Efficiencies above 16% on novel quasi-mono RGS material

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Abstract

To date, solar cells made from kerf-less and cost-effective Ribbon Growth on Substrate (RGS) Si material suffered heavily from shunting problems. In combination with the low material quality, this led to decreased fill factor values and thus to significantly lower efficiency values compared to block-cast multicrystalline (mc) Si. In this study, a novel RGS material seeded on silicon substrate is investigated. Solar cells made from this new ‘quasi-mono’ material using a lab-type process show Voc values >600 mV and average fill factor values >78%, similar to standard mc-Si. This leads to cell efficiencies >16% (certified by ISE CalLab), which is an enormous progress compared to the former efficiency record of 14.4%. The obtained higher fill factor values are most probably due to the absence of current collecting structures, in contrast to standard RGS material, as shown by infrared microscopy investigation. This was also found comparing Internal Quantum Efficiency topograms and Electroluminescence maps. For this new material, minority carrier lifetime is in the range of 18 μs (after P-gettering and hydrogenation) and hence approximately two times higher than for standard RGS, which explains the higher achieved Voc. Furthermore, the bulk quality of this novel RGS material is more homogeneous and its grain orientation is predominantly (100), allowing the use of an alkaline texture.

Keywords: Ribbon growth on substrate; kerfless; shunt; current collecting structures

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1. Introduction

The silicon wafer represents about 40% of the total module cost [1, 2]. The main reasons for this are material losses during wafer sawing, the so-called kerf loss; the expensive wafering; and the high energy consumption for crystallization. To overcome these losses, kerfless silicon wafers from sheet growth techniques such as String Ribbon (SR), Edge-defined Film-fed Growth (EFG), Ribbon on Sacrificial Template (RST), Direct Wafer (from 1366 Technologies [3]), and Ribbon Growth on Substrate (RGS) offer a possible alternative [4]. RGS material is a very cost-effective material for solar cell fabrication, because of its high production capacity (~1 wafer/s), the material savings avoiding the wafer sawing process, and the reduced energy consumption for crystallization. However, this material suffers from a high density of structural defects (grain size ~0.2 mm, dislocations) and from relatively high impurity densities (e.g. \([\text{C}] >10^{18}/\text{cm}^3, [\text{O}] >10^{17}/\text{cm}^3\)). This leads to low minority carrier lifetimes and hence, in combination with shunting problems due to current collecting structures [5], to reduced cell efficiencies compared to block-cast mc-Si. Up to now, the highest efficiency obtained for RGS material was 14.4% [6]. This work focuses on the investigation of a very promising RGS material of higher quality. After processing the different materials into solar cells, they are characterized by means of IV, spectral response, Light Beam Induced Current (LBIC) and Electroluminescence (EL) measurements, as well as by using the dark Lock-in Thermography (dLIT) technique. Subsequently, representative solar cells are selected, etched back and investigated via the microwave-detected Photo Conductance Decay (µ-PCD) method, infrared (IR) transmission microscopy, and Electron Backscatter Diffraction (EBSD).

2. Investigated materials and solar cell process

2.1. Investigated materials

The novel RGS material (RGS_A) differs from the standard RGS (RGS_Std) in the used silicon-based substrates and morphologies during crystal growth. While for crystallization of standard RGS material structured polycrystalline silicon carbide (SiC) substrates are used, the novel RGS material was crystallized on structured solid monocrystalline silicon substrate. As shown by Pichon et al. [7], a low adhesion of the solidified silicon on the substrate is necessary to allow its easy self-detachment after solidification. Both RGS materials are B doped (p-type), but the novel RGS has a significantly reduced average resistivity (0.7 Ω·cm) compared to the standard RGS (3.7 Ω·cm), although the same amount of B was added. Note that both materials are cast from the same Si melt in the same wafer fabrication run. The resistivity of this new RGS material correlates well with the added amount of B in the silicon melt. This means that all or almost all B atoms are electrically active in the novel RGS material in contrast to the standard one, because for resistivity measurement via Quasi-Steady-State Photo-Conductance decay (QSSPC) method only electrical active B atoms are taken into account. The discrepancy between the measured resistivity values (0.7 Ω·cm and 3.7 Ω·cm) can partly be explained by a possible difference between majority carrier mobilities in the two RGS materials. However, even a difference of a factor of 2 to 3 between the mobilities as has been shown in [8] comparing monocrystalline silicon and older more defect- and oxygen-rich RGS material can not solely justify this large discrepancy (of a factor of 5) between the resistivity values. For comparison, also block-cast mc-Si (p-type, 1.4 Ω·cm) was processed which is denoted as (the acronym) mc-Si_Ref.

