SILICON SOLAR CELLS WITH SCREEN PRINTED-FRONT CONTACT AND DIELECTRICALLY PASSIVATED, LASER-FIRED REAR ELECTRODE

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ABSTRACT: With respect to cost reduction the main future effort in silicon solar cell technology is to manufacture solar cells with highest possible efficiencies on the thinnest possible wafers ensuring a maximum production yield. The laser-fired contact (LFC) technology that has been developed at Fraunhofer ISE allows the implementation of a dielectrically passivated rear electrode in an easy way and therefore fits these main industry requirements. In this paper the transfer of the LFC-technology to solar cells with screen-printed front end process is reported. Laboratory type solar cells with laser-fired rear electrode have been processed on 170 µm thin, float-zone silicon (1 Ω cm) and Czochralski silicon (3-6 Ω cm) wafers. On 10x10 cm² FZ-substrates efficiencies up to 17.1 % have been reached compared to 16.4 % of standard screen-printed solar cells with aluminium back surface field. On 125 mm pseudosquare FZ-wafers even an efficiency of 17.7 % has been achieved. These results clearly demonstrate the compatibility of the LFC approach to the today industrial standard screen-printed solar cell technology.
Keywords: laser processing, back contact, manufacturing and processing

1 INTRODUCTION

Today, several developments are underway, which lead to the fact that the properties of a solar cell's rear electrode begin to play a major role in improving solar cell efficiency. There is progress in contacting lower doped emitters with screen-printed front grids [1] which results in a reduction of the emitter recombination current loss. Besides, progress has been made in supplying good quality silicon materials which furthermore lower recombination losses in the silicon bulk [2]. Last but not least the trend towards thinner wafers [3,4] demands for solar cell concepts with minimal rear surface recombination and good internal light trapping.

The today commonly used screen-printed aluminium back surface field (Al-BSF) provides a medium quality rear surface recombination velocity in the range of 500 cm/s to 5000 cm/s for p-type Si material with a doping density of 10^{16} cm^{-3} and an internal reflectance in the long wavelength range of about 70 % to 80 %. These parameters are not sufficient to prevent a reduction of efficiency with decreasing cell thickness. During processing of the Al-BSF the printed aluminium paste is alloyed into the rear surface with a fast firing process and a p^+-back surface field is formed. Because of the different thermal expansion coefficients of aluminium and silicon internal stress is introduced into the wafer and the solar cell is warped after the firing step. This technology drawback complicates the wafer handling and is a critical issue for the production yield of cells thinner than 200 µm. As could be shown by other groups a reduction of the wafer warping can partly be reached by using different paste compositions and less paste consumption per wafer [5]. The warping is linearly enhanced the larger the wafers are and it even increases to the square with decreasing wafer thickness [6].

A rear electrode concept, that fully circumvents the warping problem is the dielectrically passivated rear with local contacts, that has been introduced with the passivated emitter and rear cell (PERC) [7]. Furthermore this rear side structure is a superior alternative to the Al-BSF in terms of efficiency potential because it features a nearly perfect internal rear reflectance as well as a very low surface recombination velocity. Because of its high efficiency potential various technological approaches have been developed to implement a rear surface passivation by either the use of thermally grown SiO_2 or SiN thin films, which can be deposited by different plasma technologies [8].

2 LASER-FIRED CONTACTS - STATUS

The 'laser-fired contact' (LFC) technology discussed here has been developed at Fraunhofer ISE [9] to implement the local contacts to the silicon bulk through the insulating dielectric passivation layer.

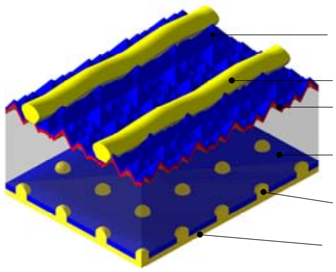

Figure 1: Sketch of a LFC-solar cell with dielectric rear passivation. The point like aluminium rear contacts are implemented by locally laser alloying the aluminium through the dielectric passivation layer.

