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Letter

Efficiency and stability enhancement of laser-crystallized polycrystalline silicon thin-film solar cells by laser firing of the absorber contacts

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ABSTRACT

Polycrystalline silicon thin-film solar cells produced by continuous-wave diode-laser crystallization at the University of New South Wales were recently reported to have reached a conversion efficiency above 10%. One drawback of these cells, however, was that they exhibited efficiency degradation within several hours after the cell fabrication was completed. In this work we show that by applying laser firing to the rear point contacts of the solar cells, it is possible to stabilize and even to enhance the performance of these devices. Our investigation indicates that it is the poor quality of the contact between the aluminum and the silicon absorber that causes the cell degradation and offers an elegant and industrial-compatible process to improve the cell performance. This is the first time that the laser firing process, initially developed for alloying an aluminum layer through a dielectric layer on crystalline silicon wafer solar cells, is being applied to polycrystalline silicon thin-film solar cells.

1. Introduction

The fabrication of thin-film polycrystalline silicon (poly-Si) solar cells by liquid phase crystallization is an emerging technology that shows promise for combining the high efficiencies of wafer silicon solar cells with the low costs of thin-film production. 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 [1] or a continuous-wave diode-laser line [2–4]. These layers have centimeter-long grains in the scan direction and a much lower defect concentration compared to solid-phase-crystallized layers, which were developed earlier for solar cell applications [5–7]. Solar cells prepared by e-beam and laser crystallization have now reached an open circuit voltage V_{oc} of around 580 mV [4,8] whereas the values reported for solid-phase-crystallized solar cells never increased significantly above 500 mV [5,6].

The solar cell efficiency record for polycrystalline solar cells prepared at UNSW has been rapidly improved over the last 2 years [2–4]. The best initial efficiency value reported so far is 11.7% and the best stabilized value is 10.4% [4], which matches roughly the efficiency record for solid-phase crystallization [6] even without an optimized light trapping structure. One of the problems that was reported with these solar cells, however, is that they exhibit an efficiency degradation within several hours after the metallization of the rear side of the cell [2]. In this work, we show that the inadequate contact between the aluminum (Al) and the silicon absorber is most likely the cause for this degradation and that by applying laser firing to the absorber point contacts, the cell performance can be stabilized and even enhanced. Laser firing has been utilized since 2002 for creating point contacts by alloying the aluminum back contact with the crystalline silicon wafer through a dielectric layer [9]. Showing that laser firing can be applied also for polycrystalline silicon thin-film solar cells on glass opens new possibilities for the development of the contact system for this type of device.

2. Experimental details

The poly-Si solar cells investigated in this study were prepared at UNSW according to the process described in Ref. [3]. The substrate used for the cells was 3.3 mm thick borosilicate float glass that was coated with a 200 nm SiO_x intermediate layer. The

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silicon absorber layer was deposited on the intermediate layers by electron-beam evaporation at 650 °C, was doped with boron (p-type), and had a thickness of about 10 μm. Then, the absorber layer was crystallized with a LIMO continuous-wave (cw) diode-laser line operating at a wavelength of 808 nm. The laser crystallization was performed at an energy fluence density of about 3 J/mm^2, a substrate preheating temperature of about 600 °C, and a scan velocity of about 10 mm/s. The laser line had a top hat intensity profile along the long axis and a Gaussian profile along the short axis (scan direction). The full width at half maximum (FWHM) of the long axis was 12 mm and of the short axis was 0.17 mm. The n-type emitter layer was formed by spinning a phosphorous source onto the surface and diffusing it into the absorber by rapid thermal annealing. The final step before starting the contacting procedure was a hydrogen plasma passivation treatment at 600 °C applied for about 10 min.

After finishing preparation of the layer stack, a rear contact scheme based on the process developed by CSG Solar [5] was utilized to form the emitter and absorber contacts. The cell size was defined by isolation laser scribes and had the dimensions of 0.6 cm × 1.7 cm. A white paint resist was then coated on the emitter and holes were produced in this layer by inkjet printing. The holes were etched down to the emitter and to the absorber. The side walls of the absorber contact holes were isolated by reflowing the resist. A 100 nm Al layer was deposited on the surface in order to form the n-type (Dimples) and p-type (Craters) contacts. Cutting the Al in order to separate the emitter and the absorber contact regions was performed by a laser. Finally, annealing at 135 °C was performed for an hour to improve the metal contacts.

At this stage, the cells were delivered to HZB for the subsequent laser firing treatment. The firing was performed by a neodymium-doped vanadate solid-state laser from Rofin operating at a wavelength of 532 nm and a pulse frequency of 20 kHz. The pulse duration of this laser was about 16 ns and it had a Gaussian intensity profile.