2.2. Solar cell process

To evaluate the efficiency potential of this novel RGS material, a PERC lab-type solar cell process was used. An isotropic plasma texture was applied on the front surface, to ensure the comparability of the different materials under investigation. The front side contacts were structured by photolithography and thin triple layers of Ti/Pd/Ag contacts were deposited using an electron beam evaporator. The rear side was passivated with an Al₂O₃/SiNₓ stack and after evaporation of a ~2 μm thick Al layer, the contact to the silicon bulk was realized via Laser Fired Contacts (LFC) [9]. This PERC-type cell process is particularly well-suited for defect-rich silicon material, because of the applied low thermal budget and excellent hydrogenation of bulk defects, as described in detail in [10]. The resulting 2×2 cm² solar cells are cut out from almost completely processed 5×5 cm² wafers after thickening the front contacts by light
induced Ag plating. Consequently, they have open pn-junctions on the edge like for most industrial processes. Finally, the solar cells can receive a second antireflection coating made from MgF₂ after the first IV measurements.

3. Results and discussion

3.1. IV parameters

In Fig. 1 box plots of IV parameters of solar cells processed from both RGS materials as well as from the mc-Si reference (mc-Si_Ref) material are shown. The presented data are for solar cells with a double antireflection coating (SiNx:H/MgF₂). For both RGS materials, the average $j_{SC}$ value (~33.9 mA/cm²) is on the same level. However, the new RGS material (RGS_A) shows higher $V_{OC}$ values than the standard RGS material (RGS_Std). The median and average values of $V_{OC}$ are for RGS_A ~10 mV higher than for RGS_Std. $V_{OC}$ values up to 608 mV were achieved, which is the highest $V_{OC}$ value realized to date for RGS material. In comparison, an average $V_{OC}$ value of 624 mV was obtained for mc_Si_Ref.

Interestingly, fill factors of solar cells made from RGS_A are ~78% (parallel resistance $R_P$ >10 kΩ-cm²) which almost corresponds to the values of the mc-Si references. On the contrary, fill factor values for RGS_Std are <72% ($R_P$ <1 kΩ-cm²). These high fill factor values for RGS_A indicate that the usual shunting problems do not exist. Also remarkable is the close distribution of the fill factor values for RGS_A. In addition to the close distribution of $j_{SC}$, $V_{OC}$ and the efficiency, this is a hint for the better homogeneity of the bulk material compared to RGS_Std. Due to the higher fill factors and higher $V_{OC}$ values, the mean efficiency value for RGS_A is ~2%abs higher than those for RGS_Std. All solar cells processed from RGS_A material show efficiencies around 16% and above (in house measurement of the best cell: 16.4%, certified efficiency by ISE CalLab up to now: 16.1%). This is a significant improvement of the former/previous efficiency record of 14.4% on RGS material [6]. For the processed mc-Si_Ref, an average efficiency of ~18.5% was achieved.

3.2. Spectral response

From each group (RGS_A, RGS_Std, and mc-Si_Ref), one representative solar cell, whose efficiency is close to the median value of the corresponding group, was selected. Fig. 2 shows the wavelength dependent Internal Quantum Efficiencies (IQE) and the reflectivities of the three chosen solar cells. Within the short wavelength range below 500 nm, the IQE values are similar for the three solar cells, whereas the values of the mc-Si_Ref solar cells are only slightly higher. Nevertheless, it can be concluded that the emitter and the front side structure are comparable for all materials.
In the wavelength range above 500 nm, there is a clear difference between the block-cast mc-Si solar cell and the two RGS solar cells. They have similar IQE values, which are significantly lower than those of the mc-Si_ref solar cell. This indicates that the material quality of the standard RGS as well as that of the new one is reduced compared to block-casted mc-Si. However, RGS_A shows a slight ‘hump’ from 950 nm to 1050 nm in comparison with RGS_Std, which is presumably due to the better bulk quality (increased \( V_{OC} \) value) and the increased reflectivity above 1000 nm. This increased reflectivity of RGS_A can be explained with the variation in cell thickness (caption of Fig. 2: ~170 μm for RGS_A and ~200 μm for RGS_Std).