In contrast to other approaches in which contact areas for metal deposition are defined by locally removing the passivation layer using photolithography and wet chemical etching, mechanical abrasion [10,11] or laser ablation [12], within the LFC process the aluminium is deposited onto the rear surface and afterwards locally laser alloyed through the dielectric layer. Therefore the laser-firing process allows to create a local aluminium back surface field underneath the contact regions which reduces the recombination rate at the solar cell's rear side even further. Hence, the LFC process forms a rear electrode performing close to that of the PERL cell (passivated emitter rear locally diffused) [13]. Efficiencies above 20 % have been realised on 2x2 cm² PERC solar cells in a range of 0.1 Ω cm to 100 Ω cm base doping [14].

Furthermore the LFC approach, that has been introduced elsewhere in more detail [15], has already proven to be a fast and potentially low-cost approach to implement the dielectrically passivated rear electrode. On 2x2 cm² solar cells so far efficiencies up to 21.6 % have been achieved, using a scanner controlled solid state laser process which enables laser-firing of a 15 x 15 cm² solar cell in about two seconds [16].

In this work the transfer of the dielectrically passivated rear electrode concept to industrial type solar cells with screen-printed front is demonstrated for the first time using the industrial feasible laser-fired contact technology. Furthermore the necessary steps towards a transfer of the LFC technology into industrial production and the possibilities to work hereon at Fraunhofer ISE are discussed and introduced. A possible production line concept for the manufacturing of a rear electrode with dielectric passivation and laser-fired contacts can be built up out of available manufacturing equipment and has already been discussed in detail in Ref. 17.

3 EXPERIMENTAL APPROACH

To demonstrate the compatibility of the laser-fired contact technology to solar cells with screen-printed front, we processed 170 µm thin solar cells on 100 x 100 mm², 1 Ωcm, p-type, float zone (FZ) silicon wafers. The cells featured a textured front surface, a homogeneous 45 Ω/sq emitter, silicon nitride anti-reflection coating prepared by plasma-enhanced chemical vapour deposition (PECVD) and screen-printed front metallisation (finger width in screen 80 µm). The back end processing was divided into two groups in order to compare the different cell performances of solar cells with standard screen-printed Al-BSF and such with LFC rear electrode. As rear surface passivation for the LFC cells a silicon dioxide layer was thermally grown into the flat rear surface in advance to the front surface texture. The process flow of the Al-BSF solar cells and of the laboratory type demonstration solar cells with LFC rear electrode is shown in Figure 2.

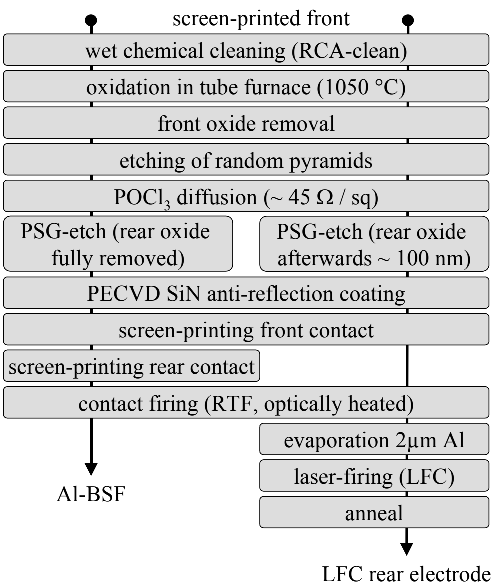

Figure 2: Process flow of the processed solar cells with screen-printed front contacts and either an Al-BSF or an oxide-passivated LFC rear electrode.

In a second experiment further LFC solar cells have been processed according to the above illustrated process flow, this time on 170 µm thin, pseudosquare, 1 Ω cm FZ–silicon wafers with an edge length of 125 mm and 150 mm in diameter. Besides the wafer size also the antireflection coating was changed from PECVD SiN deposition to SiN sputtering. Details on the sputtering of SiN anti-reflection layers can be found in Ref. 18.

In both solar cell batches the firing of the screen-printed contacts was performed in an optically heated fast firing furnace. It has to be mentioned that the firing process had to be adapted for the LFC solar cells due to the missing aluminium paste on the rear surface.

4 RESULTS AND DISCUSSION

When discussing different rear electrode concepts and their impact on the performance of identically processed solar cells measuring the cells' internal quantum efficiencies (IQE) in the long wavelength range is an appropriate choice for a direct comparison. Figure 3 shows the measured IQE and reflection of the best solar cells of the first batch with Al-BSF and LFC rear electrode respectively.

