.

  $$\eta = \mathbf{P_{max} / P_{in}}$$
  $$= \mathbf{V_m I_m / P_{in}}$$
  $$= \mathbf{FF V_{OC} I_{SC} / P_{in}}$$

- If $\mathbf{E_G}\downarrow$ then:
  - More photons have the energy required to create an EHP
  - $\mathbf{I_{SC}} \uparrow$ and $\mathbf{V_{OC}} \downarrow$
- Large $\mathbf{R_S}$ and low $\mathbf{R_{Sh}}$ reduces $\mathbf{V_{OC}}$ and $\mathbf{I_{SC}}$

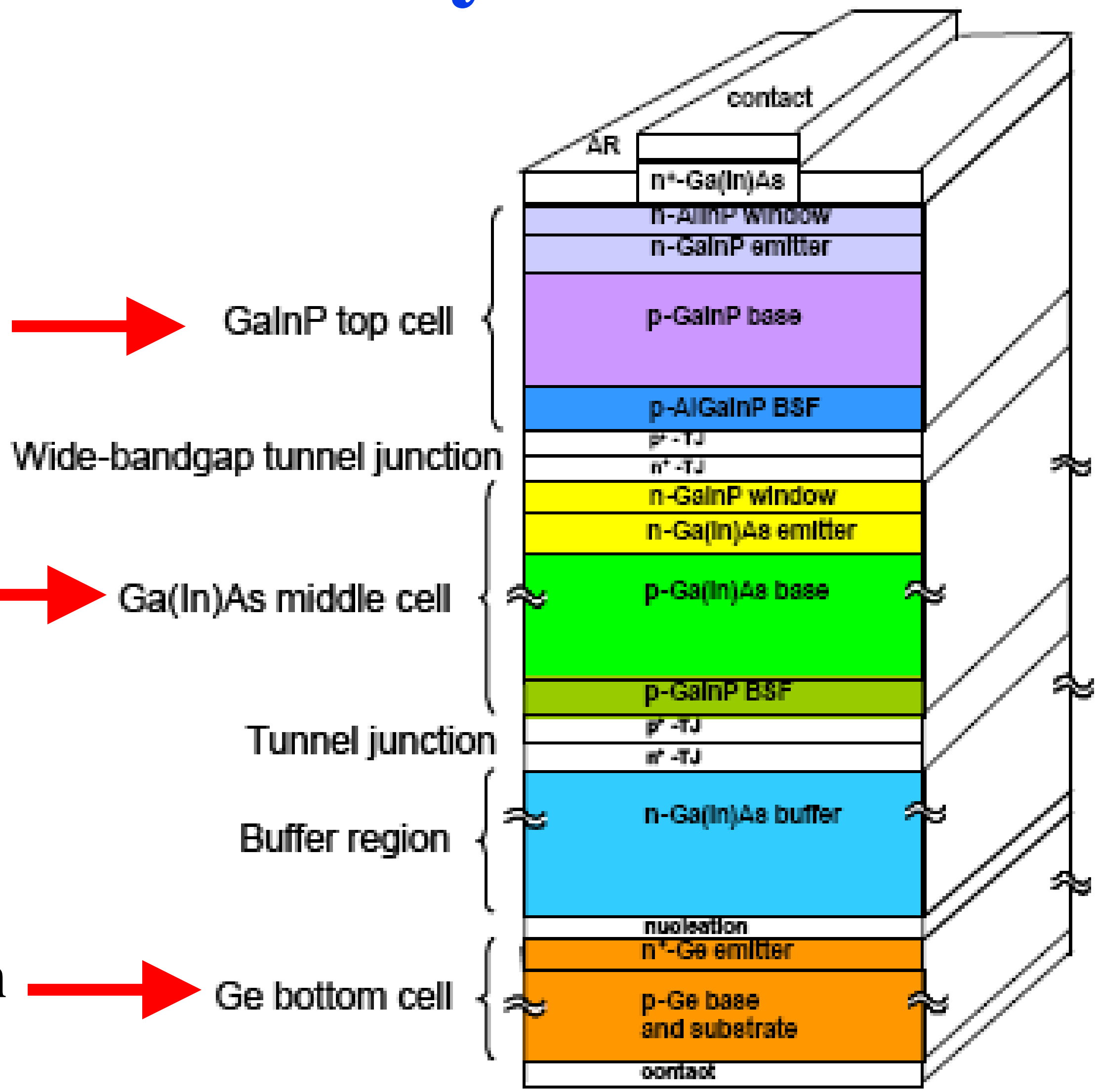


Highest Efficiency Device

1.8eV = 689nm

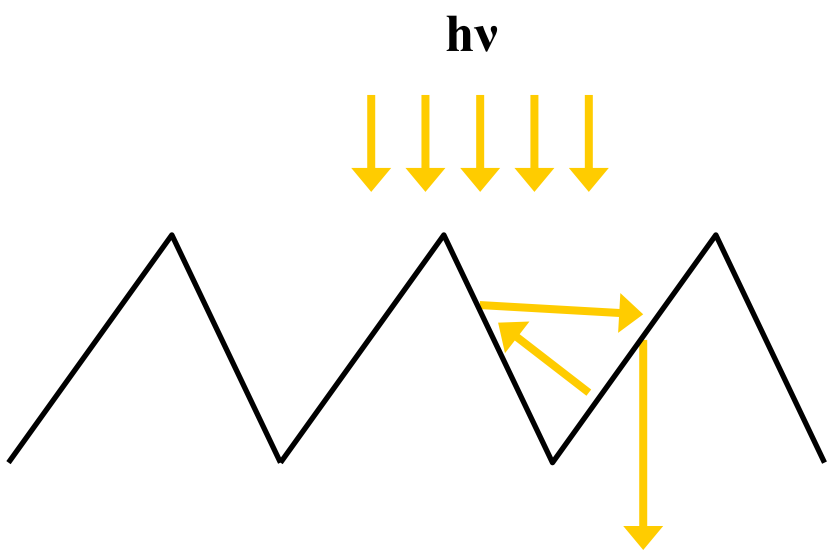
1.4eV = 886nm