The discrepancy in reflectivity observed in the short wavelength range in particular between the minima for RGS_A and RGS_Std is because of the different thicknesses of the SiNx:H antireflection coating. The measurement was performed for the mc-Si_Ref solar cell after the deposition of the second antireflection layer of MgF₂, hence its reflection curve shows two minima. This, however, has no influence on the IQE.

For the two RGS solar cells, the effective diffusion lengths \( L_{eff} \) obtained from fitting the IQE curves between 800 nm and 1000 nm according to Basore [11] are comparable. They are in the range of 77 μm (caption of Fig. 2). This value is more than a factor of 2 lower than the thickness of the cell indicating that the RGS materials do not benefit a lot from the good rear surface passivation of the lab-type cell process.

3.3. Spatially resolved investigations on solar cells: LBIC, EL, and dLIT

Fig. 3 depicts the IQE topograms and EL maps of the two selected RGS solar cells mentioned above. The comparison of the IQE and the EL maps shows a homogeneous distribution over the whole solar cell for RGS_A (see Fig. 3a and c). E.g., the encircled area 1 with higher IQE values exhibits also higher EL intensities. However, for the RGS_Std solar cell (see Fig. 3b and d), there are regions with higher IQE values (> 0.7), but low EL intensity (e.g., encircled region 2). This is a clear evidence for the presence of 3D current collecting structures as shown in [5], since the IQE mapping is linked to the spatially resolved \( j_{SC} \) and the EL measurement shows band-to-band radiation and therefore the material quality (proportional to \( V_{OC} \)). According to [5], the existence of current collecting structures is the reason for reduced fill factors and low shunt resistances for RGS_Std (\( R_p < 1 \ k\Omega \cdot \text{cm}^2 \)). Judging from this observation, the solar cell made from RGS_A does not show the presence of such structures (and therefore a higher \( V_{OC} \) and FF).
Fig. 3. **Top**: IQE topograms (at 980 nm wavelength, 25 μm spatial resolution) of 2×2 cm² solar cells of the two different investigated RGS materials. Each solar cell was chosen so that its efficiency corresponds to the median value of the respective group. **Bottom**: the corresponding EL maps (pixel resolution of 20 μm). IQE and EL maps are differently scaled to highlight the inhomogeneities on each solar cell.

Fig. 4. dLIT images taken at different forward and reverse biases of the two above mentioned solar cells from RGS_A (left column) and RGS_Std (right column). The measurements were done with a lock-in frequency of 45 Hz and an acquisition time of 10 min. To emphasize the contrast on each image, they are individually scaled.
According to the dLIT measurements at different applied forward and reverse biases shown in Fig. 4, the solar cell from RGS_A presents only nonlinear (diode-like characteristic) shunts, which are not detrimental for the fill factor and thus for the performance of the cell [12]. Indeed, the visible heat signals especially on the right edge under forward bias of 0.5 V (Fig. 4a) are not visible anymore under reverse bias of –1 V (Fig. 4c). At large reverse bias of –7.8 V (Fig. 4e), new heat signals appear in some regions of this cell. These are probably nonlinear field-induced shunts as discussed in [12].

The RGS_Std solar cell shows large bright areas under 0.5 V forward bias as well as under –1 V and –6.8 V reverse biases. These heat signals depict linear shunts which have an ohmic IV characteristic [12]. Furthermore, these regions with higher brightness in the dLIT image correlate well with regions of increased IQE values (compare left half on Fig. 3b and Fig. 4f). These shunts are presumably material-induced shunts and are most probably caused by highly conductive SiC filaments, so-called current collecting structures, as shown by Hess et al. [5]. Due to their linear behavior, they are very detrimental for the fill factor (71.8%) [12].

