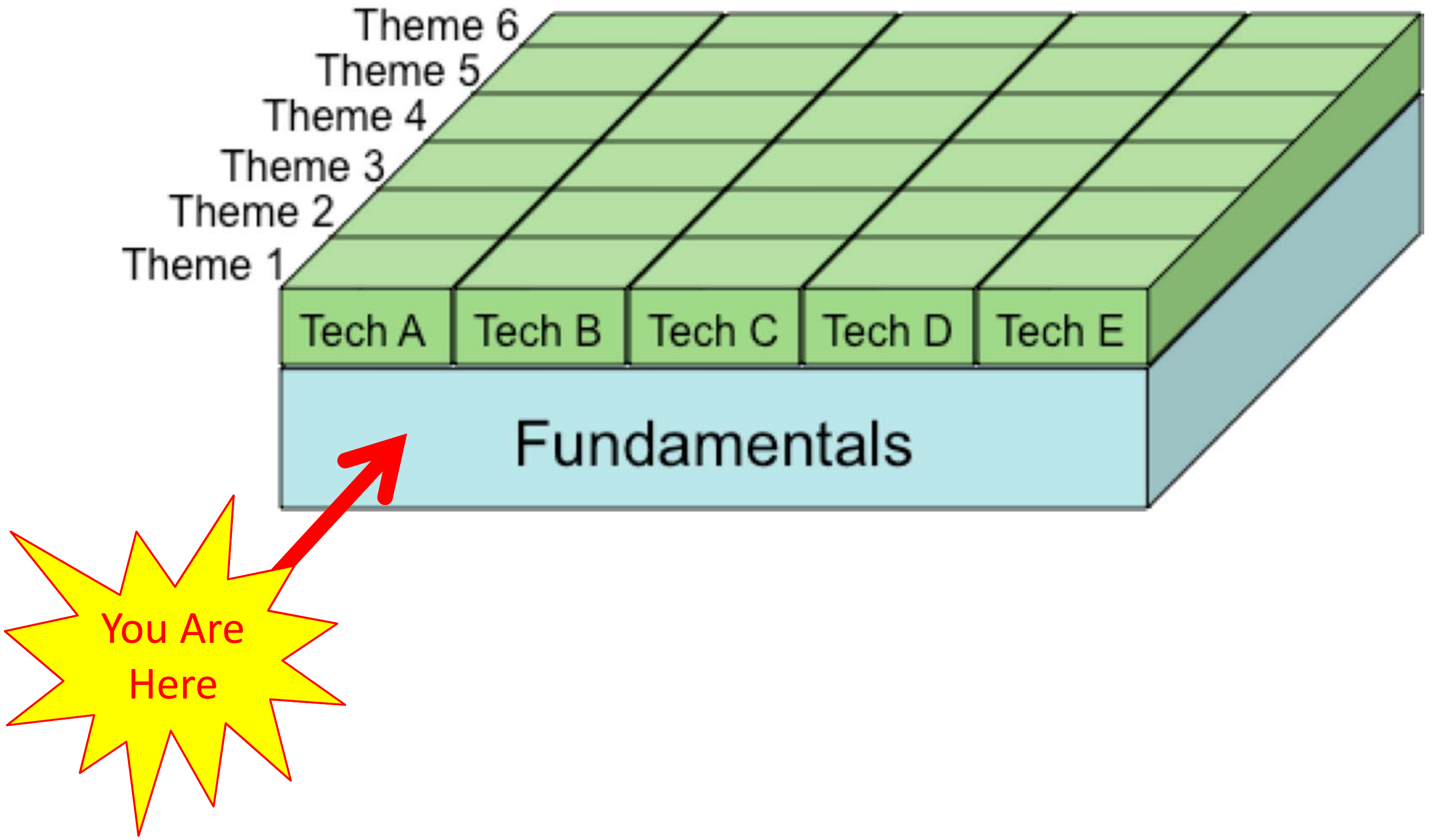
Light Absorption (and Optical Losses)

Lecture 3 – 9/15/2011

MIT Fundamentals of Photovoltaics
2.626/2.627 – Fall 2011

Prof. Tonio Buonassisi

2.626/2.627 Roadmap



2.626/2.627: Fundamentals

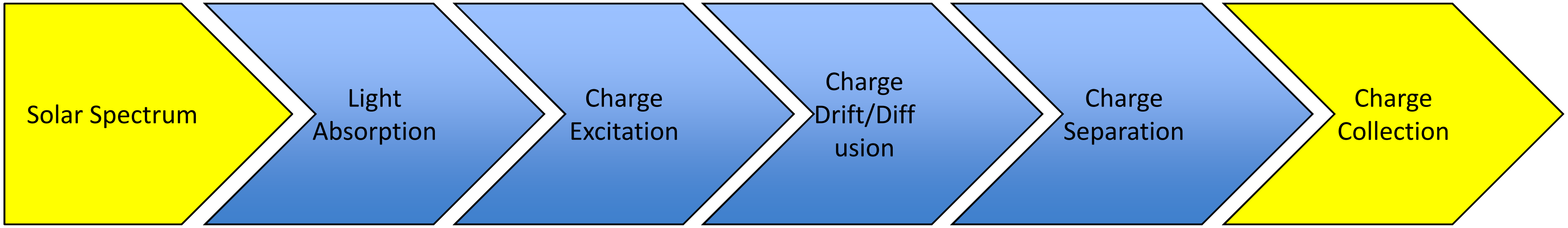
__Every__ photovoltaic device must obey:

$$\text{Conversion Efficiency } (\eta) \equiv \frac{\text{Output Energy}}{\text{Input Energy}}$$

For most solar cells, this breaks down into:

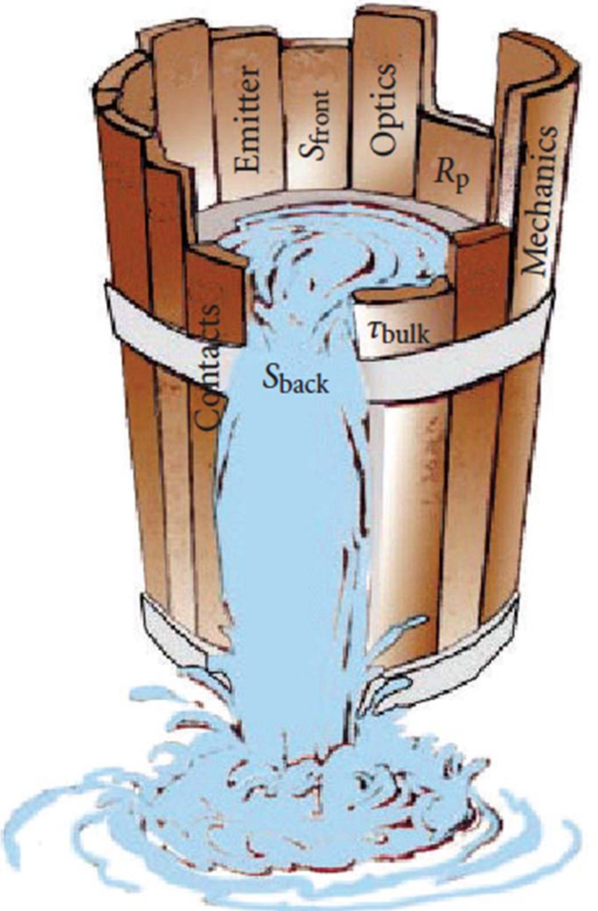
Inputs

Outputs



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

Liebig's Law of the Minimum



S. Glunz, *Advances in Optoelectronics* 97370 (2007)

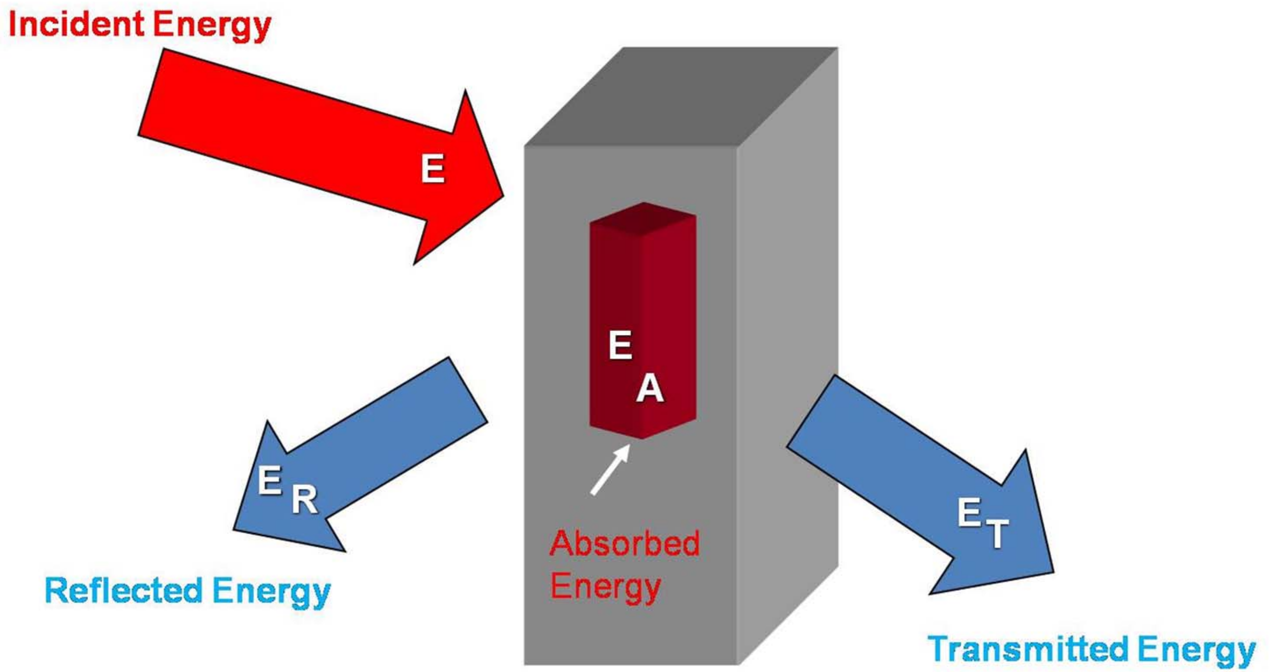
$$\eta_{\text{total}} = \eta_{\text{absorption}} \times \eta_{\text{excitation}} \times \eta_{\text{drift/diffusion}} \times \eta_{\text{separation}} \times \eta_{\text{collection}}$$

Learning Objectives: Light Absorption (Optical Losses)

- Calculate reflectance and non-absorption optical losses of a solar cell
  - Calculate reflection of an interface (semi-infinite)
  - Calculate the absorption/transmittance through layer
- Describe the physical underpinnings and implementation of four advanced methods of reducing optical losses
  - ARC/interference
  - Texturization
  - Reflective interfaces
  - Thickness
  - Plasmonics/photonics

Light Management in Solar Cells: The Big Picture

- Photons that aren't absorbed can't be used to create useful energy. (not absorbed means transmitted or reflected.)
- Only absorbed energy can make useful energy, thus we want to maximize this fraction!



