LASER-FIRED CONTACTS – TRANSFER OF A SIMPLE HIGH EFFICIENCY PROCESS SCHEME TO INDUSTRIAL PRODUCTION

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ABSTRACT

Laser-fired Contacts (LFC) have just recently been proposed as a simple way to realize local contacting for a passivated rear surface. Efficiencies above 20 % have been reported for this technology. This work aims to assess the current status of the transfer of this process scheme to industrial production. The application of laser-fired contacts to 2 Ω€cm silicon wafers yielding an open circuit voltage of more than 660 mV clearly indicates the formation of a local aluminum back surface field. A newly developed pilot type laser system with automated wafer handling is presented. Due to the use of scanning mirrors for the movement of the laser beam the LFC process time is reduced to just a few seconds per wafer. Finally the most important criteria for an industrial transfer are discussed in comparison to the standard Aluminum back surface field (Al-BSF), being the benchmark for any other rear surface passivation scheme up to now.

INTRODUCTION

The race for lower price per watt peak of industrial solar cells is the driving force in the search for processes which result in high efficiency, high yield on thin wafers and low process costs. Since wafers become thinner in order to safe material costs, the passivation of the rear surface as well as minimum mechanical stress for the fragile wafers become the predominant tasks. The standard alloying of a homogeneously screen printed aluminum paste is a non-ideal solution due to wafer warping and rather medium surface passivation. On the other hand the use of local point contacts piercing through a passivated surface is known to yield excellent results but has been related to complicated and high cost photolithographical definition of the point contact structure until recently. Within the last few years several approaches have been addressed in order to use more industrially suited technologies to perform the structuring step. Very good results have been obtained for laser and mechanical ablation of the passivating layer and subsequent aluminum deposition and sinter step [1, 2]. Just recently the authors have demonstrated a new method, how to realize the local point contact: the local laser alloying of contacts after deposition of a passivating layer / aluminum stack [3]. Besides being simpler this patent pending technology [4] also offers a higher potential if the local laser alloying is optimized in order to realize a local back surface field. The fundamental challenge to be addressed is to transfer this process sequence to an industrial environment, meeting the targets of high efficiency, minimum handling and low process costs.

EXPERIMENTAL

The laser-fired contact process consists of four main steps as demonstrated (see Fig. 1). Starting from a surface being preconditioned for passivation, a highly passivating dielectric layer of silicon dioxide or silicon nitride is deposited. The next step is the deposition of a homogeneous aluminum layer and finally the local contacts are realized by means of focussed laser pulsing.

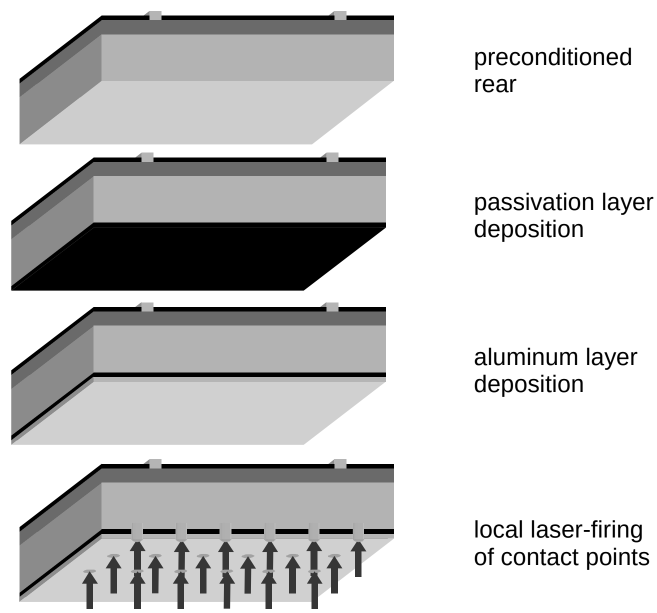

Figure 1: Sequence for the laser-fired contact process.

