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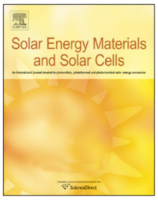

Rear-side All-by-Laser Point-contact Scheme for liquid-phase-crystallized silicon on glass solar cells

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ABSTRACT

We report here on the development of a rear-side point-contact scheme for liquid-phase-crystallized silicon on glass solar cells, which uses laser for all structuring and contact-post-treatment steps. Our contact scheme is based on the procedure developed by CSG Solar and contains two main innovations. First, we demonstrate here that it is possible to form contact holes in the back-reflector resist layer by laser ablation instead of printing droplets of an etch solution with inkjet. The use of laser for forming holes in the resist holds promise for enhancing the precision and reliability of this process. Second, we show that for both p and n-type absorbers, laser firing at the absorber-point-contacts can be used to increase the doping concentration beneath the metal contact and thereby achieve low-resistance contacts. Using the All-by-Laser Point-contact Scheme (ALPS) we were able to reach a solar cell conversion efficiency of 11.5% for a planar n-type laser-crystallized silicon absorber with an amorphous/crystalline heterojunction structure.

1. Introduction

The highest stable solar cell conversion efficiency obtained so far for a silicon thin-film solar cell device processed on glass is 13.4% for an amorphous/microcrystalline multi-junction solar cell [1]. However, due to the light absorption limitation and the low material quality of the amorphous and microcrystalline layers, this efficiency record seems to be very close to the upper limit attainable by this type of solar cell. A new technology that shows promise for overcoming this limitation and approaching the efficiencies of wafer silicon solar cells while maintaining the low costs of thin-film production is polycrystalline silicon (poly-Si) on glass solar cells prepared by liquid-phase crystallization (LPC). In the last few years it has been demonstrated that high-quality silicon absorber layers can be produced on a glass substrate by a single crystallization pass using either an electron-beam line [2,3] or a continuous-wave diode-laser line [4,5]. These layers have centimeter-long grains in the scan direction and at least a two orders of magnitude lower defect concentration compared to solid-phase-crystallized layers [6,7]. It has recently been shown that such LPC poly-Si on glass solar cells can reach an efficiency of 11.8% [8] and a remarkable open circuit voltage of 656 mV [9].

The development of a robust, scalable, and cost-effective contacting scheme is one of the critical issues for the establishment of the LPC poly-Si on glass solar cell technology. In this manuscript we present a procedure for producing a rear-side point-contact scheme based entirely on laser for the structuring and contact-post-treatment steps. Our All-by-Laser Point-contact Scheme (ALPS) procedure, developed since the middle of 2013, has shown rapid improvement in solar cell conversion efficiency up to the value, reported here, of 11.5%. The first innovation behind our development is the formation of holes through an organic resin layer for the absorber and emitter-point-contacts by the use of laser. Introducing holes to an organic resin layer for achieving point-contacts on the back side of a polycrystalline silicon solar cell was first developed at CSG Solar [10]. In contrast to our contact scheme, the holes at the CSG scheme are produced by printing droplets of an etching solution on the resin with an inkjet which is a less accurate method in terms of hole positioning compared to treating the resin by laser. Moreover the use of laser for opening the holes in the resin holds promise for increasing the reliability of this process in industrial production.

The second innovation behind our ALPS procedure is a contact-post-treatment step of diffusing dopants into the absorber by laser firing at the center of the absorber-point-contacts to increase the

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doping concentration underneath the metal and achieve low-resistance silicon/metal contacts. For the p-type absorber we have shown in a recent publication [11] that it is possible to achieve good absorber-point-contacts by firing a 100 nm thin aluminum (Al) contact layer. For the n-type absorber, we show here that low-resistance absorber-point-contacts can be achieved by coating the back metal contact, in this case silver (Ag), with phosphorus spin-on dopant (SOD) and diffusing the phosphorus through the Ag layer by laser firing. Originally, incorporating dopants into the silicon absorber from a spin-on dopant coated on the silver contact layer was carried out by a standard diffusion furnace [12].

It should be noted that applying laser for all structuring and contact-post-treatment steps is especially challenging for solar cells with a polycrystalline/amorphous silicon (poly-Si/a-Si) heterojunction structure where the thin amorphous emitter is known to be much more sensitive to heat than the emitter of a homojunction solar cell. Rearrangement of hydrogen at the a-Si:H emitter is known to occur already at temperatures around 200 °C [13,14]. Deterioration of the passivation effect of an intrinsic amorphous silicon (i-a-Si:H) layer on a crystalline silicon (c-Si) wafer has been observed by Schüttauf et al. at annealing temperatures above 150 °C [15] and by Stegemann et al. [16] at temperatures above 190 °C and was explained by hydrogen out-diffusion from the i-a-Si:H/c-Si interface. So far the CSG Solar contact scheme was only applied to laser-crystallized poly-Si solar cells containing a homojunction [4,5] and therefore in the initial developmental stage of the ALPS procedure much of the work was focused on finding suitable laser processes that do not damage the amorphous emitter. The results that we show here demonstrate that also for poly-Si/a-Si heterojunction solar cells it is possible to apply laser for all the required steps of the contacting scheme.

