EELE408 Photovoltaics
Lecture 13: Solar Cell Design I

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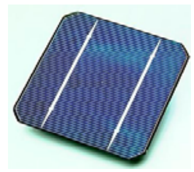
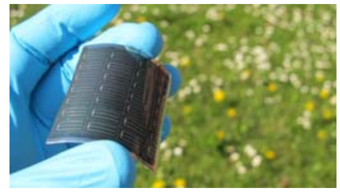
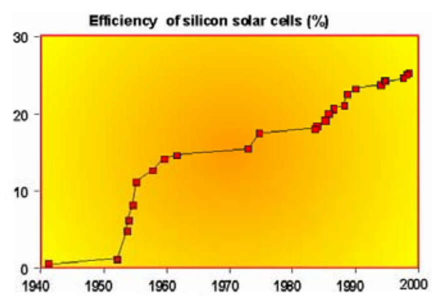
Solar Cell Design

- Specify the parameters of solar cell structure in order to maximize efficiency given a set of constraints
- Commercial→ cost of manufacture
- Research→ highest efficiency w/o regard to expense





Si Solar Cell Efficiency



Evolution of silicon solar cell efficiency.

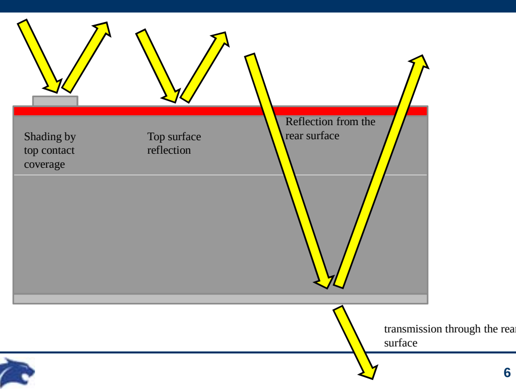
Efficiency Predictions

- 90% prediction of efficiency assumes ideal conditions
- Actual for Si silicon is 24.7% at AM1.5
- Why not 90%?
  - Assumes each photon is optimally used
    - Bandgap equals photon energy
    - Stack of ideal layers each only absorbing its energy photons
  - Assumes increased Voc by concentrating of sunlight

Principles for Maximizing Efficiency of a Single Junction Silicon Solar Cell

- Increasing the amount of light collected by the cell that is turned into carriers
- Increasing the collection of photogenerated carriers by the p-n junction
- Minimizing the forward bias dark current
- Extracting the current from the cell without resistive losses

Optical Losses



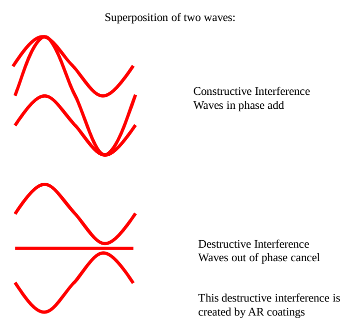
Reducing Optical Loss

- Minimize the top contact surface area
  - This may result in increasing the series resistance
- Anti-reflection coatings can be used on the top surface
- Reflection can be reduced by texturing the surfaces
- The solar cell can be made thicker to increase the absorption
  - Though light absorbed over a diffusion length from the junction will not contribute to current due to recombination
- The optical path length could be increased by texturing or light trapping

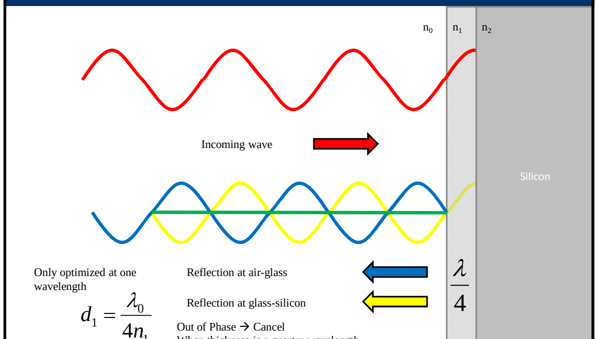
Anti-reflection (AR) Coatings

- Finished PV cell is coated with a material to reduce the amount of reflected light (just like eye glasses)
- Usually used on cells unsuitable for texturing
- Can reduce reflection to 5%
- AR Coating Materials
  - Silicon nitride
  - Silicon dioxide
  - Zinc oxide

