ET3034Tux - 1.3 - Photovoltaics

So, how can we get electricity directly from sunlight?

The mechanism in which solar light is directly converted into voltage or current is called the photovoltaic (PV) effect.

In week 2, we will discuss the photovoltaic effect in greater detail.

But to give you a first idea, I will show its principle using this simple animation.

Here we see a simplified representation of a silicon based solar cell.

It consists of the c-Si absorber layer, a pn-junction to separate the light excited charge carriers and a metal front and back contact.

Here we see the same structure, but then in a cross-sectional view.

The light enters the solar cell from the front side, in this illustration that is the top side.

The light is transmitted into the absorber layer where its energy is absorbed.

The energy is used to excite charge carriers in the semiconductor material, which are a negatively charged electron, indicated by the red dot, and a positively charged hole, indicated by the blue dot.

These charge carriers diffuse around and need to be separated, which occurs at the depletion region between the n- and p-type doped silicon and the depletion region at the back of the solar cell.

You don't have to understand yet why this happens, I will explain this in detail next week.

Then the charge carriers have to be collected at the contacts.

In this example the contacts are connected with a load, in this case a lamp.

The electron will move through the load back to the solar cell.

Both charge carriers recombine at the metal/p-layer interface.

It shows that the photovoltaic process is based on three important principles: the first is excitation of free mobile charge carriers due to light absorption, the second is separation of the charge carriers and the third one is collection of the charge carriers at the contacts.

A variety of PV technologies exist today.

We can categorize them in various ways.

The first logical way is to categorize them based on the type of absorber material; we will do that in a minute.

Another categorization approach is based on the generations, which is often used in books about PV technology.

I have some personal objections against the generation-based categorization, but as it's widely used, I will introduce it here.

For that we use the graph in which we plot on the horizontal axis the cost-price of the solar cell per area, expressed in dollar per square meter.

So solar cells made of expensive materials or using expensive processing methods will be further to the right on this axis.

The conversion efficiency is the fraction of the energy in the solar light, which is converted into electricity, which is represented by the vertical axis.

The efficiency scales with the energy yield of the solar cell.

The larger the efficiency, the larger the generated power per area will be.

This power is expressed in watts per square meters.

For example, standard test conditions for solar cells means an irradiance of 1000 watts per square meter.

This means a solar cell with conversion efficiency of 10%, produces under standard test conditions a power output of 100 watts per square meter.

It means that the slope of the dashed line is equal to the watt per dollar.

Or in other words it is reciprocally linear with the cost price per watt-peak.

The cost price per watt-peak corresponds to the cost price of the energy generated by the solar cell.

In this example the dashed line represents 0.5 dollars per watt.

If the slope of these dashed lines is very steep, the cost price per watt is low, whereas when the slope of the dashed lines becomes less steep the cost price per watt-peak is getting significantly higher.

To compete with other energy sources, you would like that your PV technology overlaps with the steepest lines in this graph.

The first generation PV technology is based on using very pure bulky semiconductor materials, like crystalline silicon (c-Si).

Pure materials means less defects and in general solar cells with a relative high efficiency can be manufactured.

However, high quality materials requires more expensive production processes, which in general makes the cost price per area solar cell larger as well.

The light grey circle roughly shows the area in which you would find the first generation PV technology.

What is the second generation PV technology?

These are PV devices, which are firstly based on thin-film solar cells.

Thin film implies that less material is used which makes the solar cells cheaper.

Secondly, these solar cells are manufactured using cheaper processing technology.

As a consequence, the materials have more defects resulting in lower performances.

Although the solar cell efficiency is lower, due to the lower cost price per area, the cost price per watt of the second generation PV technology is significant lower.

The blue area represents the so-called Shockley-Queisser limit, which we will introduce in week 3.

Given the shape of our solar spectrum and the band gap of the materials used, the Shockley-Queisser limit tells us the theoretically maximum conversion efficiency of the solar cell.

Third generation PV technologies are based on solar cell concepts, which try to tackle the Shockley-Queisser limit.

So, third generation PV technology would be solar cells with higher conversion efficiencies in reference to the first and second generations.

The current solar cell concepts being studied to beat the Shockley-Queisser limit will be discussed in week 6.

Furthermore, the cost price of the materials and processing techniques used to process the third generation solar cells are expected to be cheap as well.

