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Handle: http://hdl.handle.net/1942/28579

Damage-free laser ablation for emitter patterning of silicon heterojunction interdigitated back-contact solar cells

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***Abstract* — We present a novel process scheme for a-Si:H patterning using damage-free laser ablation, resulting in a simple, fast, and photolithography-free emitter patterning of silicon heterojunction interdigitated back-contact (SHJ-IBC) solar cells. An a-Si:H laser-absorbing layer and a stack of sacrificial dielectric layers are deposited on top of a-Si:H/c-Si heterocontact to prevent laser damage. Laser ablation only removes the top a-Si:H layer, which limits laser damage to the surface of dielectric layers. These dielectric layers form a distributed Bragg reflector with a high reflectance of 80% at the laser wavelength which results in additional protection of the bottom a-Si:H/c-Si heterocontact. The significant reduction of laser damage is confirmed by atomic-force microscopy and photo-luminescence measurements. Such damage-free laser ablation process was successfully incorporated in a SHJ-IBC process flow and a best efficiency of 21.8% was achieved.**

I. INTRODUCTION

Silicon heterojunction interdigitated back-contact (SHJ-IBC) solar cells are the subject of strong interest because of their capability to achieve a very high energy conversion efficiency. Several research groups presented impressive cell efficiencies in the range of 20.2%–25.6% [1]–[7]. Recently, Kaneka has reported the world record efficiency of 26.6% in a SHJ-IBC cell with size of 180 cm^2 [8]. Nevertheless, commercialization of the SHJ-IBC cells is still challenging. One of the key limitations is that the back-contact architecture results in additional fabrication complexity mainly due to the formation of interdigitated n- and p-type amorphous silicon (a-Si:H) strips. Laser ablation is an adequate patterning approach of a-Si:H and has been developed by different groups because of the following advantages: 1) it is a fast, single-side, and contactless process; 2) it has high process precision; 3) it allows a flexible device design [2], [9], [10]. To reduce laser damage at the a-Si:H/c-Si heterocontact during laser ablation, the use of an additional a-Si:H laser-absorbing layer and a SiO$_x$ sacrificial mask layer is reported in literature [9]–[11]. Only the top a-Si:H laser-absorbing layer is ablated, which shifts part of laser damage from the a-Si:H/c-Si heterocontact to the SiO$_x$ surface. However, when scribing line-shaped openings, an overlapping zone (OZ) of adjacent laser pulses has to be considered [11]. After ablation of the a-Si:H laser-absorbing layer, the energy of subsequent laser pulses in such OZs will be transmitted through the SiO$_x$ and absorbed by the bottom a-Si:H/c-Si, resulting in significant degradation of a-Si:H/c-Si passivation and issues with re-passivation quality [11].

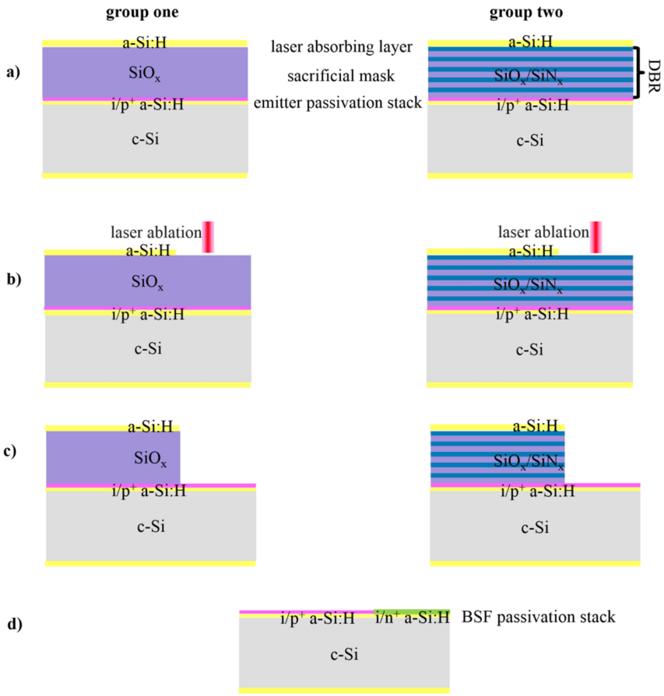

Fig. 1. Patterning process sequence of i/p$^+$ a-Si:H emitter stack and i/n$^+$ a-Si:H BSF stack: a) passivated wafers after deposition of sacrificial mask and laser-absorbing layer; b) laser ablation of absorbing layer; c) wet chemical etching of sacrificial mask; d) etching of i/p$^+$ a-Si:H followed by repassivation of i/n$^+$ a-Si:H and lift-off process.

