Laser Fired Contacts in multicrytalline silicon solar cells

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***Abstract*— The roadmap for the development of silicon solar cells requires the introduction of passivating contacts to obtain higher efficiencies as well as to reduce the cost of production to be industrially implemented. In this context, Laser Fired Contact (LFC) on p-type silicon wafers have been shown to be an effective technique to improve efficiencies, due to their ability to reduce recombination losses on the back surface of crystalline silicon solar cells. These studies have mainly focused on high quality monocrystalline silicon wafers and there are not enough developments made with multicrystalline silicon (mc-Si) wafers. Therefore, in this work, we present the optimization of the LFC process on p-type mc-Si and its application to two types of silicon devices: diffusion and heterojunction solar cells. These rear contacts have led to improved efficiencies for both types of solar cells over similar devices with thermalized aluminum rear contacts and without back passivation. These results illustrate the enormous potential of these localized laser-contacts created for mc-Si solar cells, perfectly compatible with a lower cost industrial production.**

Keywords—Laser Fired Contacts, multicrystaline silicon, solar cells.

I. Introduction

Solar photovoltaic energy is still dominated by monocrystalline (c-Si) and multi-crystalline silicon (mc-Si) solar cells due to its good efficiencies, stability and the market confidence [1]. For silicon technology, one of the major technological challenges is to reduce the high cost of production of the cells, while maintaining high efficiencies. Some strategies to reach this objective could be the reduction of the wafer thickness and the use of low-quality silicon wafers, such as mc-Si, instead of high-quality monocrystalline silicon wafers [2]. Due to the high carrier recombination in mc-Si associated to a high concentration of contaminants and defects, LFC (Laser Fired Contact technique) is particularly interesting. This is because part of the carrier lifetime degradation in mc-Si absorbents is caused by the high processing temperatures during the annealing of conventional metal contacts and antireflective coatings. Furthermore, to include a passivation back layer between the rear surface aluminium electrode layer and the mc-Si wafer could improve the performance of the devices considerably [3]. LFC is also an attractive solution to make back-contacts in solar cells fabricated with thin wafers to avoid warping, such as ultra-thin mc-Si wafers.

In this LFC technology, the back surface of the wafer is passivated with a dielectric layer (usually aluminum oxide [4], silicon carbide [5], or amorphous silicon [6]) in order to reduce the rear recombination. Then, aluminum is evaporated and sintered by local-laser firing through the dielectric layer to define the back contact between c-Si/metal. The aluminum is diffused into the c-Si bulk, even to the point that p/p^+ local regions can be obtained with the laser treatment. To achieve an efficient LFC, both good quality of the passivating layer and optimal irradiation laser parameters are required.

In this work, we present the optimization of the LFC process on p-type mc-Si, instead c-Si, and its application to two types of silicon solar cells based on these mc-Si wafers.

II. Experimental Details

A. Samples and Device Preparation

Samples and devices presented in this work were prepared using 1-2 Ω·cm–resistive, p-type boron-doped textured multicrystalline-silicon wafers (mc-Si) with a thickness of 200 µm. We present the optimization of the LFC process and its application to two types of silicon devices. The method carried out was as follows:

1.) First, we focused on the optimization of deposited intrinsic hydrogenated amorphous silicon layer, (i) a-Si:H, as rear passivation layer on monocrystalline silicon wafer. These undoped a-Si:H films were grown by 13.56-MHz Plasma-Enhanced Chemical Vapour Deposition (PECVD). Prior deposition, the native oxide on the wafers was chemically etched by immersion in a 5 % HF:DIW (hydrogen fluoride diluted in 18.2 MΩ cm-resistivity de-ionised water) solution [7]. The following PECVD conditions had been established as optimal: 53 Pa chamber pressure, 10 mW/cm^2, 20 sccm SiH_4 and 140 ºC substrate temperature. The thickness of these dielectric layers was 150 nm. The same PECVD parameters were used to grow (i) a-Si:H films on mc-Si substrates.

