ET3034TUx - 4.4 - High efficiency concepts of c-Si wafer based solar cells

In the previous block we have discussed various technological aspects on crystalline silicon wafer based PV technology.

In this block I will give you three examples of highly efficient solar cells based on crystalline silicon wafers.

As discussed earlier this week, we have various types of wafers with different qualities of silicon.

To achieve the highest efficiencies, the bulk recombination must be as low as possible.

Therefore the high-efficiency crystalline silicon solar cells are based on monocrystalline wafers.

Let's start with the first high-efficiency crystalline silicon solar cell developed by Martin Green's group at the University of New South Wales in the late 80s and the early 90s.

Here you see an illustration of the PERL concept, which uses a p-type float-zone silicon wafer.

This concept has approached a conversion efficiency of 25% and has been an example for various technology developed afterwards.

PERL is an abbreviation for Passivated Emitter Rear Locally diffused.

The name indicates the two important concepts integrated into the solar cell.

The optical losses of the PERL solar cell at the front side are minimized using three important concepts.

First, the top surface of the solar cell is textured using inverted pyramid structures.

This microscopic texture allows a fraction of the reflected light to be incident on the front surface for a second time.

This enhances the total amount of light coupled into the solar cell.

Secondly, the inverted pyramid structures are covered by a double-layer anti-reflection coating (ARC) which results in an extremely low top surface reflection.

Often a double-layer coating of magnesium fluoride and zinc sulfide is used as an anti-reflection coating.

Thirdly, the contact area at the front side has to be as small as possible, to reduce the shading losses.

In the PERL concept these very thin and fine metal fingers are processed using photolithography technology.

The emitter layer is smartly designed.

As discussed in the previous blocks, the emitter should be highly doped underneath the contacts, which in the PERL concept is achieved by heavily phosphorous diffused regions.

The rest of the emitter is moderately doped, or in other words lightly diffused, to preserve an excellent "blue response".

The emitter is passivated with an silicon oxide layer on top of the emitter to suppress the surface recombination velocity as much as possible.

The surface recombination velocity has been suppressed to the level that the open-circuit voltages with values of above 700 mV have been obtained using the PERL concept.

At the rear surface of the solar cell, point contacts have been used in combination with thermal oxide passivation layers.

The oxide operates as a passivation layer of the non-contacted area, to reduce the unwelcome surface recombination.

A highly doped boron region, created by local boron diffusion, operates as a local back surface field, to limit the recombination of the minority electrons at the metal contact.

The PERL concept as we presented here includes some expensive processing steps.

The Chinese Suntech company developed in collaboration with the University of New South Wales a more commercially viable crystalline silicon wafer technology, which is inspired on the PERL cell configuration.

A second successful cell concept which is commercialized by SunPower is the interdigitated back contact (IBC) solar cell.

The principle of interdigitated back contact concepts is that it does not suffer from shading losses of a front metal contact grid.

All the contacts responsible for collecting of charge carriers at the n- and p-side are positioned at the back of the crystalline wafer solar cell.

An advantage of these interdigitated concepts are that you are able to use monocrystalline float-zone n-type wafers.

Why is that interesting?

The n-type wafers have some advantages above p-type wafers.

First, the n-type wafers do not suffer from light-induced degradation.

In p-type wafers simultaneously boron and oxygen are present, which under light exposure start to make complexes that act like defects.

The light-induced degradation causes a reduction of the power output with 2-3% after the first week of installation.

This effect is not present in n-type wafers.

The second advantage is that n-type silicon is not that sensitive for impurities like for instance iron impurities.

As a result less efforts have to be made to make a high electronic quality of n-type silicon, meaning that high-quality n-type silicon can be processed cheaper than p-type.

On the other hand, p-doped wafers have the advantage that the boron doping is more homogeneously distributed over the wafer as for n-type.

This means that within one n-type wafer the electrical properties can vary within the same wafer.

This effect lowers again the yield of solar cell production based on n-type monocrystalline wafers.

Back contacted solar cells use, in contrast to the PERL concept, n-type float-zone monocrystalline silicon wafers.

An interdigitated back contact is lacking one large p-n junction.

Instead the cell has many localized junctions.

The holes are separated at a junction of p+ and the n-type silicon, whereas the electrons are collected using a n+ type silicon.

The semiconductor-metal interface is kept as small as possible to reduce the unwelcome recombination at this defect-rich interface.

Another advantage is that the cross-section of the metal fingers can be made much larger to reduce the resistive losses of the contacts as much as possible.

The fact that the contacts do not cause any shading losses at the back, allows them to become larger.

The passivation layer can have a low refractive index such that it operates like a backside mirror.

It will reflect the light above 900 nm, which is not absorbed during the first pass, back into the absorber layer, enhancing the absorption path length.

An interdigitated back contact solar cell would look like this.

At the back you have two metal grids.

One collects the current of the n-type contacts and the other collects the current of the p-type contacts.

At the front side the losses of the light excited charge carriers due to surface recombination is suppressed by using the same tricks like the back surface field as discussed for the rear surface for solar cells, based on p-type wafers.

The surface recombination velocity of the front surface is determined by the minority charge carriers, in this case, the electrons.

At the front side the losses of the light-excited charge carriers, due to the surface recombination is suppressed by using the same tricks like the back surface field as discussed for the rear surface for solar cells based on p-type wafers.

The surface recombination velocity of the front surface is determined by the minority charge carriers, in this case, the holes.

Consequently, we have to create a front surface field.

A higher n-doped region is placed at the front surface indicated by n+.

The interface between the higher-doped n-region and the lower-doped n-region acts again like a p-n junction.

