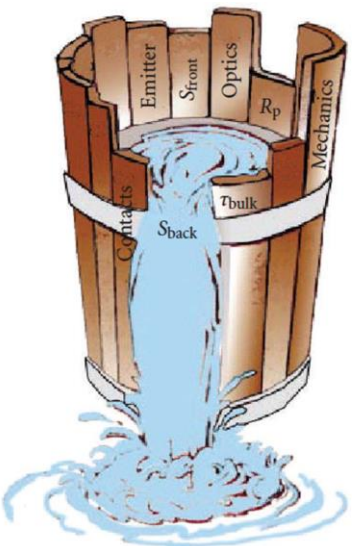
FIZ3630 SOLAR CELLS

2023-2024 FALL SEMESTER & Friday 17.00

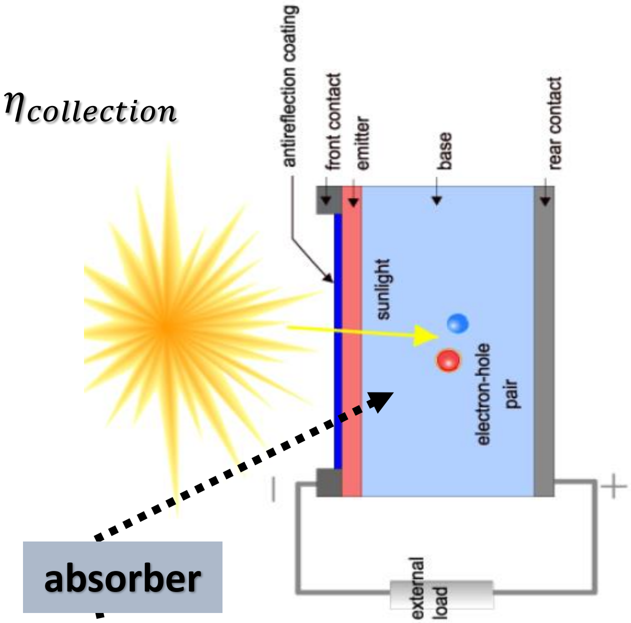
Energy Sources, Solar Energy, and Greenhouse Effect	WEEK 1	(06/10/2023)
Solar Radiation, Solar Spectrum	WEEK 2	(13/10/2023)
Interaction of light and matter	WEEK 3	(20/10/2023)
Semiconductors	WEEK 4	(27/10/2023)
Photovoltaic Effect	WEEK 5	(03/11/2023)
pn Junctions	WEEK 6	(10/11/2023)
Basic Structure of Solar Cells	WEEK 7	(17/11/2023)
Midterm Exam	WEEK 8	(24/11/2023)
Solar Cells Parameters	WEEK 9	(01/12/2023)
Effects on Solar Cells Parameters	WEEK 10	(08/12/2023)
Characterization of Solar Cells	WEEK 11	(15/12/2023)
Historical Development and Classification of Solar Cells	WEEK 12	(22/12/2023)
Concepts for Improving the Efficiency of Solar Cells	WEEK 13	(29/12/2023)
Summary, Exercises	WEEK 14	(05/01/2024)
Final Exam	WEEK 15	(12/01/2024)

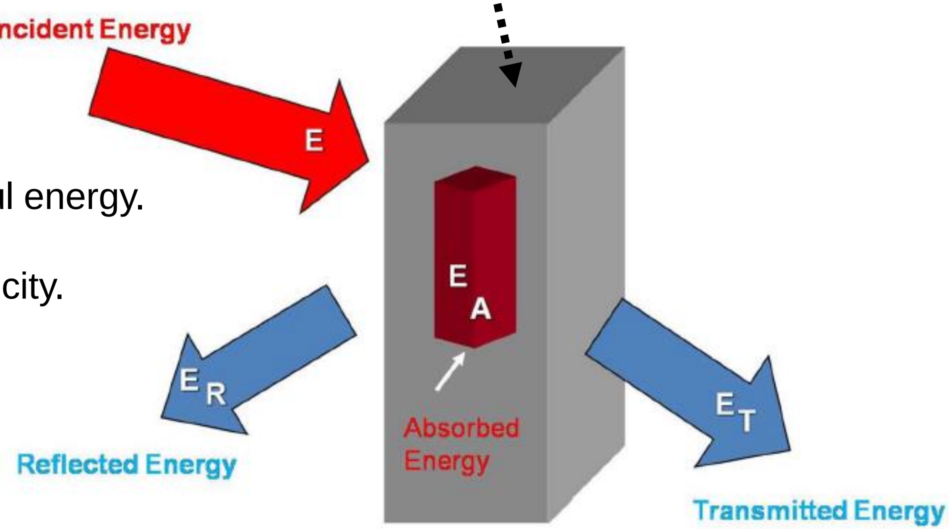
Light Management in Solar Cells: The Big Picture

$$\eta_{total} = \eta_{absorption} \times \eta_{excitation} \times \eta_{drift/diffusion} \times \eta_{seperation} \times \eta_{collection}$$



$$\eta = \frac{output\ power}{input\ power}$$





- ❑ Photons that aren't absorbed can't induce useful energy. (not absorbed : transmitted or reflected)
- ✓ Only absorbed energy can transform into electricity.

we want to maximize this fraction!

Buonassisi (MIT) 2011

Interaction of light and matter

Low-Energy Photon-Matter Interactions

At low energies typical for visible light, photons interact primarily with valence electrons.

Interactions of Visible Light with Matter

Interactions of visible light with matter can be described by the *complex index of refraction*:

$$n_c = n + ik$$

Real component
index of refraction
(phase velocity)

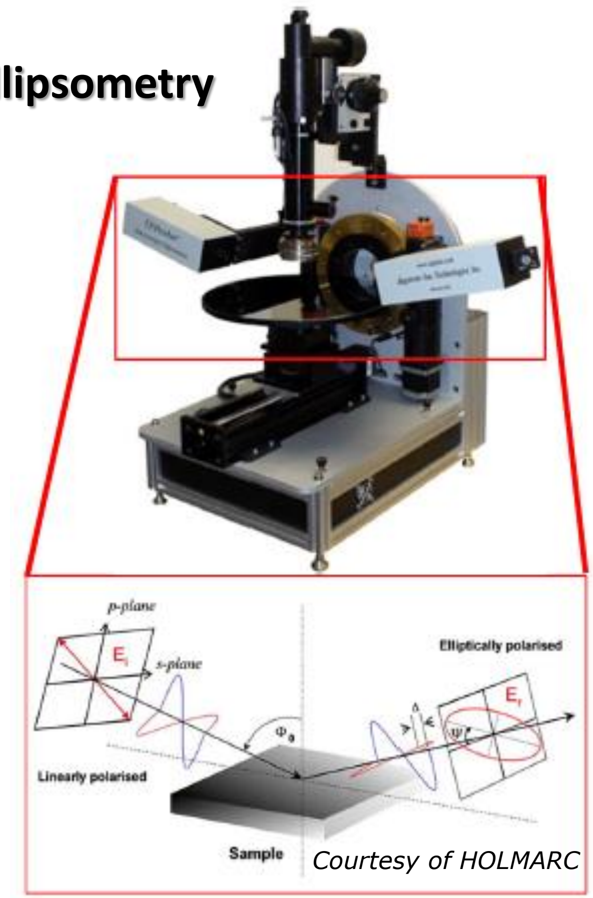
Imaginary component
extinction coefficient
(attenuation)

$$\alpha = \frac{4\pi k}{\lambda}$$

absorption coefficient

Real and Imaginary components of the index of refraction are wavelength-dependent, and are typically measured using a measurement technique called *spectroscopic ellipsometry*.