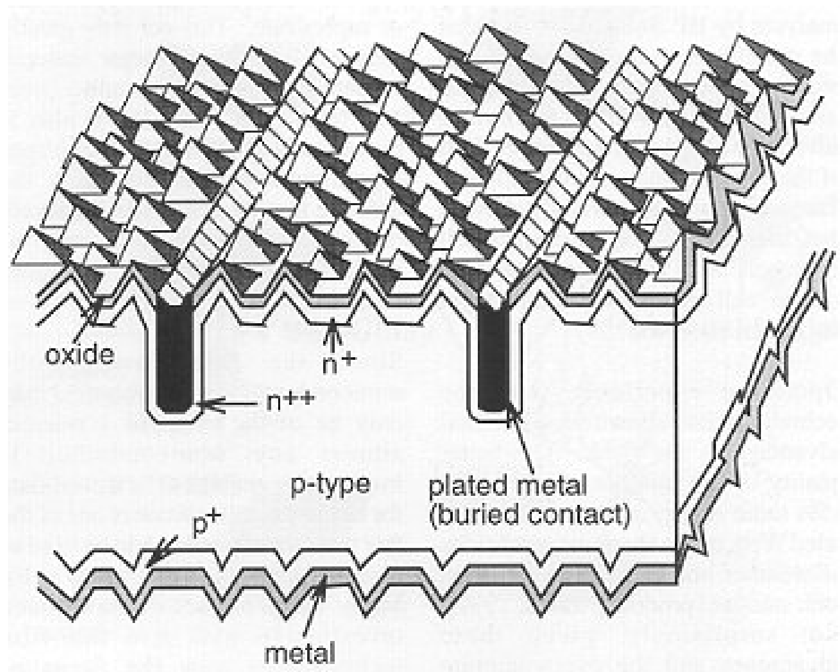
0.67eV = 1850nm

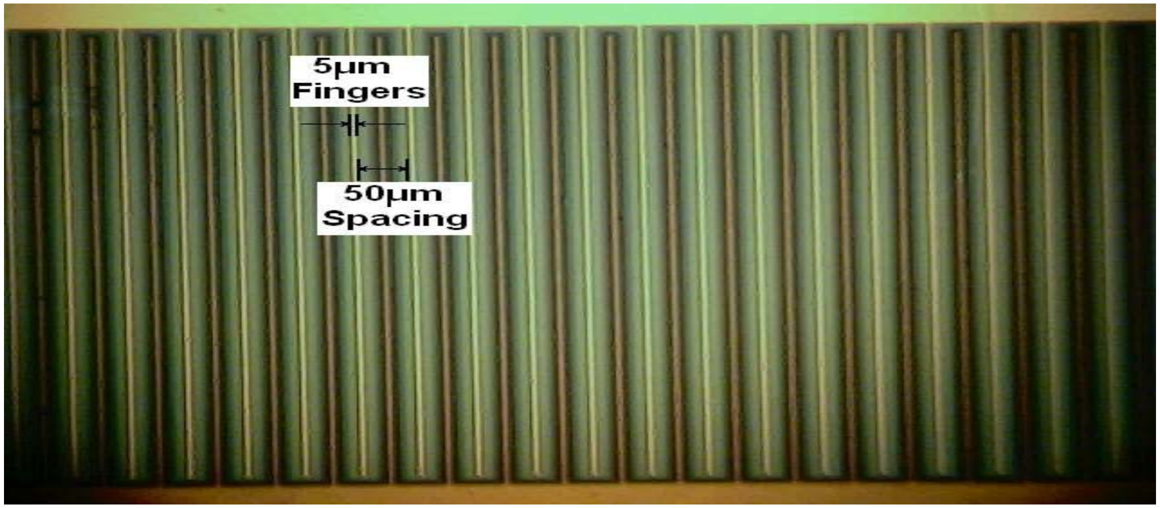


Si Technology

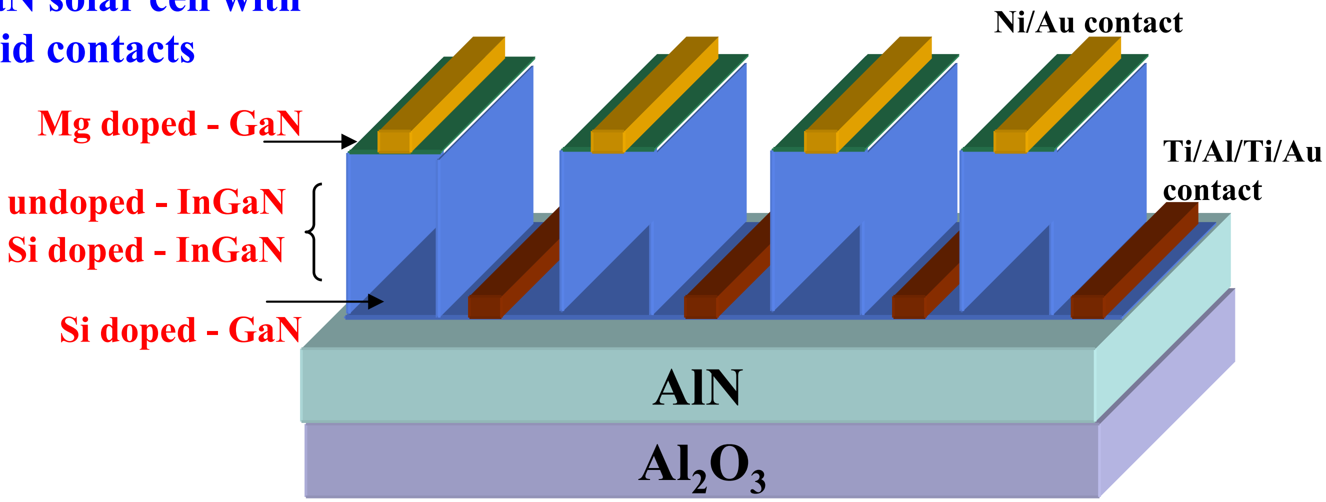
- Textured top layer
- Incident light will:
  - Become trapped
  - Bounced around in the texture
  - Absorbed in the device







