ET3034TUx - 3.3.1 - Utilization of band gap energy

In the last two weeks we have discussed the working principle of a solar cell and the external parameters that define the performance of a solar cell.

Now, we are going to look at how various solar cell concepts and photovoltaic materials affect the performance of a solar cell.

For that we have to look at some general design rules for solar cells.

I always like to show this simple diagram to my students, which summarizes the important design rules.

As you can see, I identify three important design rules: utilization of the band gap energy, spectral utilization, and the last engineering tool, which is light trapping.

First, the real energy used to generate voltage is the product of the open-circuit voltage and the elementary charge.

Under normal operation conditions, this energy is always smaller than the total band gap energy.

Open-circuit voltage is determined by the extent to which the quasi-Fermi levels are able to split, which is limited by the charge carrier recombination mechanisms.

We will show that various PV materials have different recombination mechanisms that limit the utilization of the band gap energy.

Secondly, we look at the spectral utilization.

The spectral utilization is first determined by the choice of materials which make the solar cell.

We will discuss that the band gap of the materials determine the maximum current density generated by the solar cell.

Thirdly, if we have chosen our PV material, its potential utilization of the solar spectrum and its utilization of the band gap energy, we would like to absorb as much as possible light from the solar spectrum in the PV active materials.

We have to implement tricks to trap the light in the solar cell.

This becomes an important issue if we consider thin-film PV technologies.

First, we start with the design rule: the band gap utilization.

Here you see a p-n junction, on the left the p-doped and on the right the n-doped.

Further we see the quasi-Fermi levels.

The extent of splitting between the quasi-Fermi levels determines the open-circuit voltage.

Earlier this week, we have deduced an expression for the open-circuit voltage which is shown here.

The open-circuit voltage depends on the irradiance and the diode leakage current in the dark.

This equation can be expressed in terms of the generation rate G, lifetime tau of the minority charge carriers and the intrinsic density of the charge carriers of the semiconductor material (n_i).

As the derivation of this equation is out of the scope of this lecture, we have included it as an exercise in this week's homework.

The equation tells us two important aspects of the open-circuit voltage.

If we increase the irradiance, or in other words, the generation rate of charge carriers, the open-circuit voltage is increased.

This is a welcome effect which is utilized in concentrator photovoltaics, which we will discuss later this course.

Secondly, we see that the lifetime plays an important role.

The larger the lifetime of the minority charge carrier, the larger the open-circuit voltage can be.

Or in other words, the longer the lifetime, the larger the splitting between the quasi-Fermi levels is possible and the larger fraction of the band gap energy can be utilized.

The lifetime of the minority charge carriers is determined by the recombination rate.

As discussed last week, we have three different recombination mechanisms, radiative, Auger and Shockley-Read-Hall (SRH).

Let's start with the last one, SRH recombination.

The origin of this mechanism is the trapping of the mobile electron at defects that have an energy state in the band gap.

The electron is trapped until a mobile hole finds the electron, after both charge carriers recombine.

SRH recombination depends logically on the defect density.

In the simplest approximation, the minority charge carrier lifetime is reciprocally dependent on the defect density N_t.

This means: the larger the defect density, the shorter the lifetime and the smaller the open-circuit voltage.

The defect density limits the extent to which the quasi-Fermi levels can be split.

Defects can be located in the bulk of the various semiconductor materials, but can also be present at the various interfaces between materials used in the solar cell, like: semiconductors, transparent conductive oxides and metal contacts.

Let's consider solar cells, without bulk and interface defects, then the other two recombination mechanisms start to play a role.

Let's consider Auger recombination.

Auger recombination is the process in which the momentum and energy of the recombining hole and electron is conserved by transferring energy and momentum to another hole or electron.

This electron is excited in higher levels in the electronic band.

This excited electron relaxes again, such that the energy is lost as phonon modes.

Phonon modes are lattice vibrations and is nothing different than heat.

As the recombination process is a three particle-process, the Auger recombination rate, expressed in R, is strongly dependent on the charge carrier densities.

n is the density of electrons and p is the density of holes.

The R_electron is dominant when the electrons are the majority charge carriers, whereas R_hole is dominant when the holes are the majority charge carriers.

