DIELECTRIC REAR SIDE PASSIVATION ON RIBBON GROWTH ON SUBSTRATE (RGS) SOLAR CELLS

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ABSTRACT: Ribbon Growth on Substrate (RGS) silicon wafers are cast directly from the melt onto reusable substrates. With a high production speed in the order of one wafer per second and the avoidance of material loss due to wire-sawing like in the block-casting technology, RGS is a cost-effective material. The wafers are multicrystalline with typical grain sizes between 0.1 mm to 1 mm. Up to now, the adapted solar cell process contained an open rear side metallization realized by an Al-grid [1]. This had to be implemented because of increased process induced shunting in cell areas with Al back side metallization. For rear side passivation and avoidance of possible shunting, two new cell back side designs are tested and compared to the RGS baseline process. In this work, silicon carbide as a dielectric passivation layer and its properties regarding a co-firing temperature step and the application of such a layer in the RGS solar cell process is investigated. It is found that a cell process for RGS containing a dielectric layer on the cell rear side in connection with Laser Fired Contacts (LFCs) enhances the cell performance by reducing the area of possibly contacted shunting paths further and thus increasing the parallel resistance of the solar cells. The gain in efficiency is hereby less attributed to the improved rear side passivation quality for this material with a limited diffusion length.

Keywords: Ribbon Silicon, Silicon Carbide, Laser Processing

1 INTRODUCTION

The Ribbon Growth on Substrate (RGS) [2] technology is a cost-effective approach in terms of silicon usage per watt peak in respect to material loss through e.g. wire-sawing of block-cast material. The wafers are cast directly out of the melt onto reusable substrates. The separation of pulling and crystallization direction (Figure 1) results in a high production speed in the order of one wafer per second and grain sizes between 0.1 mm and 1 mm.

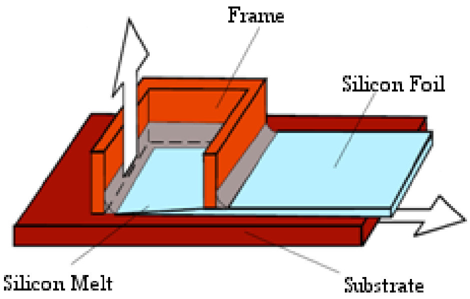

Figure 1: Diagram of the RGS wafer casting principle.

Because of the fast crystallization the wafers have a relatively high density of crystal defects [3,4] like dislocations and contain carbon and oxygen impurities.

The results achieved with wafer material cast with the laboratory scale R&D installation in the Netherlands at ECN, resulted in the decision to build a new industry scale installation operated by RGS Development B.V. This new installation is already producing silicon wafers but is in the phase of testing the process stability and optimization of casting parameters. Thus all wafers presented in this work originate from the R&D machine at ECN.

2 SOLAR CELL PROCESSES

Table I shows recent cell results from a photolithography based process (A, cell size: 2x2 cm^2) and a screen-printing based process (B, cell size: 5x5 cm^2) on RGS wafers.

Table I: Cell results of (A, cell size 2x2 cm^2) a photolithography based process, (B, cell size 5x5 cm^2) an industrial type screen-printing process.

	FF (%)	J_{sc} (mA/cm²)	V_{oc} (mV)	η (%)
A	77	29.0	594	13.3
B	73	28.4	591	12.2

The photolithography based process is an adaptation containing a single-side emitter of the University of Konstanz (UKN) high-eta process which Junge et al. reported in [5]. The industrial type screen-printing baseline process (Figure 2A) for RGS was developed by Seren et al. [6]. Prior to the processes the wafers are planarized. This is a mechanical leveling of the slightly uneven top surface as result of the substrate based casting process. After planarization, the wafers have to be etched to remove defect rich layers on the surfaces. Both processes contain a single side emitter realized via a SiN_x capping layer before $POCl_3$ emitter diffusion. After the diffusion the capping layer is removed by a diluted HF solution. For the screen-printing process, anti-reflection coating (SiN_x) is applied afterwards and the contacts are formed by screen-printing and a co-firing step. An industrial standard metallization (Figure 2B) is realized by a screen-printing of an Al metal paste with full coverage of the cell backside. In contrast, the RGS baseline process involves screen-printing of an Al-grid (~10% coverage) on the cell backside to reduce process induced shunting [6]. To test new rear side cell designs two other metallization techniques containing a dielectric layer (silicon carbide) were investigated. After applying a silicon carbide layer by Plasma Enhanced Chemical Vapor Deposition (PECVD) the metal contact is formed either by laser ablation of the SiC layer and screen-printing of Al paste (Figure 2C) or by evaporation of Al (Al layer thickness ~1.5 µm) and Laser Fired Contacts [7] (Figure 2D). Both processes use a pitch between the local contacts of 0.5 mm and a diameter of the local contacts of ~100 µm.

