ET3034TUx - 3.3.3 - Spectral utilization 2 - Shockley-Queisser limit

For a single junction solar cell, the band gap of the semiconductor material determines the theoretical maximum current density and the open-circuit voltage that can be obtained.

Therefore, considering single junction solar cells, we arrive at the next question:

what is the optimum band gap for the absorber semiconductor at which the highest conversion efficiency can be obtained, using the AM1.5 solar spectrum.

Let's find an answer to that question.

Here we see the spectral power density function again.

Let's consider the typical optical loss mechanism, for a semiconductor with a band gap E_gap.

Again we take crystalline silicon as an example.

Furthermore, we assume an EQE of 100% above the band gap for the solar cell.

Let's look at photons with energies higher than the band gap.

We know that we effectively only need the energy of the band gap to excite the mobile charge carriers.

The electrons are excited to a level higher up in the band gap and the holes down to a lower level in the valence band.

They will quickly relax back to the edges of both bands.

The rest energy is released in terms of heat.

The grey area represents the total amount of energy in the solar spectrum which is used to excite the charge carriers.

The yellow area above the band gap represents the energy which is lost as heat.

All energy present in the solar spectrum, below the band gap is not absorbed and can be considered as an optical loss as well.

Both loss processes, heating and non-absorption, depend on the band gap.

The higher the band gap, the smaller the losses due to heat, but the larger the energy losses below the band gap.

The smaller the band gap, the larger the losses due to heat, whereas the energy losses below the band gap decreases.

This suggests that if we only consider the optical losses and ignore all other losses, we will have an optimum.

The optical losses due to this mismatch between the band gap and the solar spectrum limit the maximum conversion efficiency to 48%.

However, this limit is not very realistic.

In literature people generally refer to the so-called Shockley-Queisser limit.

This theoretical limit includes two additional loss mechanisms.

First, as the solar cell is at a certain temperature, it will act as a black-body radiator itself and emit light in the far infrared.

This energy loss is roughly around 7% of the incident energy of the AM1.5 solar spectrum.

Secondly, we have to consider that we do not fully utilize the band gap energy for the open-circuit voltage.

As discussed earlier this week, the maximum open-circuit voltage is limited by the recombination of charge carriers.

In reality, we can have three charge carrier recombination mechanisms, radiative, Auger and Shockley-Read-Hall (SRH).

In the case of Shockley-Queisser limit, only radiative recombination is considered.

This means, in a very simplified picture, we make a kind of thermodynamic approach of the solar cell.

We have the AM1.5 spectrum incident on a solar cell.

We don't allow the solar cell to increase in temperature.

This means that all energy in the incoming AM1.5 spectrum can escape the system of the solar cell by either the current density generated or by the radiative recombination of charge carriers.

In this figure the energy lost as heat is indicated as excess energy.

This means that for a low band gap material, as shown here, the energy loss below the band gap is moderate.

However, the amount of excess energy of the energetic photons is significant.

Due to our restrictions, this energy has to leave the system through radiative recombination.

Therefore radiative recombination is enhanced for low band gap materials.

This means that for a high band gap material the energy loss below the band gap is dominant, and the excess energy determines the amount of charge carriers that radiatively recombine.

As a result we get this following picture.

It shows the loss mechanisms, black-body radiation, relaxation of charge carriers to the band gap edges and lost energy below the band gap.

The black part shows the useable energy in single junction solar cells according to the Shockley-Queisser limit.

The Shockley-Queisser has an optimum of 33% for band gaps in the range of 1 eV up to 1.5 eV.

For single junction solar cells, you can see that the semiconductor materials as silicon, gallium-arsenide and cadmium telluride have an optimum band gap.

However, if we look at the record efficiencies of solar cells, they are all below the Shockley-Queisser limit.

The reason for this is that additional optical losses, like reflection, parasitic absorption and electrical losses like the Shockley-Read-Hall and Auger recombinations are not considered.

The Shockley-Queisser limit only considers radiative recombination.

Therefore its efficiency limit is most valid for direct band gap materials, like GaAs .

As discussed in the previous block, due to its direct band gap, radiative recombination is the limiting recombination mechanism for the open-circuit voltage of GaAs.

Later in this course we will discuss various concepts, which might allow to pass the Shockley-Queisser limit. Here I will give an quick example.

A way to reduce the amount of excess energy is to use more than one semiconductor material or often referred to as a multi-junction.

This allows us to use more than one band gap and the match with the solar spectrum improves.

As you see in this example, the excess energy can be reduced significantly, and the spectral utilization improves.

We will discuss such multi-junction concepts in greater detail in week 5.

So we have discussed the utilization of the solar spectrum and band gap energy.

This week we will finish with the final two blocks, describing the third design rule: light trapping.