The result is that the third generation solar cell technology overlaps with the steepest dashed lines in this graph, meaning that third generation technology would have the lowest cost price per wattpeak (Wp).

However, beating the Shockley-Queisser limit for most concepts is a challenge itself, making these complex concepts cheaply is a completely different ball game.

Next to categorizing the PV technologies in the three generations, we indicate the various PV technologies based on the semiconductor material used as absorber layer in the solar cell.

The most dominant PV technology is based on c-Si wafers.

This technology represents around 90% of the current PV market and belongs to the first generation PV technology.

We will discuss this technology in great detail in week 4.

Another PV technology based on silicon is thin-film silicon.

In this case no c-Si wafers are used but very thin layers of silicon, which are deposited on glass or a flexible substrate.

The silicon does not have the same lattice structure and can be amorphous or nanocrystalline.

This technique belongs to the second generation PV technologies and will be discussed in week 5.

An alternative thin-film PV technology is based on II-VI semiconductor, the cadmium telluride (CdTe).

CdTe PV technology belongs to the so-called second generation technologies as well.

The CdTe has currently the largest market among the thin-film PV technologies.

In week 5, we will discuss this technology in great detail.

Another thin-film PV technology, based on a chalcogenide alloy is CIGS, which stands for copper indium gallium selenide.

Among the thin-film PV technologies, it has the highest demonstrated conversion efficiency on lab scale, just above 20%.

It belongs to the second generation PV technologies as well.

Another thin-film PV technology is based on organics, also referred to as the plastic solar cell.

The absorption and charge transport in the solar cell occurs in conductive organic polymers or molecules.

The dye-sensitized solar cell is a kind of photoelectrochemical system, in which a semiconductor material based on molecular sensitizers is placed between a photo-anode and an electrolyte.

We will discuss both the organic and dye-sensitized PV technology in week 5.

The final PV technology we will discuss is based on III-V semiconductor materials such as gallium arsenide (GaAs).

III-V materials are being used in multi-junction devices, often processed on germanium wafers as substrate.

The multi-junction based on III-V semiconductors are the most efficient solar cells today.

The record conversion efficiency of 44% was obtained with a metamorphic triple junction in 2012.

The III-V semiconductor solar cells are being used in concentrator PV technology and in space applications.

This technology will be discussed in week 5.

Third generation PV technologies are based on various concepts, trying to beat the Shockley-Queisser limit.

We will discuss third generation concepts in great detail in week 6.

Third generation PV technology covers a wide range of novel and innovative ideas, the most successful being multi-junctions.

You have to realize that most of these ideas still need to be proven.

Some of these ideas are quantum dots solar cells, absorber layers exhibiting multiple-exciton-generation, intermediate bandgap solar cells, hot carrier solar cells, spectral-conversion using down-converters or up-converters.

Finally, I show you here the famous chart of NREL.

It summarizes the worldwide research effort of the last 40 years and it shows the current record efficiencies of solar cells at research scale.

These solar cells are fabricated in a lab environment and have very small sizes, often not larger than 1 square centimeter.

The purple colored markers represent the III-V technology based on single, double and triple junctions and have efficiencies ranging from 26% up to 44% under concentrated light conditions.

The blue lines and dots represent the crystalline silicon technology based on monocrystalline and multicrystalline silicon.

The record efficiency ranges from 20% up to 25% under standard 1 sun illumination conditions and 27% can be achieved under 92 suns illumination.

The inorganic thin-film technologies, like thin-film silicon, CdTe and CIGS are indicated by the green markers and their record efficiencies range from 13.4 % up to 20%.

The red colored lines and markers indicate the emerging PV technologies, like organic solar cells.

You have to be aware that these are lab results of very small area solar cells and this chart does not tell you anything of the long term stability of some PV technologies, certainly not the ones indicated in red.

They indicate the potential efficiency of many PV technologies.

Nevertheless, you have to realize that most PV technologies still have a large gap between the record conversion efficiency of the lab cells and the conversion efficiency of large commercial modules.

It will be my pleasure to discuss these challenges in weeks 4 and 5.

What is the history of solar energy technology and what is the current status of PV technologies in the real world?

I mean the world of large area modules.

I will discuss that in the next two blocks.

I will begin with the history.