In this case it will act as a barrier for the light-excited minority holes in the lower doped region to diffuse to the front surface.

The front surface field behaves like a passivation of the defects at the front interface and allows to have higher levels for the hole minority densities in the p-doped bulk.

At the front side the reflective losses can be reduced using the same tricks as discussed for the PERL solar cell.

Deposition of double-layered anti-reflection coatings and texturing of the front surfaces.

SunPower is the company that has developed a cell technology based on interdigitated back contacts, and they have achieved high solar cell efficiencies of 24.2%.

An alternative concept with high efficiencies is the so-called crystalline wafer based hetero-junction solar cells as you see in this illustration.

First I have to answer the question: what is a heterojunction?

So far I have introduced you to the concept of p-n junctions with a depletion zone.

These junctions are fabricated by different doping types within the same semiconductor material.

This means the band gap in the p- and n-doped material is the same.

Such p-n junction is called a homojunction.

However, you can also make a junction by two different semiconductor materials.

For instance one semiconductor material that is p-doped and another type of semiconductor material that is n-doped.

This is what we call a heterojunction.

In the c-Si wafer based heterojunction we make use of two types of silicon based semiconductor materials.

One is again a n-type float zone monocrystalline silicon wafer, the other material is hydrogenated amorphous silicon.

This is a silicon material in which the atoms are not ordered in a crystalline lattice but in a disordered lattice.

Next week I will come back to this material when we are discussing thin-film technologies.

For the moment you only have to know that this material has a higher band gap than that of crystalline silicon.

Secondly, amorphous silicon can be n-doped and p-doped as well, using phosphorous or boron.

I won't go in detail, that is out of the scope of this course, but the electronic band diagram of a heterojunction of n-doped crystalline silicon and p-doped amorphous silicon in the dark and thermal equilibrium will look like this.

You see that next to the induced field due to the space charge region, some local energy steps are introduced.

These steps are caused by the fact that both band gaps are not the same.

At this junction you see that the valence band is higher positioned in the p-type amorphous silicon in reference to the n-type crystalline silicon.

This will allow the minority charge carriers, the holes, to drift to the p-type silicon.

However, you see in this example that the holes experience a smaller barrier.

In contrast to classical mechanics a particle cannot move through such barrier, in the case of quantum mechanics, this is still the case.

A large fraction of the holes can move through this barrier and this phenomena is called tunneling.

Now let's go to the crystalline silicon wafer based heterojunction solar cell.

This is a concept which has been invented by the Japanese company Sanyo, which is currently part of Panasonic.

The Panasonic cell is called the HIT cell, which stands for heterostructure with intrinsic thin film.

The HIT cell configuration has two junctions.

The junction at the front side is formed using a thin layer of only 5 nanometers of intrinsic amorphous silicon, which is indicated by the red color.

A thin layer of p-doped amorphous silicon is deposited on top and here is indicated with the blue color.

The heterojunction forces the holes to drift to the p-layer.

At the rear surface a similar junction is made.

First, a thin layer of intrinsic amorphous silicon is deposited on the wafer surface, indicated by the red.

On top of the intrinsic layer an n-doped amorphous silicon is deposited, indicated by the yellow color.

As discussed earlier, for high-quality wafers, like this n-type float-zone monocrystalline silicon wafer, the recombination of charge carriers at the surface determines the lifetime of the charge carriers.

The advantage of the HIT concept is that the amorphous silicon acts like a very good passivation material.

In this approach the highest possible lifetimes for charge carriers are accomplished.

The c-Si wafer based heterojunction solar cell has the highest achieved open-circuit voltages among the crystalline silicon technologies.

Panasonic achieved an open-circuit voltage of 750 mV.

How do the charge carriers travel to the contact?

The conductive properties of the p-doped amorphous silicon are relatively poor.

In the homojunction solar cells the diffusion to the contacts takes place in the emitter layer.

In contrast, in a HIT solar cell this occurs through the transparent conductive oxide material, like an ITO, which is deposited on top of the p-doped layer.

The ITO is needed as the conductivity of the p-type layer is too poor.

This results in such small diffusion lengths that a practical metal finger spacing can not be achieved using the p-type layers.

Therefore ITO is used.

An advantage of the HIT cell concept is that it allows to introduce the same contact scheme at the n-type back side.

It means that this solar cell can be used in a bifacial configuration, it can collect light from the front, and scattered and diffuse light falling on the backside of the solar cell.

Another important advantage of the HIT solar cell is that the amorphous silicon layers are deposited using cheap and straightforward plasma-enhanced chemical vapor deposition technology at low temperatures, not higher than 200 degrees Celsius.

This means that making the front surface and back surface field in this type of solar cells is very cheap.

Furthermore, this technology allows to use the n-type wafers.

Summarized, the high-efficiency crystalline silicon wafer based solar cells are shown here.

The record efficiency of a PERL solar cell was 25%, however, this was a lab-scale solar cell with an area of 4 cm^2.

The record efficiency for an interdigitated crystalline silicon solar cell has been achieved by SunPower.

They achieved an efficiency of 24.2 % on a wafer size of 155 cm^2.

Finally, for the c-Si wafer based heterojunction solar cell, Panosonic achieved an efficiency of 24.7% on a wafer size of 102 cm^2.

The efficiencies for multicrystalline silicon solar cells are lower as the wafer quality is lower.

The best efficiency achieved is 19.5% by Q-cells on a wafer with a size of 243 cm^2.

This is around 5% absolute below the record efficiencies based on monocrystalline silicon wafers.

Now we know the efficiencies of solar cells.

However, in practice we install panels on our roof.

In the next block we will answer the question: How do we make solar modules out of solar cells?