ET3034TUx - 3.3.5 - Light trapping 2 - Anti-reflection and trapping methods

How to reduce the reflection at the front surface of a solar cell and how to increase the light trapping in the absorber layers.

I will discuss some general concepts which will come back in many PV technologies, which we will be discussing the next two weeks.

In the previous block we discussed the optical loss mechanism due to reflection at the front interfaces of a solar cell.

The light passing through an interface between two media with different refractive indices, will always be partly reflected and partly transmitted at the interface.

As all types of solar cells suffer from this loss mechanism, I will discuss first some anti-reflection concepts.

First, I will discuss the physical origin of reflection of light in more detail.

The fraction of the light intensity that is reflected is given by the Fresnel coefficients.

Consider the interface between two media with refractive index n_1 and n_2.

A light ray is arriving with an angle of incidence in reference to the normal of the interface theta_i.

Part of the light is reflected under the angle of reflection theta_r.

The angle of reflection is equal to the angle of incidence.

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The light transmitted travels further under the angle of transmission theta_t to the normal.

The relation between the angle of incidence and transmission is given by Snell's law.

If refractive index of medium 1 is smaller than that of medium 2, the angle of transmittance will be smaller than the angle of incidence.

If the refractive index of medium 1 is larger than that of medium 2 it is the other way around.

In this example the waves represent the electric field oscillations in the plane of incidence.

This can be seen as we put this plane in a 3-dimensional illustration.

This is what we call p-polarized light.

The opposite situation is the configuration in which the electric field is oscillating perpendicular to the plane of incidence.

This is what we call s-polarized light.

The reflection coefficients are given by the Fresnel equations, which are functions of the refractive indices of both media, and the angle of incidence and reflection.

The transmission is one minus the reflection.

I am not going into detail, but the Fresnel equations for transmission and reflection of the p-polarized light are slightly different for that of the s-polarized light.

For light with a perpendicular incidence, that is an angle of incidence of zero degrees, the reflection and transmission are equal.

In this graph you see the relation between the reflection coefficient for s- and p-polarized light when the medium 1 has a refractive index of 1 (which is equal to air) and medium 2 has a refractive index of 1.5 (like glass).

What we can see is that the p-polarized light has an angle at which the reflection is equal to zero.

This angle is called the Brewster angle.

The grey line is the average which represents randomly polarized light.

If we look at light rays going from a material with a higher refractive index to a material with a lower refractive index, we see that the reflection becomes 100% above a certain angle.

This is called a total internal reflection and occurs above the critical angle of incidence, which can easily be calculated using Snell's law.

Using these basics, we will look at the interface of silicon, the most common used material for solar cells.

Consider an air-silicon interface and for simplicity light under a perpendicular incidence at a wavelength of 500 nm.

This example is included as an exercise in this week's homework, as well.

The refractive index of air is 1 and that of silicon is 4.3 at a wavelength of 500 nm.

The Fresnel coefficients tell us that the optical losses due to reflection are significant at this interface, the reflection is 38.8%.

Reduction of this reflection can be achieved by introducing an interlayer with a refractive index n_1 with a value between that of n_0 (air) and n_s (silicon).

Including this interlayer in the system, you can simply work out the effective reflection coefficients from the front side.

This is the reflection from the first interface plus the reflection of the second interface.

In this first approximation, we do not consider the multiple reflections within the interlayer.

We then plot the reflection coefficient of this example versus the refractive index of the interlayer.

The blue line is the reference reflection without interlayer.

The red line is the reflection with interlayer.

The red curve has a minimum.

This minimum is exactly at the value equal to the square root of the product of n_0 and n_2.

In this example, by inclusion of a single interlayer, the reflection at the interface can be reduced from 38.8% down to 22.9%.

Using more than one interlayer, also called refractive index grading, this reflection can be further reduced.

Another approach of anti-reflection is making use of constructive and destructive interference of light.

As we discussed in week 1, light can be considered as electromagnetic waves.

