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# RIBBON-GROWTH-ON-SUBSTRATE: PROGRESS IN HIGH-SPEED CRYSTALLINE SILICON WAFER MANUFACTURING

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## ABSTRACT

The Ribbon-Growth-on-Substrate (RGS) silicon wafer manufacturing technology is the most promising high-speed wafer production technique under development at the moment. It has the promise to lead to a manufacturing technology, which allows silicon wafer manufacturing at the 25 MWp/a to 50 MWp/a level.

A future development of this technology in the areas, RGS machine prototyping, wafer quality improvement and solar cell process optimization should lead to a commercialization of this technology in 2005.

In the following a status of the RGS technology today and the most probable road ahead is outlined.

## MOTIVATION

In the last years a remarkable growth of the PV industry with annual growth rates well above 25% was achieved [1]. As it is expected that PV can and will maintain growth rates at 25 to 35% in the foreseeable future [2]. This also means that the PV industry has to adjust its manufacturing capacities to satisfy the market.

To fulfill this market demand is the main challenge for PV manufacturing technology in the next years. Although it is expected that the world PV market will approach GWp module shipment levels shortly after 2006, the technology to produce PV modules efficiently on the 100 MWp scale is not available yet. Thus technological developments can be expected in all parts of the PV module production chain, from solar grade silicon, over wafer and solar cell manufacturing to module production. In the field of wafer production, the ribbon-growth-on-substrate silicon wafer technology promises the effective production of silicon wafers at low manufacturing costs, at high production rate and with almost 100% silicon usage.

## LOW COST – HIGH THROUGHPUT Si WAFER MANUFACTURING

The idea of lowering the wafer manufacturing costs by avoiding the wafer-cutting step with its silicon loss was the main motivation for the development of a number of silicon ribbon growth technologies. From these different technologies, developed in R&D programs such as the JPL Flat-plate solar module project [3], only a few are used in commercial wafer production today. The most prominent among them are the edge-defined film fed growth (EFG), the string ribbon (SR) and the dendritic web technology. But these technologies have the disadvantage that production direction is in line with the silicon crystal growth, which does not allow the combination of high production rate with good material quality (see table 1).

Other silicon ribbon technologies with the potential for high production rates by de-coupling ribbon production from crystal growth (such as the low angle silicon sheet (LASS) or the supporting web (S-Web)) are not developed to industrial production yet. The successful development of at least one of these methods would lead to a major breakthrough in silicon module productivity and manufacturing cost and plays thus a key role in the future development of the PV industry.

Table 1: Production speed and capacity of different silicon ribbon production technologies. The last column shows the number of furnaces for a 100 MWp production line. [4]

| Material | Pull speed (cm/min.) | Throughput ($cm^2$/min.) | Furnaces per 100 MWp |
|---|---|---|---|
| EFG | 1.7 | 165 | 100 |
| SR | 1 – 2 | 5 – 16 | 1175 |
| RGS | 600 | 7500 | 2 – 3 |

### The RGS technology

The ribbon-growth on substrate technology is a silicon wafer manufacturing technology, which belongs to the above mentioned class of high speed ribbon technologies, where crystallization is de-coupled from wafer production (see principle of the RGS technology in figure 1).

This technology was developed by Bayer AG [5] throughout the 80's and 90's. In this phase, two laboratory-scale machines were built to demonstrate the RGS process principles and potential.

Together with Bayer's decision to stop its solar silicon activities in 2000, a new co-operation between Deutsche Solar as successor of Bayer Solar and ECN was signed in order to set the next steps towards a commercialization of the RGS wafer manufacturing technology. This development is now undertaken by a Dutch consortium of ECN and S'Energy with the objective to commercialize the RGS technology in 2005.

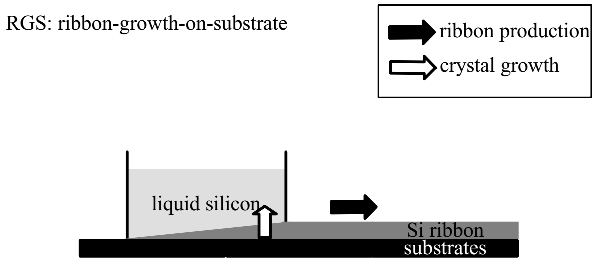


Figure 1: Principle of the RGS ribbon growth process. The relatively cold substrate extracts the crystallisation heat from the liquid silicon in the casting frame. This causes the growth of a silicon ribbon in contact with the substrate. By transporting the substrate from the casting zone into the cooling down section, crystal growth is stopped and the Si ribbon can be removed.

## RGS TECHNOLOGY DEVELOPMENT

In order to develop the RGS technology further three main technological challenges have to be met:

- The experience from the laboratory scale machines has to be transferred into the development of a continuously operating RGS silicon wafer-manufacturing machine. This prototype machine has to demonstrate the cost efficient and reliable wafer manufacturing.
- Silicon wafer quality has to be enhanced to allow the use of RGS wafers in existing and new to be built solar cell manufacturing lines. For this purpose geometrical, mechanical – and electrical wafer quality characteristics must be met.
- An RGS wafer based solar cell process has to be developed that can be implemented in existing solar cell manufacturing lines with a minimum of changes to the industrial cell process. This process must meet competitive cost per Wp ratios.