3.4. Lifetime measurement

After the complete spatially resolved investigations on cell level, the contacts, the passivation layers and the emitters of the two selected RGS solar cells were etched back. Subsequently, they were both sided passivated by Al₂O₃ and the minority carrier lifetime τ was measured by means of microwave-detected Photo Conductance Decay (μ-PCD) (Semilab WP 2000). The minority carrier lifetime τ maps depicted in Fig. 5 show similar patterns like the EL maps (Fig. 3c and d). The encircled region 2 for RGS_Std (Fig. 5b) with increased IQE values (>0.7) shows very low lifetime values. This emphasizes the suspected presence of current collecting structures in this region, as previously reported, e.g., by Hahn et al. [13] comparing L_eff (linked to IQE) topogram with μPCD map. RGS_A exhibits a higher bulk quality than RGS_Std explaining the increased V_{OC} values. The arithmetic as well as the harmonic (shown in brackets) mean values of τ are almost two times higher for RGS_A than for RGS_Std. Moreover, the bulk quality is more homogenous for RGS_A than for RGS_Std, which also illustrates the narrow distribution of the IV parameters observed above.

![Fig. 5. τ maps of samples originating from the two cells shown above in Fig. 3 and 4. To prepare the lifetime samples, solar cells were etched back and both-sided passivated with Al₂O₃. Lifetime measurement was carried out using a microwave-detected Photo Conductance Decay (μ-PCD) setup to obtain a spatially resolved lifetime map. Depicted lifetime values are arithmetic averages (corresponding harmonic mean values in brackets).](image)

3.5. Infrared transmission microscopy investigation

The former lifetime samples were mechanically polished on both surfaces and investigated by IR transmission microscopy. Since silicon (band gap of ~1.1 eV at 25°C) is transparent for infrared light with energy below 1.1 eV, only extended crystal defects (precipitates, micro-cracks and grain boundaries) can scatter and absorb IR light and thus their positions appear dark in the image [5]. In the IR microscopy image of RGS_A material depicted in
Fig. 6a, only some grain boundaries are visible. This is due to the weakly alkaline behavior of the used polishing solution. In contrast, the IR microscopy image for RGS_Std (Fig. 6b) shows distributed dark patterns along grain boundaries. Furthermore, they are parallel to each other. It was shown by Pichon et al. [14] that such dark patterns appear at the impingement between adjacent growth fronts, that their positions can be controlled by nucleation control and by the substrate roughness design. As shown in [5], they correspond to regions with increased IQE values (IQE >0.7) and are therefore responsible for the good current collection.

Fig. 6. Infrared transmission microscopy images of an area of RGS_A on the left (a) and a region of RGS_Std on the right (b) with current collecting structures. Since the used solution during polishing is weakly alkaline, grain boundaries are also visible.

3.6. Electron backscatter diffraction measurement

EBSD measurements carried out on a randomly selected area of the polished sample shows for RGS_A (Fig. 7a) a predominant (001) grain orientation. Only few grains have another orientation like (111) and (101) which are of very small size (<0.3 mm). This shows that using a silicon-based substrate with a suitable surface treatment during RGS crystallization, the crystal growth is almost epitaxial. In contrast, the EBSD map of RGS_Std depicted in Fig. 7b shows a completely arbitrary grain orientation.

Fig. 7. EBSD images of random selected regions of the two investigated RGS materials. (a) RGS_A; (b) RGS_Std. The measurements were carried out on the polished samples after the IR transmission microscopy investigation.

4. Conclusion and outlook

A novel RGS material was developed by using a silicon-based substrate with a suitable structure, resulting in quasi-mono-crystalline RGS wafers with a predominant (100) orientation. This crystal orientation allows the use of an alkaline texture.

The characteristics of this new RGS material differ considerably compared to the standard material. E.g., the measured resistivity corresponds to the added amount of B dopant in opposite to the standard RGS material where
not all B was active. Furthermore, the new material does not suffer from reduced shunt resistance (R_S > 10 kΩ cm²), which is the case in standard material (R_S < 1 kΩ cm²) due to the presence of current collecting structures.

PERC-type solar cells from this material have fill factors > 78% and V_OC up to 608 mV. Average cell efficiencies are in the 16% range, with the best cell of 16.4% efficiency. This significant improvement of the former record value (14.4% [6]) is also attributed to the higher τ values. The minority carrier lifetime τ after cell processing is almost two times higher for RGS_A than for RGS_Std. Moreover, the bulk quality of the novel RGS is more homogeneous than those of the standard RGS.

Further ongoing studies should provide detailed information on the exact cause of the presence/absence of current collecting structures in standard/new RGS materials. Also the astonishing fact, that the same amount of B dopant in the Si melt leads to significantly lower resistivity in RGS_A, will be further investigated.

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