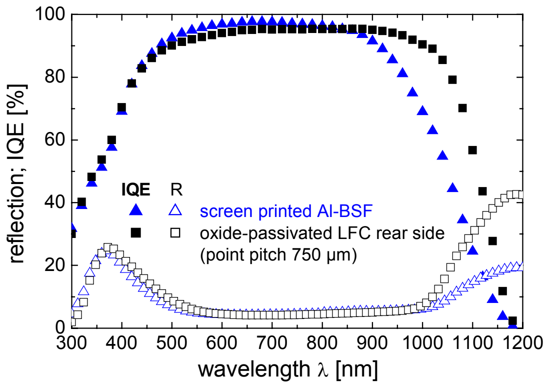

Figure 3: Comparison of measured internal quantum efficiency and reflection (external) of two solar cells processed in parallel having different rear electrodes (10 x 10 cm², 170 µm, 1 Ω cm, p-type, FZ-Si).

The solar cell with LFC rear electrode clearly shows a much higher IQE in the long wavelength range than the one with standard aluminium back surface field. This is due to the higher internal rear reflectance and the lower rear surface recombination velocity of the dielectric passivation. These superior properties of the LFC rear electrode also result in a better solar cell performance as can be seen in Table 1.

Table 1: Illuminated IV-parameters of the best 10 x 10 cm², 170 µm thin solar cells (1 Ω cm, p-type, FZ-Si) with screen-printed front end process and Al-BSF or LFC rear electrode respectively (LFC pitch: 750 µm).

cell type	A [cm²]	V_{OC} [mV]	j_{SC} [mA/cm²]	FF [%]	η [%]
Al-BSF	100	616	33.4	79.9	16.4
LFC	100	635	35.5	76.1	17.1

Compared to the screen-printed Al-BSF, the LFC rear electrode improves the open-circuit voltage of the processed solar cells about 20 mV. It also enables a short-circuit current density which is 2 mA/cm² higher than the one of the Al-BSF solar cells processed in parallel. Only the reached fill factor of 76 % is sub-optimum due to the yet non-optimised processing conditions for front contact firing within this first solar cell batch. Nevertheless this results in a superior efficiency of 17.1 % with the LFC structure compared to 16.4 % with the screen-printed Al-BSF.

In order to improve the fill factor of the LFC solar cells a further optimisation of the front contact firing process has been performed in a second run. The best results on 1 Ωcm float zone silicon and on 3-6 Ωcm Czochralski silicon can be seen in Table 2.

Table 2: Illuminated IV-parameters of the best 170 µm thin, 125 mm pseudosquare solar cells (A = 147 cm²) with screen-printed front end process and LFC rear electrode.

cell type	ρ [Ωcm]	pitch [µm]	V_{OC} [mV]	j_{SC} [mA/cm²]	FF [%]	η [%]
LFC	FZ 1	750	636	36.1*	77.1	17.7
av. of 6 LFC	FZ 1	750	636 ± 1	36.0* ± 0.2	76.6 ± 0.8	17.5 ± 0.12
LFC	Cz 3-6	500	619	35.6*	73.7	16.2

* sputtered SiN antireflection coating

The adaptation of the front contact firing increased the average fill factor level of the FZ-silicon solar cells up to 76.6 % which is above all results of the first batch. The best reached fill factor of 77.7 % still indicates potential for future improvements. The lower fillfactor of the Cz-silicon solar cells could be traced back to the front contact firing because a second laser-firing of the rear did not increase the fill factor significantly. Therefore the front contact process adaptation has to be investigated in more detail.

So far the best solar cell efficiency achieved on 1 Ω cm FZ-silicon is 17.7 %. Al-BSF solar cells which have been processed in parallel reached a lower open circuit voltage of 622 mV compared to 636 mV and a lower short circuit current density of 33.8 mA/cm² compared to 36.1 mA/cm². On 3-6 Ω cm Cz-silicon only 612 mV and 34.6 mA/cm² have been realised with the Al-BSF instead of 619 mV and 35.6 mA/cm² using the LFC technology.

These first results on laboratory type FZ- and Cz-silicon solar cells clearly demonstrate the compatibility of the LFC-technology to standard screen-printed front contact processing. Besides, higher open circuit voltages and higher short circuit current densities have been realised compared to the standard screen-printed Al-BSF on both used material types.