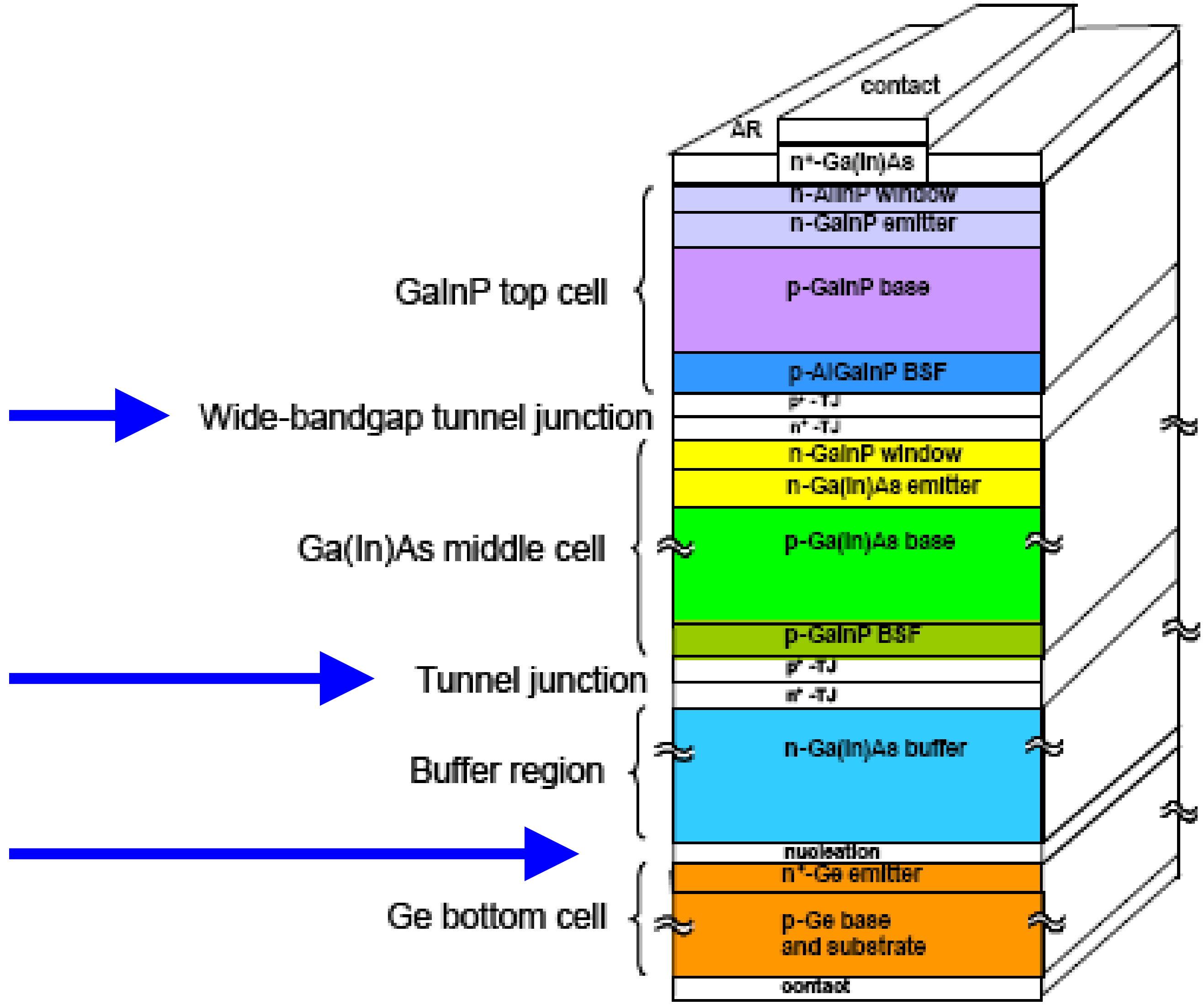
Fabricated MBE InGaN solar cell with interdigitated grid contacts