ellipsometry



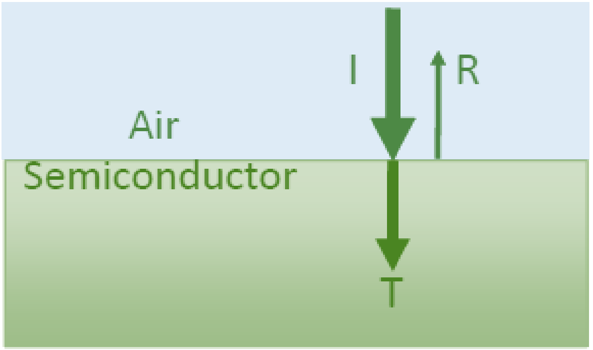
Courtesy of HOLMARC

Photons – Reflections off a Surface

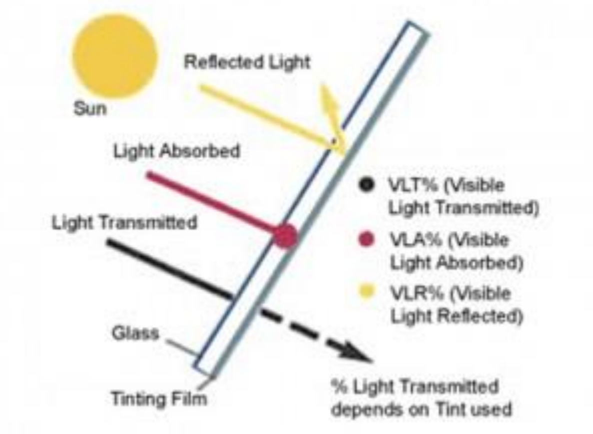
At visible wavelengths, the fraction of reflected light depends most strongly on real component of the index of refraction.

- we want to minimize the reflection !

$$R = \left(\frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}\right)$$



Reflectance from air (n_{air}=1) to a solid with n.



Tinted windows
- Why can't you see inside?
- If the glass pane was flipped, would this change anything?

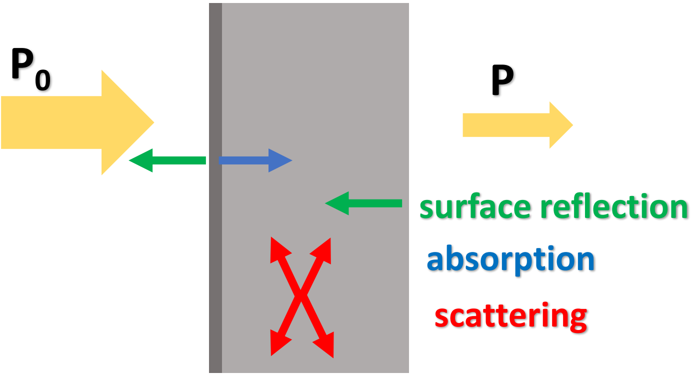
https://www.amazon.com/Blocking-Tinting-Privacy-Reflective-Adhesive/dp/B0BNQ29GCY?th=1