The laser processing has so far mainly been performed using a q-switched, flash pumped Nd:YAG laser source operating at 1064 nm in TEM00 mode. The wafer is moved on an XY-stage moving at a maximum speed of 200 mm/s. A scanning electron microscope picture of a top view of a single laser-fired contact is shown in Fig 2.

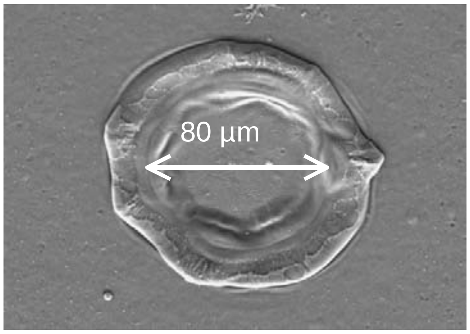

Figure 2: Top view SEM picture of a laser-fired contact.

In order to evaluate the potential of this type of process, the sequence has been adapted to our highly efficient RP-PERC (random pyramid – passivated emitter and rear cell) process [5]. This process sequence features a random pyramid front texture, a homogeneous emitter diffusion, front and rear oxide passivation and evaporated, photolithographically defined contacts. Excellent results have been obtained for 2x2 cm² cells on 250 µm thick 0.5 Ω cm p-type FZ-Si material using LFCs instead of the photolithographical defined rear pattern (η=21.3%, V_{oc}=679 mV, J_{sc}=38.6 mA/cm², FF=81.1 %) [6]. The high fill factor combined with a low surface contact fraction of approx. 0.5% show the high quality of the laser-fired contacts. The high open-circuit voltage demonstrates, that the process can be applied without severe damage to the passivating layer.

Based on these very encouraging results investigations have been focussed on the potential to form a significant local aluminum back surface field (LBSF) during the alloying process. Owing to the lower specific contact resistance and the reduced surface recombination velocity below the contacts, a LBSF helps to overcome the limitations of the PERC concept when applied to silicon wafers with resistivities above 1 Ω cm.

In order to analyse the quality of the laser alloying process, PERC cells have been processed on 0.5 and 2 Ω cm p-type Fz-Si without random pyramid texturing but otherwise using the standard Fraunhofer ISE process. Omitting the texture yields a higher sensitivity with respect to the open-circuit voltage due to a smaller front surface recombination velocity i.e. a smaller emitter saturation current density and with respect to light beam based locally resolving characterization methods like LBIC. Furthermore the thickness of the Aluminum coating has been varied in the range from 0.5 to 4 µm. The pitch between the laser contact points has been also varied, but a point-to-point pitch of 1000 µm seems to be a good choice in a wide range of parameter settings. Reference cells have been processed using the standard photolithographically defined contact areas with a pitch of 1000 µm on wafers of both mentioned resistivities.

As expected, the best results have been reached for LFC on 0.5 Ω cm wafers (η=18.7%, V_{oc}=682 mV, J_{sc}=34.1 mA/cm², FF=80.7 %), lacking in short-circuit current due to the rather medium quality light trapping behavior for untextured surfaces with a silicon oxide AR coating.

Table 1 shows the results obtained for 2 Ω cm wafers. The open-circuit voltage as well as the fill factor are significantly higher for the laser-fired contacts than for the reference cells (mean values of 12 reference cells: V_{OCREF}: 647 mV, FF_{REF}: 75.9 %). This is a clear evidence for the formation at least of a weak local back surface field. The results of these experiments are discussed in more detail in [7].

Table 1. Best and mean value (4 cells) of 2x2 cm² cells with 2 µm rear aluminum layer with laser-fired (LFC) rear contacts on 2 Ω cm. The contact pitch was 1000 µm.

contact type	V_{OC} (mV)	J_{SC} (mA/cm²)	FF (%)	η (%)
LFC (best)	661	34.3	79.2	18.0
LFC (mean)	659	34.4	78.5	17.8

TRANSFER TO INDUSTRIAL PRODUCTION

Laser processing

As mentioned before, so far experiments have been mainly performed using a standard flash pumped Nd:YAG laser system emitting at 1064 nm. The structuring of the surface is obtained by moving the wafer on an XY-stage.

