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RECORD EFFICIENCY OF 16.7 % IN EFG RIBBON SILICON

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ABSTRACT

Recently obtained results of a process monitoring based on spatially resolved lifetime measurements revealed that bulk lifetime values above 300 μs can be reached within Edge-defined Film-fed Growth (EFG) silicon ribbons with the help of gettering and hydrogen passivation steps. Therefore, recombination losses at the wafer backside have to be considered in this material with low as grown lifetimes. The solar cell processing sequence has been adapted to the needs of this material. Besides phosphorous gettering and remote hydrogen plasma passivation a screen printed back surface field has been implemented instead of an evaporated and subsequently alloyed thin Al BSF used for Al gettering. This allows to make use of low energy photons in regions with very high bulk lifetimes. In this way an independently confirmed solar cell efficiency of 16.7 % has been obtained which is the highest value that has been reported so far.

1 INTRODUCTION

Silicon ribbons can be produced cheaper than conventionally cast multicrystalline silicon wafers as they are grown directly out of the melt in the required thickness so that cost intensive wafering steps can be avoided. One of the most promising materials in this field is Edge-defined Film-fed Growth (EFG) silicon produced by RWE Schott Solar Inc. (formerly ASE Americas Inc.). The growth procedure of this material results in a specific grain structure and typical distributions of structural defects which differ strongly from those of cast multicrystalline silicon. Consequently, solar cell processes have to be adapted to the needs of this material in order to obtain sufficiently high efficiencies. Therefore, there was a need for studying the material's reaction on different applied processing steps. This had been done in former lifetime investigations [1, 2].

2 EXPERIMENTAL APPROACH

2.1 Gettering and hydrogenation

Former studies had shown that it is crucial for the effectivity of a microwave-induced remote hydrogen plasma passivation (MIRHP, see [4]) in EFG material that a gettering step precedes the hydrogenation. Otherwise the influence of the atomic hydrogen is much less benefical [1, 2]. Therefore, a P gettering step has been implemented before the hydrogen incorporation.

2.2 Back surface field

In [1, 2] spatially resolved lifetime measurements had shown that some regions in EFG silion can be improved significantly by gettering and subsequent hydrogen passivation steps reaching bulk lifetimes of more than 300 μs, whereas other areas with about the same as grown lifetime values are merely enhanced. In order to obtain good solar cells it is therefore necessary to ensure a better use of the regions showing very high bulk lifetimes. For that reason a screen printed back surface field (BSF) has been implemented instead of an evaporated and afterwards alloyed thin Al BSF that is usually used for Al gettering. In this way the back surface recombination velocity should be reduced leading to a higher quantum efficiency for low energy photons in the areas of high bulk lifetime, and according to the calculations shown in Fig. 1 to a higher cell efficiency.

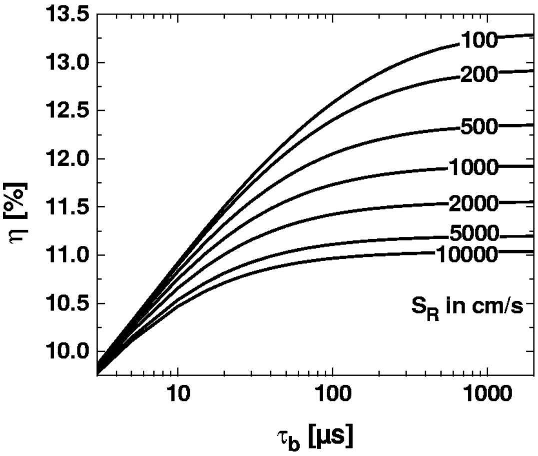

Fig. 1: Calculated influence of the effective rear surface recombination velocity S_R on the efficiency of an untextured monocrystalline solar cell without any antireflection coating. Simulations have been carried out using PC1D [3].

2.3 Solar cell processing sequence

At the beginning all wafers were acidically etched in order to obtain comparable wafer surfaces. In the following an open tube phosphorous diffusion, which simultaneously served as P gettering step, was performed. Afterwards a thermal oxide was grown onto the wafer surfaces. Half of the wafers were Al gettered by evaporating a thin Al layer onto their backsides and alloying them afterwards as shown in scheme I of Fig. 2. In contradiction to that, according to scheme II a thick Al layer was screen printed onto the other wafers and fired in a conventional belt furnace. In a next step both, the evaporated as well as the screen printed Al layers were etched back. In the following a photolithographically defined front grid and an Al back contact were evaporated and the front metallisation was completed by an electroplating step. Furthermore, the edges were isolated with the help of a dicing saw resulting in full area solar cells covering an area of $2 \times 2\,\text{cm}^2$. Finally, these cells were passivated in a MIRHP system [4].