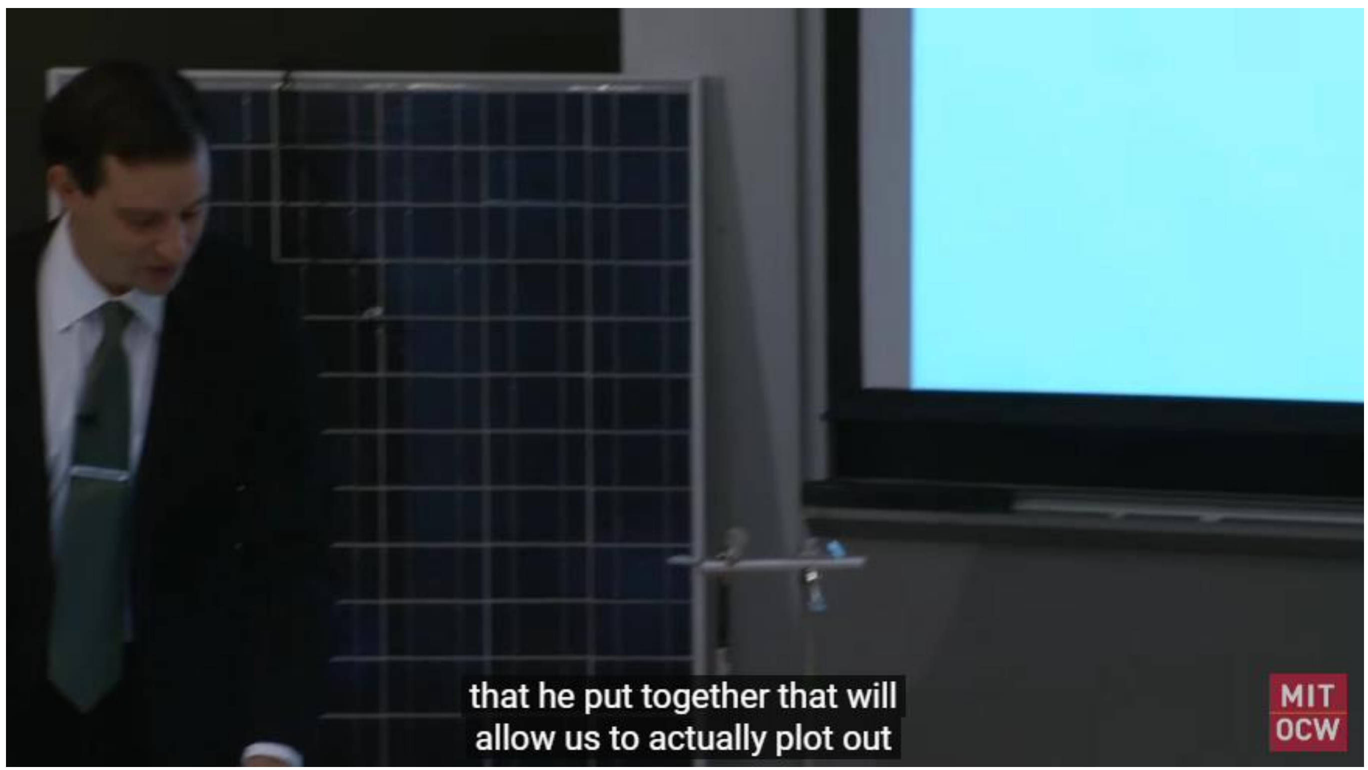
Interaction of light and matter

Bulk Absorption

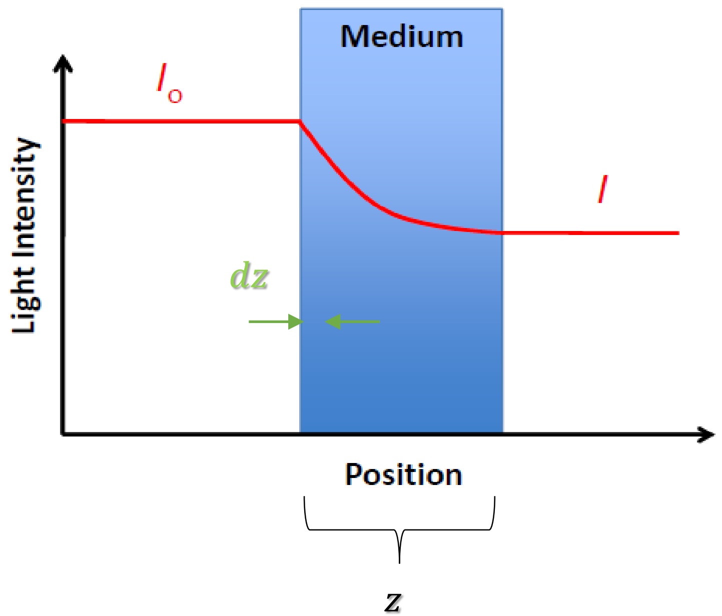
The Beer-Lambert's Law

$$I = I_o e^{-\alpha z}$$





Photons – Transmission Through a Medium



$$dI \propto -Idz$$
$$dI = -I\sigma N dz$$

$$\frac{dI}{I} = -\sigma N dz$$

$$\int_{I_0}^{I} \frac{dI}{I} = -\sigma N \int_0^z dz$$
$$\ln(I) - \ln(I_0) = -\sigma N z = -\sigma N(z-0)$$
$$ln\frac{I}{I_0} = -\sigma N z$$

$$I = I_o e^{-\alpha z}$$

absorption events

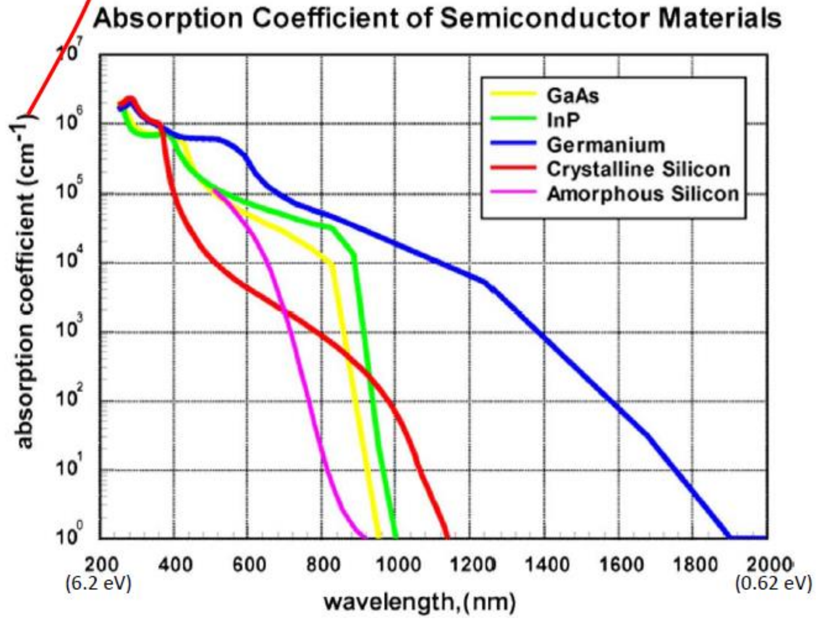
- ✓ may result in generation of free charge.
- ❑ may just heat material up and generate phonons.

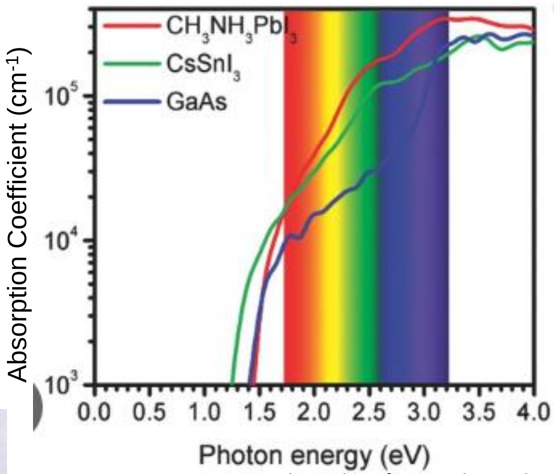
absorption coefficient : α is a function of the wavelength of light and property of the medium.
σN =α vary as a **function of wavelength** inside of a material due to the physical absorption mechanisms are varying as a function of wavelength.

Absorption Coefficient for different materials

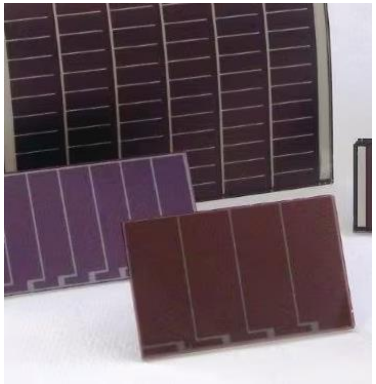
$$I = I_o \cdot e^{-\alpha \cdot l}$$

http://www.pveducation.org/pvcdrom

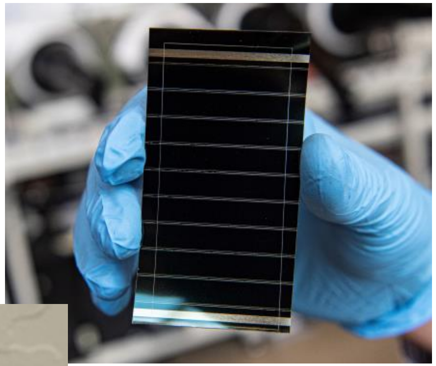




Yin, Wan-Jian, Tingting Shi, and Yanfa Yan Advanced materials 26.27 (2014): 4653-4658.



https://www.digikey.pl/pl/product-highlight/p/panasonic/amorphous-silicon-solar-cells

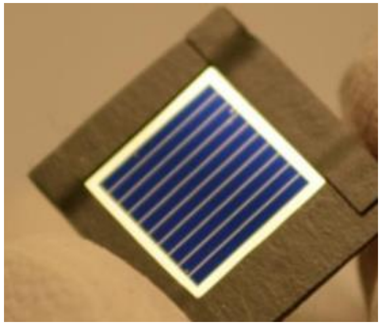


https://www.energy.gov/eere/solar/perovskite-solar-cells

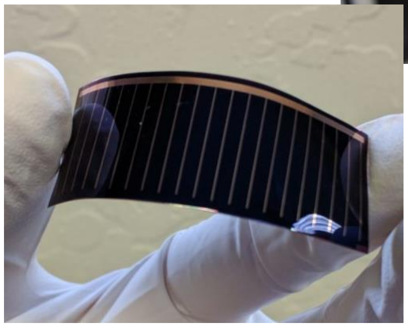
Monocrystalline silicon solar cell

Polycrystalline silicon solar cell

Saga, Tatsuo. "Advances in crystalline silicon solar cell technology for industrial mass production." npg asia materials 2.3 (2010): 96-102.