Schematic of the interdigitated grid contacts

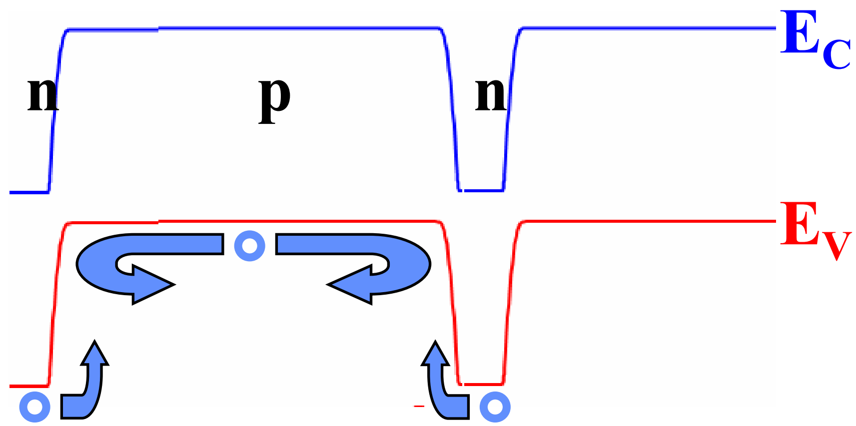
InGaN bandgap:
2.8eV = 442nm

What is a Tunnel Junction?



