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Extremely High Currents in RGS (Ribbon Growth on Substrate) Silicon Solar Cells by 3D Carrier Collecting Channels

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Abstract

RGS (Ribbon Growth on Substrate) silicon could be the crystalline silicon material for PV of the future. Its very fast production technique avoiding any material losses due to sawing will drastically reduce the wafering costs. On the other hand one has to deal with more crystal defects (grain boundaries, dislocations, impurities) which limit especially the diffusion length L_{diff} and normally result in small short circuit current densities J_{sc}. The charge carrier collection probability can be increased by a macroscopic V-texture of the surface, but even more effective is a 3-dimensional emitter structure within the whole bulk cell volume. This was observed in RGS solar cells showing minority carrier lifetimes of only around 0.2-0.4 µs but J_{sc} of >34 mA/cm^2. In these cells the whole bulk volume is collecting current despite of the small diffusion lengths.

This behaviour was investigated using spatially resolved IQE (Internal Quantum Efficiency) mappings, capacitance measurements and a special EBIC technique where the electron beam hits the backside of the wedge-shaped solar cell. From our results we conclude that the collecting structures may be caused by inversion in combination with the high O and C content. Cells with large areas of collecting channels exhibit lower fill factors (FF) but nearly no loss in open circuit voltage V_{oc} as compared to standard RGS cells. For both types of cells confirmed record efficiencies of 12.5% have been obtained.

Introduction

The Bayer RGS technique [1] could play a major role in a more cost effective production of multicrystalline Si wafers for PV. A decoupling of the directions of crystallisation and pulling leads to high pulling speeds of ~10 cm/s and therefore a production rate of ~1 wafer/s. The fast process results in grain sizes <1 mm, dislocation densities of 10^5-10^7 cm^{-2} and diffusion lengths <20 µm [2]. The high oxygen and carbon concentrations (~$2*10^{18}$ cm^{-3} respectively) require special cooling techniques in order to avoid the formation of the so-called New Donors [3]. Therefore RGS material is currently produced in two forms which can be distinguished by their cooling rates after crystallisation [4,5].

- Using a very fast cooling rate allows the oxygen to remain in interstitial form. Subsequent process steps in the temperature range of 600-900 °C have to be avoided during solar cell processing.
- An annealing step >1000 °C forms large oxygen precipitates and reduces the interstitial oxygen concentration by one order of magnitude. The formation of New Donors is now no critical issue anymore.

All cells investigated within this study have been processed using the latter cooling rate including the high temperature annealing step. During this step oxygen and carbon precipitates at crystal defects, especially at dislocations, which could be shown by TEM (Transmission Electron Microscopy). These precipitates may play the key role in the observed 3-dimensional emitter structure in RGS solar cells described in the following.

Solar Cell Process and IV-Data

The RGS solar cells have been processed following the sequence shown in Fig. 1. After a mechanical levelling step to flatten the surface and to remove segregated impurities a macroscopic V-texture was applied using a dicing saw with bevelled blades. This results in a lower reflectivity and a higher carrier collection probability as could be shown in previous studies [6,7]. After emitter formation, thermal oxide passivation and gettering/BSF formation an optimised H-passivation step using the MIRHP (Microwave Induced Remote Hydrogen Plasma) technique was applied.

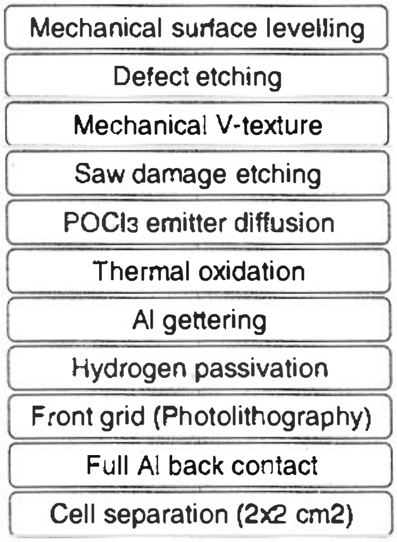

Fig. 1: Applied RGS solar cell processing sequence including a V-texturing and an optimised hydrogen passivation step.

Table 1: IV-data of the two best RGS solar cells within this study (cell size 4 cm^2, independently confirmed by JRC, Ispra).

Cell	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
1	549	34.5	65.9	12.5
2	560	31.1	71.6	12.5

The best cells received a ZnS/MgF_2 ARC (AntiReflection Coating) and the IV-data of all cells have been determined. Tab. 1 shows IV-parameters of the best two cells. Both cells show identical efficiencies of 12.5%, which is the highest value obtained on RGS material so far. Nevertheless J_{sc} and FF of both cells differ strongly. The extremely high J_{sc} value of cell 1 can not be explained assuming a planar emitter structure on the V-textured surface and lifetimes far below 1 µs as it is the case for RGS.