To come to an acceptable market introduction time all three fields must be developed in parallel. For this purpose two R&D projects were started, the Dutch RGSolar project with main emphasis on RGS prototype machine development and wafer process technology and the EC co-financed RGSells project where RGS wafer based solar cell process technology is developed.

### RGS prototype machine development

The strategy in the development of the new RGS wafer-manufacturing machine was based upon the following ideas:

- The machine should translate the process of the batch-wise operating single shot machine into a continuously operating machine.
- The machine should maintain operation even in the case of limited duration processing problems. For this purpose silicon melt control, replacement of substrates on the fly and many other safety mechanisms will be included in the machine.
- In opposite to silicon ingot growth or CZ crystal pulling, RGS wafer production involves mechanical movement with high precision at high temperatures. The design was made in a way that the mechanical movement is not in contradiction with the demand of minimum contamination of the hot silicon by particles from metallic parts of the machine.

Although building silicon crystal pulling machines is state-of-the-art technology in the semiconductor and solar industry, the intended RGS machine will push the limits of silicon technology. The continuous Si melting rate will be a factor of 2 higher than the melting rate achieved during CZ-growth melt replenishment. Substrate materials have to be developed and optimized that can withstand the repetitive contact with liquid silicon and the temperature cycles in the machine for a long time. Mechanical and thermal stress of the wafers and machine parts has to be minimized while operating at high speed under large temperature variations.

All these conditions combined with the experience of the consortium lead to a machine design, which will be realized in the near future (cross section see figure 2).

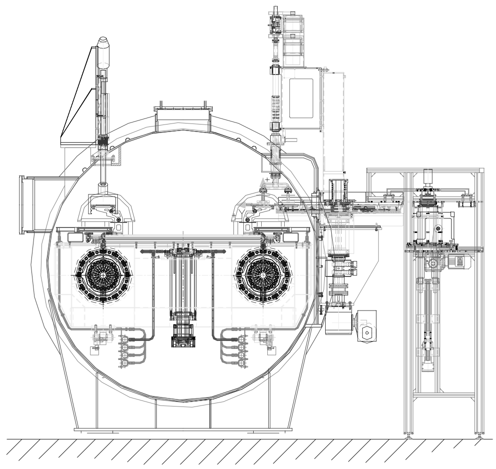

Figure 2: Cross section of the RGS machine. In the lower part of the vacuum vessel the mechanical drive is enclosed, while in the upper section the furnace and casting sections are situated. Wafer stacker and wafer load lock is shown on the right. The diameter of the machine will be about 3.5 m.

### RGS process development

The most important field of research in the development of the RGS wafer manufacturing process is clearly the silicon-substrate interaction. The thermal behavior of the substrate has a major influence on the growth conditions of the silicon wafer and determines its crystallographic and electronic properties. As the substrate will be re-used in the RGS process the changes to the surface of the substrate caused by its contact with silicon are of major importance. The number of growth cycles (lifetime) of the substrate is one of the major factors in the economics of the RGS process (see fig. 3).

Liquid silicon is very well known to cause erosion to almost any material. It is forming low temperature alloys with most metals, it is dissolving quartz, and it is reacting with graphite. Furthermore it is very sensitive to small amounts of impurities, that might infiltrate from substrate materials such as ceramic materials with metallic binders. Thus the number of materials that can be used as substrates in contact with silicon is restricted.

Further boundary conditions that have to be taken into account when designing an optimum substrate material are the heat removal properties, the wetting behavior, the chemical reactivity and the thermal expansion. These factors influence the crystal growth, the separation of substrate and silicon ribbon as well as the economics of the process.

Since the beginning of the RGSolar project, major progress in substrate material development has been made, which lead to a substrate lifetime increase by one order of magnitude. In the future, it is expected that a deeper understanding of silicon - substrate interaction will lead to further improvements mainly in the field of crystal quality. Depending on substrate costs, lifetimes in the range between 100 and 1000 growth cycles must be achieved in order to make RGS wafer manufacturing cost competitive.

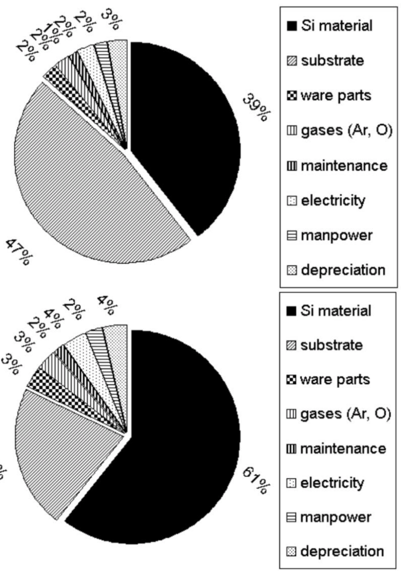


Figure 3: Calculated wafer manufacturing cost distribution in the case of a 300 (top chart) respectively a 1000 growth cycle substrate lifetime. In the second case silicon material causes more than 50% of the wafer costs, while in the first case the substrate costs are a key factor. Due to the high machine productivity, other costs are less restrictive.