2. Experimental details

2.1. Solar cell stack preparation

The solar cell layer stack was prepared on a 3.3 mm thick borosilicate float glass substrate that was coated with SiN_x, SiO_x, SiO_xN_y intermediate layers using an industrial-type (AKT1600) plasma-enhanced chemical vapor deposition (PECVD) tool. Different intermediate layer combinations were tested to assure mechanical stability of the cell stack especially after laser crystallization, high anti-reflection, and blockage of contamination diffusing from the glass substrate into the absorber [17]. The intermediate layer stack used for our best cell had the following structure: 20 nm SiN_x/200 nm SiO_x/60 nm SiN_x/20 nm SiO_xN_y. The silicon absorber layer was deposited on the intermediate layers by the same PECVD tool, doped either with boron or phosphorus, and had a thickness of about 9 μm. In order to remove hydrogen prior to the laser crystallization, the samples were annealed at 650 °C for 24 h. Then the absorber layer was crystallized with a LIMO continuous-wave (cw) diode-laser line, 3 cm long and 0.17 mm wide (FWHM), operating at a wavelength of 808 nm. The laser crystallization was performed at an energy density of about 140 J/cm^2, a substrate preheating temperature of 700 °C, and a scan velocity of 10 mm/s. A representative photograph of a silicon absorber crystallized with the cw-diode laser can be seen in Fig. 1. At this stage a hydrogen plasma passivation treatment is applied to the samples at 600 °C for 30 min [18]. To remove defects at the surface of the absorber generated during the crystallization and the hydrogen plasma treatment, a silicon etch solution containing HF, HNO_3, and H_3PO_4 was applied before and after the hydrogen-passivation treatment to etch off each time about 400 nm of silicon from the surface. The final step before starting the contacting procedure was to deposit a 13 nm i a-Si/13 nm doped a-Si emitter and a 250 nm transparent conductive oxide (TCO) layer, either ZnO:Al or ITO, onto the absorber.

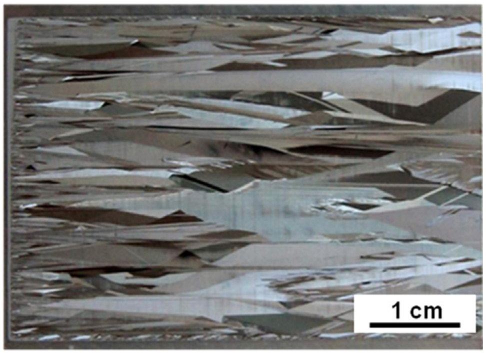

Fig. 1. Photograph of a 10 μm silicon layer crystallized with a LIMO cw-diode laser line using a laser fluence of 140 J/cm^2 and a scan velocity of 10 mm/s. The laser line passed over the sample from left to right a single time. A standard pyramid etching procedure with KOH/IPA was applied to the sample to make the grain structure visible.

2.2. Device preparation

The contacting scheme developed in this work is based on five laser processing steps that are illustrated in Fig. 2. The laser steps were applied to the cell stack using a Rofin laser tool with pulsed nano-second neodymium-doped vanadate ($\lambda = 532$ nm) and pico-second neodymium-doped YAG ($\lambda = 1064$, 532, 355 nm) solid-state lasers. The 355 nm (UV) pico-second laser beam was modified in the last stage of the solar cell development presented here from a Gaussian to a “top-hat” profile to enable better processing homogeneity. The first step of the contacting scheme is defining the cell size, currently 1.02 cm^2, by scribing isolation scribes with the 1064 nm (IR) pico-second laser from the substrate side. After this step a 5 μm to 8 μm TiO_x-impregnated back-reflector resist is spin-coated on the TCO layer and the absorber contact holes are formed by the 355 nm (UV) pico-second laser. The hole formation procedure is described in detail in the results section and contains first a “gentle” laser marking with sufficiently low laser fluences and afterwards selective etching to form a complete opening through the resist using 1.3–1.5% KOH in H_2O. This step is followed by a short wet-etching through the TCO with HF and afterwards, through the emitter with an etch solution containing KMnO4 and HF in order to achieve a contact with the absorber. Then the emitter contact holes are formed by UV laser marking and KOH etching through the resist till the TCO without additional etching steps. At this stage the sample is introduced into a vapor atmosphere of a solvent, which causes the resist to soften and to reflow over to the edges of the point-contacts, thus assuring that the emitter is isolated at the side walls of the absorber-point-contact holes. Next, a 100–200 nm thick aluminum for p-type absorber or a stack of silver and phosphorus SOD for n-type absorber is deposited on the entire sample area and is structured into interdigitating emitter and absorber grid lines by a UV laser separation cut. A top-view sketch of the contact scheme design used in this work can be seen in Fig. 3. The final step in this scheme is to fire the aluminum for the p-type absorber or the phosphorus SOD for the n-type absorber at the absorber-point-contacts with the nano-second laser.

3. Results

The key development behind the ALPS procedure is the way the holes are formed in the back-reflector resist. Initially the pico-second