SHORT COMMUNICATION

Solar Cells with 11% Efficiency on Ribbon-growth-on-substrate (RGS) Silicon

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Solar cells have been prepared on Bayer ribbon-growth-on-substrate (RGS) crystalline silicon. This low-cost material contains a fair amount of impurities and crystal defects whose adverse effect on solar cell performance may be significantly reduced by gettering and bulk passivation treatments. This is demonstrated in solar cells by having a mechanical surface texturization, an aluminium gettering as well as a hydrogen passivation step which led to an open circuit voltage V_{oc} of 538 mV, a short circuit current density J_{sc} of 28·5 mA cm^{-2}, a fill factor of 72·4% and a confirmed record efficiency η of 11·1% (2×2 cm^2). Strong improvements in the diffusion length could be observed after the hydrogen treatment. © *1998 John Wiley & Sons, Ltd.*

A major problem of crystalline silicon photovoltaics is the relatively high cost of the base material. At present the Si wafer is responsible, on average, for about 46% of the total module cost.[1] Recent studies[2,3] have demonstrated that this figure will further increase in a very large scale (500 MWp year^{-1}) module fabrication scenario based on standard-cast multicrystalline Si.

In recent years tremendous efforts have been undertaken to develop ribbon Si production techniques, namely edge-defined film-fed growth (EFG)[4], the spin-casting concept[5] and ribbon growth on substrate (RGS).[6] These methods aim at a fast direct fabrication of Si sheets from the melt thereby avoiding material losses due to ingot casting and wafer cutting. Among these methods RGS is a very fast process that relies on the casting of a layer of molten silicon on a supporting substrate with the crystallization front lying nearly parallel to the ribbon surface. At the end of the process the wafer (thickness about 300–350 µm) is automatically separated from the reusable graphite substrate. A detailed description of the RGS process is given in Ref. 6. With this production technique the cost of a Si wafer is expected to be significantly reduced with respect to a conventionally prepared cast multicrystalline silicon wafer.

Because of its particular growth process, RGS contains impurities and crystal defects after the crystallization.[7] The interstitial oxygen concentration is above 10^{18} cm^{-3} and the dislocation density is in the range 10^5–10^7 cm^{-2} with metal impurities present. Therefore the application of techniques that increase the minority charge carrier diffusion length L_{diff} during the process is essential in order to obtain a good solar cell performance. Aluminium gettering has shown a beneficial effect due to the reduction of

metal impurities in the silicon bulk[7-9]. Another tool in solar cell processing is the passivation of crystal defects in a hydrogen treatment.[10,11] In the present work the influence of both Al gettering and microwave induced remote hydrogen plasma (MIRHP) passivation on RGS solar cell performance was studied.

In order to reduce the reflection of solar cells a texturing of the cell front surface is desired. For monocrystalline Si anisotropic etchants can be used to produce pyramidal textures. This procedure is not as effective for multicrystalline or ribbon Si because of deviations from the required (100) crystal orientation. In this work we studied the influence of a more effective mechanical texturing method which is based on macroscopic V-grooves being formed by mechanical abrasion using a conventional dicing saw and bevelled sawing blades.[12,13] This technique leads to an enhanced charge carrier collection probability because of an enlarged emitter area surrounding the absorber volume.[14] Efficiency gains on multi-crystalline silicon solar cells of up to 13% relative were reported when applying mechanical saw blade texturization,[15] and a record conversion efficiency of 17·2% on high-quality conventional cast multi-crystalline Si[16] has been obtained with this method.

The RGS sheets used in this study had a size of 75×110 mm^2 and a thickness of about 300 μm. They were cut into 5×5 cm^2 wafers on which four 2×2 cm^2 solar cells were processed. The average crystallite grain diameter was approximately 0·5 mm. In order to study the impact of macroscopic V-grooving and the influence of MIRHP passivation, a solar cell process sequence as outlined in Figure 1 was applied.