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Photons – Quanta of Light

- Quantum theory describes the frequency dependence of photon energy.

<u>*Particle-wave duality:*</u>

Photons have discrete quanta of energy.
Photons have momentum.
Light can be polarized.
Light can be diffracted.
Light waves can destructively and constructively interfere.

Relevant Equations:

$$E_{\mathrm{ph}} = h\nu = \frac{hc}{\lambda}$$

$$p_{\mathrm{ph}} = \hbar k = \frac{h}{\lambda}$$

Photons – Quanta of Light

- Quantum theory describes the frequency dependence of photon energy.
- Visible photon wavelengths are in the hundreds of nanometers (nm) (solar spectrum peak ~ 550 nm).
- Visible photon energies are in the range of 0.6-6 electron volts (eV) (solar spectrum peak ~2.3 eV)

Relevant Equations:

$$E_{\mathrm{ph}} = h\nu = \frac{hc}{\lambda}$$

$$p_{\mathrm{ph}} = \hbar k = \frac{h}{\lambda}$$

Low-Energy Photon-Matter Interactions

- At low energies (single eVs) typical for visible light, photons interact primarily with valence electrons.

http://friends.ccathsu.com/bart/solarcooking/parabolic/parabolic_solar_cooker_pg_3_html.htm

Interactions of Visible Light with Matter

Interactions of visible light with matter can be described by the *index of refraction*, which is a complex number:

$$\hat{n}_c = \hat{n} + i\hat{k}$$

Interactions of Visible Light with Matter

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$$\hat{n}_c = \hat{n} + i\hat{k}$$

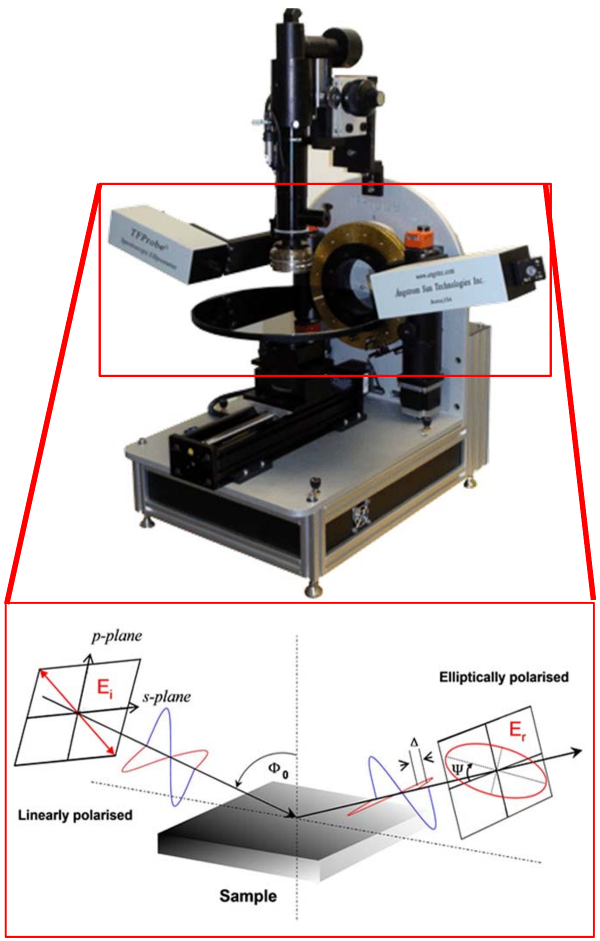
Real Component (indicates phase velocity)

Imaginary component, Extinction coefficient(indicates attenuation)

Interactions of Visible Light with Matter

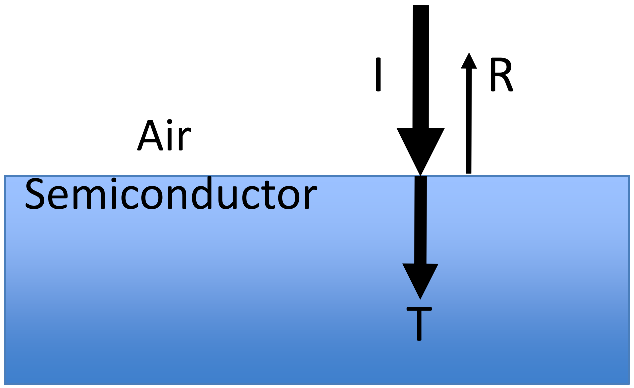
Interactions of visible light with matter can be described by the *index of refraction*, which is a complex number:

$$\hat{n}_c = \hat{n} + i\hat{k}$$

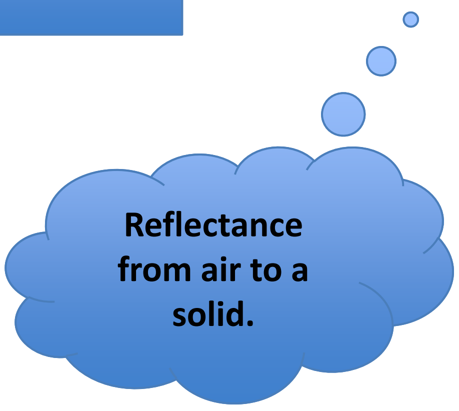


Real and Imaginary components of the index of refraction are wavelength-dependent, and are typically measured using a measurement technique called *spectroscopic ellipsometry*.

Photons – Reflections off a Surface

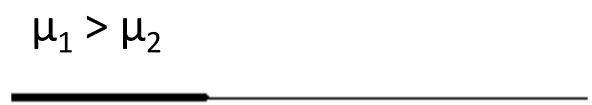


At visible wavelengths, the fraction of reflected light depends most strongly on the real component of the index of refraction:



Mechanical Engineering Analogy

Change in index of refraction (ignoring absorption) is similar to reflection of string wave at interface! Replace n with z = μ*c.



$$R_{light} = \left(\frac{n_1/n_2 - 1}{n_1/n_2 + 1} \right)^2$$

$$R_{string} = \left(\frac{z_1/z_2 - 1}{z_1/z_2 + 1} \right)^2$$

$$z = \mu c$$

$$c = \sqrt{\frac{T}{\mu}}$$

$$T = tension$$

$$\mu = linear\_density$$

Concept Question

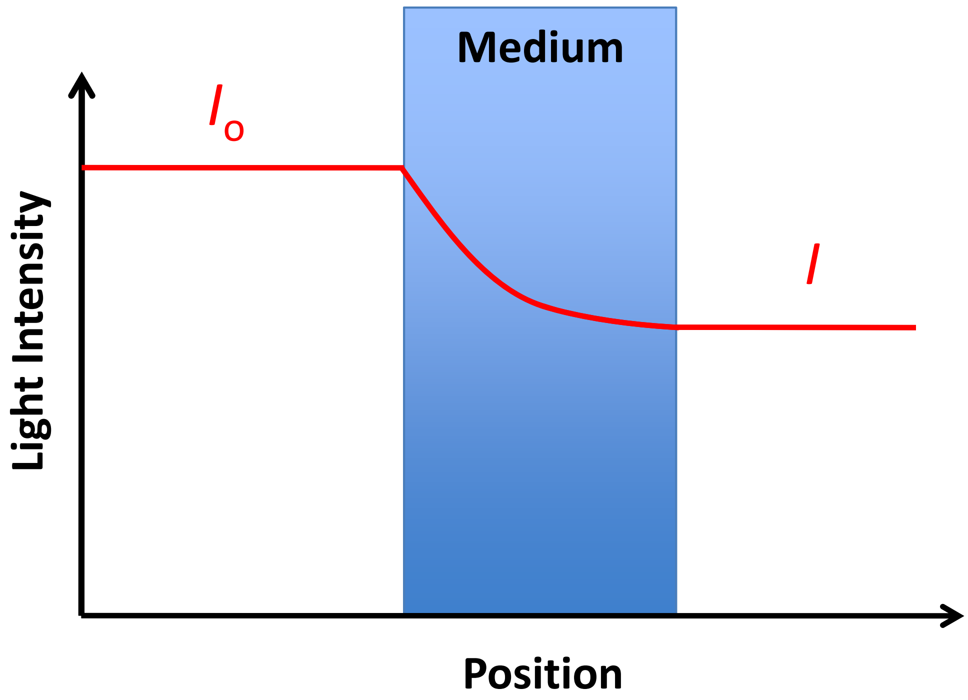
Tinted window questions:

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

Bulk Absorption

Beer-Lambert's Law Demo

Photons – Transmission Through a Medium



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

Simple Derivation of Beer-Lambert's Law:

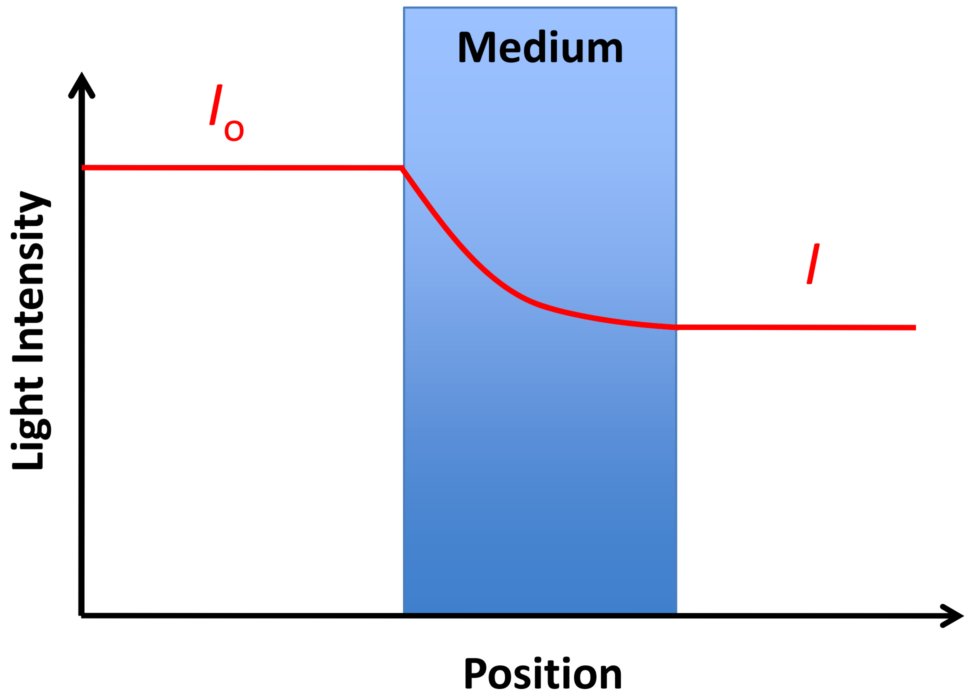
$$\frac{dI_z}{I_z} = -\sigma \cdot N \cdot dz$$

$$\ln(I_z) = -(\sigma \cdot N \cdot z) + C$$

$$\ln(I_0) - \ln(I_l) = -(\sigma \cdot N \cdot 0) + C + (\sigma \cdot N \cdot l) + C = \sigma \cdot N \cdot l$$

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

Photons – Transmission Through a Medium

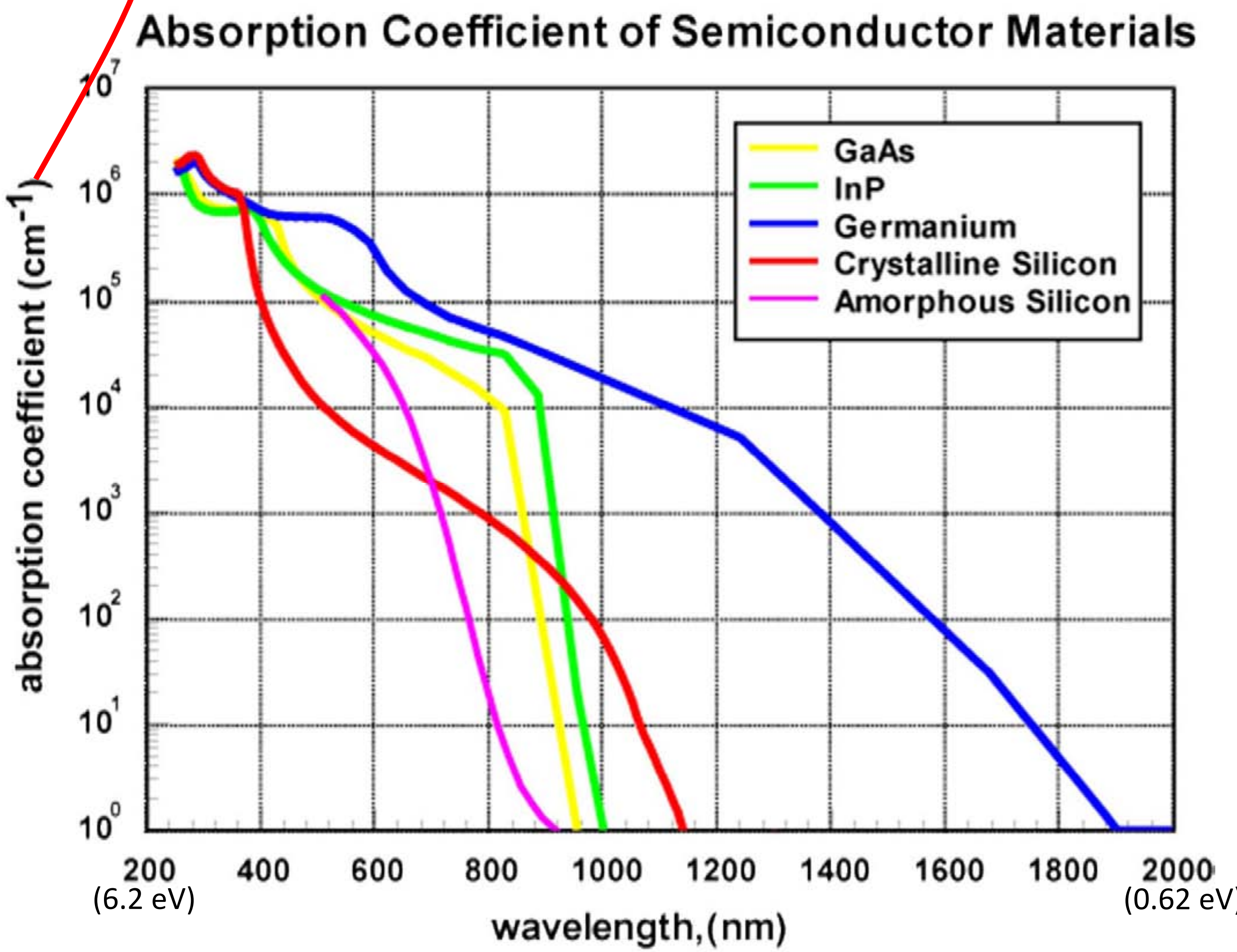


$$I = I_o \cdot e^{-\alpha \cdot l}$$

α is a function of the wavelength of light, and property of the medium.

Absorption Coefficient (α) for different materials

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



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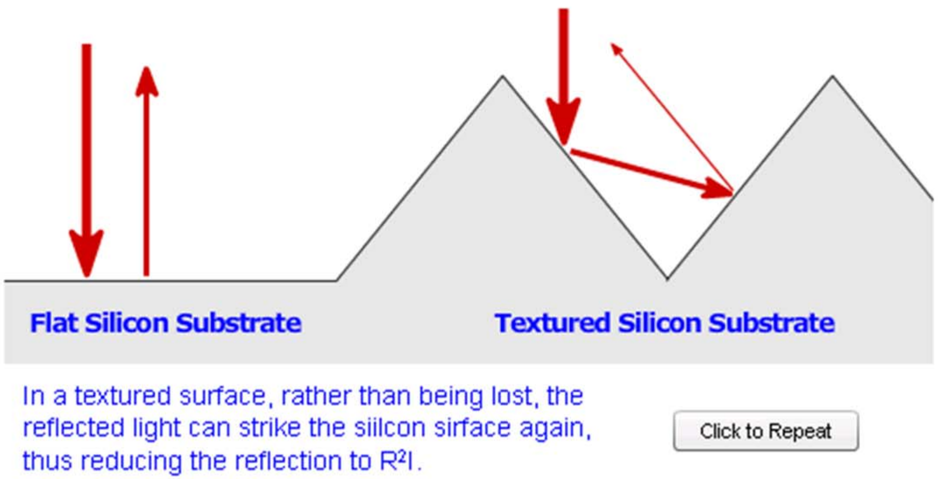
Methods to Improve Optical Absorption (Light Management Methods)

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

1. Texturization

Multiple reflections on surface:

- Increase probability that light enters device.
- Increase effective path length of incoming light.



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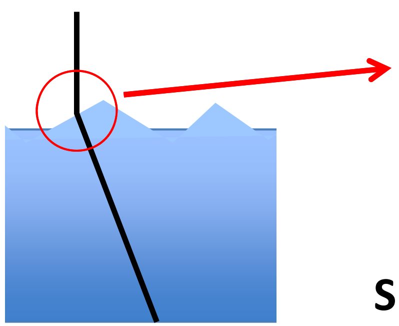
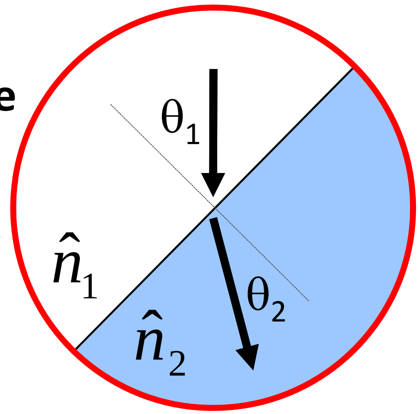
Snell's Law

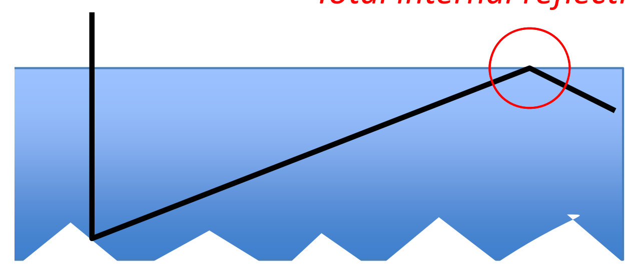
A change in refractive indices results in a "bending" of light.