AR mechanism



AR Coating



$$d_1 = \frac{\lambda_0}{4n_1}$$

$$\frac{\lambda}{4}$$

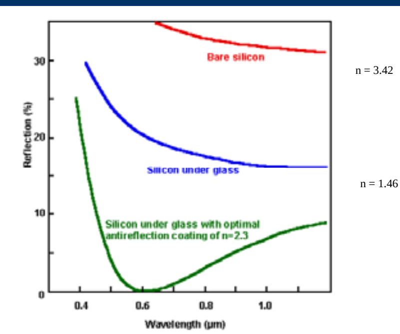
Index of AR coating

- Thickness for silicon dioxide
- The reflection is further minimized if the AR coating layer index is the geometric mean of the index of material on each side
- For air to silicon $d_1 = \frac{\lambda_0}{4n_1} = \frac{0.6}{4(1.46)} = 0.1027\mu$

$$n_1 = \sqrt{n_0 n_2}$$

$$n_1 = \sqrt{n_0 n_2} = \sqrt{(1)(3.42)} = 1.85$$

Surface Reflections w/ & w/o AR



Broadband AR coating

- By adding more layers the reflectivity can be reduced over a wide range of wavelengths
- This is usually too expensive for most commercial solar cells

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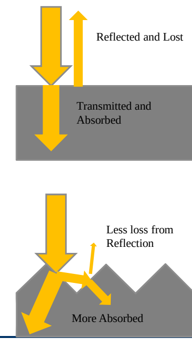
Texturing

- Formed by Anisotropic etching different crystal planes etch at different rates
- Reduces total reflection by reflecting light into another pyramid instead of away
- Increases the chances of absorbing the light
- 30% reflection from polished Si reduced to 10% for textured Si



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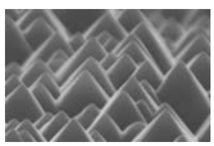
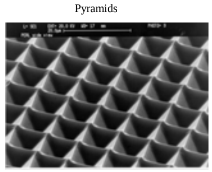
Texturing

- Reduce the reflectivity of the surface of wafers by forming microscopic structures
- Works mainly for single crystal surfaces



Pyramids



Inverted Pyramids

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Material Thickness

- Essential to absorb all the light in the silicon solar cell
- The amount of light absorbed is a function of the optical path length and the absorption coefficient

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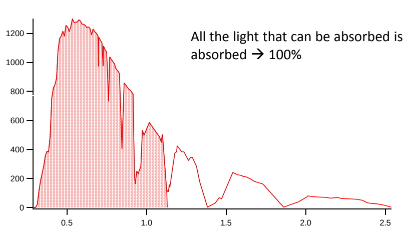
10mm Thick



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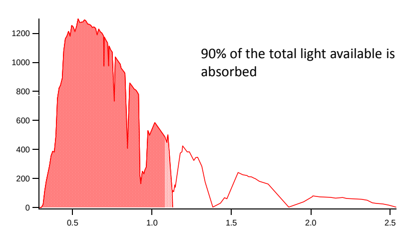
1000 micron Thick



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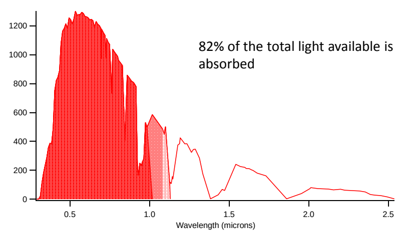
350 micron Thick