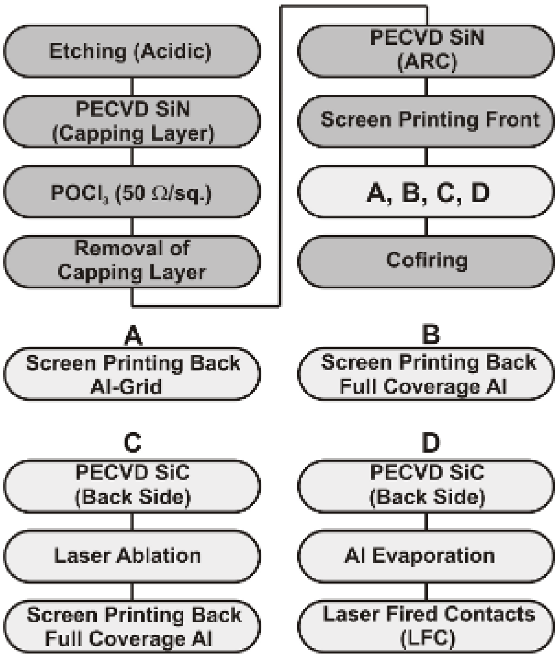

Figure 2: RGS solar cell processes. A) Standard UKN RGS cell process. B) Standard industrial metallization. C) Dielectric layer and laser ablation. D) Al evaporation and "Laser Fired Contacts".

3 SiC AS SURFACE PASSIVATION

Prior to the integration of the dielectric silicon carbide layer into the cell process several investigations including the stability of the surface passivation under metal paste co-firing conditions (peak temperatures at ~ 860 °C) are carried out. This temperature regime is not optimal for achieving a good surface passivation. Annealing at other temperatures and/or an application of stacks with different dielectric layers can result in a far better surface passivation [8]. However, this process design is chosen to simplify integration in the existing RGS baseline solar cell process.

Multicrystalline samples are damage etched and RCA cleaned before the deposition of the SiC layer on front and rear surface. A Quasi Steady State Photo Conductance (QSSPC) measurement is carried out before and after the firing step to determine the development of the surface passivation quality. The first experiment is carried out using a SiC layer thickness of 70 nm, while the samples in the second test are prepared with a layer stack of SiC (70 nm, first layer) and a SiO layer (70 nm, second layer) which is also deposited using a lab-type Oxford Plasmalab 100 PECVD system. Experiments to add a third SiN_x layer with an industrial PECVD setup show poor results (~1-5 µs), most likely because the SiC and SiO layers are damaged by the plasma pre-clean steps.

In the experiments the ratio of gas flow of CH_4 to SiH_4 for the silicon carbide is varied. This is done because a change in the gas flow ratio and therefore a change in the composition of the silicon carbide layer has a strong influence on passivation quality and temperature stability [8].

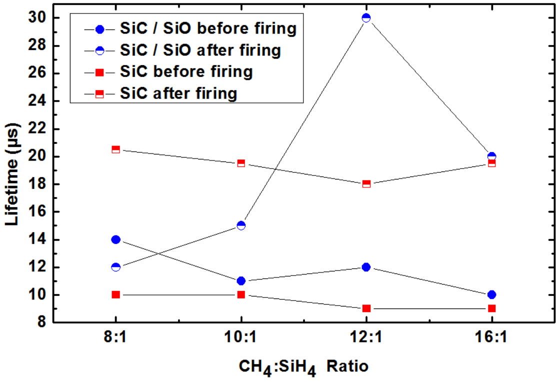

Figure 3: Minority charge carrier lifetimes (measured by QSSPC) of mc wafers with different surface passivation layers before and after a firing step (peak temperatures ~860 °C).

Before the temperature step all lifetimes are in the range of 10 µs and after firing in the range of 20-30 µs (see Figure 3). In order to anneal and/or passivate the dielectric/Si interface a Microwave Induced Remote Hydrogen Plasma (MIRHP) process is applied after firing. However, the lifetimes changed only in the range of ~1 µs. Annealing and rehydrogenation at lower temperatures without a process step including such high temperatures (~860 °C) is wide more effective [8] in terms of enhancement of the passivation quality. Therefore it is assumed that the temperature of the standard metallization co-firing conditions heavily affects the SiC layer.