A. Textured Front Surface





B. Textured Back Surface

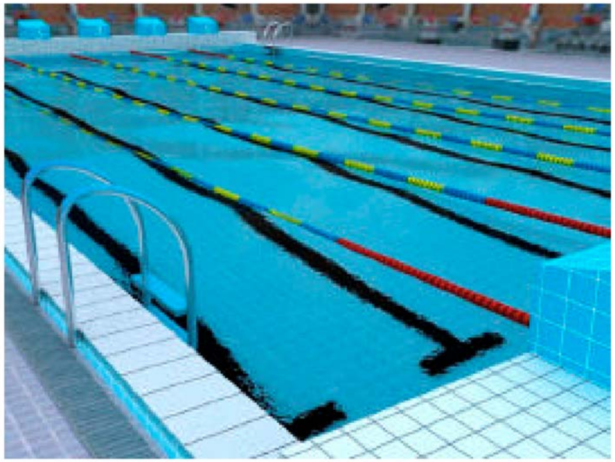


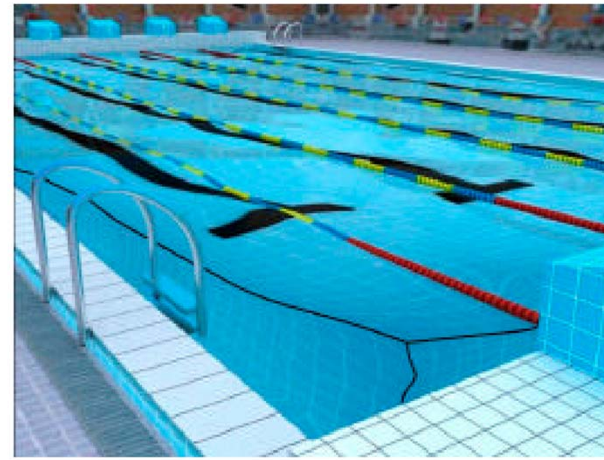
Snell's Law:

$$\hat{n}_1 \sin\theta_1 = \hat{n}_2 \sin\theta_2$$

To engineer front & back surface reflectance, carefully select refractive indices!

Snell’s Law & Reflectance: Pool Example





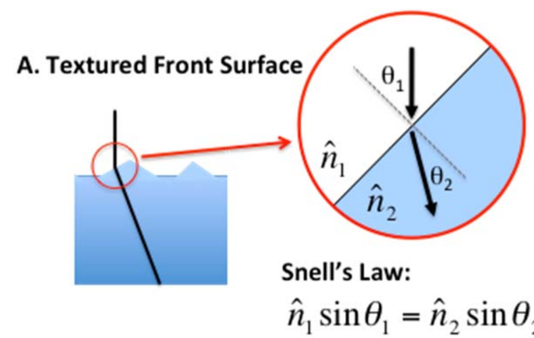
Pool filled with water n = 1.3

Pool filled with substance having n = 0.9

Dominant Effect: Reflection

Pool filled with negative index material n = -1.3

Dominant Effect: Refraction



http://spie.org/x34206.xml?ArticleID=x34206

Lambertian Reflector

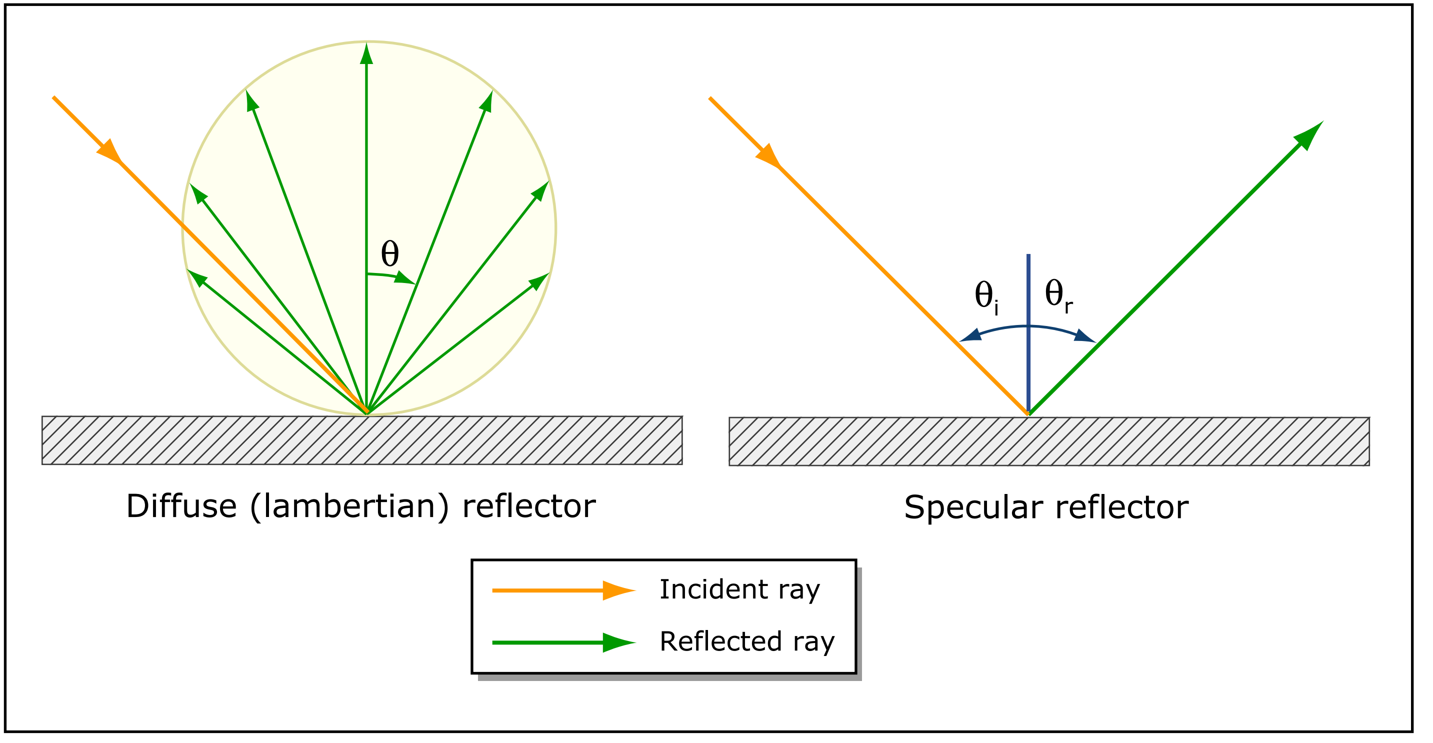
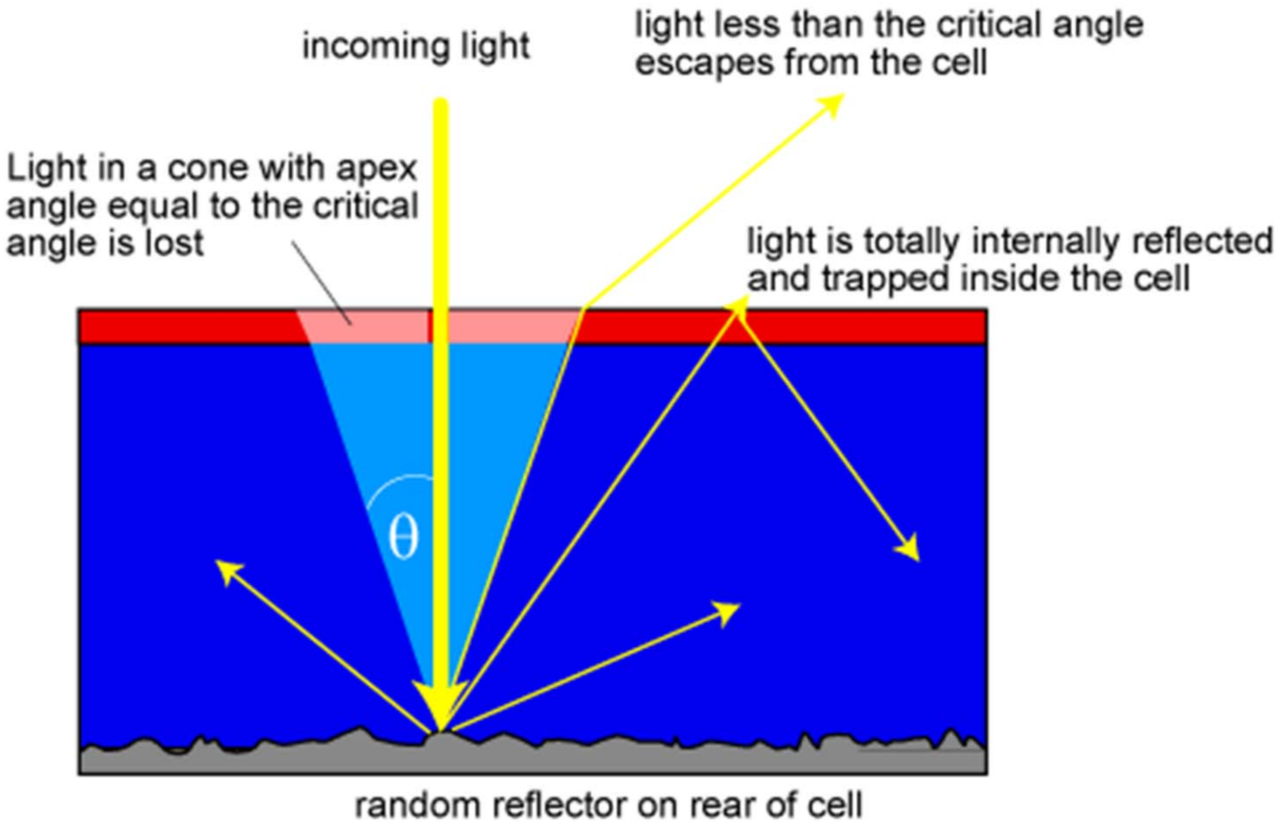


Image by MIT OpenCourseWare.