Results and Discussion

In Fig. 2 the spatially resolved IQE mappings at 905 nm reveal that in cell 1 large areas have exceptionally high values close to 1 whereas in cell 2 only a smaller fraction within the cell shows

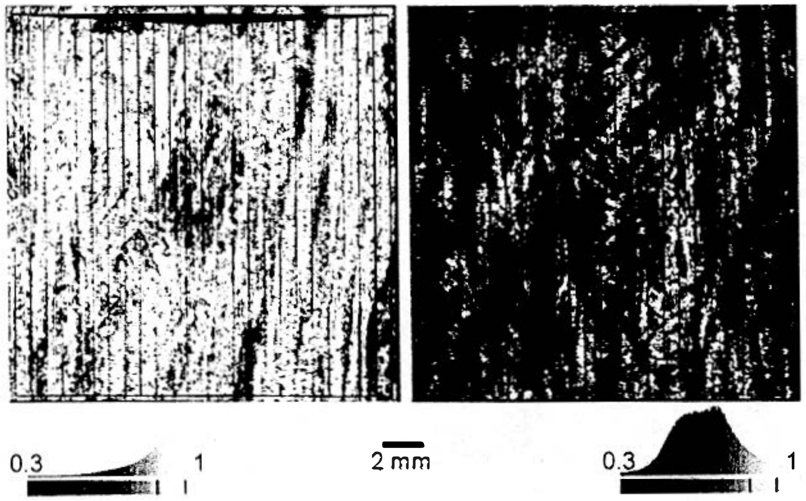

Fig. 2: IQE mappings (905 nm) of RGS cells 1 (left) and 2 (right). In cell 1 a large fraction of the cell shows exceptionally high IQEs whereas in cell 2 a mixture of high IQEs and the "normal" behaviour is visible.

this behaviour. In the rest of cell 2 "normal" values of the IQE can be seen, which are compatible with the measured low lifetimes.

Capacitance measurements have been carried out in order to study the nature of the current collecting structures. For all cells the capacitance was measured using a low frequency of 100 Hz (C_{LF}) and a high frequency of 100 kHz (C_{HF}). In Fig. 3 the difference of the signals C_{LF} - C_{HF} is given in dependence on the cell parameters.

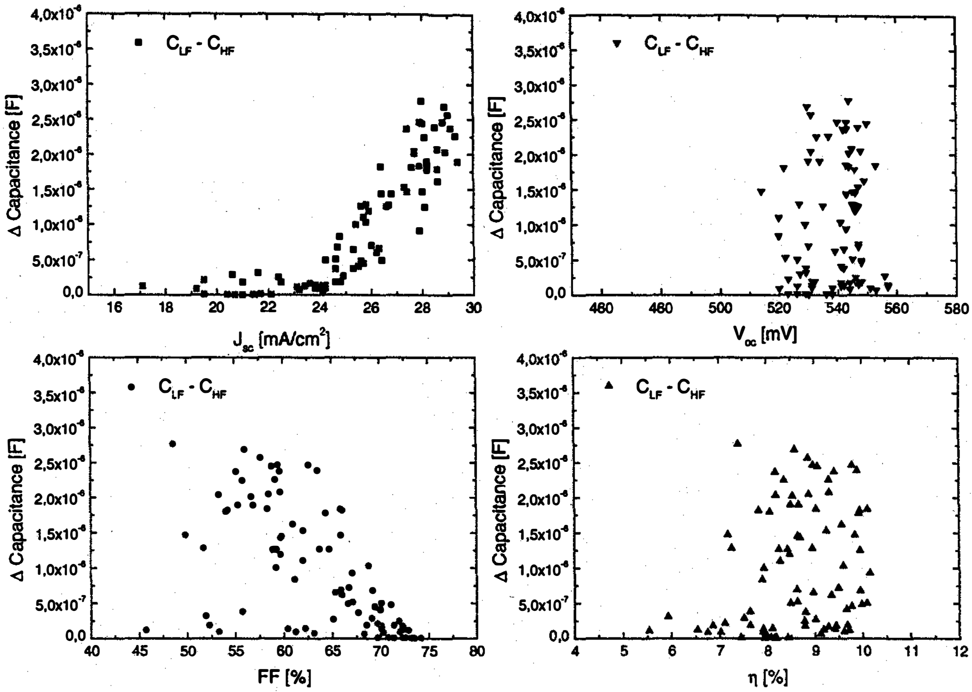

Fig. 3: C_{LF} - C_{HF} of the processed RGS solar cells (4 cm^2) without ARC in dependence on the cell parameters. Especially J_{sc} and FF are affected.

A large difference of both capacities (C_{LF} - C_{HF}) indicates a slow charge carrier exchange which contributes only to C_{LF} and is typical for minority charge carriers. Therefore an inversion channel model was developed and published [5]. It is based on n-type channels along grain boundaries and/or dislocations which form an extension of the P-doped surface emitter into the p-type silicon bulk. Minority charge carriers in the bulk do not have to diffuse to the cell surface but are collected within the channels which are in contact with the surface emitter. If the typical distance between the channels is in the order of L_{diff} (~20-40 μm after cell processing) even carriers generated deeply in the bulk are collected.

