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Simple emitter patterning of silicon heterojunction interdigitated back-contact solar cells using damage-free laser ablation

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ABSTRACT

In early 2017, the world record efficiency for single-junction crystalline silicon (c-Si) solar cells was achieved by merging amorphous silicon (a-Si:H)/c-Si heterojunction technology and back-contact architecture. However, to fabricate such silicon heterojunction interdigitated back-contact (SHJ-IBC) solar cells, complex a-Si:H patterning steps are required to form the interdigitated a-Si:H strips at the back side of the devices. This fabrication complexity raises concerns about the commercial potential of such devices. In this work, a novel process scheme for a-Si:H patterning using damage-free laser ablation is presented, leading to a fast, simple and photolithography-free emitter patterning approach for SHJ-IBC solar cells. To prevent laser-induced damage to the a-Si:H/c-Si heterocontact, an a-Si:H laser-absorbing layer and a dielectric mask are deposited on top of the a-Si:H/c-Si. Laser ablation only removes the top a-Si:H layer, reducing laser damage to the bottom a-Si:H/c-Si heterocontact under the dielectric mask. This dielectric mask is a distributed Bragg reflector (DBR), resulting in a high reflectance of 80% at the laser wavelength and thus providing additional protection to the a-Si:H/c-Si heterocontact. Using such simple a-Si:H patterning method, a proof-of concept 4-cm^2 SHJ-IBC solar cell with an efficiency of up to 22.5% is achieved.

1. Introduction

Crystalline silicon (c-Si) PV dominates the current solar-cell market with a market share of more than 90% of the approximately 100 GW_{peak} of PV modules installed in 2017 [1]. To further increase the installation capacity and contribution to global electricity production, the economic competitiveness of commercial c-Si PV with respect to traditional energy sources should be improved. One of the routes is to further raise the energy conversion efficiency of c-Si solar cells, while maintaining a low fabrication cost.

During the past few years c-Si solar cell efficiencies exceeding 25% have been reported by different companies and research institutes (25.1%, Kaneka [2]; 25.2%, Sunpower [3]; 25.6%, Panasonic [4]; 25.7%, Fraunhofer ISE [5]; 26.1%, Fraunhofer ISFH [6]). Notably, all these impressive cell results have been achieved by using passivated contacts, which are either silicon oxide based [6] or low-temperature hydrogenated amorphous silicon (a-Si:H) based, so-called silicon heterojunction (SHJ) technology [7–9]. The excellent a-Si:H/c-Si passivation quality can significantly minimize the minority charge carrier recombination losses at c-Si surface and thus a high open-circuit voltage (V_{oc}) of 750 mV has been achieved [10]. Moreover, interdigitated back-contact (IBC) technology has been widely utilized to maximize short-circuit current density (J_{sc}) [11]. The IBC technology features both electron and hole collection contacts at the rear side of the solar cells, eliminating front grid shadowing and minimizing optical reflection and parasitic absorption losses. This has yielded a high J_{sc} of 42.65 mA/cm^2 [12]. Most recently in early 2017, Kaneka reported the new world record efficiency of 26.7% in a SHJ-IBC solar cell [12].

Although the potential of high efficiency SHJ-IBC solar cells has been demonstrated, commercializing this type of cells still remains challenging. One of the key limitations is that the back-contact scheme requires a sophisticated fabrication process mainly due to the formation of interdigitated p- and n-type a-Si:H strips at the rear side of the device. So far, several a-Si:H patterning approaches have been developed, including photolithography [7,13–15], screen printing [16], inkjet printing [17], lift-off [14,18,19], shadow mask deposition [20–22], and laser ablation [18,19,23,24]. Whereas photolithography is commonly used at laboratory scale, it turns out to be a costly technique and thus

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not applicable for mass production. Screen printing and inkjet printing are consolidated industrial techniques. However, it still consists of minimum three steps, including an etch resist printing, wet-chemical etching, and resist stripping [16,17,20]. In comparison, shadow mask deposition is a simpler method, but it has been reported that special care needs to be taken to reduce several detrimental effects such as a reduction of the a-Si:H deposition rate as well as tapering of the a-Si:H thickness towards the edge of the deposited feature [20,25,26]. As an alternative to these patterning methods, laser ablation is a promising industrial-viable approach because of the following three aspects: it is a fast, dry, contactless, maskless, and single side process; it has high process precision; and it permits flexible device design.