Yin, Xingtian, et al. "19.2% Efficient InP heterojunction solar cell with electron-selective TiO2 contact." ACS photonics 1.12 (2014): 1245-1250.

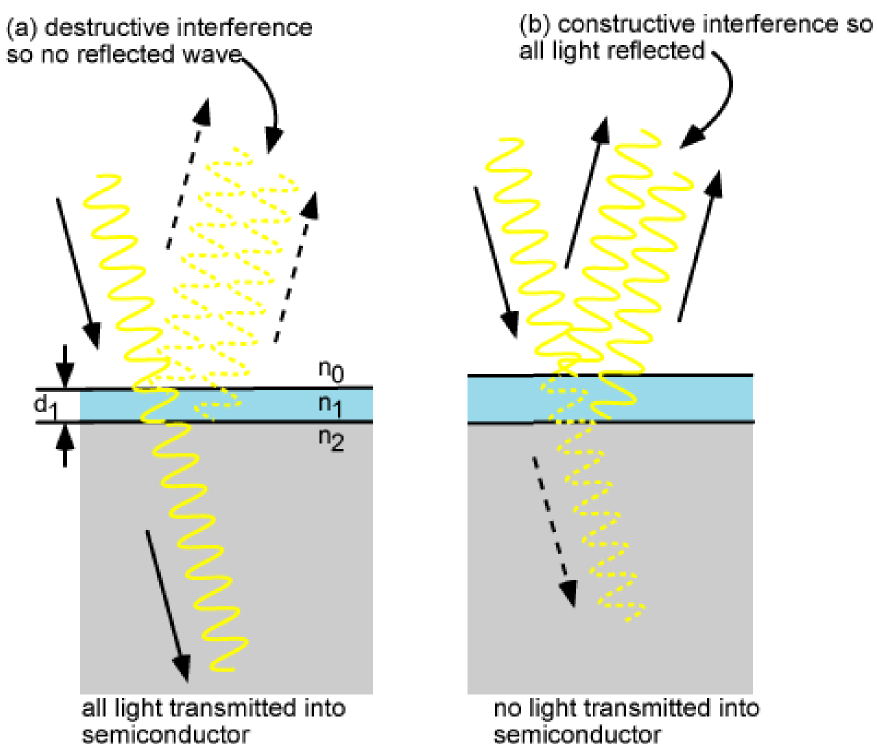


Kenning, T. "Alta Devices sets GaAs solar cell efficiency record at 29.1%, joins NASA space station testing." (2018).

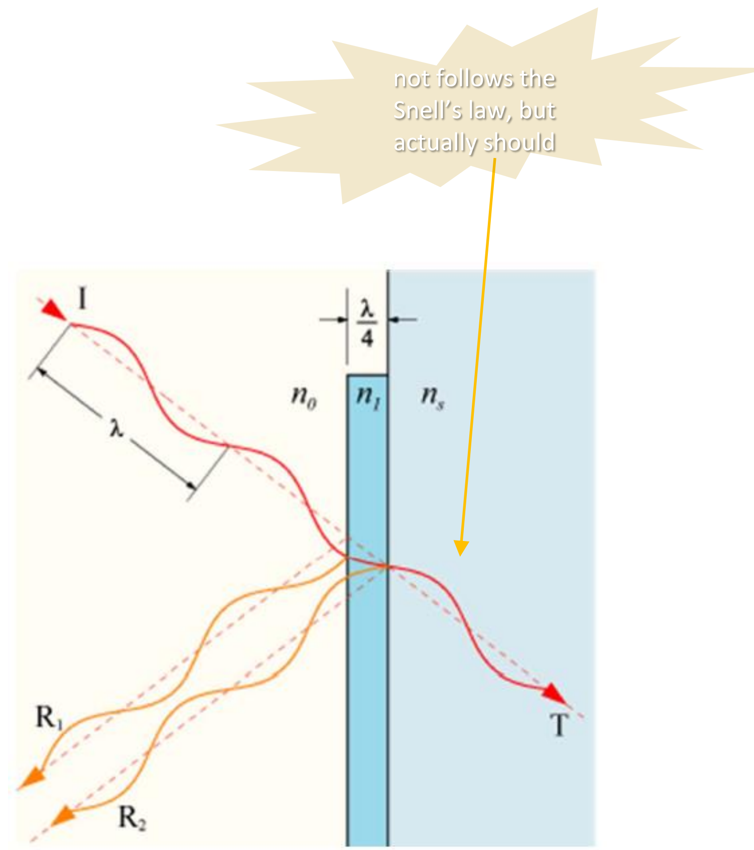
Methods to Minimize Optical Losses : Light Management

- Antireflection coatings (ARCs)
- Snell's Law
- Texturization
- Back surface reflection, total internal reflection

Anti-Reflection Coatings



Thin Film R Reflectance



Interaction of light and matter

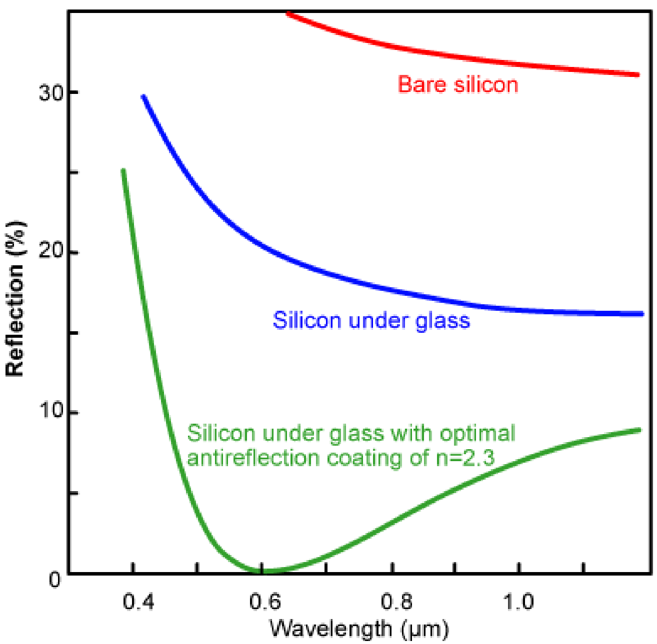
Anti-Reflection Coatings

The thickness of ARC is chosen so that wavelength in the dielectric material is one quarter the wavelength of the incoming wave.

