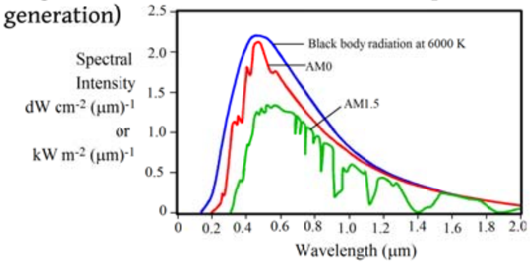
Photodetectors

Solar Cell

- Solar energy spectrum
- Photovoltaic device principles
- I-V Characteristics

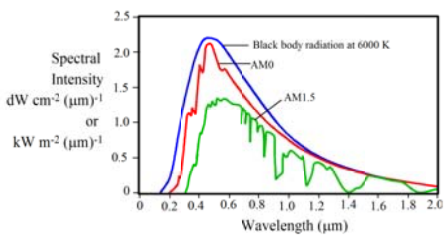
Solar Energy Spectrum

- Photovoltaic devices (solar cells) convert the incident solar radiation energy into electrical energy.
- Absorbed photons → photogeneration → current (photo-current) in external circuit
- Power range: from < mW (calculator) to few MW (photovoltaic power generation)



Solar Energy Spectrum

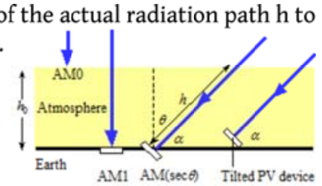
- Spectral intensity I_λ: Intensity per wavelength.
- $I_\lambda \delta\lambda$: intensity in a small interval $\delta\lambda$.
- Total intensity I: integration of I_λ over the whole spectrum.
- **Solar constant** or **air-mass zero** (AM0): the total intensity above earth's atmosphere, approx. constant at 1.353 kW m^{-2}.



Solar Energy Spectrum

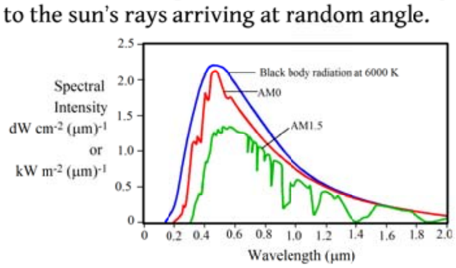
- On sunny day, light intensity on earth's surface is about 70% of the intensity above the atmosphere.
- Absorption and scattering effects increase with the sun beam's path through the atmosphere.
- The shortest path through the atmosphere is when the sun is directly above that location and the received spectrum is called **air mass one** (AM1).
- **Air mass** *m* (AM*m*): the ratio of the actual radiation path h to the shortest path h_0, $m = h/h_0$.

  Since $h = h_0 \sec\theta$, AM*m* is AMsecθ.



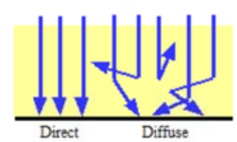
Solar Energy Spectrum

- The spectral distribution AM1.5 has several sharp absorption peaks at certain wavelengths which are due to those wavelength being absorbed by various molecule in the atmosphere, such as ozone, air, and water vapor molecules.
- Dust particles scatter the sun light → reduces the intensity and gives rise to the sun's rays arriving at random angle.



Solar Energy Spectrum

- Thus, the terrestrial light has a **diffuse** component in addition to **direct** component.
- Cloud and sun position → increase diffuse component → spectrum shifted toward the blue light.



- Scattering also increase with decreasing wavelength.
- On a clear day, diffusion component can be about 20% of the total radiation.
- The amount of incident radiation depends on the position of the sun. Flat photovoltaic device flat will receive less solar energy by factor cosθ. However it can be tilted to directly face the sun to maximize the collection efficiency.

Definitions: PV Cell

- **Cell:** The basic photovoltaic device that is the building block for PV *modules*.