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

Lambertian Reflector



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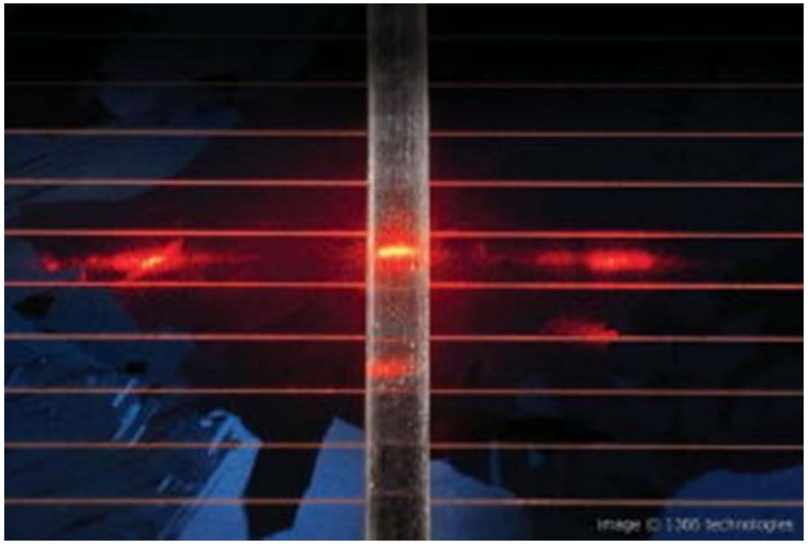
http://www.pveducation.org/pvcdrom/design/lambertian-rear-reclectors

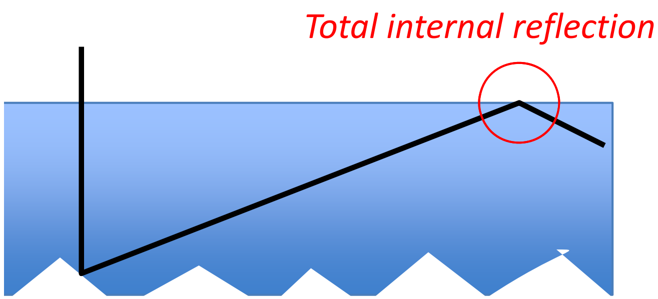
Total Internal Reflection

A. Textured Busbar



Courtesy of 1366 Technologies. Used with permission.

B. Textured Back Surface

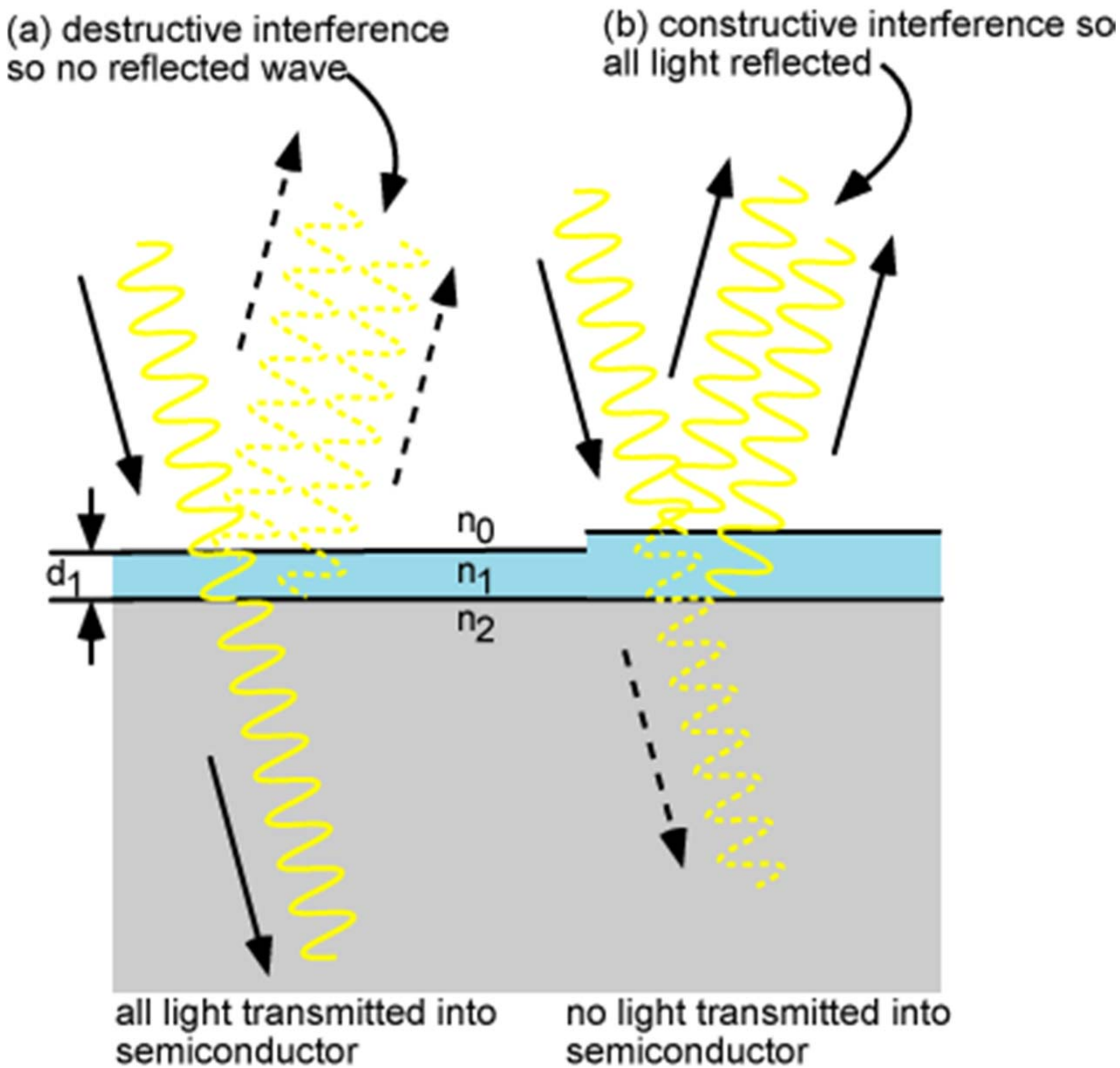


White backskin, textured busbar on modules helps with light capture (via total internal reflection)!

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

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

Antireflection Coatings (ARCs)



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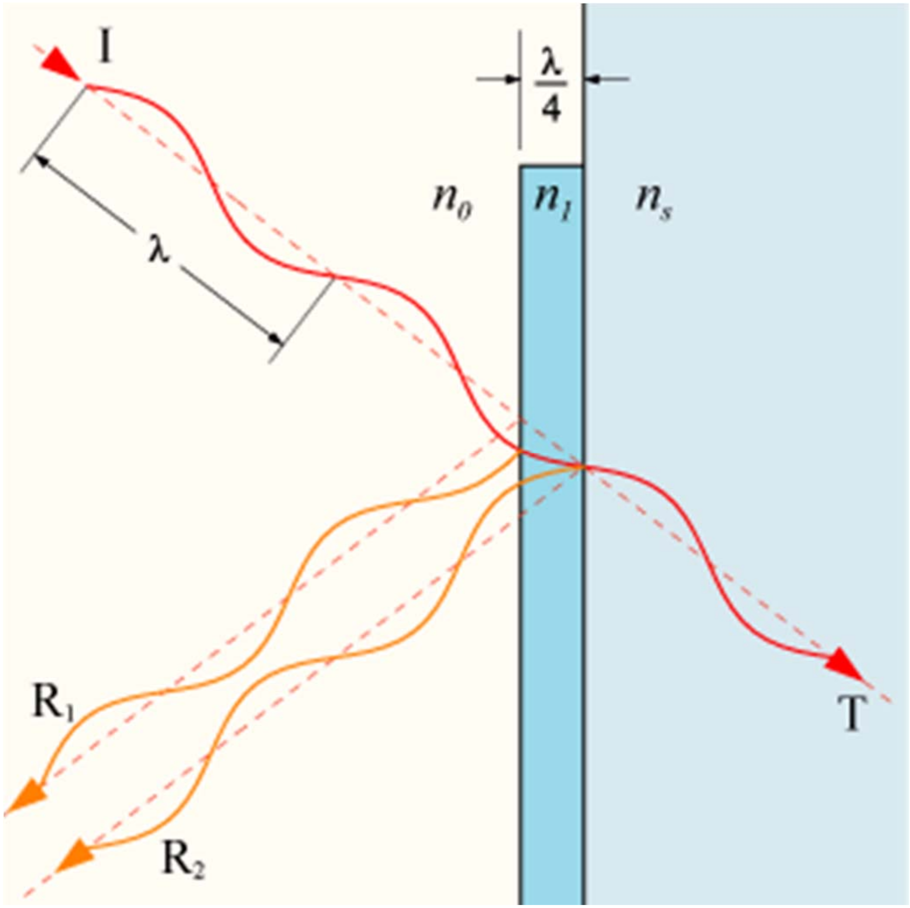
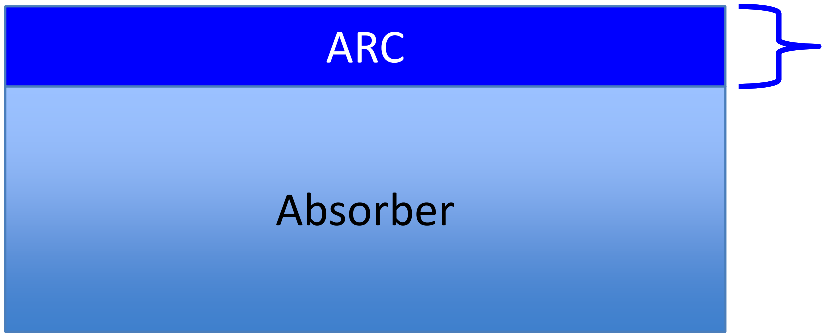
For source and animation, see: http://pveducation.org/pvcdrom/design/anti-reflection-coatings

Antireflection Coatings (ARCs)



Antireflection Coatings (ARCs)



Optimal ARC film thickness:

$$t = \frac{\lambda_o}{4\hat{n}}$$

where λ_o is photon wavelength at the peak of the solar spectrum

Qualities of an optimized ARC:

- Index of refraction between absorber and superstrate (air, glass)
- Thickness on the order of a quarter wavelength (normalized for refractive index).
- Stable
- Enhances electrical performance by passivating dangling bonds at the surface and repelling charges from the surface (*e.g.*, through fixed charges).