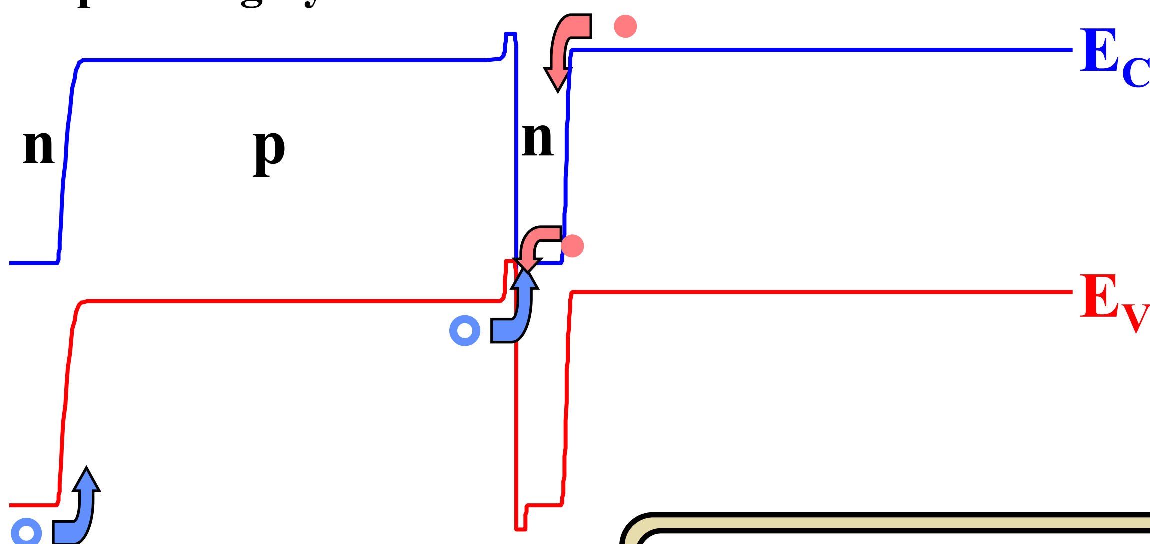
Tunnel Junction

Non-degenerately Doped

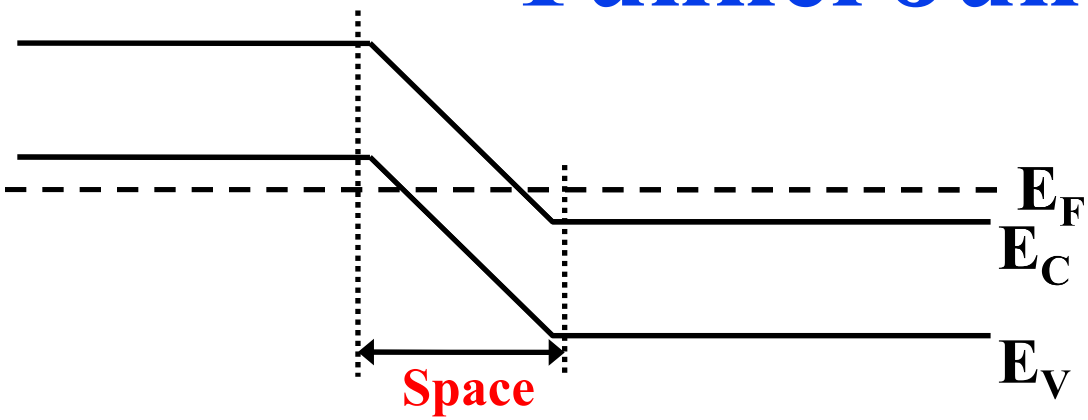


Tunnel junction requires degenerate doping!

Degenerately Doped – highly material

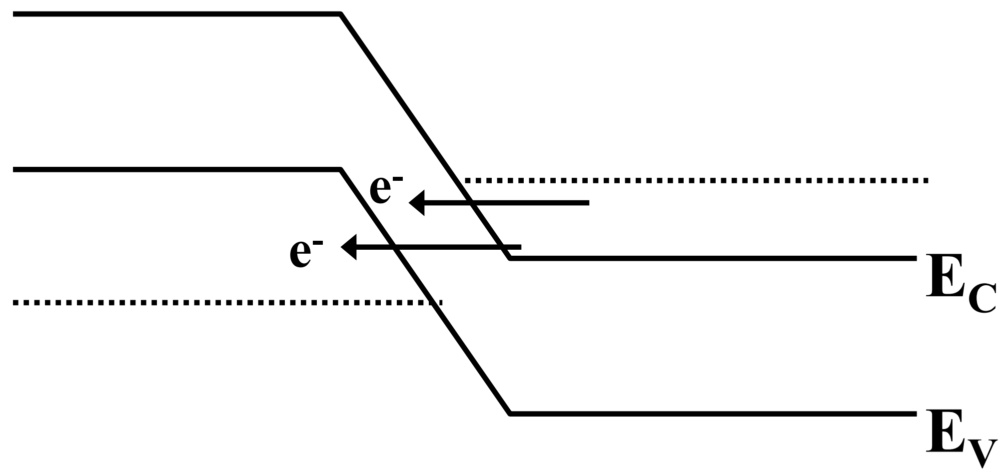


Tunnel Junction



❖ Energy-band diagram in thermal equilibrium – n and p-region are degenerately doped

❖ Large forward-bias voltage – the maximum number of electrons in the n-region is opposite the maximum number of empty states in the p-region; maximum tunneling current is produced.



❖ Increased forward-bias voltage – the number of electrons directly opposite the holes decreases and the tunneling current decreases.

Non-Idealities

- Bulk defects – dislocations and stacking faults, due to lattice mismatch with the substrate.
- Surface recombination defects – EHP generated by the absorption of light can recombine before they cross the junction, therefore not contributing to the power output of the solar cell.
- Bulk recombination defects – EHP generated further away from the junction have a large probability of recombining before they reach the device terminals.
- Insufficient photon energy: $h\nu < E_g$
- Excessive photon energy : $h\nu > E_g$
- Solar cell is too thin – some of the light of the appropriate energy is not coupled into the cell and is passed through the device.
- Open circuit Voltage (V_{OC}) losses – recombination of EHP in trap levels in the depletion region that lowers $V_{OC.}$
- Fill Factor losses – related to V_{OC}, series resistance, and shunt resistance.
- Reflection losses

Anti-Reflection Coating

- Prevents incident light from reflecting off of the device.
- The AR coating needs to have the correct refractive index for the material system and be transparent.
- Deposited as noncrystalline or amorphous layer which prevents problems with light scattering at grain boundaries.
- A double layer AR coating reduces the reflection of usable sunlight to ~ 4%.