- Thin wafers of silicon
  - Similar to computer chips
  - much bigger
  - much cheaper!
- Silicon is abundant (sand)
  - Non-toxic, safe
- Light carries energy into cell
- Cells convert sunlight energy into electric current- they do not store energy
- Sunlight is the "fuel"

PV Cells have efficiencies approaching 21.5%

Definitions: PV Module

- **Module:** A group of PV *cells* connected in series and/or parallel and *encapsulated* in an environmentally protective *laminate*.

PV Modules have efficiencies approaching 17%

Solarex MSX60
60 watt polycrystalline

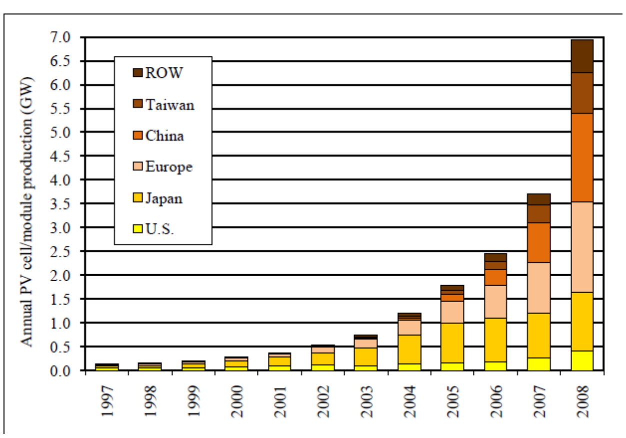
Siemens SP75
75 watt single crystal

Definitions: PV Panel

- **Panel:** A group of *modules* that is the basic building block of a PV *array*.

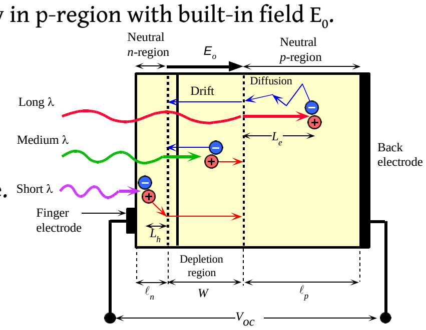
Definitions: PV Array

- **Array:** A group of *panels* that comprises the complete PV generating unit.



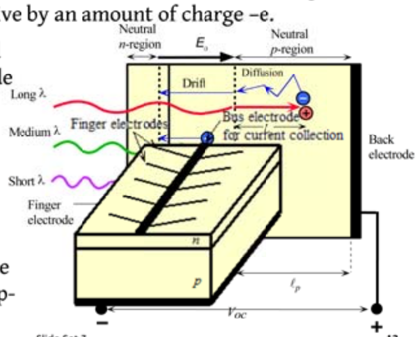
Photovoltaic Device Principles

- Consider pn+ junction with very narrow n-region.
- The illumination is through then thin n-side.
- The SCL extend mainly in p-region with built-in field E_0.
- Electrode at n-side must allow illumination to enter the device and at the same time result in a small series resistance.
- This electrode is formed from array of finger electrodes.



Photovoltaic Device Principles

- Photons are absorbed in SCL within the neutral p-side (l_p) → photogenerated EHP in this region.
- The electron drifts and reaches the neutral n^+ side whereupon it makes this region negative by an amount of charge –e.



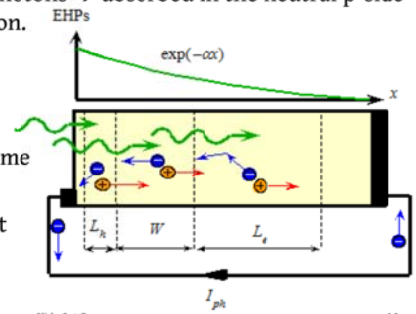
- Similarly, hole drifts and reaches the neutral p-side and thereby makes this side positive -> **open circuit voltage** between terminals of the device.
- If there is external load, electron will travel through it and recombine with the excess holes in p-side.