As Figure 3 shows, the passivation quality of a SiC layer alone and a SiC/SiO stack after a firing step at high temperatures are comparable. The SiC/SiO stack at a ratio of 12:1 shows a peak lifetime of 30 µs. However, for a probable industrial application the use of a single SiC layer is easier implementable and it shows a more constant behavior under varying conditions and the lifetimes are in the same order of magnitude. Therefore, a single SiC layer at a CH_4:SiH_4 ratio of 10:1 was used as rear side passivation layer in the RGS solar cell process.

4 CELL RESULTS

RGS wafers from the same casting run are processed as shown in Figure 2A, 2C and 2D. Table II shows the best results.

Table II: RGS cell results (5x5 cm^2). A, C and D correspond to the processes shown in figure 2.

Process	FF (%)	J_{sc} (mA/cm²)	V_{oc} (mV)	η (%)
A	68.2	28.6	587	11.4
C	68.5	28.2	584	11.3
D	71.9	29.1	591	12.4

Since the R&D machine works discontinuously, the material quality of wafers from different casting runs may differ because of adjusted casting parameters. But processes with other RGS casting runs show comparable tendencies. The screen-printing based cell process (A) with an open rear side metallization results on average in slightly better cell performance than the process with a silicon carbide layer opened by a laser (C), in particular concerning the fill factor. In all cases, the LFC process (D) led to the best results. The dominant factor of the decreasing of the fill factor of RGS solar cells is a low parallel resistance. The cells of the LFC process have a ~2-4 times higher parallel resistance than the average of all differently processed cells.

5 DISCUSSION

Compared to other materials, the relatively strong variation of cell parameters on different RGS cells can be addressed to material quality variations due to the batch-type casting process of R&D lab-type machine. However, a trend of better fill factors of the open rear side process (A) compared to the laser ablation process (C) on average is detectable. This can be explained by the different size of the actual contacting area. The Al-grid contacts around ~10 % of the wafer rear side but the laser ablation process only around ~3 %, which corresponds to an increased contribution to the cells series resistance. Due to these two effects, the passivation property of the silicon carbide layer shows no clear observable influence in cell parameters. Another uncertainty is the damage of the silicon crystal by the local laser ablation of the SiC layer. The LFC process (D) showed in all cases the best cell parameters. However, this seems also not to be a result of the improved back surface passivation due to the silicon carbide layer but more probably the result of the way of contacting in terms of improving the parallel resistance. Figure 4 shows long wavelength Internal Quantum Efficiency (IQE) curves of representative differently processed RGS wafers.

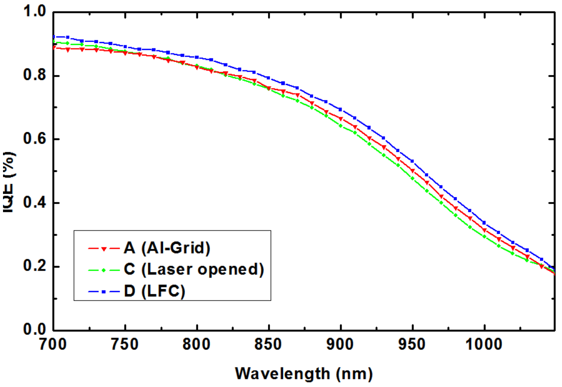

Figure 4: Long wavelength IQE curves obtained by Spectral Response measurements of differently processed RGS solar cells.

The IQE in the long wavelength regime (>800 nm) reflects, besides the material quality which is assumed to be comparable for all cells, the quality of the rear side passivation. The overall trend that the solar cells processed with LFC show a higher IQE is observable but it is still near the area of uncertainty provided by the variations between different RGS cells. The effective diffusion length of minority charge carriers, obtained by a Basore fit [9], was on all RGS cells between ~60-80 µm. With a cell thickness of ~220-250 µm a possible effect of a passivation provided by the silicon carbide layer would therefore be difficult to see. The impact of an increased rear side reflection of the evaporated Al in the LFC process and therefore an increase in J_{sc} is not clearly distinguishable from other effects.