In this contribution, a novel process scheme for a-Si:H patterning using damage-free laser ablation is presented. A distributed Bragg reflector (DBR) with reflectance of 80% at laser wavelength is used to replace SiO$_x$, substantially reducing laser damage to the underlying a-Si:H/c-Si [12]. The reduction of laser damage has been confirmed by atomic-force microscopy (AFM) and photoluminescence (PL) images. Functional SHJ-IBC cells were fabricated on n-type float zone (FZ) wafers using the developed laser ablation for i/p$^+$ a-Si:H emitter patterning.

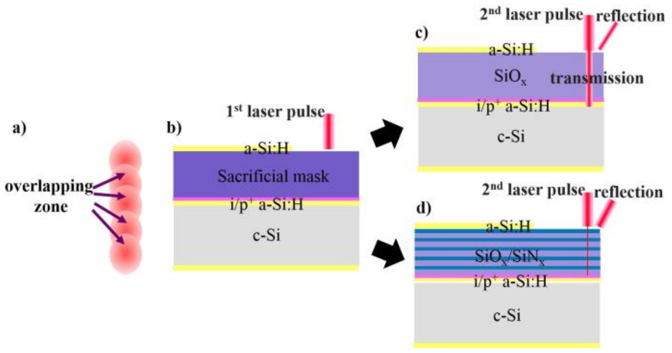

Fig. 2. a) Schematic diagram of laser scribed line. OZ is irradiated by two laser pulses; the cross-sections (not drawn to scale) of samples in OZ after, b) ablation of a-Si:H laser-absorbing layer by 1st laser pulse, c) and d) irradiance by 2nd laser pulse.

II. RESULTS AND DISCUSSION

A. Process sequence for a-Si:H patterning

The samples were prepared using polished (100) n-type FZ silicon wafers. As shown in Fig. 1, the front side of the wafer was passivated with an intrinsic a-Si:H layer and the rear side was passivated with an i/p$^+$ a-Si:H emitter stack using plasma-enhanced chemical vapor deposition (PECVD). Then the wafers were split into two groups depending on the sacrificial mask layers. Group one had PECVD SiO$_x$ sacrificial mask deposited at the rear side of the wafer, followed by deposition of a-Si:H laser-absorbing layer. Group two had five bi-layers of PECVD SiO$_x$/SiN$_x$ deposited to form the DBR [13], followed by an identical a-Si:H layer deposition. Laser ablation of line patterns was carried out using a pulsed 355 nm laser (12 ps) with laser energy fluence of 0.2 J/cm^2. Four different laser processing speeds ranging from 0.7 m/s to 1.6 m/s were tested, corresponding to overlap of adjacent laser dots within one laser line from 50% to 0%. The width of the laser scribed lines is around 7 µm. The distance between lines was set to 12 µm to minimize OZ among adjacent lines. A PL image of the wafer was taken after laser ablation. The sacrificial dielectric layers were etched by dipping in HF:HCl:H$_2$O (1:1:20). Then AFM measurements were performed at the laser processed regions to identify laser damage. Finally, the i/p$^+$ a-Si:H stack was etched and the substrate was re-passivated with an i/n$^+$ a-Si:H back surface field (BSF) stack, which was patterned by a self-aligned lift-off process using SiO$_x$ or SiO$_x$/SiN$_x$ as sacrificial layers.

B. Reflectance measurements

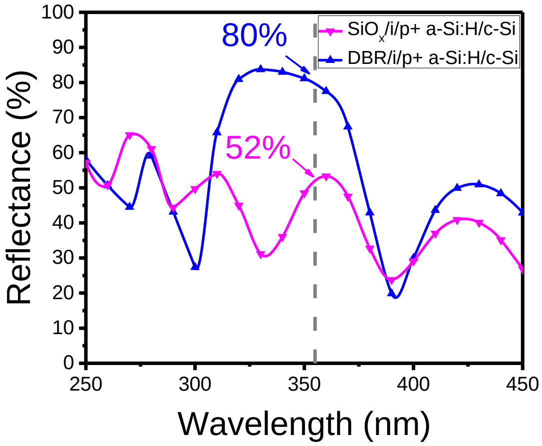

Fig. 3. Comparison of reflectance of SiO$_x$/i/p$^+$ a-Si:H/c-Si and DBR/i/p$^+$ a-Si:H/c-Si. 80% and 52% correspond to the reflectance of SiO$_x$ and DBR samples at the laser wavelength of 355 nm, respectively.