Photons – Reflections off a Surface

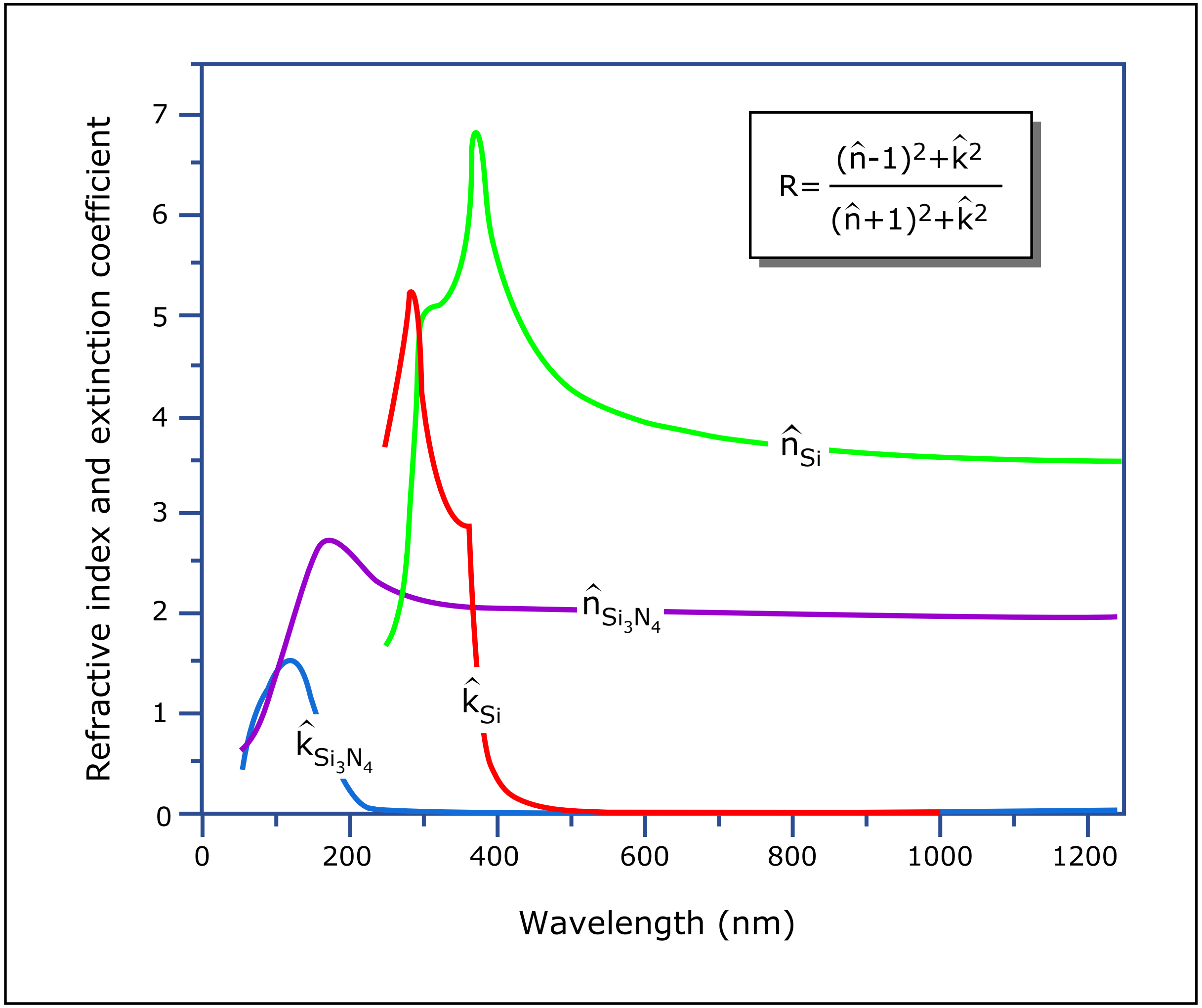
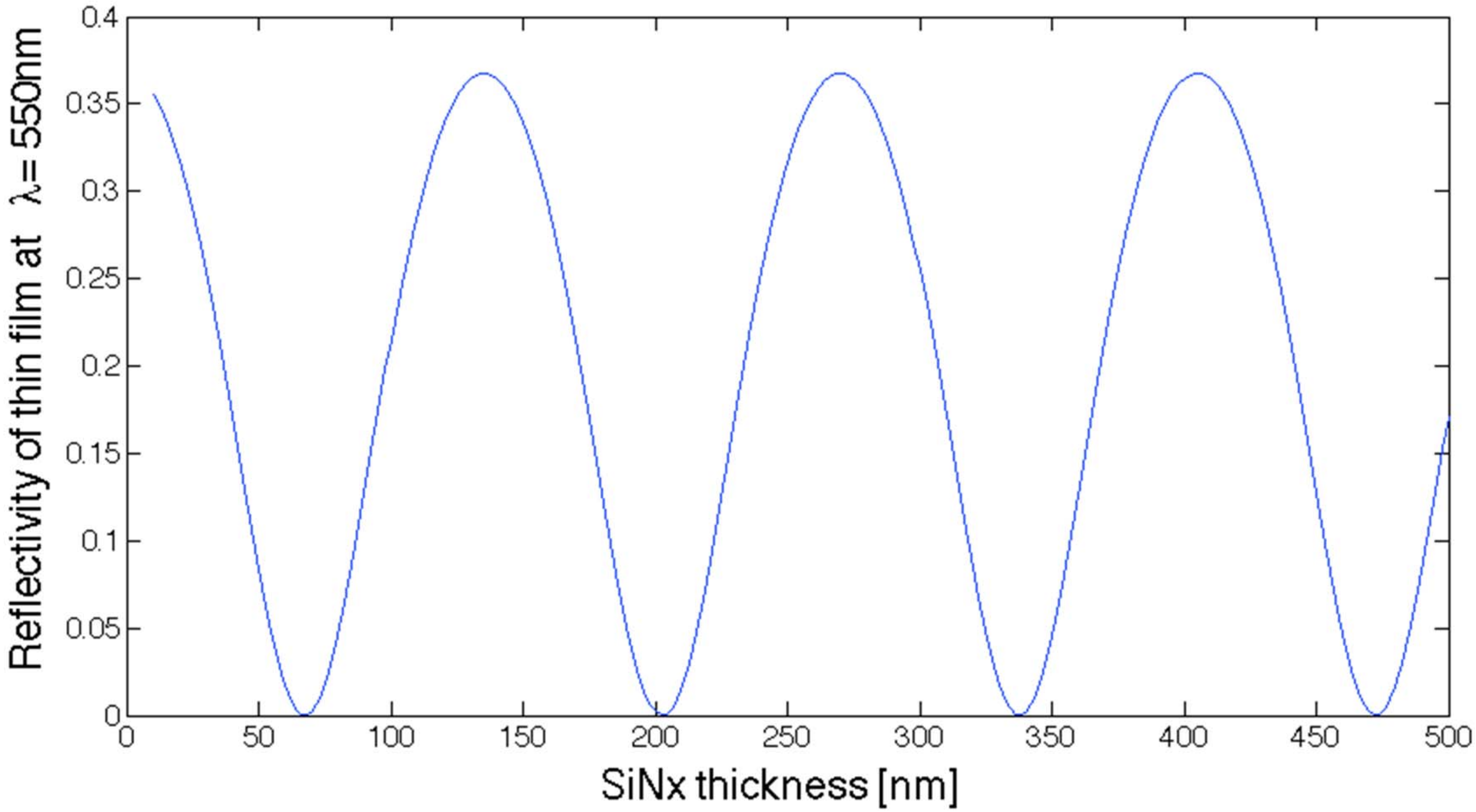


Image by MIT OpenCourseWare.

Thin films require accounting of Phase information

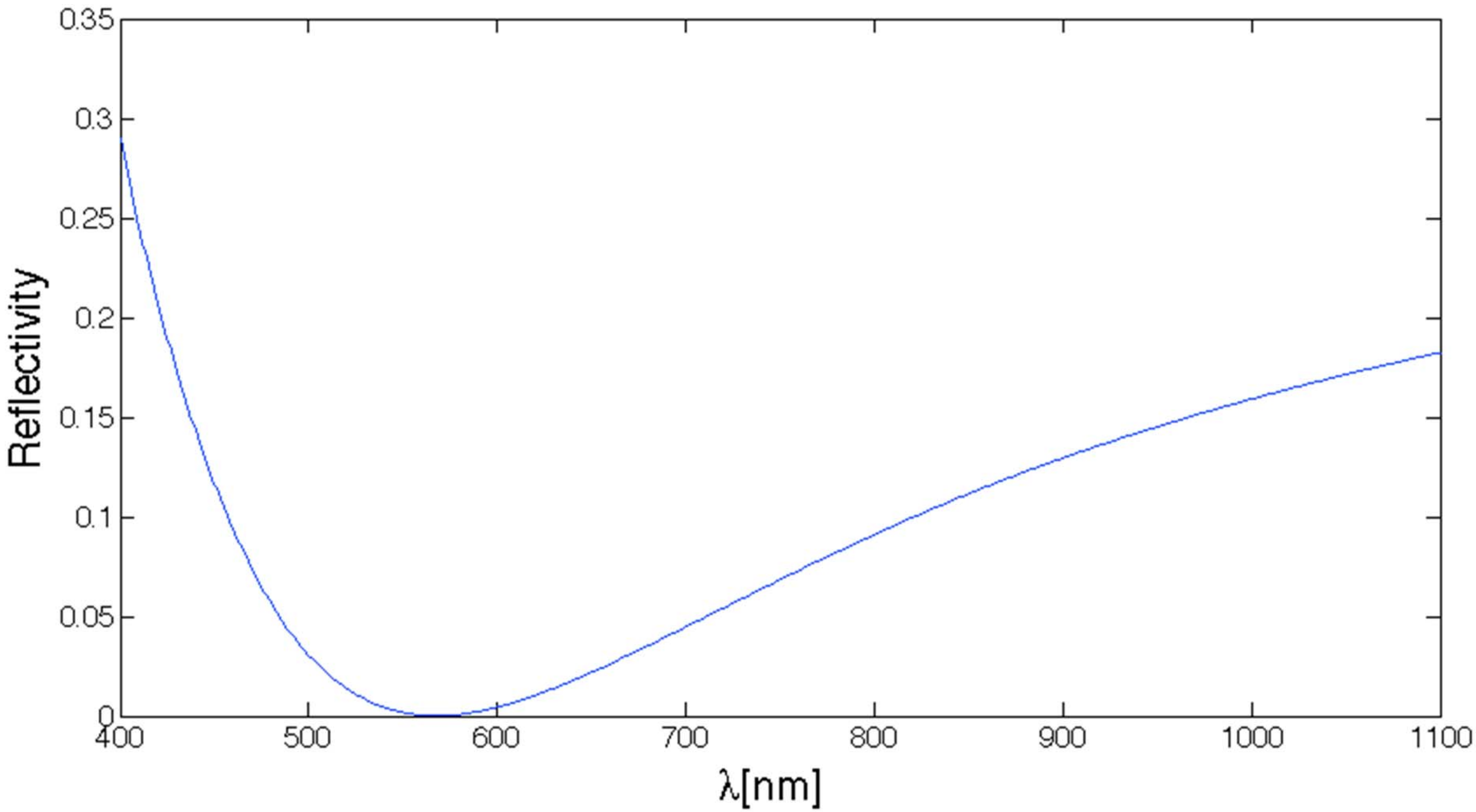
- When EM waves (light) are interacting with matter that has interfaces that are spaced very close together, we need to account phase information when understanding how light moves through a medium.
- We do this to account for destructive and constructive interference.