Thus, it seems that mainly the way of contacting shifted the solar cell results to better values. This is in agreement with earlier investigations in which was found, that standard Al metal pastes heavily affect the RGS crystal structure resulting in cell shunting. An investigation of the depth of the Al-BSF formation showed a metal penetration at grain boundaries up to 70 µm within the crystal [10]. Comparing spatially resolved Lock-In Thermography measurements with parallel resistances in this and other RGS solar cell process runs, suggest not only a penetration of Al due to the firing process but a deep spiking of the Al and therefore shunting and short-circuiting of the cells. Thus, the focus of future work was to replace the fully covering backside metallization with an open rear side metallization realized by an Al-grid.

Figure 5 shows Light Beam Induced Current (LBIC) maps of two different RGS cells (originating from the same RGS casting run). The two image parts correspond to the laser ablation (Fig. 5A) and the LFC process (Fig. 5B). In both cases a regular pattern which could be affiliated to the local SiC openings is not visible. In contrast to the laser opened cell, the LFC cell shows an increased average IQE.

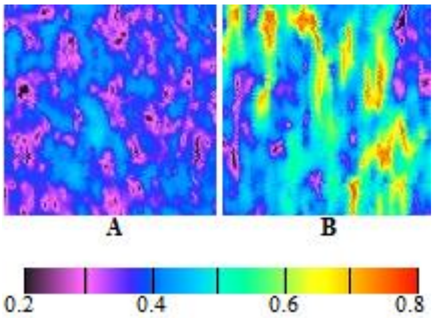

Figure 5: The two LBIC maps show the IQE for a 980 nm laser wavelength. The size corresponds to 2.5 mm^2 each. The cells were processed via laser opening (A) and LFC (B).

Interestingly, LBIC maps of the same differently processed RGS cells did show only small difference in distribution of the IQE (which is comparable to figure 4) when using a laser wavelength of 910 nm for the measurement. Therefore the effects of laser damage, metallization and dielectric passivation seems to be located only near the cells rear side. An effect of the reflection of the differently processed cells at these wavelengths is not distinguishable from other effects and cannot be a solely explanation for this behavior.

Lock-In Thermography measurements did not show any regular pattern of increased local temperature due to process induced defects, which could be correlated to shunting along the local contacts, too.

6 SUMMARY

RGS wafers from the batch-type lab-scale machine at ECN have been processed to solar cells. Three different rear side designs are investigated. Besides the current RGS industrial-type screen-printing baseline process with an open rear side metallization (Al-grid, 10 % coverage) two new back side designs are tested. Both contain a silicon carbide layer as dielectric passivation, which was locally opened via laser ablation or by a LFC process. On all cells the LFC process results in better cell parameters relative to the two other processes. Spectral Response measurements reveal that in the long wavelength regime (> 800 nm) all the cells show similar properties with a trend of slightly better IQEs for the LFC process. This is understandable since the cells have an effective diffusion length of minority charge carriers around ~60-80 µm with a cell thickness of ~220-250 µm. The effect of an improved rear side passivation due to the SiC layer is therefore difficult to see. A contribution of the different back side reflections to the current densities of the cells is not clearly distinguishable from other effects.

From earlier investigations, it is known that Al metal pastes relatively heavily interacts with the crystal structure of RGS during metal firing. Consequently, the rear side contact areas often show up as the preferred locations for cell shunting. Additionally due to the low diffusion length, it is not clear how much the laser damage of the laser ablation process affects the cell parameters. Therefore, it is suggested that the trend of better cell results of the applied LFC process is unlikely the effect of the rear side passivation but of the way of contacting the RGS solar cells it in terms of reducing the contacted rear side area and possibly the avoidance of the industrially used Al metal pastes.

7 OUTLOOK

The results of this work apply to the RGS wafers cast by the discontinuous operating R&D machine. Since the new industrial scale installation was planned and built to improve the material quality in terms of diffusion length and crystal structure, a reassessment of rear side passivation investigations for wafers from the continuous working production machine will be necessary.

However, it was demonstrated that either by contact area reduction or by reducing possible spiking of commercial Al pastes during metal sintering, the solar cell characteristics could be improved. Therefore, the application of modern laser processed, local back contacts has clear advantages for RGS wafer based solar cells.

8 ACKNOWLEDGMENTS

Part of this work was funded by the BMU in the OP-RGS (0325056) project. The supply of RGS wafers by RGS Development B.V. and ECN is gratefully acknowledged. The content of this publication is the responsibility of the authors.

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