In a simple approximation the lifetime is 1 over the density of charge carriers squared.

As a consequence Auger recombination becomes dominant in photovoltaic materials with high densities of charge carriers, like in highly doped c-Si, or solar cells under strong illumination, like concentrator solar cells.

The last recombination mechanism is radiative recombination.

In the three recombination mechanisms energy and momentum are transferred from charge carriers to phonons or photons.

The efficiency of these processes depends on the nature of the band gap of the semiconductor material used.

Last week I have introduced the physical principle of the band gap.

However, I did not discuss the difference between a direct or indirect band gap.

I will explain the nature of both types of band gap now.

For that we have to look in the energy-momentum space of the electrons.

On the vertical axis we have the energy state in the electronic bands.

On the horizontal axis we got the momentum of the charge carrier.

This momentum is also called the crystal momentum.

Important to realize is that the position of the valence and conduction band may differ in different directions of the lattice coordination.

For indirect band gap the highest point of the valence band is not aligned with the lowest point of the conduction band.

This means that exciting an electron from the valence to conduction band requires energy provided by a photon and momentum provided by a phonon.

In contrast, a direct band gap has the highest point of the valence band vertically aligned with the lowest point of the conduction band in the energy-momentum space.

This means that exciting an electron from the valence to conduction band requires only the energy provided by a photon without any additional momentum transfer.

This means that the excitation of an electron induced by photon absorption is more likely to happen for direct band gap materials than for indirect band gap materials.

For direct band gap materials no additional matching momentum coming from phonons has to be delivered.

Or in other words, the absorption coefficient for direct band gap materials is significantly higher than for indirect band gap materials.

The same concept makes the reverse process of radiative recombination more likely to happen in a direct band gap material.

In an indirect band gap material additional momentum is required to make the electron and hole recombine.

Crystalline silicon is an indirect band gap material.

If we ignore SRH recombination by defects, the radiative recombination in the indirect band gap material like crystalline silicon is inefficient and recombination will be dominated by the Auger mechanism.

For the direct band gap material as GaAs under moderate illumination conditions, radiative recombination will be the dominant loss mechanism of charge carriers.

For very high illumination conditions, Auger recombination starts to play a role as well.

If we now go back to the open-circuit voltage, it means that in defect rich solar cells, the open-circuit voltage is limited by the SRH recombination.

In defect free solar cells based on indirect band gap materials, the open-circuit voltage is limited by Auger recombination.

In defect free solar cells based on direct band gap materials, the open-circuit voltage is limited by the radiative recombination.

Next to the band gap utilization, I would like to discuss the relation between the maximum thickness for the absorber layer of a solar cell and the recombination mechanism as well.

The recombination mechanism, as we have discussed last week, also affects the diffusion length of the minority charge carrier.

The diffusion length is given by the simple equation L, which is the square root of the diffusion coefficient D times the lifetime tau of the minority charge carrier.

This leads to one additional limitation of the solar cell design.

The absorber layer of a solar cell cannot be thicker than the typical diffusion length.

Why is that the case?

This is demonstrated in this simple animation.

Let's consider photons that would penetrate far into the absorber layer before they are being absorbed.

We want these charge carriers to be separated at the p-n junction or the back contact.

But, let's assume that these charge carriers are excited at a depth deeper than the typical diffusion length.

The excited charge carriers recombine within the typical diffusion length before arriving at the p-n junction.

In other words, their lifetime is too short.

This means that all charge carriers generated at a depth greater than the diffusion length from the p-n junction cannot be collected.

If the charge carriers are generated at a depth shorter than the diffusion length, they can be collected.

This means that the diffusion length of the minority charge carrier, limits the maximum thickness of the solar cell.

Summarized, the open-circuit voltage is limited by the dominant recombination mechanism.

The dominance of radiative, Auger or Shockley-Read-Hall recombination depends on the type of semiconductor materials integrated into the solar cell and the illumination conditions.

In the coming weeks I will give various examples of various PV technologies.

In the next block I will discuss the second design rule: spectral utilization.

We answer the question of how much current density can we generate with a certain semiconductor material?