At the beginning the comparatively uneven front surface of the RGS wafers was levelled with a planarization blade. This step was found to be necessary to enable the usage of a photolithography step and to remove the segregation layer of about 25 μm from the front surface of the ribbon. A subsequent defect etching removes the resulting sawing damage and a carbon-rich layer on the back surface. In the following step the ribbon front surface was mechanically textured with a V-groove-like pattern by using a bevelled saw blade. The surface texture thus obtained had a depth and a groove pitch of about 60 μm. A POCl$_3$ emitter diffusion was carried out at 820°C, resulting in a sheet resistance of 80 Ω sq.$^{-1}$. A dry thermal oxide of thickness 11 nm was grown in a subsequent step at 900°C. Afterwards 2 μm of Al was
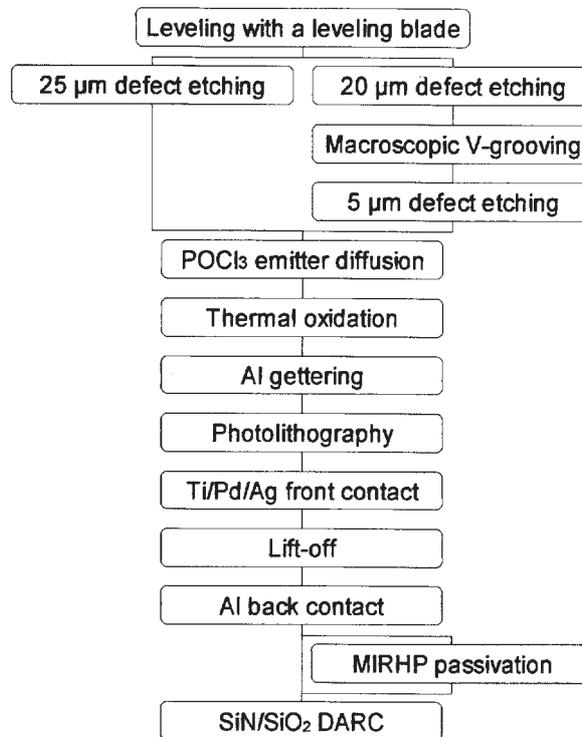

Figure 1. Schematic overview of the applied process sequence for RGS solar cells

Table I. Current–voltage (*IV*) characteristics of four V-grooved 2×2 cm^2 solar cells without MIRHP passivation and DARC from the same 5×5 cm^2 RGS wafer demonstrating the excellent homogeneity of the material used

	Cell 4a	Cell 4b	Cell 4c	Cell 4d
V_{oc} (mV)	513	508	511	511
J_{sc} (mA cm^{-2})	22·9	22·5	22·7	22·9
Fill factor (%)	72·2	72·3.	72·2	72·2
η (%)	8·5	8·3	8·3	8·4

evaporated onto the back side and a gettering step was applied for 30 min at 800°C. The photolithography for contact definition was followed by the evaporation of a 50 nm/50 nm/3 μm Ti/Pd/Ag front contact and a 2 μm Al rear contact. After separating the individual cells from the ribbons by dicing, a selection of cells was submitted to a 2-h MIRHP passivation treatment at 350°C. A plasma-enhanced chemical vapour deposition (PECVD) non-stoichiometric hydrogen-rich SiN/SiO$_2$ double antireflection coating (DARC) finishes the solar cell process.

In order to investigate the base material quality and its distribution among the different ribbons used in this study, surface photovoltage (SPV) measurements were carried out that determined the minority carrier diffusion length L_{diff} before solar cell processing. It could be shown that all ribbons exhibit an L_{diff} of about 10 μm, such that a comparison between different wafers should be possible up to a certain degree.

The RGS silicon under investigation appeared to be very homogeneous on the scale of the 75×110 mm^2 substrate. In Table I solar cell data are presented from four V-grooved cells without MIRHP passivation and DARC that originate from the same 5×5 cm^2 wafer of an RGS sheet. Only small variations have been observed, which indicates that impurities and crystal defects are homogeneously distributed in the present RGS material.

In Figure 2 the results of spectral response measurements of V-grooved RGS cells with and without MIRHP passivation before and after DARC are given. Cells 4a and 4d were taken from the same 5×5 cm^2 wafer. Before DARC they both show a nearly identical absolute internal quantum efficiency (IQE) as further proof of the excellent material homogeneity. L_{diff} was estimated by fitting the measured IQE by two-dimensional computer simulations as described in Ref. 17. This procedure resulted in an L_{diff}
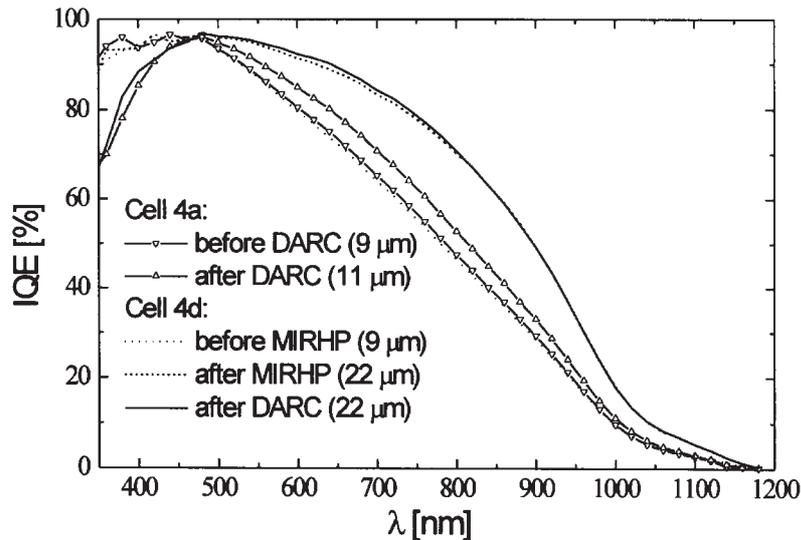