The analysis of the throughput limitations shows, that a high number of typically 10^4 point contacts are to be written for a typical industrial solar cell. This shouldn't be critical due to the high pulse rates of q-switched lasers, as they are in the range of several tens of kHz. On the other hand due to the high mass of the moving wafer chuck, the velocity of the structuring process is limited. The laser beam has to travel a typical distance of more than 10 m for a standard wafer size of 125 x 125 mm². This means, that in order to reach a throughput of 1000 cells/hour the laser beam velocity should be significantly above 1 m/s, being a difficult task even for state-of-the-art XY–stages.

A significant throughput enhancement can be realized using a scanning laser system. Here the movement of the wafers in relation to the laser beam is performed by guiding the beam using two rotating mirrors. A further advantage of a scanning system compared to the XY-stage is that the wafer may rest during the process being highly valuable for fragile thin wafers.

Just recently a scanning laser system has been installed at Fraunhofer ISE (compare Fig. 3). The diode pumped Nd:YAG laser can be operated at 1064 nm and, frequency-doubled at 532 nm. The focal length of the objective lens of the laser scanner is typically chosen to be 254 mm resulting in a working area of 180x180 mm^2 and a high depth of focus being tolerant to uneven wafer surfaces. Using the laser scanner, laser-firing of the whole rear of a 125x125 mm² can be performed in just a few seconds.

Figure 3: Pilot type scanning laser system with automated wafer handling.

The system is further equipped with automated loading and unloading including the positioning of the wafers. Special care has been taken to control the process atmosphere in order to enable steady conditions, being a rather difficult task for scanning systems. This pilot type laser system has been developed together with the German company ACR GmbH and may serve as an ideal tool in order to assess automated high throughput laser processing for manufacturing purposes.

Process integration

One important feature of the laser-fired contact process is the chance to integrate all individual process steps in one vacuum unit, if silicon nitride is used as the passivating layer. First the surface is prepared for passivation by a plasma etching step, which can also be used to remove a parasitic emitter being formed during diffusion. Second the passivating silicon nitride layer is deposited by means of plasma enhanced chemical vapor deposition or sputtering. Third aluminum is deposited using a physical vapor deposition method. Finally the laser-firing can be performed within or outside of the vacuum chamber.

A single tray can then be used in order to carry the wafers through the individual compartments. An example of such an unit is shown in Fig. 4. So far processes have been realized on single wafer equipment only. Each individual step will now be addressed in order to upscale the process and the corresponding equipment will be set-up at Fraunhofer ISE.

Furthermore it has to be mentioned that also different process schemes might be of interest. Highly surface passivating silicon nitride coatings typically show a high density of fixed charges leading to an inversion layer. This inversion layer is typically shunted when local contacts are applied without performing local isolation [8]. In comparison, the passivation of a thermally grown silicon dioxide layer is much more based on a reduction of the density of surface states and shows much lower surface charge densities. The inversion channel is less significant. Thus up to now, for the application of the passivated rear concept silicon dioxide outperforms the silicon nitride passivation. As a consequence further investigations will be directed to solutions for the shunting problem and the development of process scenarios in which the passivating layer can also be a thermally grown silicon dioxide.

A further advantage of the LFC-process is, that during this step a laser edge isolation can be performed [9].

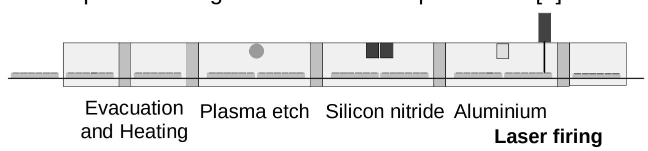

Figure 4: Integrated laser-fired contact production line.