The current collecting channels can be investigated by using a special EBIC technique. The electron beam hits the backside of the solar cell which was ground in a wedge-shape from the backside. In this way the Al back contact is removed and the electron beam penetrates into the silicon. Results from the EBIC investigation are presented in Fig. 4.

The density of the channels visible allows carriers generated deeply in the bulk to be collected very efficiently leading to the observed high J_{sc}. The presence of collecting channels presently lowers the FF as can be seen in Fig. 2. This might be due to shunting problems (n-type channels in contact with the Al backside metallization) and/or the fact that in forward (operation) direction the inversion channels act as preferred injection sites leading to enhanced leakage currents [5]. If these problems can be overcome, inversion channels may lead to higher efficiencies of RGS solar cells with small diffusion lengths.

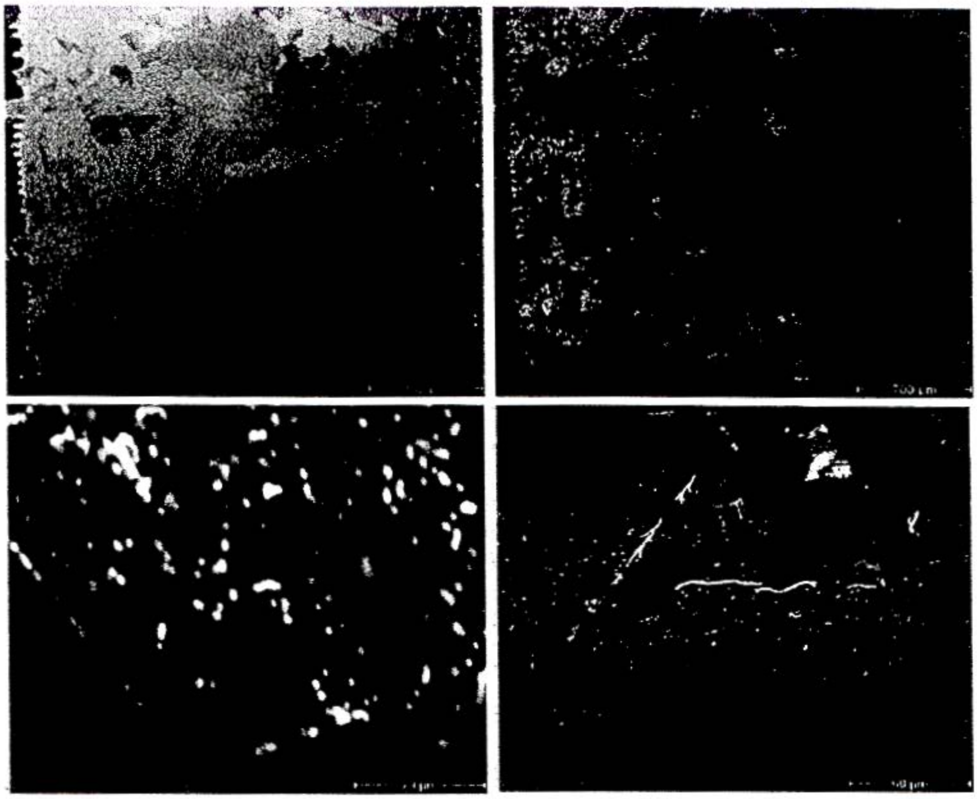

Fig. 4: EBIC investigation of a RGS cell showing an exceptionally high J_{sc}. **Top left:** SEM (Scanning Electron Microscope) picture (5 kV) of the wedge-shaped cell from the back. In the left part the thickness is zero, in the right part the remaining Al back contact is visible. **Top right:** EBIC image (5 kV) of the same area. Even in thick areas close to the back contact an efficient current collection is visible. **Bottom left:** Close-up of the top EBIC image resolving individual channels (5 kV). **Bottom right:** Cross section of the cell revealing the V-texture and the collecting channels within the whole bulk volume of the cell (2 kV).

Conclusion

12.5% efficient solar cells made from RGS silicon with small L_{diff} have been processed partly showing extremely high values of J_{sc} exceeding 34 mA/cm^2. This behaviour can be explained by current collecting channels which form a 3-dimensional continuation of the front side emitter into the silicon bulk. These channels can be visualised by EBIC measurements and are most probably caused by segregation of impurities (O and/or C) at dislocations/grain boundaries during the high temperature annealing step after crystallisation. The microscopic/chemical explanation is unclear yet and has to be investigated further. Cells with collecting channels and an optimised hydrogen passivation show the same maximum efficiencies as compared to cells 'without' channels, but FF is lowered. If this is due to shunting problems between the channels and the cell back contact, avoiding a direct contact could further improve the efficiency of RGS cells containing channels.

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