## Solar cell process development

Record solar cell efficiencies achieved with RGS wafer based solar cells show a remarkable trend over the last 10 years. One of the main reasons for this development was the good co-operation between wafer manufacturer (Bayer AG), solar cell process developers as well as basic silicon material research and development (HEXSi, KoSi projects). This lead to an increased understanding of the material characteristic and the behavior of the RGS wafer in a solar cell process. The consequences of this development can be seen by the steady efficiency increase as shown in figure 4.

In the future, it is expected that this development can be continued at the same or even increased speed. In order to do so, the next step will be to reduce the high oxygen content of the wafers. This limits at the moment the effect of hydrogen in-diffusion and thus the efficiency of an RGS solar cell in an industrial-type cell process. Further efficiency influencing factors are the formation of oxygen related recombination centers (thermal and new donors) [6, 7, 8].

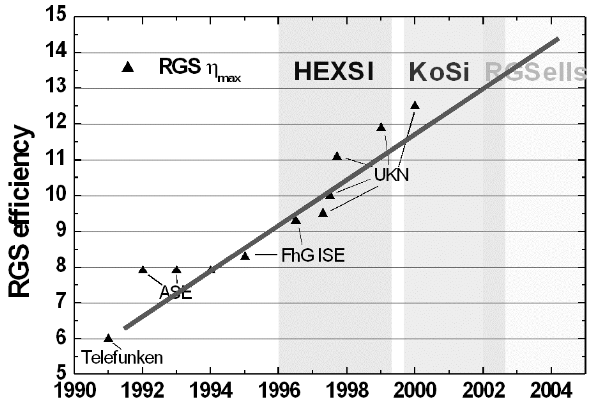


Figure 4: Record RGS solar cell efficiencies. Earliest results were from Telefunken and its successor ASE. In later projects the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) and the University of Konstanz (UKN) held the efficiency records. [9].

With the RGS wafers today, hydrogen in-diffusion during an industrial type firing-through-silicon-nitride-process is limited to less than 10 µm in depth. In figure 5, a near surface photoconductance measurement (QSSC) of an RGS wafer is shown [11]. The difference between 'as grown' and 'after cell process' curve clearly demonstrates the effect of hydrogen passivation (lifetime limit at high injection levels). After removing a 30 µm silicon layer (recycling) the effect of the hydrogen passivation is no longer visible.

Another eye-catching effect of the apparent lifetime curves is the strong increase of the apparent lifetime at lower injection levels. This is most probably caused by carrier trapping effects [10], which can be influenced by thermal processing. When RGS wafers with lower oxygen content are grown, the trapping behavior is completely different. This indicates that the observed traps are related to oxygen.

By better silicon melt treatment and by improving RGS wafer growth conditions, lower oxygen concentrations in the wafer are possible. This should increase the diffusivity of hydrogen in the material and lead to sufficient hydrogen passivation even in short-duration processing steps such as a PECVD SiN coating with successive metallisation firing process. The implementation of these steps should bring RGS wafers a step closer to standard industrial processing.

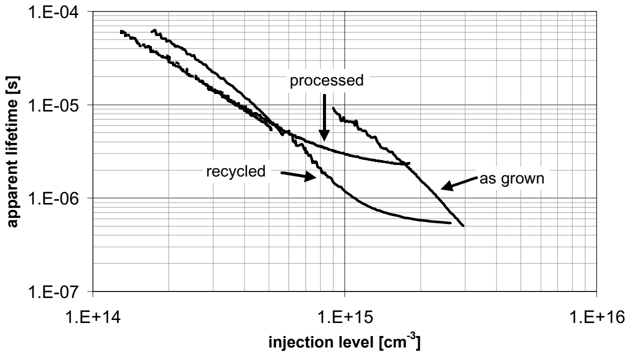


Figure 5: Injection level dependent apparent lifetime measurements (QSSC measurement [11]). The difference between 'as-grown' and 'processed' curve shows the effect of cell processing (increased carrier lifetime, reduced trapping). After chemical removal of a 30 µm silicon layer the passivation was no longer visible.

## SUMMARY

Ribbon-Growth-on-Substrate silicon wafer manufacturing technology is one of the most promising technological developments for the further improvement of silicon wafer based PV modules. Its productivity rate in the 25 MWp to 50 MWp range allows the construction of a 100 MWp wafer production facility with only 2-4 RGS machines.

In two R&D projects RGSolar and RGSells, the three important areas of RGS technology are developed in parallel. The design of RGS prototype machine is now in a state that the machine can be build. Wafer manufacturing process development and solar cell processing techniques are developed in parallel in order to maintain the efficiency increase speed that was characteristic for RGS in the past. It is expected that a lower oxygen content of the RGS wafers will make them more compatible to industrial type cell processing and will lead to a step in solar cell efficiency.

These results and the promises of high-speed, low-cost silicon wafer manufacturing are the driving force to push this technology forward to commercialization in 2005.

## ACKNOWLEDGEMENT

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