BENCHMARK Al-BSF

The standard screen printed back surface field is the bench mark for any alternative rear surface passivation and contacting approach. This process consists of just two steps, the printing of the aluminum paste and the drying and firing in an infrared belt furnace. Soldering of the alloyed aluminum rear is difficult, thus an AgAl paste is typically printed on the designated areas before firing, which makes up two more steps one for printing and one for the extra drying step. Most of the industrial solar cells feature a screen printed front contact. For these the firing step is standard anyway and shouldn't be addressed to the cost for the Al-BSF formation process.

The contact resistance of a homogeneously screen printed and alloyed back surface field is very low (typically far below 0.1 Ω cm²). As a consequence the contribution of the rear contact resistance to the total series resistance of the cell is typically very low enabling high fill factors. The contact resistance of a locally contacted rear is typically higher, since it is the result of an optimization of the geometrical input parameters for the rear contact structure.

The internal reflection of a screen-printed and co-fired Al-BSF has been determined to be typically about 80% for the spectral range of interest. In the same spectral range of interest, for a sufficiently thick dielectric layer (e.g. more than 200 nm silicon dioxide) the internal reflectance of the silicon/dielectric layer/aluminum stack is above 99%.

Effective surface recombination velocities (SRV) of down to 200 cm/s have been reported for an Al-BSF, e.g. in Ref. [10]. For industrial purposes i.e. cofiring of screen printed aluminum pastes the SRV is typically supposed to be in the range of 10^3 cm/s. The open circuit voltage of approx. 660 mV on 2 Ω cm p-type silicon reported above for LFC corresponds to an effective surface recombination velocity below 200 cm/s.

Both rear contact schemes need an additional step in order to enable good and reliable soldering of interconnectors. For the cofired Al-BSF this is typically performed using an AgAl paste in the designated contact areas. For the LFC two possibilities are feasible. Either a thin layer of silver is deposited on top of the aluminium during the vacuum processing or specific low temperature soldering pastes are applied.

The in-situ gettering during the Al-BSF formation process can be highly important for low quality material. For the LFC process sequence two approaches are possible in order to improve the material quality. In the case of a silicon nitride passivation layer, hydrogen passivation is possible from the rear side. Furthermore a designated step for gettering could be implemented for specific materials. In this case optimised gettering conditions could be used instead of the standard Al-BSF alloying which is bound to the firing conditions for the front metallisation. Currently investigations are under way in order to assess the potential of these material quality enhancement steps. Finally for thinner wafers to be manufactured in the future the material quality will be of reduced importance.

The fundamental problem with the Al-BSF is the warping of the wafers during the process. This interferes with the current tendencies to save costs in crystalline silicon solar cell manufacturing by using thinner and larger wafers. Though it has been reported that the warping can be reduced applying designated pastes breakage losses are typically due to such bowing. For the LFC concept bowing can be excluded for wafers down to 100 µm.

The cost of the Al-BSF formation is dominated by the consumption of Al paste. The quality of the Al-BSF is strongly correlated to the quantity of paste applied. A cost of 0.07 to 0.2 €/Wp results if a paste price of 0.3 €/g and an amount of 0.5 to 1.5 g Al paste used for a 125x125 mm² cell with 14% efficiency is assumed.

The cost of an LFC process using a vacuum system as described before has been calculated from investment, consumable and personnel costs based on a model published elsewhere [11]. The computed cost-of-ownership is approx. 0.1 €/Wp being in the same range as for the standard alloyed Al-back surface field. For LFC the process costs are rather dominated by the interest for the equipment, since consumable costs are much lower. Thus upscaling of the production equipment will help to reduce the cost-of-ownership.

CONCLUSION

The simplicity of the LFC process combined with the feature of a LBSF for adapted process parameters makes it superior to other approaches as laser and mechanical ablation to implement dielectric rear surface passivation into industrial production. The development of appropriate LFC equipment and processes will challenge the screen printed co-fired Al-BSF as the standard rear passivation scheme.

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