Importance of SiN_x thickness



Note that minima appear at $\lambda/(2n)$ intervals!

Spectral Reflectivity for Optimized SiN_x optimized at 550nm



When SiNx thickness is optimized for a specific wavelength, other wavelengths suffer!

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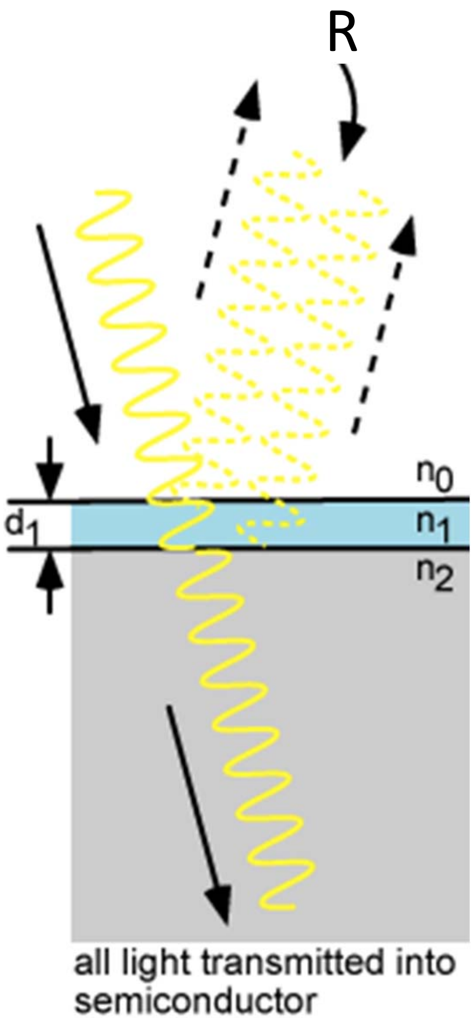
Equations Governing Thin Film Reflectance



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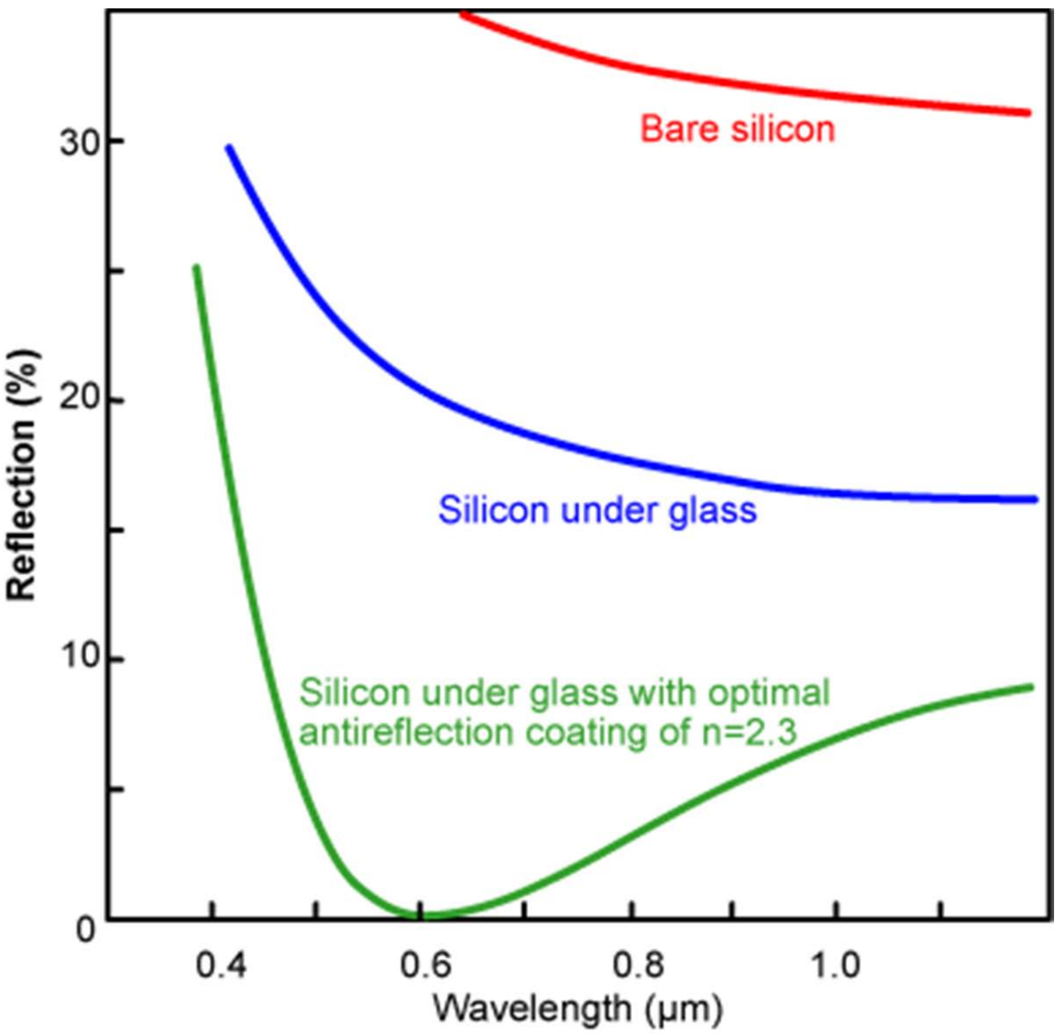
$$R = \frac{r_{01}^2 + r_{12}^2 + 2r_{01}r_{12}\cos 2\varphi_1}{1 + 2r_{01}r_{12}\cos 2\varphi_1 + r_{01}^2 r_{12}^2}$$

$$r_{ij} = \frac{n_i - n_j}{n_i + n_j}$$

$$\varphi_i = \frac{2\Pi n_i d}{\lambda}$$

ARC: Impact on Reflectance



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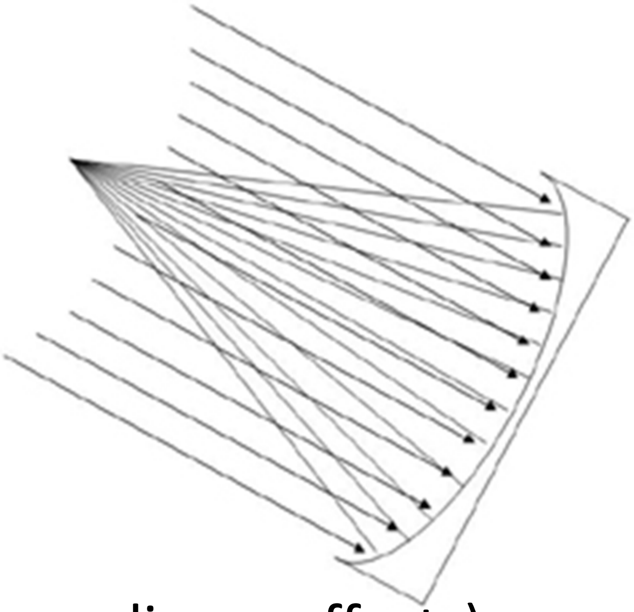
Ray Tracing Software

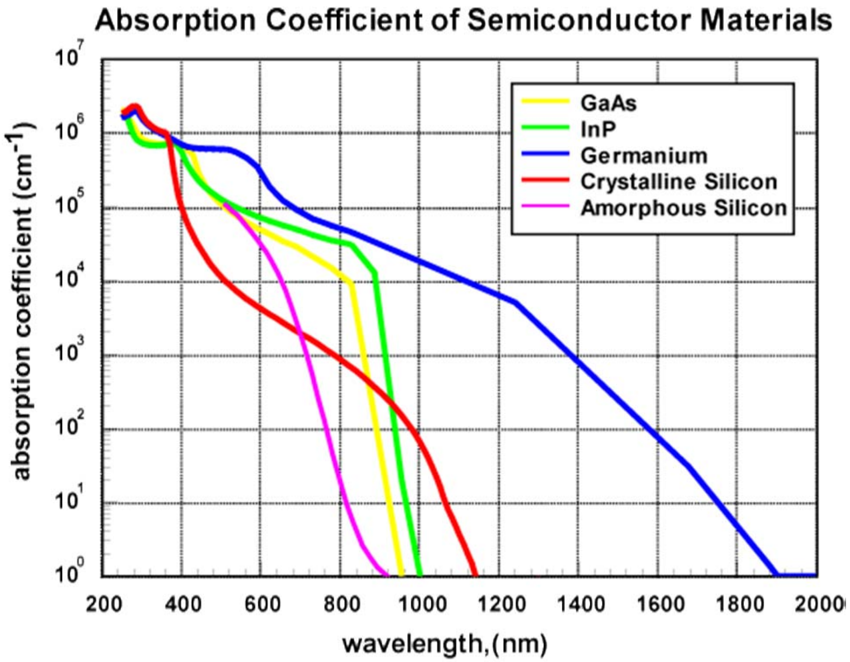
RaySim (free!):
http://www2.pv.unsw.edu.au/Links/RaySim6/HomeOfRaySim6.htm



More sophisticated analysis (incl. non-linear effects):
Finite difference time domain (FDTD) method (good for large frequency ranges)