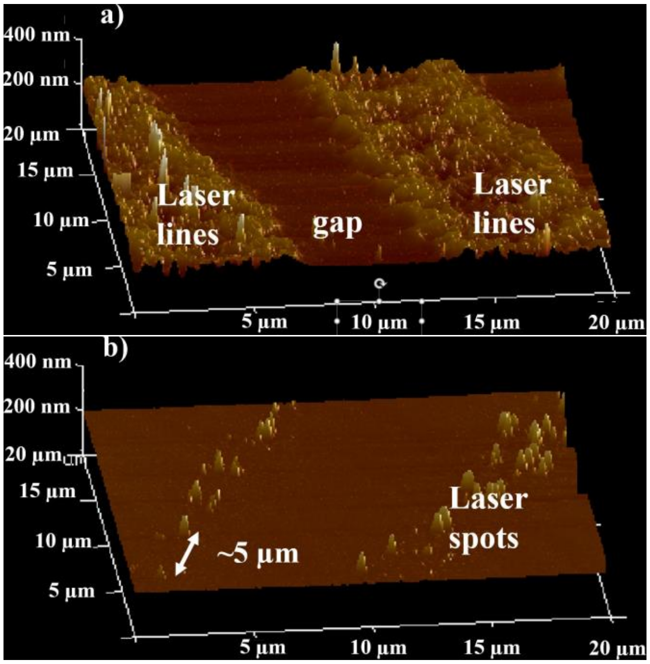

Fig. 4. The 3D AFM images of a) SiO$_x$, and b) DBR samples after laser ablation and sacrificial mask etching.

The key factor to reduce laser damage at the i/p$^+$ a-Si:H/c-Si heterocontact is reducing the laser light transmission through the sacrificial dielectric layers, to minimize the laser energy absorption in the bottom i/p$^+$ a-Si:H/c-Si. This is even more important in the OZ where two laser pulses irradiate the same area. As shown in Fig. 3, the reflectance of SiO$_x$/i/p$^+$ a-Si:H/c-Si at laser wavelength of 355 nm is 52%. So approximately half of the laser light that reaches the SiO$_x$ in OZ will be absorbed by the i/p$^+$ a-Si:H/c-Si due to the transparency of SiO$_x$ at 355 nm. However, the reflectance can be increased up to 80% by using the bilayers of SiO$_x$/SiN$_x$ to form the DBR. Note that our method is not limited to ultraviolet laser (e.g. 355 nm). The process window with high reflectance can be shifted to other wavelengths by simply modifying the thickness of sub-layers in DBR.

C. AFM measurements

A laser processing speed of 0.7 m/s was used for laser ablation of both SiO_x and DBR samples. As shown in Fig. 4 a), for the SiO_x sample, traces of the laser scribed lines are clearly observed in the form of roughness at the i/p^+ a-Si:H/c-Si interface. This indicates that the laser light is absorbed by the i/p^+ a-Si:H/c-Si and laser damage (e.g. roughness, thermal damage) is induced not only in the OZ but also in the areas processed by one laser pulse. In contrast, on DBR samples only very limited traces of separate laser spots are observed as illustrated in Fig. 4 b). The distance between rough areas is around 5 µm, corresponding to the distance between the OZs. It suggests that laser damage at i/p^+ a-Si:H/c-Si interface is prevented at the areas irradiated by one laser pulse. Nevertheless, the presence of limited laser damage in the OZ is still observed. To reduce such damage, the OZ has to be reduced.

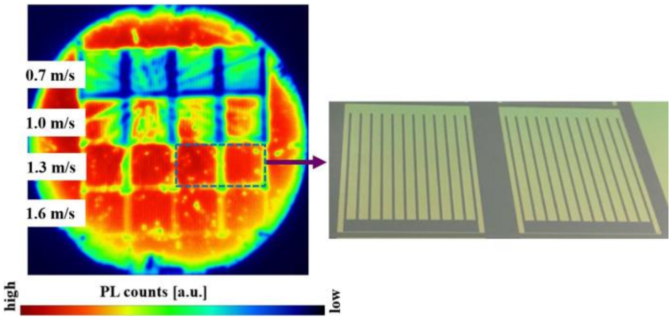

Fig. 5. Uncalibrated PL image of a DBR sample after laser ablation with processing speeds ranging from 0.7 m/s to 1.6 m/s (left); photographic image of two SHJ-IBC cells with active device area of 3.97 cm^2 after emitter patterning using laser ablation and sacrificial mask etching (right).