5 TECHNOLOGY TRANSFER

Based on these results achieved on solar cells with screen-printed front contacts future efforts will be directed towards the transfer of the proven efficiency potential of the dielectrically passivated rear electrode to industrial production. This means, that different process sequences will be investigated to develop an industrial type process flow that allows the transfer of the LFC technology to manufacturing equipment. A possible process sequence involving SiN deposition for rear surface passivation is shown in Figure 4. Manufacturing equipment to implement this process flow is installed in the demonstration laboratory at Fraunhofer ISE. The feasibility of large area silicon nitride passivation as well as aluminium coating will be investigated.

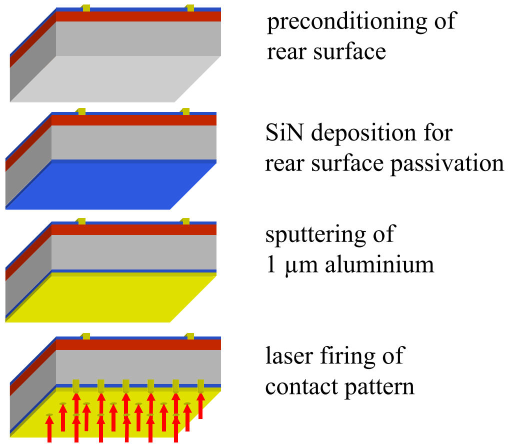

Figure 4: Sketch of the laser-fired contact (LFC) approach. After surface passivation, e.g. by a SiN layer, a 1 µm thin aluminium layer is deposited on top and then locally laser-alloyed through the passivation layer.

As a further step, the adaptation of the LFC technology to multicrystalline silicon wafers, which also can benefit from dielectric rear passivation, will be examined. In other investigations at Fraunhofer ISE the transfer of the LFC technology to high-efficiency multicrystalline silicon solar cells has already successfully been demonstrated [19]. Because aluminium gettering, which is known to be a beneficial step for multicrystalline material, will not be involved in a LFC-process sequence for instance phosphorous gettering and plasma processing for removal of a residual rear side emitter may be alternative midterm routes.

6 SUMMARY AND CONCLUSION

First 10x10 cm² solar cells with laser-fired rear electrode, homogeneous 45 Ω/sq emitter and screen-printed front contacts have been processed on 170 µm thin, 1 Ω cm float-zone silicon wafers. Compared to solar cells with screen-printed aluminium back surface field, which were processed within the same batch, an increase in open circuit voltage and a higher short circuit current density has been demonstrated. Also, measurements of the internal quantum efficiency clearly prove the superiority of the laser-fired contact approach in comparison to a standard screen-printed Al-BSF.

In a second batch processed on 125 mm pseudosquare silicon wafers (W=170 µm, A=147 cm²) solar cells with homogeneous 45 Ω/sq emitter and LFC rear electrode reached an open-circuit voltage of 619 mV and a short-circuit current density of 35.6 mA/cm² on 3-6 Ω cm Czochralski material. On 1 Ω cm float zone material even an open circuit voltage of 636 mV and a short circuit current density of 36.1 mA/cm² have been realised resulting in an efficiency of 17.7 %.

As these solar cells are limited by the properties of the front surface structure (emitter, passivation, ...) future work will concentrate in processing solar cells with higher emitter sheet resistance and therefore reduced emitter saturation current to fully develop the efficiency potential of the LFC technology.

The presented results clearly prove the compatibility of the LFC approach to the screen-printed front process that is a standard processing sequence in industrial production. Due to the prevention of wafer warping and the contactless laser processing LFC does not introduce mechanical stress into the solar cell either. Furthermore the in-line ability of laser technology allows the minimisation of handling measures. Compared to a standard Al-BSF the LFC technology therefore seems to have a higher potential to realise a high production yield also on thin silicon wafers.

Furthermore, LFC ensures optimum rear surface features near those of a PERL solar cell. This means, that the LFC – technology can be used to implement the dielectrically passivated rear electrode that is a proven high-efficiency concept enabling highest efficiencies also on thin silicon solar cells [20]. The future production of thinner solar cells having the same or even better efficiencies than today is the main cost saving potential of the silicon solar cell technology.

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