There is intense competition in the market for photovoltaic systems. With constantly new innovations, the manufacturers are reducing their production costs and are increasing the efficiency of the cells and modules. For this purpose they are improving the production processes along the chain from silicon to the module. Companies and research facilities are working together to produce high-quality silicon crystals and wafers that save as much material as possible. They are also improving the material quality using an innovative solidification process for quasi-monocrystalline silicon. And with a new separation process they are producing more wafers from the same amount of silicon.

Wafers made of monocrystalline or multicrystalline silicon are usually used for silicon-based solar cells. Multicrystalline silicon is produced cost-effectively by means of ingot casting, but does not attain the efficiency of standard monocrystalline silicon, which is grown in a complex process using the Czochralski method. The standard cell efficiencies achieved by this method of more than 21 % can also be attained, however, using the newly developed quasi-mono silicon, which researchers from SolarWorld can produce more cost-effectively using a new, crucible-free crystal growing process. This replaces the ingot casting method customarily used for microcrystalline silicon cells, in which the crucible and its coating provide a source for impurities and disruptive foreign nucleating agents. The new process enables them to produce a monocrystalline, dislocation-free and low-oxygen silicon.
In the next step, the crystal is cut into fine slices known as wafers. In order to improve this production step, the researchers are replacing the previously used lapping abrasive-based sawing technology with diamond wire cutting and specially adapted cooling liquid. Diamond saws can cut the crystals more quickly into wafers with less material loss. These are currently about 180 μm thick. Substantial material savings are still possible here, and within the next ten years the researchers want to attain 100 μm. By way of comparison, a sheet of paper is about 80 μm thick.

Before the wafers can be further processed into solar cells, they have to be cleaned. With newly developed processes, residues from the coolant and lubricant are removed along with organic adhesions and particles.

Crystallisation: Directional solidification

Directional solidification is the established process used for the large-scale production of multicrystalline silicon ingots for solar cells. New solidification concepts are aimed at producing quasi-monocrystalline silicon ingots that have higher efficiencies and fewer defects that reduce the life of solar modules. Here magnetic flux fields are also used. They allow the melt currents, which are mainly influenced by magnetic fields generated by the resistance heaters, to be adjusted specifically at the solid-liquid growth front, thereby improving the solidification process. A measurement method for such flow structures developed with the TU Freiberg confirms the results of the numerical simulations carried out in the research project.

The researchers developed the current process based on a previous project in which they melted polycrystalline silicon in the crucible to produce quasi-mono material. For this purpose, they laid monocrystalline silicon on the bottom of the crucible, allowed the crystal to grow from there, and then gradually lowered the temperature from below upwards. The process requires very accurate temperature control. It is also more complicated than the production of polycrystalline material as the monocrystalline crystallisation seeds are only allowed to melt slightly. Since disturbances in the crystal structure and impurities from the crucible still limit the efficiency that can be achieved with this method, the researchers developed the crucible-free quasi-mono process. In addition to improving the structural quality of the crystals with fewer dislocations and smaller recombination-active grain boundaries, this process also enables them to achieve a considerably lower concentration of impurities such as oxygen, carbon and metals. This in turn improves the efficiency of the processed solar cell.

Within the scope of the experimental work, they used various raw material deposits and seed templates, and selectively varied process parameters such as the heat outputs or the growth rate.

In order to further improve the manufacturing process and the furnace, the researchers used a newly developed simulation software for the crucible-free technology as well as a new measuring system. This model enables them to predict dislocations and dislocation clusters caused by thermo-mechanical stresses, as well as the distribution of residual stresses in the cooled crystal.

Diamond wire slices the brick into thin wafers

In the next step, the silicon rods are sliced into many thin silicon disks – the wafers. The industry generally uses thin steel wire for this sawing process combined with a silicon carbide suspension as an abrasive medium in the cooling liquid. Many wire loops are used to divide up the crystal ingot within a sawing step. Whereas smooth wires were previously used for this purpose, the developers are now using an optimised wire covered with diamond grains together with a newly developed lubrication and cooling fluid. Together with the manufacturers, they have adapted the saw wire and auxiliary materials for the new saw technology. The diamond wire consists of a steel core wire to which the diamond particles are attached with metal or synthetic resin deposits. With a diameter of 100-120 μm, the core wire is approximately as thick as a human hair, and the diamond grains used are 5-25 μm in size. The diamond wire enables the wire saw process to be sped up. Less than 3 hours is now required for the cutting, whereas this previously took more than 6 hours. In addition, the researchers are also experimenting with thinner wires less than 70 μm thick. This makes an even narrower cutting gap possible. This would reduce the material loss by about 30-40 % and thus achieve a greater wafer yield.

