

**Figure 10.9:** Illustrating the lost excess energy in (a) a single-junction and (b) a multi-junction solar cells.

illumination conditions. We will discuss several different cases on Part III on PV technology.

### 10.4.2 Spectral utilisation

The spectral utilisation is mainly determined by the choice of materials from which the solar cell is made of. As we have seen in Section 10.2, and mainly Eq. (10.13), the photocurrent density is determined by the bandgap of the material. For a bandgap of 0.62 eV corresponding to a wavelength of 2000 nm, we could theoretically generate a short circuit current density of 62 mA/cm<sup>2</sup>. If we consider c-Si, having a band gap of 1.12 eV (1107 nm), we arrive at a theoretical current density of 44 mA/cm<sup>2</sup>.

The optimal bandgap for single-junction solar cells is determined by the Shockley-Queisser limit, as illustrated in Fig. 10.6. For single junction solar cells, semiconductor materials such as silicon, gallium arsenide and cadmium telluride have a band gap close to the optimum.

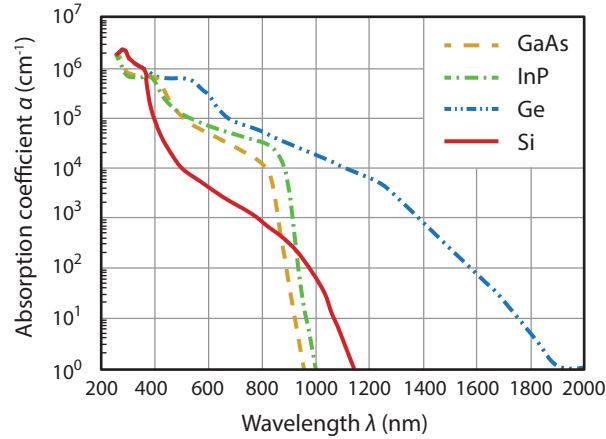
In Part III we will discuss various concepts that allow to surpass the Shockley-Queisser limit. Here, we will briefly discuss the concept of *multi-junction solar cells*. In this devices, solar cells with different bandgaps are stacked on top of each other. As illustrated in 10.9, the excess energy can be reduced significantly, and the spectral utilisation will improve.

### 10.4.3 Light management

The third and last design rule that we discuss is *light management*. In an ideal solar cell, all light that is incident on the solar cell should be absorbed in the absorber layer. As we have discussed in Section 4.4, the intensity of light decreases exponentially as it travels through an absorptive medium. This is described by the Lambert-Beer law that we formulated in Eq. (4.25),

$$I(d) = I_0 \exp(-\alpha d). \quad (10.30)$$

From the Lambert-Beer law it follows that at the side, at which the light is entering the film, more light is absorbed in reference to the back side. The total fraction of the incident light



**Figure 10.10:** Absorption coefficients of different semiconductors.

absorbed in the material is equal to the light intensity entering the absorber layer minus the intensity transmitted through the absorber layer,

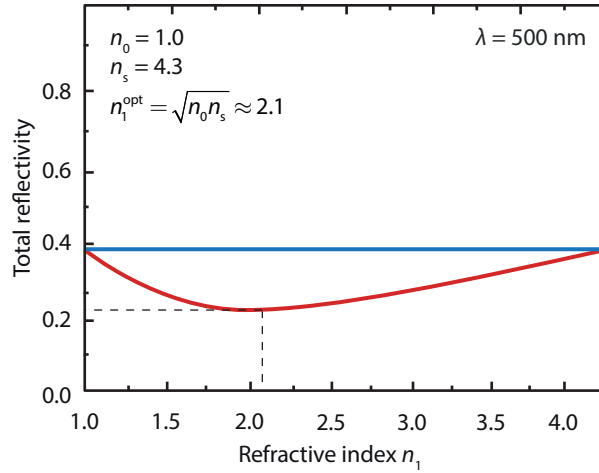
$$I^{\text{abs}}(d) = I_0[1 - \exp(-\alpha d)]. \quad (10.31)$$

Ideally, we would like to absorb a solar cell 100% of the incident light. Such an absorber is called *optically thick* and has a transmissivity very close to 0. As we can see from the Lambert-Beer law, this can be achieved by either absorbers with a large thickness  $d$  or with very large absorption coefficients  $\alpha$ .

Figure 10.10 shows the absorption coefficients for four different semiconductor materials: germanium (Ge), silicon (Si), gallium arsenide (GaAs) and indium phosphide (InP). We notice that germanium has the lowest band gap. It starts to absorb at long wavelengths, which corresponds to a low photon energy. GaAs has the highest band gap, as it starts to absorb light at the smallest wavelength, or highest photon energy. Secondly, if we focus on the visible spectral part from 300 nm up 700 nm, we see that the absorption coefficients of InP and GaAs are significantly higher than for silicon. This is related to the fact that InP and GaAs are direct band gap materials as discussed earlier. Materials with an indirect band gap have smaller absorption coefficients. Only in the very blue and ultraviolet part below 400 nm, Si has a direct band gap transition. Silicon is a relatively poor absorber. Therefore for the same fraction of light thicker absorber layers are required in comparison to GaAs.