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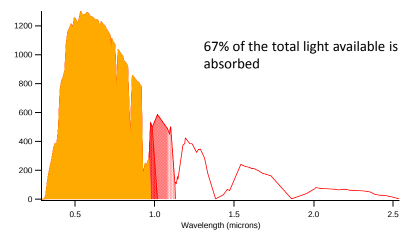
100 micron Thickness



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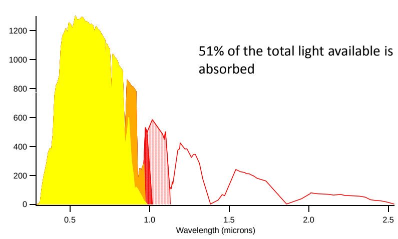
35 micron Thickness



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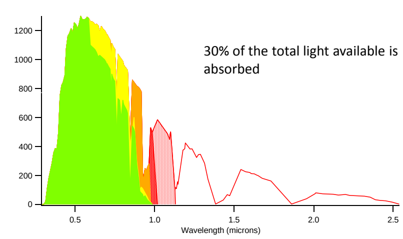
10 micron Thickness



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Light Trapping

- Optical Path Length is several times the actual device thickness
- Absorb light within a diffusion length of the junction
- Achieved by changing the angle that light travels in the solar cell
- Snell's law $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- Total Internal Reflection

$$n_1 \sin\theta_1 = n_2 \sin(\theta_2 = 0)$$

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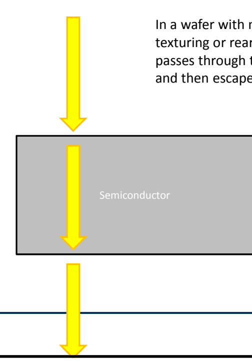
No Surface Texturing or Rear Reflector

In a wafer with no surface texturing or rear reflector the light passes through the solar cell once and then escapes out the rear.



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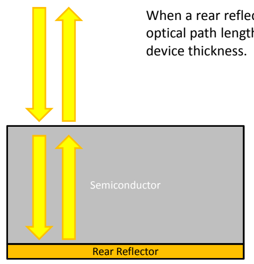
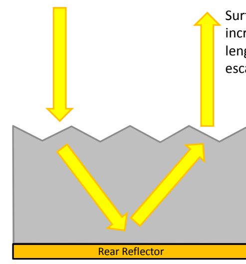
With Rear Reflector



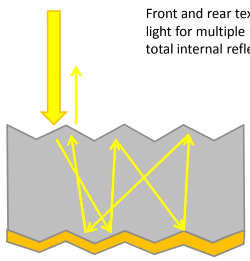
When a rear reflector is added the optical path length is twice the device thickness.

Surface Texturing With Rear Reflector



Surface Texturing increases the path length but light still escapes

Front and Rear Texturing

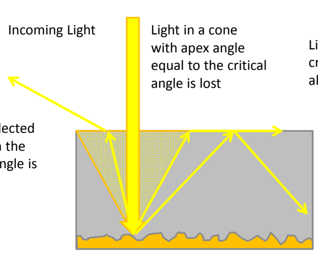


Front and rear texturing can trap light for multiple passes due to total internal reflection.

Lambertian Rear Reflectors

- Randomizes the reflection off the rear surface
- Light reflected at angles greater than the critical angle gives total internal reflection
- Creates optical path lengths that are up to 50 times the physical device thickness

Lambertian Rear Reflectors



Incoming Light

Light in a cone with apex angle equal to the critical angle is lost

Light reflected at the critical angle travels along the surface

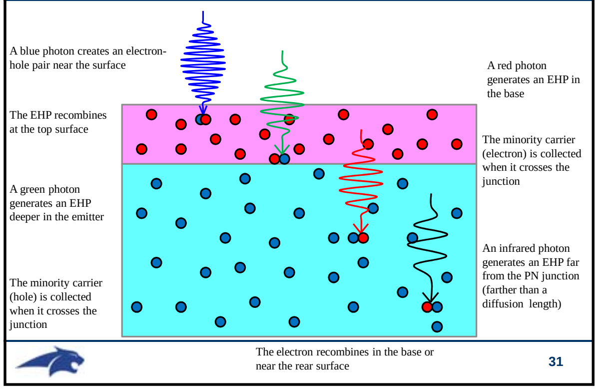
Light reflected less than the critical angle is lost