A further research project intends to further improve the diamond wire separation process with the aim of reducing the manufacturing costs in the cut-off process by about one-third.
Optimal adaptation of the wire and lubricant

In order to prepare for industrial use, the researchers investigated the wires and their wear behaviour. They examined how wire parameters such as the size, shape, distribution and density of the diamond grains as well as the type of bonding influence the sawing efficiency of the separation process. A cost-determining factor is how many silicon wafers a diamond wire can cut before the cutting properties diminish and the quality of the wafer is compromised.

During the investigations to optimise the process and prevent damage to the wafer surface, they used a special single-gap saw device and modelling software to illustrate the relationship between the process parameters and damage mechanisms. The cost of producing saw wires covered with diamond grains has already been significantly reduced in recent years.

Compared with the conventional wire saw process with abrasive slurry, the diamond wire process can be made more resource-saving and cost-effective. In cooperation with the manufacturer, the researchers have developed for this purpose special lubricants and coolants from a water-surfactant mixture as well as suitable processing methods. This new coolant is cheaper and more recyclable than glycol-based lubricants. It has to meet a wide range of requirements:

- Chip transport and cooling,
- lowest possible surface tension,
- non-corrosive to the metal parts of the machine,
- as environmentally friendly as possible.

The physicochemical properties of the surfactants used in coolants and cleaners have a considerable influence on the further wafer processing: a cooling lubricant with a good wetting and rinsing effect helps to increase the surface quality of the wafers. A very clean cutting gap can significantly reduce the breakage rate and significantly simplify downstream process steps.

The researchers have also developed special filtration techniques to enable the cooling lubricant to be recycled. These are necessary to separate the accumulated abrasive particles, the smallest of which are only a few hundred nanometres in size.

Before their further processing to form solar cells, the wafers are cleaned and then undergo an intensive final inspection. The purified wafer surface must be absolutely clean, as firmly adhering residues from the cooling lubricants from the separation process would interfere with the subsequent cell production processes.

The researchers have developed a cleaning method that removes not only the residual kerf as a waste product of the separation process, but also metallic and organic contaminants. For this purpose they have also adapted an ultrasonic method to meet these special requirements.

Production of mono- and polycrystalline solar silicon

The production of monocrystalline silicon is complex. It is usually carried out using the so-called Czochralski method. A seed crystal is introduced into the liquid silicon melt. When the seed crystal is slowly rotated and extracted, a single crystal with a homogeneous structure is formed. Monocrystalline silicon can achieve an efficiency of 25 % under laboratory conditions and about 21 % in industrial production.

Poly- or multicrystalline silicon is generally produced in a controlled melting and cooling process by casting ingots in a coated crucible of high-purity quartz material. Crystals grow from the bottom of the crucible upwards. The size, structure and purity of the crystals influence the performance of the later solar cells. Multicrystalline silicon can be produced more cost-effectively, but the industrial and laboratory efficiencies remain about 2 % below that of single-crystal silicon.

The new quasi-mono process takes a middle position between ingot casting and the Czochralski method. It functions without a crucible, so no impurities can diffuse from the crucible during crystallisation. In the furnace, molten silicon drips onto a rotating monocrystalline plate and grows to form a quasi-monocrystalline brick. This makes it possible to achieve a cell efficiency of more than 21 %.
Increased efficiency, reduced costs

The price-induced pressure to innovate in the photovoltaic industry is leading to rapid progress in the production and efficiency of PV systems. As a result, the production costs for photovoltaic electricity are declining significantly: they currently amount to 3-8 cents per kilowatt hour for new solar power plants.

Of the total costs required for a PV module, approximately 15% is incurred by the production of the Si wafers and the solar cells, while the module production now requires more than half.

The research project focused – with crystallisation and wafering – on optimising two steps in crystalline silicon technology. In the widespread silicon photovoltaics industry, such innovations can be introduced relatively quickly into existing production lines. This enables the industry to improve the efficiency and cost structure while maintaining proven production processes.

In the dominant field of silicon photovoltaics, research facilities and companies are developing solutions that make it possible to generate solar power more cost-effectively at all stages of the cell and module production. For example, they are working on bilaterally active bifacial modules as well as on new tandem solar cells based on silicon in order to achieve even higher efficiencies.

A new kerfless wafer process developed by Nexwave, a spin-off from Fraunhofer ISE, eliminates the melting, crystallisation and sawing steps required in conventional processes. By means of gas-phase deposition, the monocrystalline silicon wafers instantly grow to the required material strength on a multi-reusable seed wafer. Efficiency records are soon surpassed by new ones not only in the case of silicon but also with other photovoltaic technologies such as thin-film, perovskite and organic PV.

It is important that these research results and innovations are transferred as quickly as possible into industry so that photovoltaic electricity can be produced even more efficiently and economically in the future.

Project participants

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