In general, for all semiconductor materials the absorption coefficient in the blue is orders of magnitude higher than in the red. Therefore the penetration depth of blue light into the absorber layer is rather small. In crystalline silicon, the blue light is already fully absorbed within a few nanometers. The red light requires an absorption path length of 60  $\mu\text{m}$  to be fully absorbed. The infrared light is hardly absorbed, and after an optical path length of 100  $\mu\text{m}$  only about 10% of the light intensity is absorbed.

As the absorption of photons generates excited charge carriers, the wavelength dependence of the absorption coefficient determines the local generation profile of the charge



**Figure 10.11:** Illustrating the effect of an interlayer with refractive index  $n_1$  in between  $n_0$  and  $n_s$  on the reflectivity.

carriers. At the front side where the light enters the absorbing film, the generation of charge carriers is significantly higher than at the back side. It follows that the EQE values measured in the blue correspond to charge carriers generated close to the front of the solar cell, whereas the EQE in the red part represents charge carriers generated throughout the entire absorber layer.

Further, it is important to reduce the optical loss mechanisms such as *shading losses*, *reflection*, and *parasitic absorption* that we already discussed in Section 10.3.1.

For reducing the reflection, anti-reflective coatings (ARC) can be used. Light that is impinging onto a surface between two media with different refractive indices will always be partly reflected and partly transmitted. In order to reduce losses, it is important to minimise these reflective losses.

The first method is based on a clever utilisation of the Fresnel equations that we introduced in Eqs. (4.12) and (4.13). For understanding how this can work, we first will take a look at interfaces with silicon, the most common used material for solar cells. Let us consider light of 500 nm wavelengths falling onto an air-silicon interface perpendicularly. At 500 nm, the refractive index of air is  $n_0 = 1$  and that of silicon is  $n_s = 4.3$ . With the Fresnel equations we hence find that the optical losses due to reflection are significant with 38.8%.

The reflection can be significantly reduced by introducing an interlayer with a refractive index  $n_1$  with a value in between that of  $n_0$  and  $n_s$ . If no multiple reflection or interference is taken into account, it can easily be shown that the reflectivity becomes minimal if

$$n_1 = \sqrt{n_0 n_s}. \quad (10.32)$$

This is also seen in Fig. (10.11), where  $n_1$  takes all the values in between  $n_0$  and  $n_s$ . In this example, including a single interlayer can reduce the reflection at the interface from 38.8% down to 22.9%. If more than one interlayers are used, the reflection can be reduced even further. This technique is called *refractive index grading*.

In another approach constructive and destructive interference of light is utilised. In Chapter 4 we already discussed that light can be considered as an electromagnetic wave. Waves have the interesting properties that they can interfere with each-other, they can be *superimposed*. For understanding this we look at two waves  $A$  and  $B$  that have the same wavelength and cover the same portion of space,

$$A(x, t) = A_0 e^{ikx - i\omega t}, \quad (10.33a)$$

$$B(x, t) = B_0 e^{ikx - i\omega t + i\phi}. \quad (10.33b)$$

The letter  $\phi$  denotes the *phase shift* between  $A$  and  $B$  and is very important. We can superimpose the two waves by simply adding them

$$\begin{aligned} C(x, t) &= A(x, t) + B(x, t) \\ &= A_0 e^{ikx - i\omega t} + B_0 e^{ikx - i\omega t + i\phi} \\ &= A_0 e^{ikx - i\omega t} + B_0 e^{ikx - i\omega t} e^{i\phi} \\ &= (A_0 + B_0 e^{i\phi}) e^{ikx - i\omega t}. \end{aligned} \quad (10.34)$$

The amplitude of the superimposed wave is thus

$$C_0 = A_0 + B_0 e^{i\phi}. \quad (10.35)$$

Depending on the phase shift, the superimposed wave will be stronger or weaker than  $A$  and  $B$ . If  $\phi$  is *in phase*, i.e. a multiple of  $2\pi$ , i.e.  $0, 2\pi, 4\pi, \dots$ , we will have maximal amplification of waves,

$$C_0 = A_0 + B_0 \cdot 1 = A_0 + B_0. \quad (10.36)$$

This situation is called *constructive interference*.

