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IBC c-Si(n) solar cells based on laser doping processing for selective emitter and base contact formation

Gerard Masmitja*, Pablo Ortega, Isidro Martín, Gema López, Cristobal Voz, Ramón Alcubilla

Departament d’Enginyeria Electrònica, Universitat Politècnica de Catalunya, C/Jordi Girona 1-3, Mòdul C4, 08034 Barcelona, Spain

Abstract

In the last years, there is a clear trend in c-Si solar cell fabrication to place both emitter and base contacts on the back side leading to the so-called Interdigitated Back Contacted (IBC) solar cell structure. This solar cell architecture requires excellent front and rear surface passivation as well as a very low recombination emitter. Moreover, laser doping may be an attractive technique to create both selective emitter and base contacts using appropriate dielectric layers as dopant sources, i.e. Al₂O₃ and a-SiCₓ(n) stacks for the p⁺ and n⁺ regions respectively. In this study, we report on a simplified fabrication process for IBC n-type c-Si solar cells combining laser doping and a conventional boron emitter passivated by Al₂O₃ films. Results show very low emitter recombination currents in the ~10-50 fA/cm² range before laser processing. In addition, selective emitter contacts can be created by laser doping with recombination current densities at each contact point around 4.4 pA/cm² in relatively low and shallow doped boron doped profiles (sheet resistance ~400 Ω/sq). Finally, IBC solar cells, 3 x 3 cm² device area, were fabricated combining selective laser-doped emitter and base contacts reaching efficiencies up to 20.8 %.

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Keywords: IBC; c-Si solar cells; boron; laser doping; surface passivation; Al₂O₃; silicon carbide

* Corresponding author. Tel.: +34-93-4015671; fax: +34-93-4016756.
E-mail address: gerard.masmitja@upc.edu
1. Introduction

Laser processing may be an attractive alternative to make doped contacts in solar cells because of the simplification in the fabrication process, avoiding high temperature and photolithography steps to open and dope simultaneously base and emitter contacts [1-4]. In this approach, a laser beam impinges the silicon surface covered by either a sacrificial dopant material or a structural dielectric layer which is used as a passivation layer as well as dopant source. In the last case, irradiated areas are ablated to form the contacts, and simultaneously p+ or n+ regions are created depending on the dielectric film dopant.

In this work we apply laser processing on IBC n-type c-Si solar cells where base n+ contacts are made from a plasma-enhanced chemical vapor deposition (PECVD) a-SiCx(n) stack as phosphorous-doped source. Additionally selective p+ emitter contacts are created on homogeneous boron doped diffused emitter passivated with atomic layer deposited (ALD) Al2O3 film [5]. In this case, Aluminum is the p-type dopant.

This paper is divided in the following sections: first we study the boron emitter surface passivation quality provided by the ALD Al2O3 films considering different boron doping profiles, i.e. different emitter sheet resistance (Rsh). Next, the effect of the laser doping step on selective emitters applying optimized laser parameters [6] is analyzed. Finally, results of IBC n-type c-Si cells using laser doping technique to create both selective base and emitter doped contacts are shown.

2. Test devices

2.1. ALD Al2O3 boron emitter passivation

High quality n-type (2.5±0.3 Ω-cm) c-Si FZ double side-polished wafers of thickness 280±10 μm and <100> orientation were used to fabricate test devices as well as IBC cells. After a RCA cleaning sequence both sides of the samples were doped at different diffusion temperatures (Td) in the 850-1000 ºC range resulting in symmetrical p+n+p+ structures. The samples underwent a modified RCA1 bath (NH4OH:H2O2:H2O, 400:200:1200 ml) and a HF dip (5%). Next a low thermal oxidation (LTO) at 650 ºC during 30 minutes and an extra HF dip (5%) were done to remove undesirable boron silicate glass (BSG) as well as boron rich layer (BRL) resulting in hydrophobic surfaces. In order to emulate the final doping profile of finished IBC cells (see baseline process in Fig.2a), an extra oxidation/drive-in step in O2 ambient (at 1080 ºC for 90 min) was performed. Subsequently, the SiO2 grown during the drive-in was removed and Rsh was measured using a four-point probe system. After an additional RCA cleaning, a 50 nm ALD Al2O3 layer was deposited on both sides of the samples. Surface passivation was activated using an annealing in forming gas at 400 ºC for 10 min and the quality of the passivation was measured by the quasy-steady-state photocurrent (QSS-PC) technique (Sinton, WCT-120). Effective lifetime (τeff) values were extracted for an excess carrier density (Δn) of 10^{15} cm^{-3}, whereas the implied open circuit voltage (iVoc) was measured at 1 sun illumination. Additionally, the emitter recombination current (J0e) was determined from the slope of the 1/τeff -1/iVoc curve at high injection levels, where τin is the lifetime related to intrinsic recombination mechanisms (band-to-band and Auger) using the Richter et al. parameterization [7]. As it can be seen in Table 1, excellent J0e values (<~ 20 fA/cm^{2}) are achieved for Rsh > 100 Ω/sq emitters with iVoc up to 702 mV.