Waves have the interesting properties that they can interfere with each other.

Waves can be super imposed.

As demonstrated in this animation.

So in the case of light the amplitude of the electric field of the wave A and B at certain position x,y,z at time t are super imposed.

It means that the resulting amplitude of a wave A + B can be larger or smaller than the original waves A and B.

When two waves A and B are travelling in the same direction and are in phase, the resulting amplitude is larger than for a single wave.

This situation is called constructive interference and is shown on the left.

When waves A and B are in antiphase, the amplitude of the resulting wave is equal to zero.

This situation is shown on the right and is called destructive interference.

One can design an anti-reflection coating based on this principle.

Look at this animation.

Again, we have placed an interlayer between two media.

The green wave shows the reflection back from the first interface and the red wave shows the wave which is reflected back from the second interface.

If we look at the two waves coupled out of this system, they appear to be in antiphase.

As a result the total amplitude of the electric field of the outgoing wave is smaller and the total irradiance coupled out of the system is smaller as well.

The maximum destructive interference occurs when the product of the refractive index and thickness of the interlayer is equal to the wavelength divided by 4.

Or in other words, the thickness is the wavelength divided by 4 times the refractive index of the coating.

Using an anti-reflection coating based on interference means that the typical length scale of the interlayer thickness must be in the order of the wavelength.

A last and completely different approach for anti-reflection is using textured interfaces.

The length scale of the textured features is larger than the typical wavelength of light.

The reflection and transmission of the light rays are determined by the Fresnel equations and Snell's law.

The texturing helps to enhance the coupling of light into the layer.

For example, for light that is perpendicular incident, light that is reflected at the textured surface, can be reflected at angles in which the trajectory of the light ray is incident somewhere else on the interface.

Here part of the light will be transmitted into the layer and effectively less light will be reflected in reference to a flat interface.

Summarized, we have discussed three types of anti-reflection approaches, a Rayleigh film, anti-reflection coating based on destructive interference and enhanced incoupling of light due to scattering at textured interfaces.

Secondly, if the absorber layer is not thick enough to absorb all the light, part of the light will be transmitted.

As the absorption coefficients are larger in the blue spectral part, this usually plays a role in the red to infrared part of the solar spectrum.

The light transmitted can be reflected back, which is a so-called back reflector.

Some of the light can also be absorbed at the back contact.

This can again be considered as a parasitic absorption loss.

In week 5 we will discuss thin-film solar cells, where back reflectors and light scattering under angles starts to play an important role.

For these type of solar cells you would like to scatter the light back under the critical angle.

I will explain the importance of the critical angle right now.

Consider a single film of absorber material with a higher refractive index than its surroundings.

For some magic reason, which we for the moment ignore, the light scatters under a certain angle into the film.

The light is scattering between the two interfaces, down and up.

In the ideal case, you would like to have all light trapped in the absorber layer, making the absorption path length so long that all the light is absorbed.

Unfortunately, at every internal reflection part of the light is transmitted out of the film.

However, this is not the case when there is a total internal reflection.

From the Fresnel equations we know that above a critical angle the internal reflection becomes 100%.

This means that if the light is scattered into the film above a critical angle, the light would be trapped.

The critical angle is a function of the refractive index of both media.

If we consider silicon and air, this critical angle is rather small, 13.4 degrees.

However, absorber layers are usually confined between supporting layers.

If we would consider glass, with a refractive index of 1.5, the critical angle becomes 20.4 degrees.

If we consider ZnO, a typical transparent conductive oxide, we find a critical angle of 30.3 degrees.

In the coming weeks we will discuss various tricks to scatter the light under angles into the absorber layer.

Here you can see an example of scattering at microscopic texture, which enhances the absorption path length into the absorber layer.

Summarized, this week we have learned some important concepts.

We have discussed how we determine the performance of a solar cell using the external parameters.

In addition, we have discussed some important design rules for solar cells.

Next week we shall discuss the most dominant PV technology in the market: crystalline silicon.

So, see you next week!