Figure 2. Spectral response data for the V-grooved RGS solar cells under investigation in different stages during cell processing. The absolute internal quantum efficiency and values for L_{diff} as calculated by two-dimensional computer simulations are shown

of 9 μm for both cells. After SiN/SiO$_2$–DARC, cell 4a shows a slight increase of its IQE for long wavelengths. This increase in IQE (and therefore in L_{diff}, of about 2 μm) occurs as a result of the indiffusion of hydrogen during the deposition of the SiN layer with the consequence of an additional bulk passivating effect.

Cell 4d was subsequently submitted to a MIRHP passivation step for 2 h at 350°C before DARC deposition. A large increase in IQE for the long wavelength region and an L_{diff} of 22 μm were obtained, which is more than twice the value without hydrogen passivation (see also Fig. 2). The following DARC deposition had no additional benefit on L_{diff}, in contrast to cell 4a, because a sufficient passivation of bulk crystal defects was already accomplished by the MIRHP passivation.

For wavelengths below 400 nm, a slight decrease in IQE was observed for cells with a DARC. This is due to surface damage caused by a non-optimized PECVD, an effect that can be further minimized.

Both cells 4a and 4d were annealed after DARC deposition. While we saw an increase in all cell parameters for cell 4a, cell 4d with the MIRHP passivation step showed a slight decrease in all parameters and therefore an efficiency loss of 0·2% absolute. This result was obtained before the final certified measurement has been carried out.

Table II summarizes the performed *IV* characterization of all cells under investigation. Cell 9c is an untextured reference cell, which was processed on an RGS wafer with slightly larger initial diffusion length than the base material of cells 4a and 4d. As expected in theoretical simulations for materials with small diffusion lengths,[14] the macroscopic V-texture causes a slight decrease in V_{oc} but results in a much enhanced J_{sc}. The latter is due to a reduced reflection and an increased charge carrier collection probability in the V-tip volume, which overcompensates for the decrease in V_{oc}.

When comparing cells 4a and 4d after DARC and annealing, the impact of the largely enhanced L_{diff} is clearly visible. The additional MIRHP treatment of cell 4d causes an increase in V_{oc} of 21 mV and a gain in J_{sc} of 1·4 mA cm^{-2} with respect to cell 4a. The former cell showed a V_{oc} of 538 mV, a J_{sc} of 28·5 mA cm^{-2}, a fill factor of 72·4% and a resulting record efficiency η of 11·1% (measurement certified at Fraunhofer ISE, Freiburg, 22 July 1997). This is, to our knowledge, the highest efficiency reported so far on RGS silicon.[18]

In conclusion, the first solar cell results have been presented on Bayer RGS silicon, which is a promising low-cost alternative to standard-cast multicrystalline and Czochralski-grown silicon. At the present level of material development, the presence of impurities and crystal defects in RGS enforces the need for gettering and bulk passivation treatments during solar cell processing in order to reach cell efficiencies above 10%. Macroscopic mechanical V-grooving led to the typical slight decrease in V_{oc} but a large increase in J_{sc} and therefore to a net gain in solar cell efficiency. In comparison with completed DARC structures an additional MIRHP passivation step has resulted in an increase in V_{oc} of 21 mV and in J_{sc} of 1·4 mA cm^{-2}, thus leading to a gain in efficiency of 1·1% absolute. The combination of Al gettering, MIRHP passivation and macroscopic mechanical V-texturization of the cell surface led to a record efficiency η of 11·1%. It is expected that in the near future the performance of RGS solar cells can be improved further by additional phosphorus gettering, an optimized Al gettering treatment as well as further improvements in RGS base material quality.

Table II. Current–voltage (*IV*) data for three RGS solar cells (untextured reference cell 9c, V-grooved without MIRHP passivation cell 4a and V-grooved with MIRHP passivation cell 4d) in various stages during processing

	Untextured cell 9c		V-grooved cell 4a		V-grooved 4d		
	No DARC	DARC	No DARC	DARC	No DARC	MIRHP	MIRHP, DARC[a]
V_{oc} (mV)	511	526	513	517	511	538	538
J_{sc} (mA cm^{-2})	17·4	26·1	22·9	27·1	22·9	25·7	28·5
Fill factor	71·1	69·2	72·2	71·2	72·2	74·6	72·4
η (%)	6·3	9·5	8·5	10·0	8·4	10·3	11·1

[a]Results certified by the Fraunhofer ISE in Freiburg, Germany.

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