2.) Then, we optimized the laser firing process using a diode-pump solid-state laser (Explorer ONE from Spectra Physics) emitting at 532 nm with a pulse duration of 15 ns, with two pulses by spot, 20 kHz as pulse frequency and a beam radius of 15 µm in the processing area. We focused on the applied pulse energies from 0.005 to 0.020 J (corresponding to laser fluence-range: 1.41-5.76 J/cm^2) and on the fraction of contacted area (Fc ≈ 0.2 - 5 %) in order to obtain the lowest specific contact resistance (r_c) and the best solar cells' performance.

3.) And finally, optimized LFC was tested in commercial diffusion solar cells (referred to as Diff. in the following figures) without back contacts and in silicon heterojunction solar cells (SHJ) manufactured in our laboratory. Diff solar cells have a complete front contact (i.e., antireflection coating and metallic grid), but no back contact, allowing the present experiment. Both types of solar cells were compared with similar devices with thermalized aluminium rear contacts and without back (i) a-Si:H passivation films.

SHJ solar cells were made by depositing (i) a-Si:H onto the rear surface by 13.56-MHz PECVD and (i) a-Si:H / (n) a-Si:H emitters onto the front surface of the mc-Si wafers. Prior to a-Si:H deposition, the native oxide on the wafers was chemically etched by immersion in a 5% HF:DIW solution. The PECVD conditions of the front thin passivating (i) a-Si:H layers were: 93 Pa chamber pressure, 36 mW/cm^2 density power, 20 sccm SiH_4 and 175ºC substrate temperature. The PECVD conditions of the front thin (n) a-Si:H emitters were: 267 Pa, 36 mW/cm^2 , 33 sccm SiH_4 and 13 sccm PH_3 [PH_3 (2%) + H_2 (98%)] flow rates and 175ºC substrate temperature. On the other hand, the passivating back (i) a-Si:H layers were prepared using the same PECVD parameters indicated in subsection 1.) (i.e., 53 Pa, 10 mW/cm^2, 20 sccm SiH_4 and 140ºC). After PECVD deposition, the samples were cooled down under vacuum and taken out from the reactor. Then a thin ITO film (approximately 85-nm thick) was deposited onto the (n) a-Si:H emitter using a commercial UNIVEX 450B Oerlikon Leybold Vacuum RF magnetron sputtering. The ceramic target was In_2O_3:SnO_2 (90:10 wt %) with 4 inches of diameter. The temperature was room temperature (RT), the working pressure was set to 0.17 Pa and 25 W the direct-current power. The front-grid contact, titanium + silver, was thermally evaporated immediately after using a commercial UNIVEX 300 Oerlikon Leybold Vacuum at RT.

Finally, the rear side of both types of solar cells, Diff and SHJ, were manufactures in the same way: a passivating (i) a-Si:H back-layer deposited by PECVD, an evaporated aluminum layer of similar thickness (~1µm), and equal LFC conditions according subsection 2.) to achieve the back contact. The distances between laser spots (*pitch*) used were 200 and 300 µm to evaluate the optimum area fraction of the LFC back-contacts

B. Characterization

In relation to the characterization of samples and devices have been proceeded as follows:

1.) The superficial recombination of the passivated silicon wafers was evaluated by Quasi-Steady-State Photoconductance (*QSSPC*) measurements with Sinton WCT-120 equipment. This technique was applied to determine the minority carrier lifetime (τ) and the so-called implicit open-circuit voltage (*implicit-*V_{oc}) at 1 sun.

I2.) The LFC was characterized electrically, estimating its specific contact resistance according to [8], and morphologically by a confocal microscope (Leica DCM3D).

The electrical characterization was measured by the transverse resistance, R_{LFC}, with 9 front spot-contacts of the heterostructures according to the schematic device showed in Fig.1. Current-voltage characteristics (*I-V*) of these devices were measured to obtain r_C from R_{LFC}, according to [8], for different laser-beam irradiation conditions. The distance between front-laser spots assayed were 100, 200 and 300 µm. The internal spot-diametre to calculate the fraction of area contacted were estimated through the confocal microscope. To ensure a good rear ohmic contact, a 1µm aluminium layer was evaporated in the opposite side and then was irradiated with the same laser system, at 20 kHz and 5.76 J/cm^2 in the whole area.