Light Management

- <u>"Light Management" Ensures Absorptance is High.</u>
- Ensuring that light enters the absorber (minimize reflection).
- Ensure good light trapping inside the absorber.
  - *Light trapping methods described on previous slide.*
  - *Change wavelength of incoming light to enhance optical absorption coefficient.*
  - *Change optical absorption coefficient of material by manipulating band structure.*



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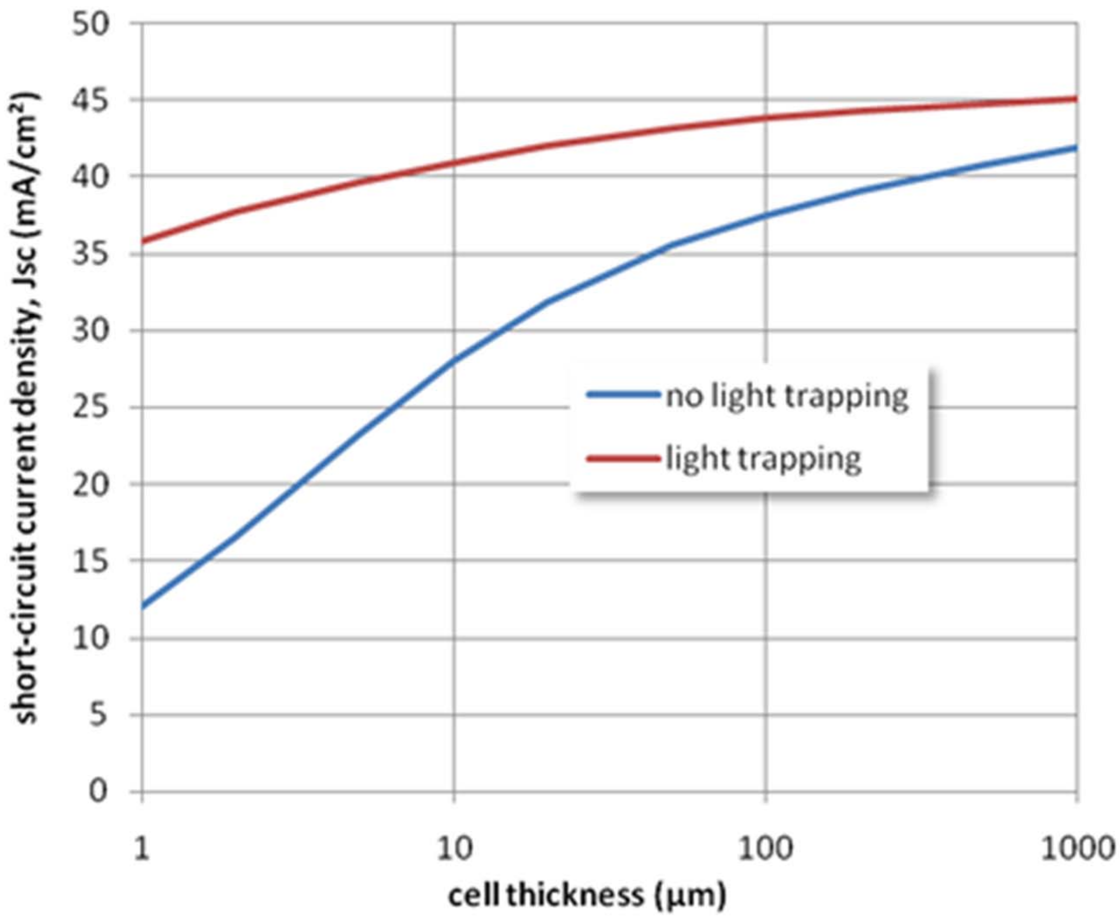
Light Management is Necessary



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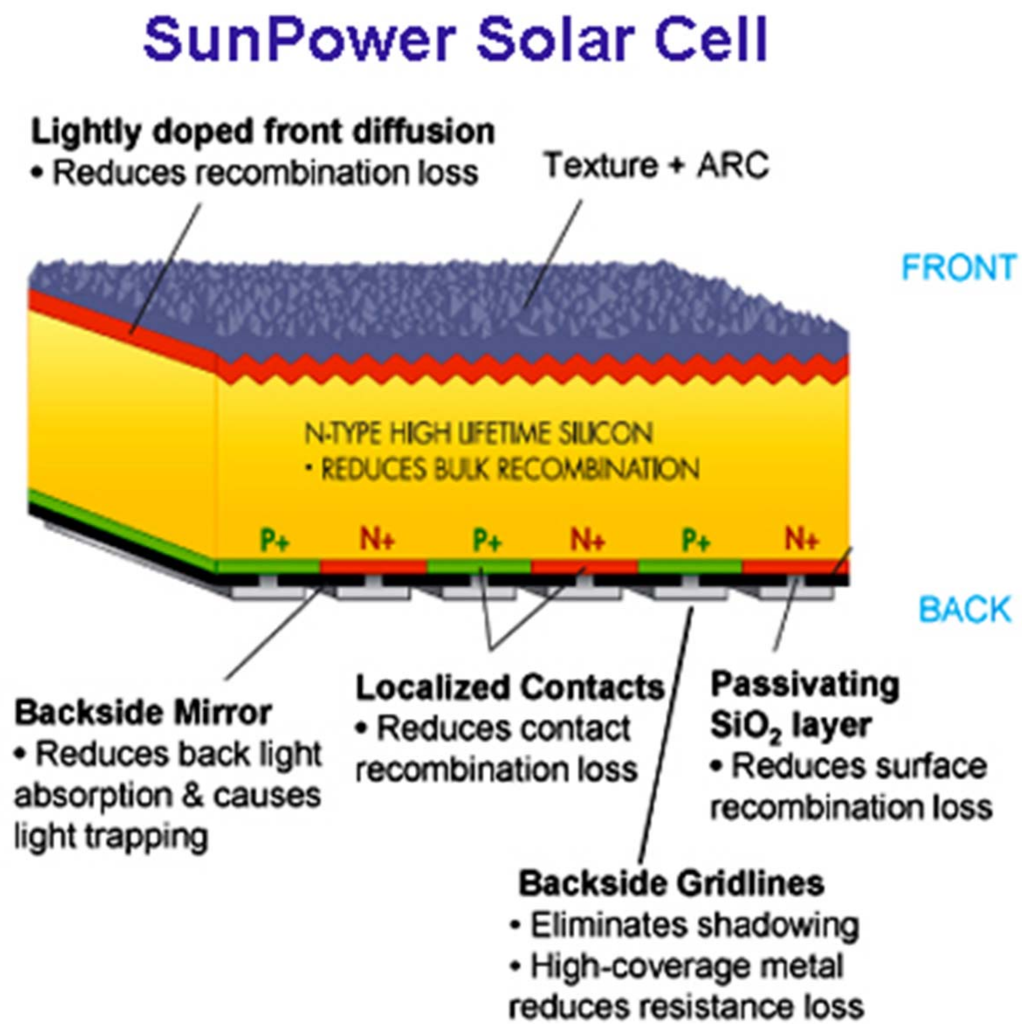
Light Management is Necessary



http://solarcellcentral.com/companies_page.html

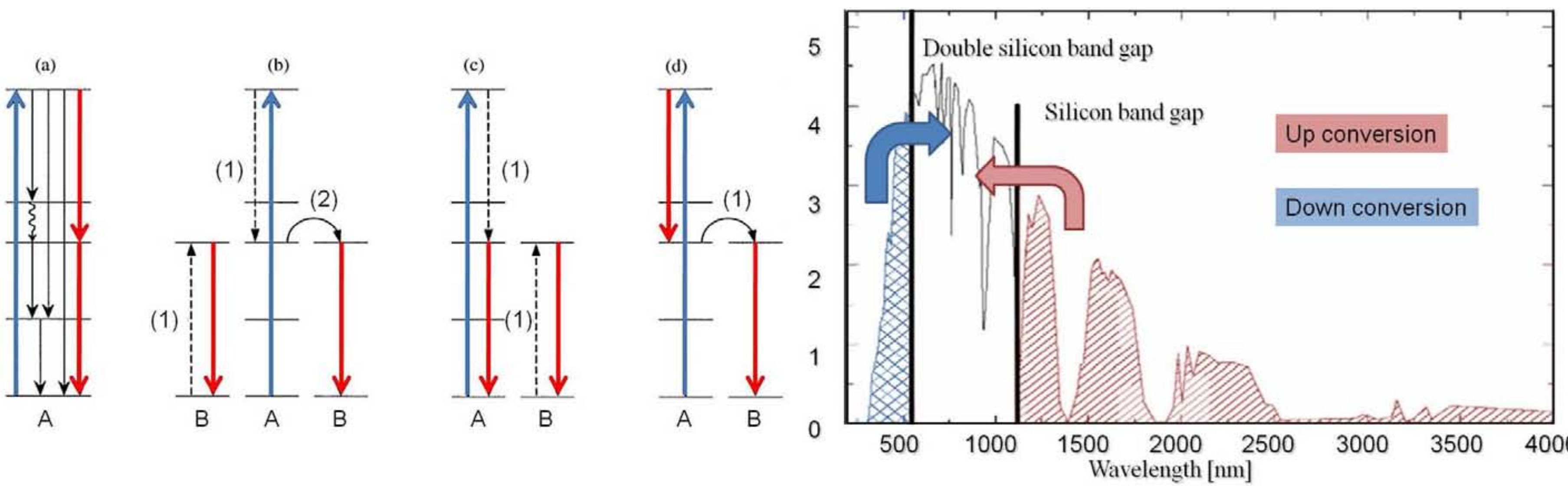
“Bending Light” via Anomalous Refraction

Yu, N., P. Genevet et al. “Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction.” Science 334, no. 6054 (2011): 333-337.

Photon Up/Down Conversion

Jennifer Dionne (“Solar Cells That See More Light”), one of Technology Review’s Innovators Under 35.

Alombert-Goget, G., D. Ristic et al. "Rare-Earth Doped Materials Enhance Silicon Solar Cell Efficiency." SPIE Newsroom, 2011.



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2.627 / 2.626 Fundamentals of Photovoltaics
Fall 2013