Photovoltaic Device Principles

- Therefore the existence of built-in field E_0 is important to create accumulated electrons in the n-side and holes in the p-side.
- For long wavelength photons → absorbed in the neutral p-side → no E field → diffusion.
- Minority carrier diffusion length L_e.

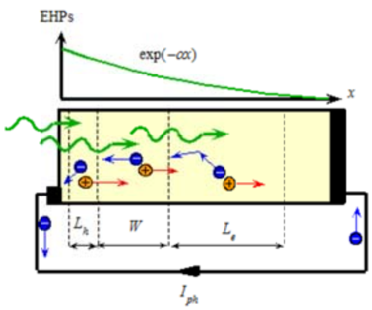
$$L_e = \sqrt{2D_e\tau_e}$$

- τ_e: recombination lifetime of electron.
- D_e: diffusion coefficient in the p-side.



Role of Diffusion Length

- Only those EHPs photogenerated within the L_e to the depletion layer can contribute to the photovoltaic effect.
- Those photogenerated EHPs further away from SCL than L_e are lost by recombination.
- Thus, it is important to have the minority carrier diffusion length L_e as long as possible. By choosing Si pn junction to be p-type which makes electrons to be minority carriers; the electron diffuse length in Si > the hole diffusion length.

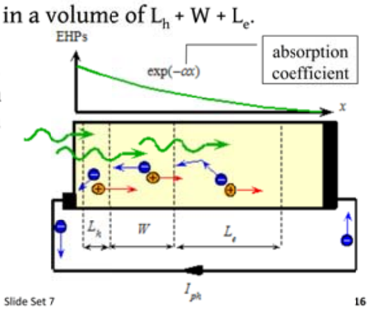


Role of hole diffusion length and s/c current

- For EHPs photogenerated by short-wavelength photons absorbed in the n-side, within diffusion length L_h, can reach SCL and swept across to the p-side.

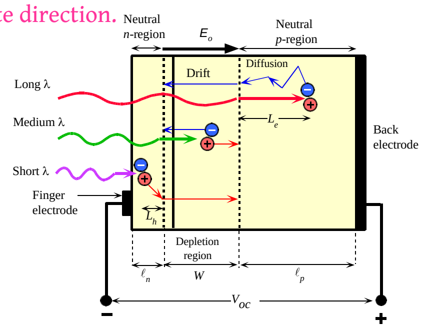
The photogenerated of EHPs that contribute to the photovoltaic effect occurs in a volume of L_h + W + L_e.

- If the terminals are shorted then the excess electrons in the n-side can flow through the external circuit to neutralize the excess holes in the p-side -> this current is called **photocurrent**.



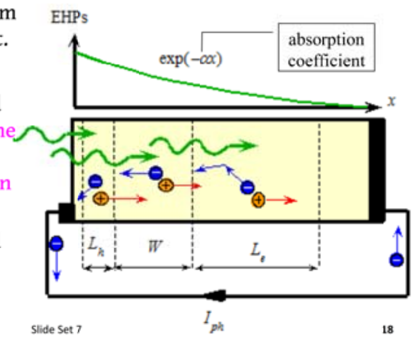
Photovoltaic Device Principles

- Under steady state operation → no net current through an open circuit solar cell → Photocurrent inside the device due to photo generated carriers must be balanced by a flow of carriers in the opposite direction.
- Those are minority carriers that become injected by the appearance of the photovoltaic voltage across the pn junction as in normal diode.



Device optimization and carrier losses

- For long wavelengths, 1 – 1.2 μm, α is small → absorption depth 1/α is typically greater than 100 μm. → Need a thick p-side and long minority carrier diffusion length L_e.
- Thus, p-side is 200 – 500 μm and L_e is shorter than that.
- Si has E_g = 1.1 eV -> correspond to a threshold wavelength of 1.1 μm → The incident energy with wavelength > 1.1μm is then wasted (~ 25%).
- Photons are absorbed and recombined near the crystal surface -> losses.