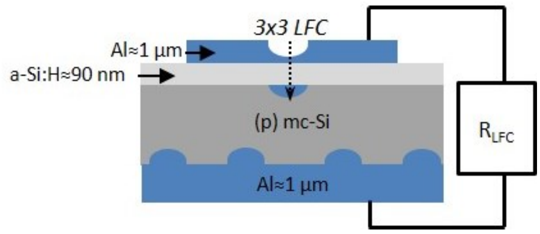

Fig. 1. Schematic device used to evaluate r_c. The front-metal contact area was 5 mm x 5 mm with N=9 spot contacts (3x3 matrix). In the rear contact, the pitch was 400 µm, irradiated at 407 mW (5.76 J/cm^2) in the whole area of the sample.

3.) Both types of silicon solar cells were characterized by current density-voltage characteristics (J-V) under illumination calibrated at AM1.5G irradiance and 100 mW/cm^2 at RT, using an A-class solar simulator. The main photovoltaic parameters, i.e., short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), fill factor (*FF*) and efficiency (η), were derived in the usual way. Internal quantum efficiencies (IQE) have been obtained from absolute spectral responses and cell hemispherical-reflectance spectra.

II. Results

A. Passivated back layer (i) a-Si:H

The (i) a-Si:H passivating layers deposited by PECVD have been previously optimized by using monocrystalline silicon wafers of high-quality as reference, until obtaining an effective lifetime higher than 2.6 ms and an implicit-V_{oc} above 725 mV, thus ensuring that an excellent superficial passivating to be grown on mc-Si wafers.

B. LFC's electrical and morphological results

To achieve high efficiencies in the LFC silicon solar cells, not only a good passivation in the rear face of the cells is needed, but also an ohmic back-contact. To reach this goal, the fluence of the laser pulses was varied between 1.41 and 5.46 J/cm^2. Regardless the laser parameters used, r_c values less than 0.2 mΩ·cm^2 were obtained (Fig. 2), even with low power or pulse energy applied. These values are low enough to assure the creation of a good aluminum contact to be employed in silicon solar cells.

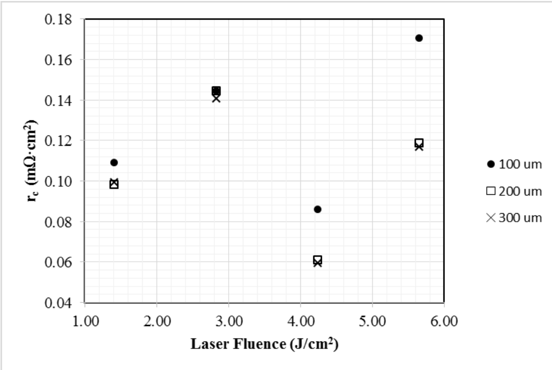

Fig. 2. Experimental r_C values obtained for different laser fluences (1.41-5.76 J/cm²) and pitch (100, 200 and 300µm).

According to the confocal images, diameters and heights of the laser contacts increased as the laser pulse fluence was higher. Diameters were ranged from14 to 30 µm and heights between 0.6 and 5.5 µm. In Fig. 3, the topography and depth profile of one of the obtained laser contact is shown as an example. The appearance of this crater was similar for the other laser conditions tested in this work.

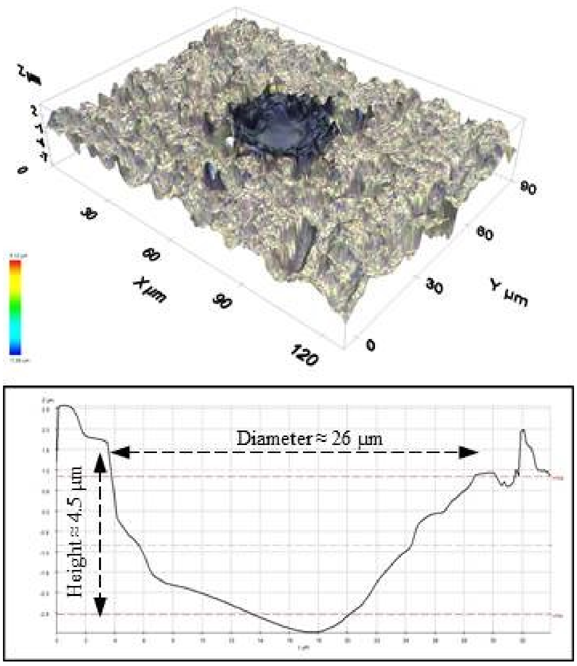

Fig. 3. Micrograph and depth-profiles of LFC obtained using a confocal microscope. The image of this crater corresponds to a LFC created with a laser fluence of 5.76 J/cm², 0.4 W (diameter ~ 26 µm and crater depth >4 µm).

