Optics for Energy
Lecture 13
Anti-reflection coatings
What is anti-reflection?

Important to couple light into solar cells.
(1) refractive index
\[ n_{\text{film}} = \sqrt{n_{\text{air}} \cdot n_{\text{glass}}} = 1.23 \]

(2) thickness of the coating = \( \lambda / 4 \)

Important to couple light into solar cells.
Quarter-wave coating

Interference

Rays A and B are out of phase by \( \pi \) or \( \lambda/2 \), & destructively interferes.

What is the thickness of an anti-reflective coating of silicon nitride to reduce reflection from a silicon surface at normal incidence? At 45 degrees.

- Silicon nitride
- Silicon
Interference
Rays A and B are out of phase by pi or lambda/2, & destructively interferes.
Depends upon angle of incidence

Relationship between angle of incidence and amount of reflected light
What is the thickness of an anti-reflective coating of silicon nitride to reduce reflections from a silicon surface at normal incidence? at 45 degrees incidence?

| silicon nitride | silicon |
Multiple layers such that index varies from 1 to n smoothly

Incoherent compared to quarter-wave (no interference effects)

Can you think of other ways to achieve this same effect? (Brainstorm)
2 layer ARC see http://pveducation.org/pvcdrom/design/dlarc
Black Silicon to Revolutionize Solar Industry

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Scientists from the National Renewable Energy Laboratory (NREL) have come up with a black silicon technology, seeking to make solar power more competitive with other types of energy over the next decade.

New Jersey-based Natcore will benefit from their findings, exploring the new path to launch a new generation of products, cheaper and much more advanced.

The silicon wafer licensed recently could count as a game-changer on the market of solar-powered appliances, since experts talk about potential improvements posed by infra-red imaging systems and night-vision.

According to its developers, the material displays a sensitivity to light up to 500 times bigger than its predecessor, the common, widely-used silicon detectors.

Financial benefits are also expected, since cell processing costs could decrease by 8%, due to the ingenious invention.

The collaboration between NREL and Natcore aims to make the black silicon technology even more affordable while boosting a new generation of solar cells more energy-efficient, harnessing optimal amounts of sunlight throughout the entire day.
2 layer ARC see http://pveducation.org/pvcdrom/design/dlarc
\[ T_{\text{inc}} = \text{transmission from air to PMMA}. \]

\[ \gamma = \text{absorption factor at rear surface of PMMA (including transmission into silicon)} \]

Reflected light = \( T_{\text{inc}} (1 - \gamma) \)
We can also calculate absorption at each reflection event & add these up. Silicon is assumed to absorb everything.

First absorption = $\eta \text{Time} (1 - \eta)$

2nd absorption = $\eta \text{Time} (1 - \eta^2)$

Reflected fraction is $\eta^2 \text{Time} \left(1 - \frac{\eta}{2n^2}\right)$

\[ p^{th} \text{ absorption} = \gamma \text{ Time} \left( 1 - \eta \right)^p \left( 1 - \frac{T_{100}}{2n^2} \right)^p \]

Total absorption =

\[ \gamma \text{ Time} \left\{ 1 + (1 - \eta) \left( 1 - \frac{T_{100}}{2n^2} \right) + \right. \]

\[ \left( (1 - \eta)^2 \left( 1 - \frac{T_{100}}{2n^2} \right)^2 + \ldots \right\} \]

\[ = \gamma \frac{\text{Time}}{1 - (1 - \eta) \left( 1 - \frac{T_{100}}{2n^2} \right)} \]
For $n_{PMMA} = 1.5$ & $n_{Si} = 3.5$ $\rightarrow$

$$\eta = \left(1 - \frac{n_{Si} - n_{PMMA}}{n_{Si} + n_{PMMA}}\right)^2 = 1 - \left(\frac{3.5 - 1.5}{3.5 + 1.5}\right)^2 = 0.84$$

$$T_{inc} = 1 - \left(\frac{n_{PMMA} - 1}{n_{PMMA} + 1}\right)^2 = 1 - \left(\frac{1.5 - 1}{1.5 + 1}\right)^2 = 0.96$$

We can approximate $T_{exc} \approx T_{inc}$

$$\text{Absorption} = \frac{T_{inc} \eta}{1 - (1-\eta)(1-\frac{T_{exc}}{2n^2})} = 0.923$$
~90% of light gets absorbed in Silicon & the PMMA/Si interface. So ~10% of light is reflected back. So, PMMA on top of randomly textured silicon acts as a decent ARC.

Note that if no PMMA or texturing was present, the reflectivity of a polished silicon wafer would be

\[
\left( \frac{n_{Si} - 1}{n_{Si} + 1} \right)^2 = 31\%
\]
Case of simple index matching. Design an ARC for polished Si.

\[
\text{air (n = 1)}
\]

\[
\underline{\text{ARC (n)}}
\]

\[
\text{Si (n = 3.5)}
\]

What is the total loss by reflection of the ARC?
\[ n = \frac{(1 + 3.5)}{2} = 2.25 \]

\[ \text{Reflection}_1 = \left( \frac{2.25 - 1}{2.25 + 1} \right)^2 = 0.15 \]

\[ \text{Reflection}_2 = \left( \frac{8.5 - 2.25}{3.5 + 2.25} \right)^2 = 0.074 \]

\[ \text{Total reflection} \approx 0.15 + 0.07 \approx 0.22 \]
So, the PMMA + texturing proves to be an effective ARC due to effective light-trapping. Reflectivity ~ 10%. Note that all solar cells are encapsulated in glass for protection from the elements. So, there is always a reflectivity of ~4% off the top (n ~ 1.5). So reducing this to 11% is pretty good since ~4% is the best one can hope to achieve.