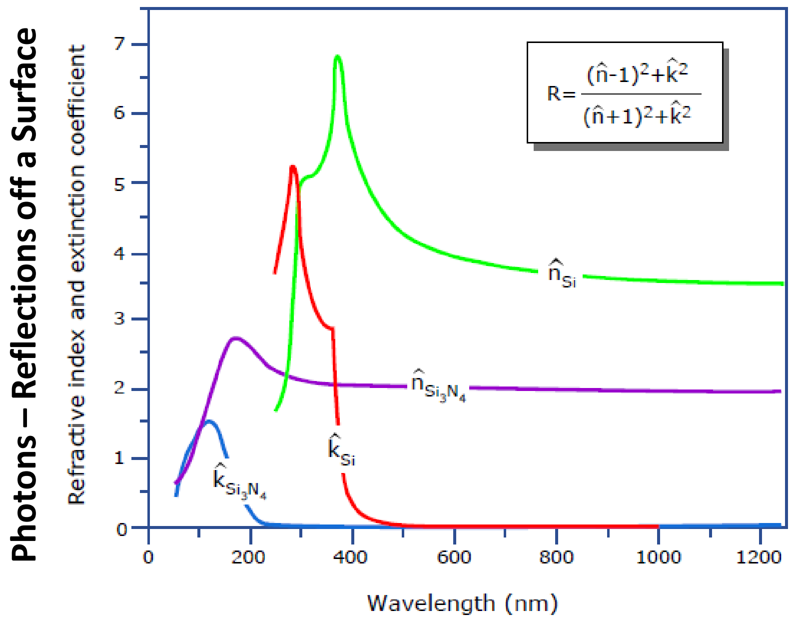
$$d_1 = \frac{\lambda_0}{4n}$$

Optimal ARC thickness: λ_0 is photon wavelength at the peak of the solar spectrum (550 nm mostly)

Silicon has a high surface reflection of over 30%. The reflection is reduced by texturing and ARC !



G. Bauer, "Absolutwerte der optischen Absorptionskonstanten von Alkalihalogenidkristallen im Gebiet ihrer ultravioletten Eigenfrequenzen", Annalen der Physik, vol. 411, no. 4, pp. 434 - 464, 1934.



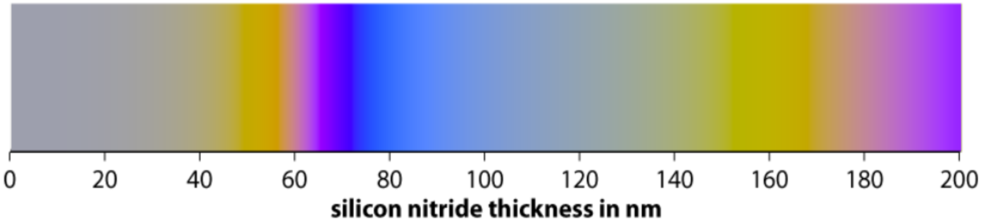
Qualities of an optimized ARC:

- Index of refraction between absorber and superstrate (air, glass)
- Thickness on the order of a quarter wavelength
- Stable
- Enhances electrical performance by passivating dangling bonds at the surface and repelling charges from the surface

Interaction of light and matter

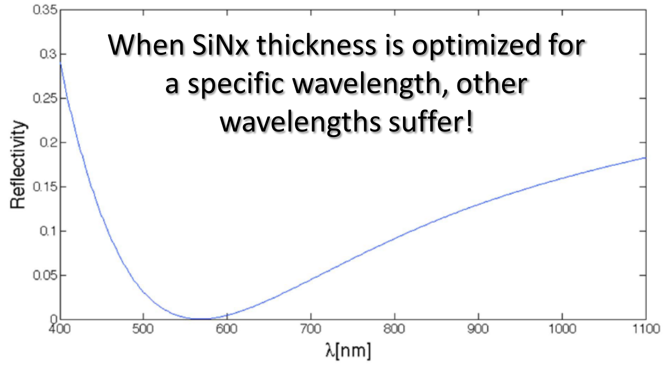
Thickness of Anti-Reflection Coatings

Four multicrystalline wafers covered with films of silicon nitride. The difference in color is solely due to the thickness of the film. The green wafers are very thick films and so don't appear in the color chart of the below figure.



https://www.pveducation.org/pvcdrom/design-of-silicon-cells/anti-reflection-coating-color

Spectral Reflectivity for Optimized SiN_x optimized at 550nm

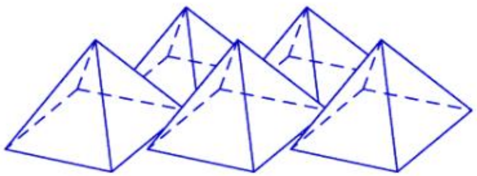


Color Chart for Films of SiO_2 under fluorescent lighting

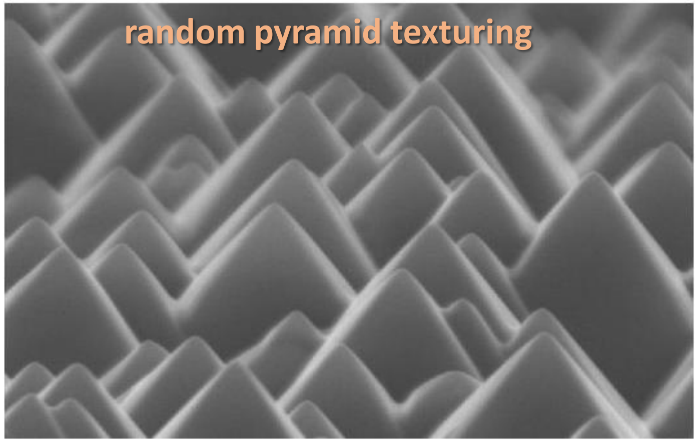
$Film_{Thickness}$ (µm)	Colour
0.05	Tan
0.07	Brown
....	
0.20	Light gold to yellow; slightly metallic
0.22	Gold with slight yellow orange
0.25	Orange to melon
0.27	Red violet
0.30	Blue to violet blue
....	
0.42	Carnation pink
0.72	Blue green to green (quite broad)
1.19	Red Violet
1.21	Violet red
1.24	Carnation pink to salmon
1.25	Orange
1.28	"Yellowish"
1.32	Sky blue to green blue
1.40	Orange
1.45	Violet
1.54	Dull yellow green

Texturization

Multiple reflections on surface:
- Increase probability that light enters device.
- Increase effective path length of incoming light.

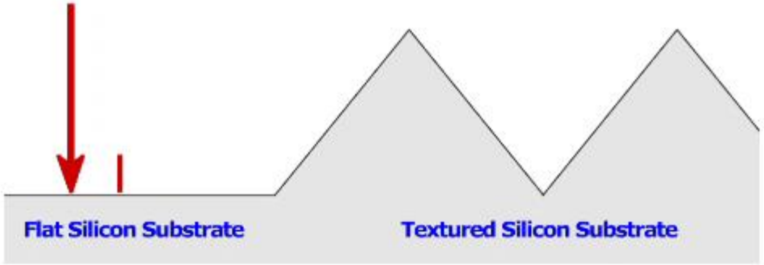


A square based pyramid which forms the surface of an appropriately textured crystalline silicon solar cell.