D. PL measurements

In order to study this, four different laser processing speeds ranging from 0.7 m/s to 1.6 m/s were tested on a DBR sample. PL images were recorded after laser ablation. As depicted in Fig. 5, dramatic degradation of the surface passivation is observed at the region processed by laser of 0.7 m/s due to laser damage of the bottom i/p^+ a-Si:H/c-Si in the OZ (see Fig. 4 b)). The degradation is diminished by increasing the laser speed. For the areas processed by laser of 1.3 m/s and 1.6 m/s, passivation can be maintained. It suggests that laser damage on i/p^+ a-Si:H/c-Si has been prevented by using higher laser speed and DBR to replace SiO_x. Several methods which are capable of reducing laser damage have been reported [2], [11]. However, in these methods additional etching steps of an a-Si:H laser-absorbing layer and/or SiO_2 sacrificial mask layers are always needed after laser ablation. In contrast, our approach is simpler because only the sacrificial DBR layers need to be etched using a short HF dip.

E. Device results

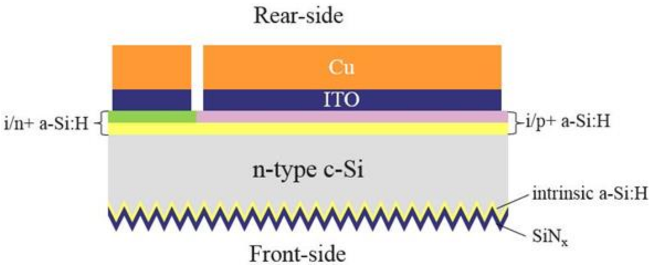

Fig. 6. Schematic of the SHJ-IBC solar cell architecture (not drawn to scale).

TABLE I SUMMARY OF THE CELL RESULTS

Cells	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)	pseudo-FF (%)	pseudo-η (%)
Average	41.5	723	71.4	21.4		
Best	41.6	724	72.6	21.8	80.6	24.2

SHJ-IBC solar cells with active area of 3.97 cm^2 were fabricated using DBR mask layers and a process sequence, as shown in Fig. 1. Details of the integration flow including front-side process and rear-side metallization steps have been reported elsewhere [14]. The cross-section of the SHJ-IBC solar cells is depicted in Fig. 6. The cell results are summarized in Table I with the best efficiency of 21.8%. The J-V curve of the best cell is plotted in Fig. 7. As far as we know, this is the highest reported efficiency of SHJ-IBC cell using laser ablation for a-Si:H patterning. The V_{oc} of 724 mV is similar to that of our previous cells, which used photolithography for a-Si:H patterning [3, 5]. It indicates that the impact of laser damage on the c-Si surface passivation quality has been prevented, which is also confirmed by the PL measurements. The efficiencies are limited by moderate FF values (⩽72.6%) mainly due to high series resistance (R_s). Suns-V_{oc} measurements predict that efficiencies can potentially reach >24 % by solving the R_s issue.

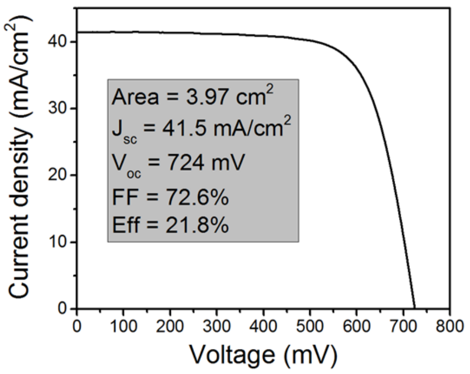

Fig. 7. J-V curve of the best SHJ-IBC cell.

III. CONCLUSION AND OUTLOOK

A damage-free laser ablation process for emitter patterning of SHJ-IBC solar cells has been presented. Laser damage on the i/p$^+$ a-Si:H passivation layer and c-Si substrate is prevented by using optimized laser conditions and a DBR. As such, the i/p$^+$ a-Si:H/c-Si interface passivation can be maintained after laser ablation, as confirmed by PL images. It is worth to notice that our method can be also applied to other laser wavelengths by simply modifying the thickness of sub-layers in the DBR.

Laser ablation and lift-off process result in a simple and photolithography-free a-Si:H patterning approach. To demonstrate the developed process, functional SHJ-IBC cells were fabricated on n-type FZ wafers with the best efficiency of 21.8%. Current developments focus on improvement of FF and further process simplifications, including in situ re-passivation and selective deposition of a-Si:H to replace lift-off process, opening a pathway to efficiencies in the range of 24%

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of imec's industrial affiliation program for Si-PV. The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 657270. This project has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727523.

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