C. mc-Si Difussion Silicon Solar Cells with LFC

LFC made with varying pulse energies and pitch values were tested in commercial diffusion silicon solar cell (

Table I). According to previous results in section B, to ensure good LFC in solar cells manufactured with mc-Si wafers that have a superficial roughness of the order of microns and considering that the thickness of evaporated back-aluminium is around 1µm, it is necessary to achieve a laser contact depth greater than 1µm. For this reason, to avoid problems in the back contacts, laser fluence applied were between 2.93 and 5.73 J/cm² (0.2-0.4W), excluding the lowest power previously tested (0.1W, 1.41 J/cm²).

The efficiencies obtained for these diffusion solar cells (ranged from 12.8% to 14.9%) significantly improved compared to the same cell with a thermalized aluminum back contact (identified as PV2 in

Table I, Eff=8.3%). V_{oc} and FF of this last cell were extremely low, probably due to the lack of the passivating layer led to a high carrier recombination in the back interface.

As can be also observed in

Table I, a tendency of the efficiencies of LFC solar cells with the laser conditions is not clear, except that F_c needs to be greater than 0.2% to achieve the best results (i.e., Eff ≥ 13% and FF ≥ 0.7).

Table I. Cell-performance parameters of diffusion silicon solar cells made with mc-Si as a function of the laser conditions, i.e., Laser Fluence and distance between contacts. The grey-shaded row corresponds to the diffusion solar cell with Al-thermalized back contact instead of LFC.

ID	Laser Fluence (J/cm²)	Pitch (µm)	F_C (%)	J_{sc} (mA/cm²)	V_{oc} (mV)	FF	Eff (%)
BGJ	2.93	200	0,4	32,4	597	0,76	14,8
BGN	4.29	200	1,1	32,8	588	0,70	13,5
BGO	5.76	200	1,5	33,1	600	0,75	14,9
BGM	2.93	300	0,2	32,2	590	0,67	12,8
BGK	4.29	300	0,5	32,3	592	0,71	13,6
BGL	5.76	300	0,7	32,7	597	0,74	14,3
PV2	-	-	-	32,5	527	0,54	8,3

D. mc-Si Silicon Heterojunction Solar Cells with LFC

LFC made with varying pulse energies and pitches were also tested in SHJ solar cells. Similarly to the results obtained in diffusion solar cells, the efficiencies also improved compared to the same cell with an aluminum thermalized contact (see cell-performance parameters in Table II and also J-V characteristics in Fig. 4-A).

The maximum efficiency obtained in SHJ solar cells was 11.8%, for the LFC made with the highest laser pulse fluence and the greatest fraction of contacted area (BIC-cell). A priori, better efficiencies in SHJ cells would be expected than in diffusion ones. The reason for not achieving higher efficiencies may be due because a better adjustment of the frontal emitters on mc-Si wafers for SHJ could be necessary, as inferred from the low IQE at short wavelengths (λ<650 nm) in SHJ solar (see Fig. 4-B). As a result, a lower current-density than diffusion solar cells has been obtained. Furthermore, the mc-Si wafers employed for the diffusion solar cells had the bulk previously passivated with hydrogen thus providing a quality improvement over the wafers used for the SHJ solar cells. This passivating hydrogen is provided from the front-antireflection coating of silicon nitride that was previously thermalized during the front-metallization firing process of these commercial cells [9], [10], [11]. As consequence of this bulk passivation with hydrogen, V_{oc} and FF values were also higher in diffusion solar cells than in SHJ solar cells presented in this work. In fact, the maximum values of effective lifetimes and implicit-V_{oc} obtained with the SHJ cells tested, were only 15 µs and 600 mV respectively. One way to improve these results could have been by previously passivating with hydrogen the bulk of the wafers used in these SHJ cells, according to the method described in the reference [11].