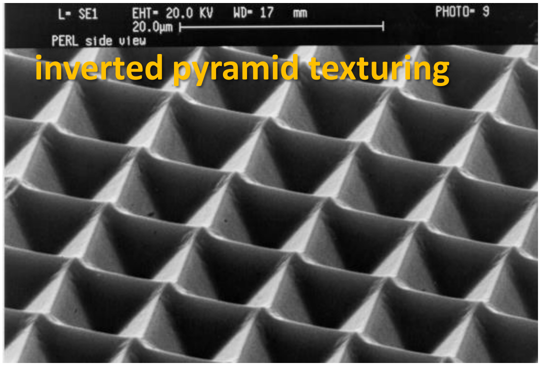


Scanning electron microscope photograph of a textured silicon surface. Image Courtesy of The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

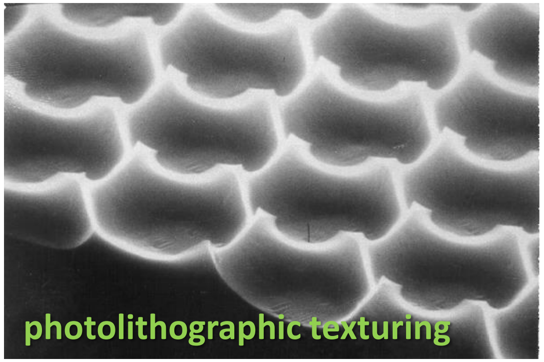
https://www.pveducation.org/pvcdrom/design-of-silicon-cells/surface-texturing



The reflected light from the surface, RI, is reflected at the same angle at which the incoming light strikes the surface.



S. C. Baker-Finch, McIntosh, K. R., and Terry, M. L., "Isotextured Silicon Solar Cell Analysis and Modeling 1: Optics", IEEE Journal of Photovoltaics, vol. 2, no. 4, pp. 457 - 464, 2012.



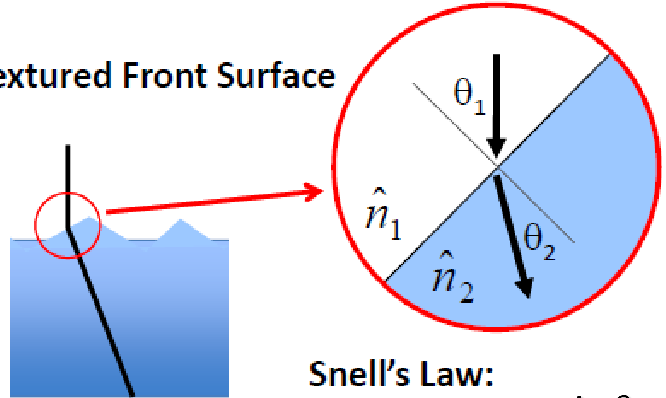
Scanning electron microscope photograph of a textured multicrystalline silicon surface. Image Courtesy of The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

Interaction of light and matter

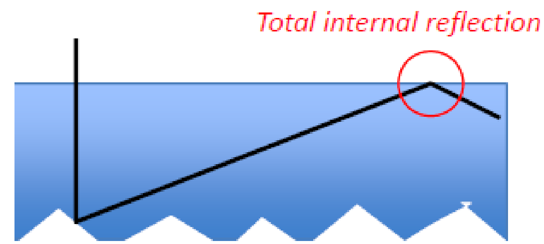
Snell's Law

A change in refractive indices results in a "bending" of light.

A. Textured Front Surface

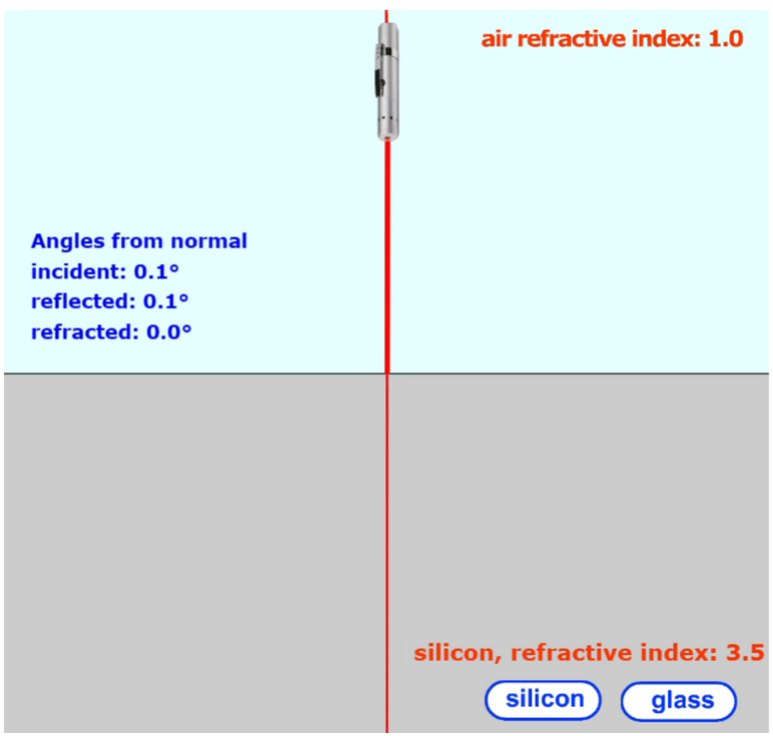


B. Textured Back Surface



Snell's Law:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

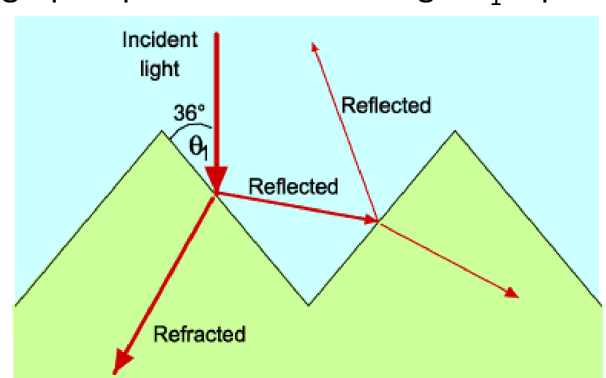


Refraction of a ray of light at a dielectric boundary.