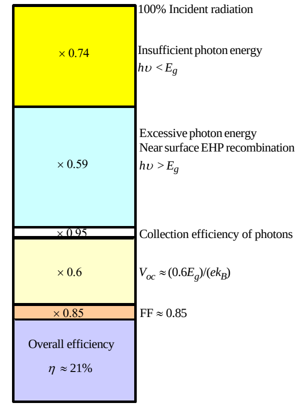


Sources of carrier losses

- Photons are absorbed and recombined near the crystal surface → losses → severely reduce efficiency.
- Crystal surface and interface contain high concentration of **recombination-center**.
- Those facilitate the recombination of photogenerated EHP near the surface.
- The losses due to this event as high as ~ 40%.
- These combined effect bring the efficiency down to about 45%.
- Anti-reflection coating is also contributing the reduction of photons collection due to imperfection with factor of 0.8 – 0.9.
- And including the limitation of photovoltaic action the upper limit to a photovoltaic device that uses single crystal of Si is about 24 – 26% at room temperature.

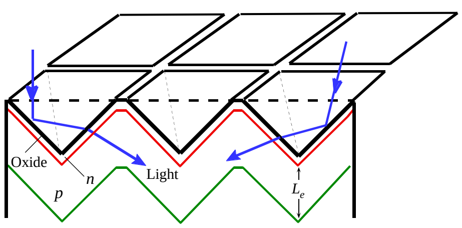
Solar Cells Materials, Devices & Efficiencies

- For a given solar spectrum, conversion efficiency depends on the semiconductor material properties and the device structure.
- Si based solar cell efficiencies 18% for polycrystalline and 22 – 24% for single crystal devices.
- About 25% solar energy is wasted → not enough energy → unable to generate EHPs.
- Considering all losses, the maximum electrical output power is ~20% for a high efficiency Si solar cell.



Solar Cells Materials, Devices & Efficiencies

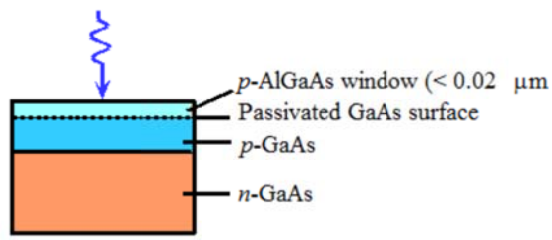
- Si homojunction solar cell efficiencies ~24%. Single crystal PERL (Passivated Emitter Rear Locally-diffused) cells.



Inverted pyramid textured surface substantially reduces reflection losses and increases absorption probability in the device

Solar Cells Materials, Devices & Efficiencies

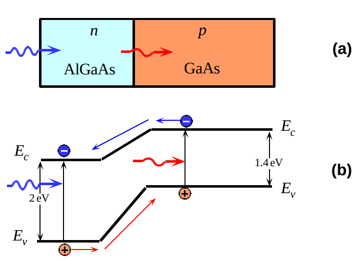
- Semiconductor alloy III-V → different bandgap with the same lattice constant → Heterojunction.



AlGaAs window layer on GaAs passivates the surface states and thereby increases the low wavelength photogeneration efficiency

Solar Cells Materials, Devices & Efficiencies

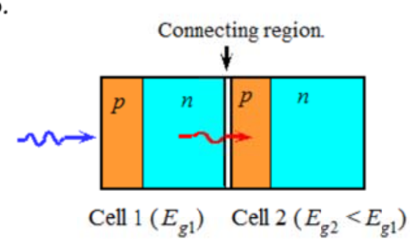
- Example *n*-AlGaAs with *p*-GaAs.



A heterojunction solar cell between two different bandgap semiconductors (GaAs and AlGaAs)

Solar Cells Materials, Devices & Efficiencies

- To further increase the absorbed photons → tandem or cascade cells (use two or more cells in tandem), such as GaAs – GaSb.



A tandem cell. Cell 1 has a wider bandgap and absorbs energetic photons with $h\upsilon > E_{g1}$. Cell 2 absorbs photons that pass cell 1 and have $h\upsilon > E_{g2}$.