But if  $\phi$  is *in antiphase*, i.e. from the set  $\pi, 3\pi, 5\pi, \dots$  we have maximal attenuation of the waves, or *destructive interference*,

$$C_0 = A_0 + B_0 \cdot (-1) = A_0 - B_0. \quad (10.37)$$

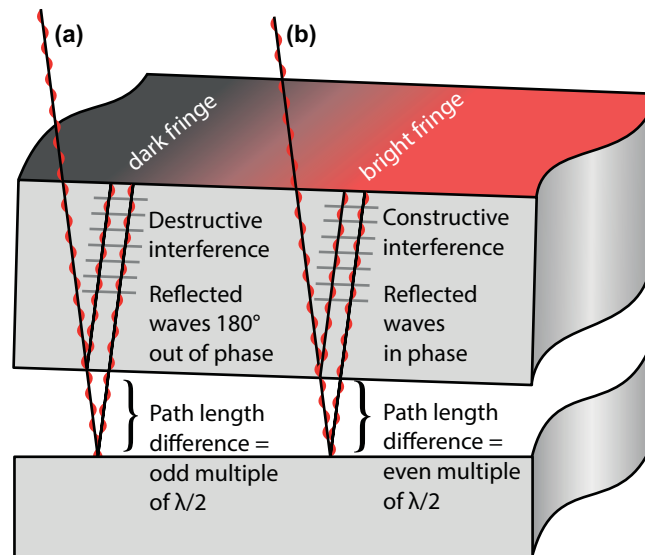
Based on this principle, we can design an anti-reflection coating, as illustrated in Fig. 10.12. The green wave shows the reflection back from the first interface and the red wave shows the outgoing wave which is reflected back from the second interface. If we look at the two waves coupled out of this system, they appear to be in antiphase. As a result the total amplitude of the electric field of the outgoing wave is smaller and hence the total irradiance coupled out of the system is smaller as well.

It can be shown easily that the two waves are in antiphase, when the product of the refractive index and thickness of the interlayer is equal to the wavelength divided by four,

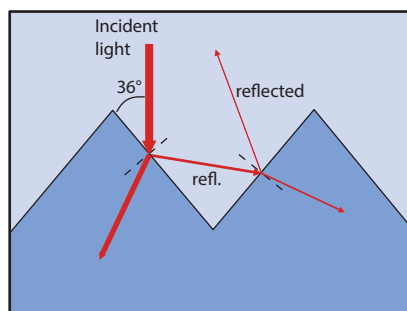
$$n_1 d = \frac{\lambda_0}{4}. \quad (10.38)$$

Using an antireflection coating based on interference demands that the typical length scale of the interlayer thickness must be in the order of the wavelength.

The last approach that we discuss for realising antireflective coating is using *textured interfaces*. Here, we consider the case where the typical length scales of the surface features



**Figure 10.12:** Illustrating the working principle of an anti-reflective coating based on interference [40].



**Figure 10.13:** Illustrating the effect of texturing.

are larger than the typical wavelength of light. In this case, which is also called the *geometrical limit*, the reflection and transmission of the light rays are fully determined by the Fresnel equations [Eqs. (4.12) and (4.13)] and Snell's law [Eq. (4.11)].

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 one part of the textured surface can be reflected into angles in which the trajectory of the light ray is incident a second time somewhere else on the interfaces, as illustrated in Fig. 10.13. Here, another fraction of the light will be transmitted into the layer and effectively less light will be reflected, when compared to a flat interface in-between the same materials.

In summary, we have discussed three types of anti-reflective coatings: Rayleigh films with intermediate refractive indexes, anti-reflection coatings based on destructive interference and enhanced in-coupling of light due to scattering at textured interfaces.

At the end of this chapter, we want to discuss something that is very important for thin-film solar cells. Because of reducing production cost but also because of reducing bulk recombination it is desirable to have the absorber layer as thin as possible. On the other hand, it should be *optically thick* in order to absorb as much light as possible. In principle, if the light can be reflected back and forth inside the absorber until everything is absorbed. However, at every internal reflection part of the light is transmitted out of the film.

But if the light would travel through the layer at an angle larger than the critical angles of the front and back interfaces of the absorber, it could stay there until everything is absorbed without any loss. Unfortunately, it is very difficult if not impossible to design such a solar cell.

Note that textured interfaces do not help in this case. For the same reason more light can be coupled into the absorber because of texturing, also more light is coupled out of the absorber!

## 10.5 Exercises

- 10.1 Consider two solar cells: solar cell *A* has a bandgap energy of 1 eV and solar cell *B* has a bandgap energy of 1.7 eV. From all kind of possible losses, assume only the optical losses. Which of the following statements is true?
- Non-absorption losses are higher in solar cell *A* than in solar cell *B*.
  - Heating losses are higher in solar cell *A* than in solar cell *B*.
  - According to the Shockley-Queisser analysis, radiative recombination is more important in solar cell *B* than in solar cell *A*.
  - According to the Shockley-Queisser analysis, solar cell *A* can have an efficiency up to 50%.
- 10.2 Consider an incoming monochromatic light beam of wavelength  $\lambda = 800$  nm incident on a c-Si layer. How thick should the layer be in order to absorb 90% of the incoming light? Assume the absorption coefficient to be  $\alpha(800 \text{ nm}) = 10^3 \text{ cm}^{-1}$ .
- 10.3 The typical thickness of the absorber layer of a c-Si solar cell is around 300  $\mu\text{m}$ . Assume that the absorption coefficient for infrared light is  $\alpha(1100 \text{ nm}) = 10 \text{ cm}^{-1}$ . How much of the light with  $\lambda = 1100$  nm is not absorbed by the absorber layer? Give the answer as a percentage of the incident intensity  $I_0$ .