Table II. Cell-performance parameters of SHJ solar cells with p-type mc-Si absorbents as a function of laser conditions: Laser Fluence and distance between contacts. The grey-shaded row corresponds to the SHJ cell with Al-thermalized back contact (BIN-cell).

ID	Laser Fluence (J/cm^2)	Pitch (µm)	F_C (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF	Eff (%)
BID	2.93	200	0,7	25,9	576	0,51	7,6
BIC	4.29	200	1,2	31,7	580	0,64	11,8
BIE	2.93	300	0,3	26,1	567	0,64	9,4
BII	5.76	300	0,7	28,9	533	0,62	9,9
BIN	-	-	-	26,4	540	0,58	8,3

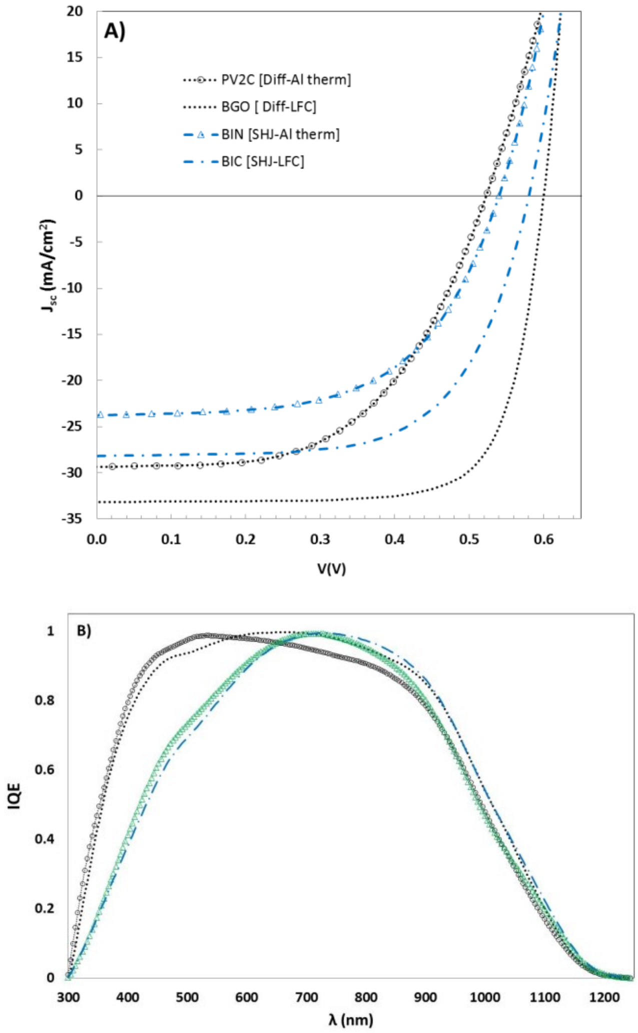

Fig. 4. A) JV characteristics and B) normalized-IQE curves, of diffusion (Diff.) and silicon heterojunction (SHJ) solar cells with mc-Si wafers, both structures with LFC (BGO & BIC) and with Al-thermalized back contacts (PV2 & BIN).

IV. Conclusion

Laser fired contact as an alternative to thermalized aluminium rear contact on p-type mc-Si solar cells has been addressed as a means to obtain higher efficiencies as well as to reduce the cost of production with this type of absorbents. Previously, these studies have mainly focused on high quality monocrystalline silicon wafers and not on multicrystalline silicon wafers. In this context, we have presented the optimization of the LFC process on mc-Si absorbents, obtaining a specific contact resistance r_c<0.2 mΩ·cm^2 and its application to two types of silicon devices: diffusion and heterojunction solar cells. These rear contacts have led to improved efficiencies for both types of solar cells over similar devices with a thermalized aluminium rear contact and without back passivation. In view of this result, LFC could be considered as a promising technique to improve the performance of mc-Si solar cells while being easy to be industrially implemented.

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