Light reflected greater than the critical angle is totally internal reflected and trapped in the solar cell

Recombination Losses

- Recombination effects both the current collection → short circuit current and the forward bias injection current → open circuit voltage
- Classified by the region where the recombination occurs
  - Surface recombination
  - Bulk recombination
  - Depletion area recombination

Recombination Sites



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Current Losses due to Recombination

- Bulk and Surface recombination must be minimized to maximize efficiency
- Conditions for Current collection
  - The carrier must be generated within a diffusion length from the junction, so that it can diffuse to the junction before recombination
  - The carrier must be generated closer to the junction than to a recombination site such as
    - Unpassivated surface
    - Grain boundary in multicrystalline solar cells

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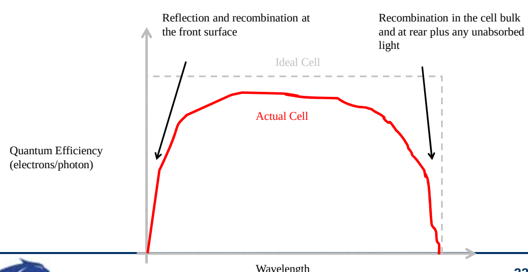
Quantum Efficiencies

- The quantum efficiencies quantifies the effect of recombination on the light generated current



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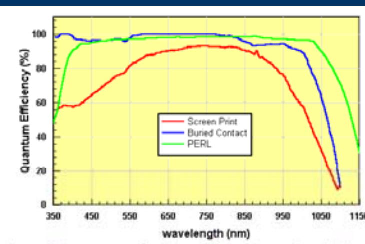
Quantum Efficiency Curves



Quantum efficiency curves for three different types of crystalline silicon solar cells. The buried contact and screen printed curves are internal quantum efficiencies, while the PERL is an external quantum efficiency. The PERL cell has the best response to infrared light since it has a well passivated, highly reflective rear incorporating light trapping.

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Voltage Losses due to Recombination

- Open circuit voltage is the voltage in which the forward bias diffusion current is equal to the short circuit current
- High recombination increases the forward bias diffusion current and reduces the open circuit voltage
- The parameter which gives the recombination in forward bias is the diode saturation current

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Open circuit voltage parameters

- Number of minority carriers at the junction edge
  - Minimizing the equilibrium carrier concentration reduces the minority carriers at the junction edge
  - This is achieved by **increasing the doping**
- Diffusion length
  - **Maximizing the diffusion length** reduces the recombination
  - High doping reduces the diffusion length→←
- Surface recombination
  - High recombination sources close to junction increases recombination
  - **Surface passivation** reduces surface recombination

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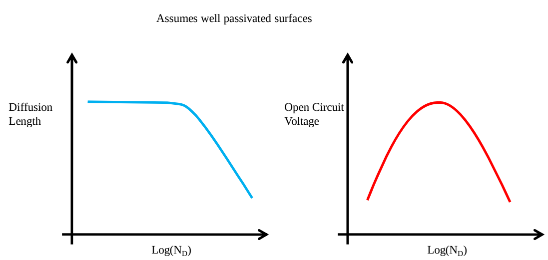
Effect of Doping Concentration (N_D)



Surface Passivation

- High recombination rates at front surface have detrimental impact on short circuit current since top surface also corresponds to highest generation region in solar cell
- Lowering the recombination rate at the front surface is accomplished by reducing the number of dangling bonds by growing silicon dioxide on the surface to passivate the bonds

Reduction Techniques