In this contribution, we present a photolithography-free process sequence for a-Si:H patterning to form the back-contact architecture by using a damage-free laser ablation and a self-aligned lift-off process. An ultraviolet picosecond laser is utilized to ablate an a-Si:H laser-absorbing layer on top of a stack formed by a dielectric mask/p^+/i a-Si:H/c-Si substrate. The dielectric mask consisting of SiO_x and SiN_x layers forms a distributed Bragg reflector (DBR) to replace the previously reported SiO_x [18,19], resulting in a high reflectance of 80% at the laser wavelength. This can substantially reduce the laser-induced damage to the underlying a-Si:H/c-Si interface, which is demonstrated by atomic-force microscopy (AFM), photoluminescence (PL) imaging, and Quasi-steady-state photo-conductance (QSSPC) measurements. After laser ablation of the top a-Si:H layer, the dielectric mask and p^+/i a-Si:H stack are patterned by etching. The remaining dielectric mask is used as a sacrificial layer to perform a lift-off process for patterning of the subsequently deposited n^+/i a-Si:H stack. A proof-of concept 4-cm^2 SHJ-IBC solar cell is fabricated using such simple a-Si:H patterning steps, reaching 22.5% efficiency for the best cell.

2. Process flow of SHJ-IBC solar cell

The 200-µm thick n-type float zone (FZ) monocrystalline silicon wafers (150 mm diameter, < 100 > , 3 Ω cm) are cleaned and then used for solar cell fabrication. The front side of the wafers is textured in a tetramethyl ammonium hydroxide based solution. The detailed descriptions of wafer cleaning and texturing have been provided elsewhere [14]. According to our device design, approximate 80% of the rear-side device area is covered by the p^+/i a-Si:H emitter stack. We pattern the p^+/i a-Si:H first and thus only 20% of the device area needs to be removed during patterning steps. The fabrication process sequence of a SHJ-IBC solar cell is shown in Fig. 1. An p^+/i a-Si:H emitter stack is deposited at the rear side of the wafer using plasma enhanced chemical vapor deposition (PECVD), followed by depositions of the dielectric mask and an a-Si:H laser-absorbing layer of 40 nm. Laser ablation is performed to remove only the top a-Si:H laser-absorbing layer according to the predesigned pattern. An ultrashort-pulsed laser (12 ps, 355 nm, repetition rate of 200 kHz, spot area of 8.33×10^{-7} cm^2, Gaussian distribution profile) with a threshold laser energy fluence of 0.2 J/cm^2 is used in this work. Then the dielectric mask is patterned by a short wet-chemical etching in $HF:HCl:H_2O$ (1:1:20) for 1 min using the laser-patterned absorbing layer as an etch mask. Next, the bottom p^+/i a-Si:H emitter stack is patterned by NF_3/Ar plasma etching using the patterned dielectric layers as an etch mask [27]. The laser pattern is thereby transferred to the p^+/i a-Si:H emitter stack. A blanket n^+/i a-Si:H stack is then deposited by PECVD, and patterned by a lift-off process in $HF:HCl:H_2O$ (2:1:20) for approximately 20 min using the dielectric mask as sacrificial stack, thus eliminating an alignment step [14]. Hence, the interdigitated p^+/i a-Si:H emitter and n^+/i a-Si:H back surface field (BSF) areas are formed using this simple process. Notably, a-Si:H removal in this work is realized by single-side processing, which is either laser ablation or NF_3/Ar plasma etching. Therefore, damage to the front-side pyramids during rear-side a-Si:H patterning steps can be avoided with respect to the methods reported in [18,19].