Rearranging Snell's law, angle at which light enters the solar cell (the angle of refracted light) can be calculated:

$$\theta_2 = sin^{-1}\left(\frac{n_1}{n_2} sin\theta_1\right)$$

In a textured single c-Si solar cell, the presence of crystallographic planes make the angle θ_1 equal to 36°



Interaction of light and matter

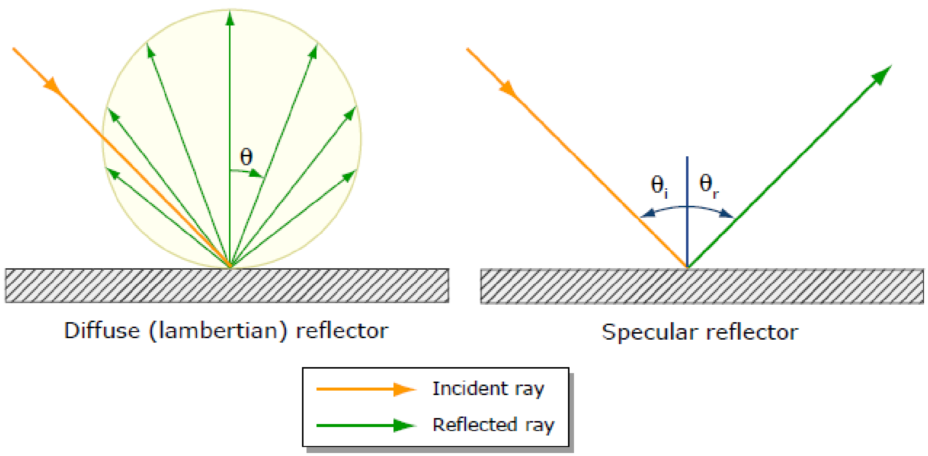
Back surface reflection, Total internal reflection

The amount of light reflected at an interface is calculated from the fresnel reflection formula.

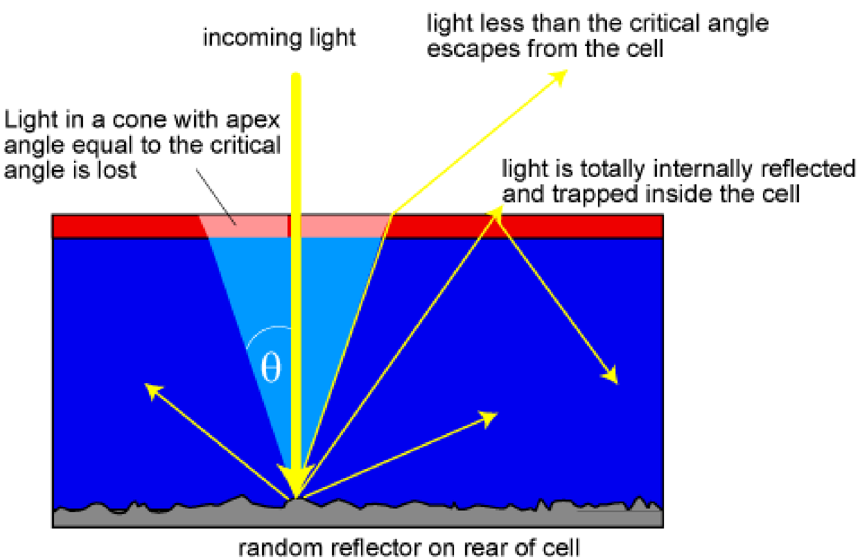
If light passes from a high refractive index medium to a low refractive index medium, there is possibility of total internal reflection (TIR).
The angle at which this occurs is the critical angle and is found by setting θ_2 in Snell's law to 0.

$$\theta_1 = sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Lambertian Rear Reflectors

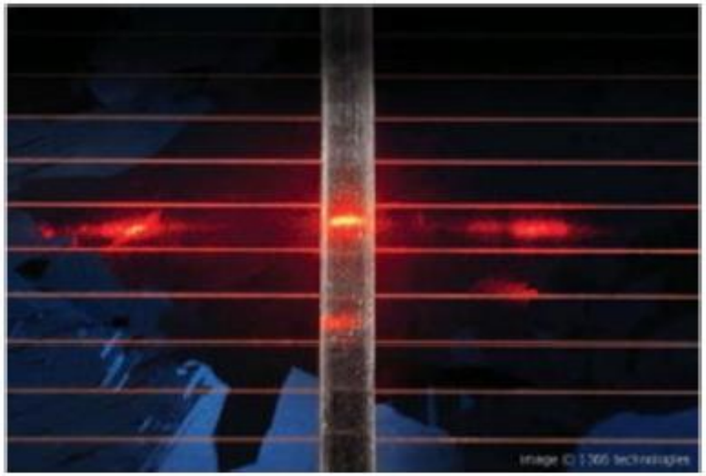


http://www.ecse.rpi.edu/~schubert/LightEmitting-Diodes-dot-org/chap10/chap10.htm

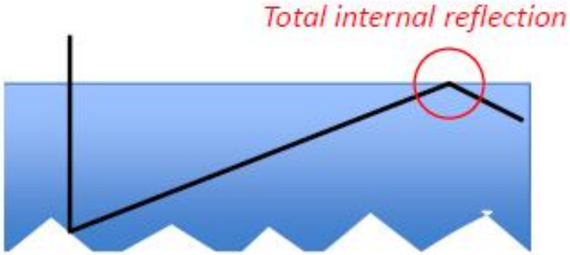


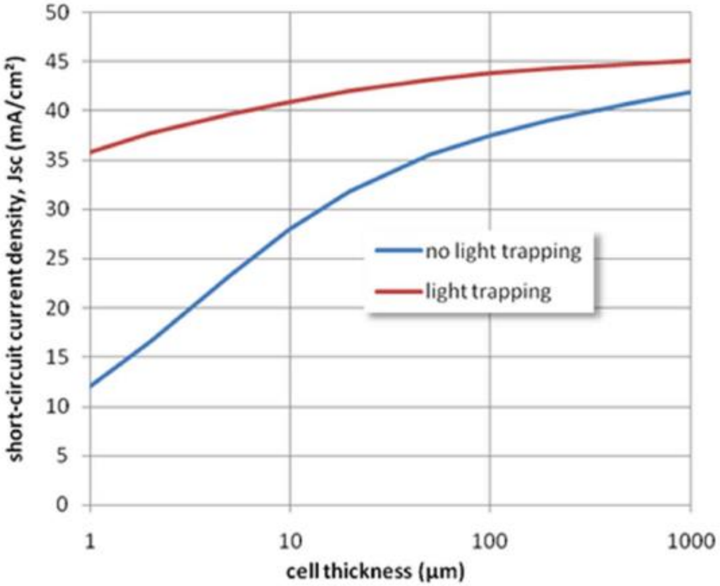
Back surface reflection, Total Internal Reflection

A. Textured Busbar



B. Textured Back Surface





White backskin, textured busbar on modules helps with light capture (via total internal reflection)!