Table 1. Parameter values of boron diffused emitters passivated with ALD Al2O3.

<table>
<thead>
<tr>
<th>Td (ºC)</th>
<th>Rsh (Ω/sq)</th>
<th>τeff (µs)</th>
<th>iVoc (mV)</th>
<th>J0e (fA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>62</td>
<td>225</td>
<td>641</td>
<td>49</td>
</tr>
<tr>
<td>950</td>
<td>119</td>
<td>408</td>
<td>666</td>
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<td>379</td>
<td>663</td>
<td>17</td>
</tr>
<tr>
<td>850</td>
<td>411</td>
<td>1200</td>
<td>702</td>
<td>9</td>
</tr>
</tbody>
</table>
2.2. Selective emitter contact characterization

The quality of selective emitter contacts was studied using vertical diode test structures (see Fig. 1d) with a 1.44 cm² device active area. The same dielectric layers involved in IBC solar cell fabrication was utilized to emulate final IBC devices results. The cathode contact at the rear side was made by laser processing of a PECVD a-SiCₓ(i)/a-Si(n)/a-SiCₓ stack (4 nm/20 nm/35 nm) with a pitch of 600 μm [6]. Anode front surface consist of an Al₂O₃/a-SiCₓ (50 nm/35 nm) passivated homogeneous boron emitter. The top a-SiCₓ film in both cases is a stoichiometric silicon carbide layer which is used to protect the underneath films against subsequent chemical processes and to improve laser contact formation [3]. In order to simplify the IBC solar cell fabrication process (see section 3), the a-SiCₓ(n) stack used for the base region was also deposited on the dielectric stack of emitter regions.

Boron diffusion temperature was performed at 850 °C in all samples, including the corresponding drive-in step, resulting both in low surface boron densities and shallow doping profiles (Rₓn ~400 Ω/sq) in order to determine optimum laser powers to perform selective p⁺ emitters. Additionally, front and rear surfaces were fully metallized with Ti/Al by e-beam. Finally a 275 °C for 10 min annealing was performed.

![Fig. 1. a) I-V curves of test devices using different laser powers and the same pitch on selective emitter contacts. b) A zoom view of the I-V curves in the 0.4-0.6 V forward voltage range. c) Total recombination current density J₀ vs. contacted area fraction of selective emitters. d) Cross-section sketch of a diode test structure.](image-url)
The laser employed for all the experiments was a lamp pumped Nd:YAG (StarMark SMP 100II Rofin-Baasel) Gaussian beam operating at 1064 nm and 4 kHz repetition frequency. Optimal laser power to create the selective emitter p⁺ contacts was achieved studying dark current-voltage (I-V) characteristics considering constant contact pitch (200 µm) for different laser power in the range of 0.9 to 1.2 W, as can see in Fig.1a-b. The best laser power choice results as a trade-off between current recombination losses, being the recombination current density \( J_0 \) the related parameter, and both low contact resistance and the reliability to create all laser emitter points, resulting in optimum laser powers around 1 W.