At the textured front side, a thin intrinsic a-Si:H passivating layer is deposited and then covered by a silicon nitride (SiN_x) antireflection coating (ARC), yielding good light in-coupling and excellent c-Si surface passivation. In our case, such optimized i-a-Si:H and SiN_x stack results in a front surface recombination velocity S as low as 2.6 cm/s at one sun illumination, which are among the best reported S values of SHJ solar cells [10,22]. Such low S values are very important to efficiently collect minority charge carriers in IBC solar cells [28,29].

To finish the device, a stack of indium-doped tin-oxide (ITO) and Cu is deposited at the rear side of the solar cell, and patterned by photolithography and wet chemical etching to form the metal contacts. In this study, the laser line width and line pitch are chosen to match the existing photolithography mask. Nevertheless, the metallization steps can be made upscaled by using either screen printing or inkjet printing to replace photolithography [16,17,20,22]. Thermal annealing at temperatures below 200 °C is applied to the finished cells in order to improve contact behavior.

2.1. *a-Si:H patterning using damage-free laser ablation*

Key to this approach is that laser-induced damage to the p^+/i a-Si:H/c-Si substrate should be substantially reduced or preferably avoided. Several methods have been developed by either optimizing the absorption coefficient of an SiN_x dielectric mask at the laser wavelength, or by using an additional a-Si:H laser-absorbing layer on top of a SiO_x mask [18,19,24]. For the latter method, only the top a-Si:H absorbing layer is ablated, shifting part of the laser damage from the bottom p^+/i a-Si:H/c-Si heterocontact to the SiO_x surface. Nevertheless, when scribing line-shaped openings, overlapping zones (OZs), which are irradiated by two adjacent laser pulses, must be considered [18]. As shown in Fig. 2a)–c), after ablation of the a-Si:H absorbing layer by the first laser pulse, the subsequent laser pulse in OZs will transmit through the SiO_x and finally be absorbed by the bottom p^+/i a-Si:H/c-Si. This can result in severe laser damage and thus significant degradation of c-Si surface as well as issues with re-passivation quality [18].

To solve the problem, we propose a novel method of using a more reflective dielectric mask layer to replace the SiO_x layer. In that way, the laser light transmission through the mask and the resulting laser energy absorption in the bottom p^+/i a-Si:H/c-Si can be reduced (see Fig. 2d)). In this work, a stack of alternating SiO_x and SiN_x layers is deposited on p^+/i a-Si:H/c-Si. To form a DBR structure, the required thicknesses of SiO_x and SiN_x layers are determined to be 60 nm and 48 nm, respectively, using optical refractive indices ($n_{SiOx} \approx 1.5$, $n_{SiNx} \approx 1.9$ @ 355 nm) measured by spectroscopic ellipsometry [30,31]. The SiO_x samples are included as references. As shown in Fig. 3, the measured reflectance of SiO_x/p^+/i a-Si:H/c-Si at the laser wavelength of 355 nm is 52%. So approximately half of the laser light that reaches the SiO_x is eventually absorbed by the underlying p^+/i a-Si:H/c-Si due to the transparency of SiO_x at 355 nm. However, the reflectance can be increased to 64% by using one bilayer of SiO_x/SiN_x and further increased up to 80% using five bilayers of SiO_x/SiN_x. Note that the mask in our method is not limited to PECVD SiO_x/SiN_x layers, but can also consist of other layers deposited using other low-cost methods as long as such layers can be easily etched and have the high refractive index difference that is needed to form a DBR [32–37]. Additionally, our approach is also applicable to other laser wavelengths. For instance, the process window with high reflectance can be shifted to other laser wavelengths by simply modifying the thicknesses of the sub-layers in the DBR structure.

The AFM images of laser-ablated samples after dielectric mask etching are illustrated in Fig. 4. For the a-Si:H/SiO_x sample processed by a laser speed of 0.7 m/s, traces of laser-scribed lines are clearly observed in the form of roughness on the p^+/i a-Si:H/c-Si stack as shown in Fig. 4a). This suggests that the laser-induced damage (e.g. roughness, thermal damage) is present not only in OZs but also in the