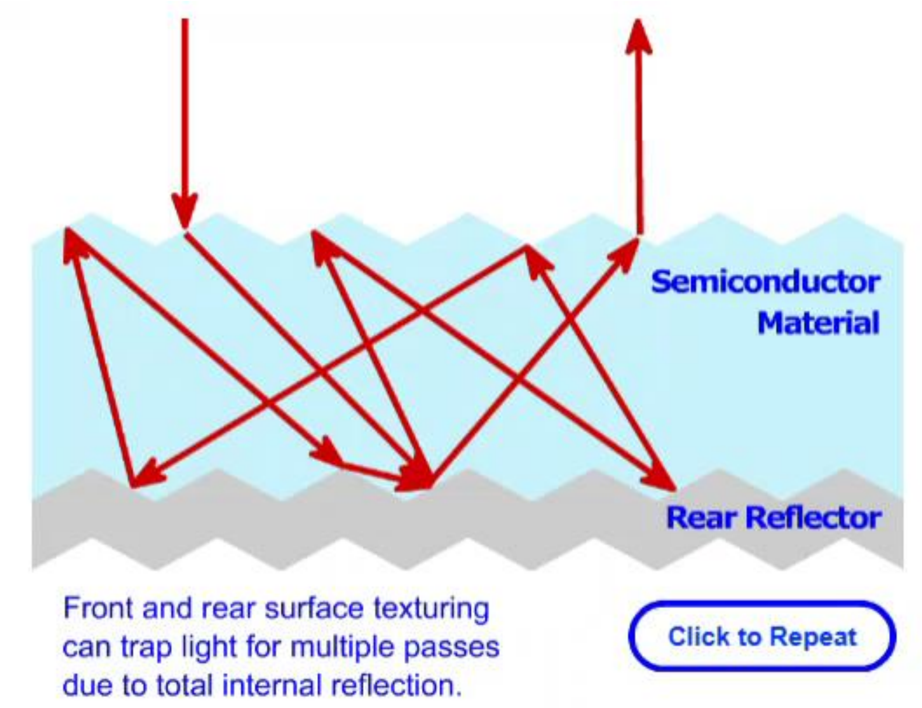
There is a limit for light trapping!

Yablonovitch Limit

$4n^2$ = maximum increase in optical path length

E. Yablonovitch & G.D. Cody, IEEE Trans. Electron Dev. ***29****, 300 (1982)*

Light Management is Necessary



- ✓ increases absorptance
- ✓ minimizes reflectance
- ✓ ensures light trapping

Using total internal reflection, light can be trapped inside the cell and make multiple passes through the cell, thus allowing even a thin solar cell to maintain a high optical path length.

Additionally we can

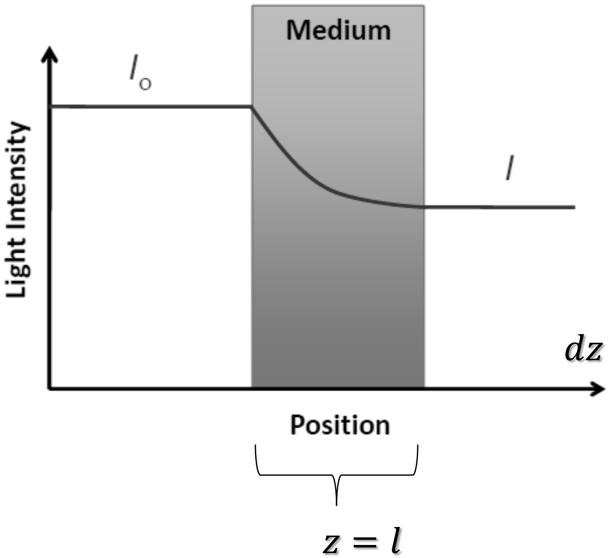
- ❑ change wavelength of incoming light to enhance optical absorption coefficient.
- ❑ change optical absorption coefficient of material by manipulating band structure.

https://www.pveducation.org/pvcdrom/design-of-silicon-cells/light-trapping

Interaction of light and matter

Table presents the common semiconductor materials for solar cells and their properites at the center of the visible-light spectrum. To achieve a total absorption of 95% investigate the required semiconductor thicknesses for each material.

Material	**Ge**	**$CuInSe_2$**	**Si**	**GaAs**	**CdTe**
Type	indirect	direct	indirect	direct	direct
E_G (eV)	0.67	1.04	1.11	1.43	1.49
Absorption edge (μm)	1.85	1.19	1.12	0.87	0.83
Absorption coeficient (cm^{-1})	$5.0\ 10^4$	$1.0\ 10^5$	$1.0\ 10^3$	$1.5\ 10^4$	$3.0\ 10^4$



$$Beer\ Lambert\ Law: I = I_o e^{-\alpha l}$$

95% absorption I=0.05 and I_o=*1.00*

$$-\alpha l = \ln\left(\frac{I}{I_0}\right) \quad l = -\frac{1}{\alpha} ln\left(\frac{I}{I_0}\right) = -\frac{1}{\alpha}(-2.996) = \frac{2.996}{\alpha}$$

$$l_{Ge} = \frac{2.996}{5.0\ 10^4} cm = 0.5992\ 10^{-6} m = 0.6\ \mu m$$

$$l_{CuInSe2} = \frac{2.996}{1.0\ 10^5} cm = 2.996\ 10^{-7} m = 0.3\ \mu m$$

$$l_{Si} = \frac{2.996}{1.0\ 10^3} cm = 2.996\ 10^{-5} m = 30\ \mu m$$

$$l_{GaAs} = \frac{2.996}{1.5\ 10^4} cm = 1.997\ 10^{-6} m = 2.0\ \mu m$$

$$l_{CdTe} = \frac{2.996}{3.0\ 10^4} cm = 0.9986\ 10^{-6} m = 1.0\ \mu m$$

Interaction of light and matter

A 100 μm thick Si solar cell is covered with an ARC and exposed to illumination with a single wavelength 600 nm and constant light intensity. Absorption coefficient of Si is given as 3.88 10^4 cm^{-1} for this condition, find the absorbed light percentage at 1000 nm distance from the surface.

$$\text{Beer Lambert Law: } I = I_o e^{-\alpha l}$$

$$\text{At the surface } L=0 \;\; ; \quad I = I_o$$

$$\text{At } L = 1\ \mu m = 10^{-4} cm\ ;\ I = I_o e^{-\alpha L} = I_o e^{-3.88\ 10^4 10^{-4}}$$

$$I = I_o e^{-3.88} = 0.02\ I_o \quad \text{98\% of light absorbed}$$

Consider a Si solar cell (n_{Si}=3.50) coated with a layer of silicon dioxide (n_{SiO2}=1.45) ARC to maximize the efficiency. Calculate the minimum ARC thickness that will minimize the reflection at the wavelength of 705 nm where the solar cell is most efficient.

for destructive interference we found the optimum thickness formula for ARC;

$$d_{ARC} = \frac{\lambda_0}{4 n_{ARC}} = \frac{705\ nm}{4\ \ 1.45}$$

$$d_{ARC} = 121.55\ nm$$

GaAs is a semiconductor with a band gap of 1.43 eV. Find the maximum wavelength of photons required to excite electrons from the valance band to the conduction bandn of GaAs?

$$E = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E} = \frac{1240}{1.43\ eV} eV\ nm = 867.1\ nm$$