In a second set of samples, the emitter regions were laser processed (laser power \( \sim 1 \) W) using different pitches, i.e. different contacted area fractions (\( f_c \)), in order to extract the recombination current density of each p⁺ point contact (\( J_{0ec} \)) as follows: total diode recombination current density (\( J_0 \)) for the different contacted area fractions (\( f_c \)) was extracted by fitting the I-V curve measured under dark conditions using a two-diode model [8]. The contribution to \( J_0 \) of base (\( J_{0b} \)) and passivated non-laser processed emitter regions (\( J_{0n} \)) was determined by extrapolating the \( J_0(f_c) \) curve for \( f_c = 0 \) %, (see Fig.1c), leading to about 180 fA/cm². Simultaneously, we can calculate \( J_{0ec} \) from the slope of the linear fit of the \( J_0(f_c) \) curve once the size of the laser spot is introduced (~50 µm diameter round spots) yielding ~4.4 pA/cm². Despite this value seems too high to fabricate high-efficiency devices, the optimum contacted area fraction in the emitter regions is typically about 1-5 % which means that the contribution of the contacted regions to \( J_0 \) is reduced by this factor. As a result, a contribution in the range of 50-200 fA/cm² due to the emitter contacts is expected in the final device.

3. IBC solar cell results

IBC solar cells were made using the process flow shown in Fig.2a. A cross section sketch detail is depicted in Fig.2b. Front surface was covered with an Al₂O₃/a-SiCx (50 nm/35 nm) stack for passivation and antireflection coating purposes. Back side consist of strip-like base and diffused emitter regions passivated with their corresponding dielectric stacks. Laser contacts were performed in the middle of each emitter and base strips with a pitch of 250 µm. Notice that base contacts using a-SiCₓ(n) stacks as a dopant source were performed using optimum laser conditions reported in a previous work [6]. Once laser processing is made, e-beam Ti/Al (25 nm/3 µm) metallization was carried out and interdigitated electrodes were patterned using standard photolithography.

Fig. 2. (a) Process flow and (b) cross-section sketch of the n-type IBC solar cell.
The external quantum efficiency (EQE) and current-voltage I-V curves of the best IBC solar cell (3 × 3 cm² area) are shown in Fig. 3. In this device, the emitter coverage (fe) and contacted fraction area are 67 % and 2.3 % respectively. Photovoltaic parameters for this cell are summarized in the inset of Fig. 3b. Efficiency up to 20.8 % was achieved with short circuit current density (Jsc), open circuit voltage (Voc) and fill factor (FF) of 40.4 mA/cm², 675 mV and 76.6 % respectively. Table 2 summarizes IBC cell results for different fe values in the 67 to 86 % range.

These results demonstrate that combining the use of a laser-doped selective emitter and base contacts with a very well Al2O3 passivated boron emitter allows obtaining high efficiency IBC solar cells using a simplified baseline fabrication process.

Table 2. Main parameters of the fabricated IBC solar cells measured under AM1.5G solar spectrum at 25 ºC.

<table>
<thead>
<tr>
<th>fe (%)</th>
<th>fc (%)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (mV)</th>
<th>FF (%)</th>
<th>Efficiency (%)</th>
</tr>
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<tr>
<td>67</td>
<td>2.3</td>
<td>40.4</td>
<td>675.1</td>
<td>76.6</td>
<td>20.8</td>
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<tr>
<td>80</td>
<td>1.4</td>
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<td>86</td>
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<td>40.3</td>
<td>673.4</td>
<td>69.6</td>
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</tbody>
</table>

4. Conclusions

In this work we report on a simplified fabrication process for IBC c-Si(n) solar cells using laser processing. In this approach, ALD Al2O3 and a-SiC(n) stacks are used to passivate front and rear surfaces, as well as dopant sources in the laser stage to create p⁺ and n⁺ contacts on both boron-doped emitters and n-type base regions respectively. Homogeneous boron doped emitters were passivated with ALD Al2O3 films achieving recombination currents densities as low as 9 fA/cm². Optimum laser powers to create p⁺ selective emitter contacts were determined using diode test structures resulting in values of ~1W. Finally, we combine outstanding surface passivation provided by Al2O3 and a-SiC(n) stacks with laser processing to fabricate n-type IBC solar cells (3 × 3 cm² device area) reaching efficiencies up to 20.8 % by only one thermal step (boron diffusion), paving the way for obtaining a full cold process to fabricate high efficiency IBC solar cells.
Acknowledgements

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