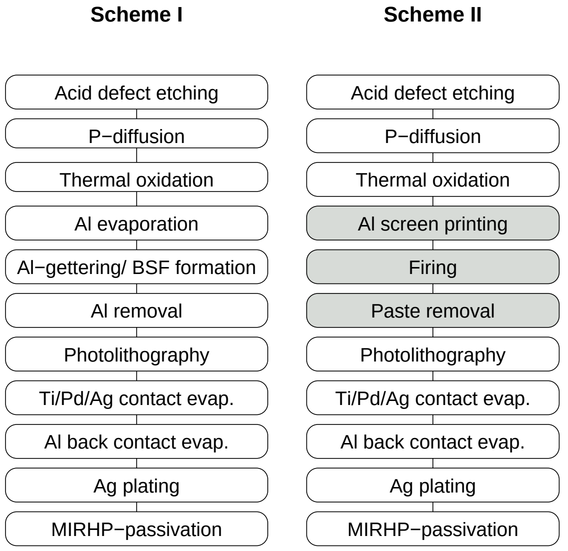

Fig. 2: Adjacent wafers with comparable grain structure were processed either according to scheme I, which includes Al gettering and a thin Al BSF, or according to scheme II covering a screen printed thick Al BSF.

3 RESULTS

The hydrogen passivation preceded by a P gettering step as described in section 2.1 has led to a mean efficiency enhancement of 2.2% absolute in 15 solar cells (standard deviation 0.4% absolute). This improvement tends to be stronger for cells with a comparably poor efficiency before hydrogenation and vice versa. The impact of the MIRHP passivation on the internal quantum efficiency (IQE) is shown in Fig. 3. It can be seen that the graph of the Al gettered solar cell as well as the one of the cell with the thick screen printed Al BSF are both significantly enhanced, especially in the long wavelength range.

These solar cells are neighboured ones, that means they originate from the same wafer and were once adjacent to each other, as it is visible in Fig. 4. Therefore, they have comparable grain structures so that the IQE data of the differently processed solar cells in Fig. 3 can be compared to each other. Doing so, one finds that after hydrogenation the solar cell with the screen printed thick Al BSF shows a significantly better exploitation of low energy photons as the one with the evaporated Al layer. This is due to a lower back surface recombination velocity caused by the thick screen printed layer as it was expected in section 2.2.

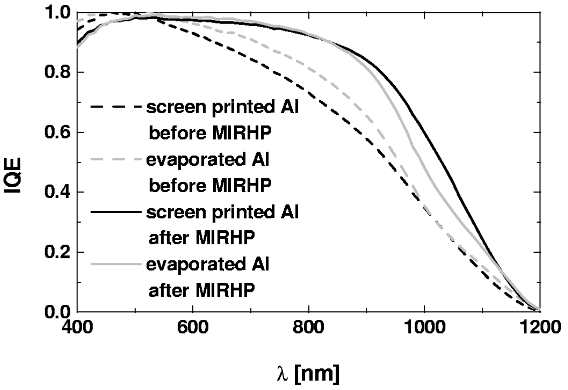

Fig. 3: Internal quantum efficiencies of adjacent solar cells before and after hydrogen passivation. One was processed using a thick screen printed Al BSF, whereas the other one was Al gettered using a thin evaporated Al layer.

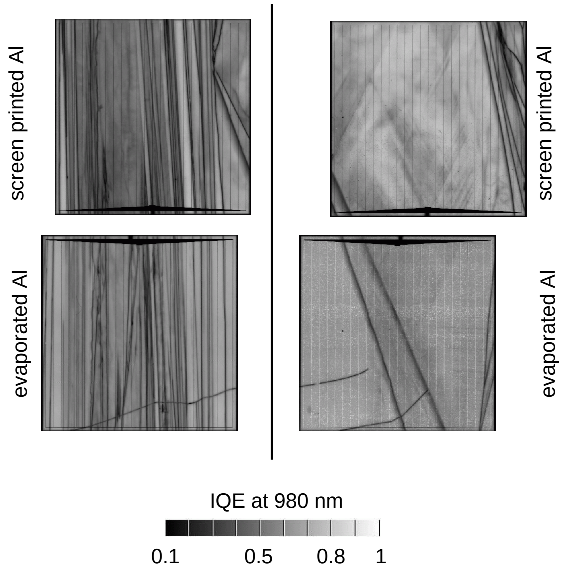

Fig. 4: IQE mappings at 980 nm of neighboured but differently processed solar cells after hydrogen passivation. The two images at the right hand side belong to the same cells as the IQE graphs in Fig. 3.

The fact that a reduced back surface recombination velocity enhances the internal quantum efficiency can also be seen if one compares the upper right IQE mapping of Fig. 4 to the lower right one (both at 980 nm). Nevertheless, things look different for the two solar cells on the left side. In this case the evaporation of Al followed by an annealing step for gettering leads to somewhat higher quantum efficiencies at 980 nm as compared to the cell with a screen printed Al layer. Consequently, it cannot be concluded that the screen printing of Al paste leads to better solar cells in general. It depends on the material properties of the individual wafer. If lifetimes after processing are still rather low, there is no benefit from a thicker Al BSF or lower S_R values, respectively. Instead, the more effective Al gettering step in scheme I can lead to slightly higher IQE values like in the case of the right solar cells in Fig. 4.

Moreover, it has been shown in [1, 2] that there exist regions of comparable as grown lifetimes within EFG silicon which react very differently on applied gettering or hydrogen passivation steps, and that such regions are inhomogeneously distributed according to usual wafer sizes. Consequently, it is not possible to measure as grown lifetimes in a wafer and decide afterwards whether a thin or a thick Al layer should be applied. However, if sufficiently high bulk lifetimes can be provided in EFG material by a combination of gettering and hydrogenation steps (more than 300 μs have been reached in [1]!) it is essential to provide a good back side passivation in order to profit from the high lifetime values.

Table I: Independently confirmed parameters of an untextured, full area and 4.0 cm^2 sized EFG solar cell showing a new record efficiency of 16.7 %. *IV*-parameters have been measured without any masking of the front metallisation.

J_{SC} [mA cm^{-2}]	V_{OC} [mV]	*FF* [%]	η [%]
35.1	601	79.0	16.7

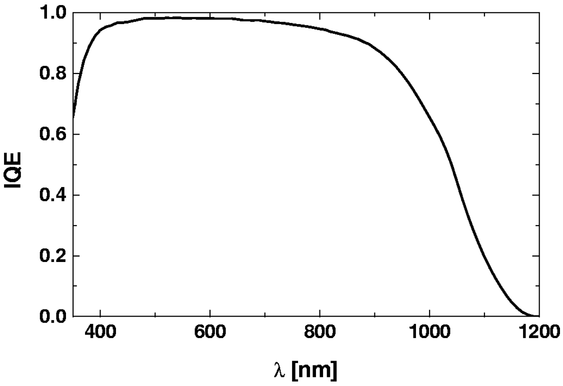

Fig. 5: IQE graph of the solar cell showing a new record efficiency.

Under such circumstances high solar cell efficiencies can be reached. Particularly, this was the case for a solar cell that has been fabricated together with those mentioned before. Besides of a combination of P gettering and MIRHP passivation a thick screen printed Al BSF has led to an enhanced quantum efficiency in the long wavelength range visible in the IQE graph in Fig. 5. Reflection losses have been reduced with the help of a ZnS / MgF$_2$ double antireflection layer. In this way an efficiency of 16.7% has been reached which is the highest one reported so far for EFG silicon and which has been independently confirmed by the EC Joint Research Centre in Ispra. The corresponding cell parameters are given in Table I. Moreover, an IQE map at 980 nm is shown in Fig. 6 which illustrates that the solar cell is not located in a monocrystalline region of the EFG material but includes typical structural defects like grain boundaries.

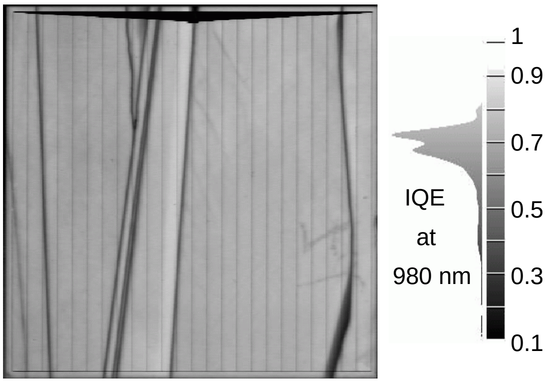

Fig. 6: IQE mapping at 980 nm of the 16.7 % efficient solar cell.

The processed solar cells have not been textured at all so that further efficiency improvements are possible by the application of a chemical or mechanical surface texturing. Moreover, the edges were isolated at the end of the cell process by using a dicing saw. This causes an open *pn*-junction at the edges and, as a consequence, lowered V_{OC} and *FF* values. Therefore, a more sophisticated treatment of the edges would result in even better *IV*-parameters.

SUMMARY

Former studies had shown that by gettering and subsequent hydrogen passivation bulk lifetimes of partly more than 300 μs can be reached in EFG silicon ribbons. In order to turn areas of such high bulk lifetimes to profit it is necessary to reduce the surface recombination velocity at the backside of the solar cells. For that reason a screen printed Al back surface field has been integrated in the solar cell processing sequence leading to enhanced quantum efficiencies in wafer areas with comparable high lifetime values.

In this way an independently confirmed efficiency of 16.7 % could be reached on a full area, 4.0 cm^2 sized EFG solar cell, whereas the *IV*-measurements have been performed without any masking of the front side metallization. This is the highest value that has been achieved so far for this ribbon material.

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