3. Results

Section 3.1 presents the effect of firing with a single laser shot whereas Section 3.2 deals with laser firing performed by multiple irradiations on the same spot. The quality of the laser-fired contacts is evaluated in Section 3.3 using the transfer length method (TLM) and finally in Section 3.4 the effect of the laser firing on the solar cells is presented.

3.1. Aluminum ablation threshold

Since a very thin Al layer of about 100 nm was used for the back contact of the poly-Si cells, a crucial experiment was to test at what laser fluence this layer ablates. Fig. 1 shows scanning electron microscopy (SEM) images of the Al regions that were exposed to a single laser shot with different laser fluences. In part (a) of the figure, the laser fluence was set at 1.46 J/cm^2, causing some small regions in the laser spot to ablate. As the laser fluence increases in part (b) to 1.85 J/cm^2, the sample surface becomes rough but according to the broken sample edge the Al layer still covers the poly-Si layer completely. In part (c) where the laser fluence was 2.7 J/cm^2, it can be seen that the Al piles up at the rim of the irradiated spot and is absent at the center. Our investigation revealed that the appearance of an elevated Al ring at the circumference of the laser spot indicated that ablation occurred at the center of the spot. The critical laser fluence for ablation was found to be about 2 J/cm^2.

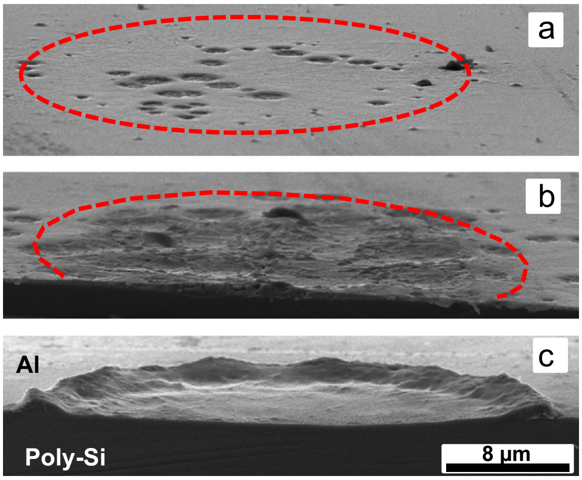

Fig. 1. Scanning electron microscopy images of 100 nm aluminum on a polycrystalline silicon absorber that was fired with a single pulse of a nanosecond laser, operating at a wavelength of 532 nm, using a laser fluence of a) 1.46 J/cm^2, b) 1.85 J/cm^2, and c) 2.7 J/cm^2. The dashed line marks the area of the laser treatment.

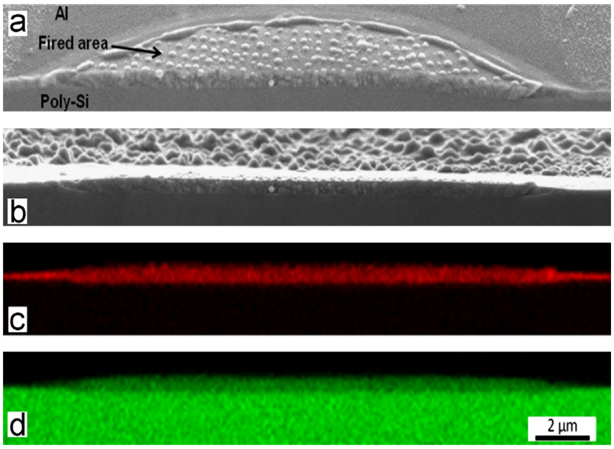

Fig. 2. Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) investigation done on a laser-fired spot that was broken in the middle. The laser firing was done with about 60 laser shots and a laser fluence of about 1.5 J/cm^2. a) SEM of the sample tilted by 30°. b) SEM of the sample tilted by 0°. c) EDX cross-section map of Al. d) EDX cross-section map of Si. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3.2. Laser firing with multiple irradiations

Applying multiple laser shots on the same spot is a method to enlarge the parameter window in which a sufficient amount of energy can be deposited into the Al layer without causing ablation. Fig. 2 shows two SEM images and two energy dispersive X-ray (EDX) maps from a spot that was irradiated with about 60 laser shots and then broken in the middle for investigation. Parts (a) and (b) show the SEM image of the laser-fired spot with a 30° surface tilting and with no tilting, respectively. In both images it is possible to see that a fine-grained layer of about 400 nm is formed on the sample surface. Parts (c) and (d) show the EDX map of the elements aluminum and silicon, respectively. The black regions stand for no signal and the brightness of the red (Al) or the green (Si) color corresponds to the concentration of the element. The EDX results show that the laser firing causes Al and Si to intermix and to be distributed over the entire region of the fine-grained layer seen in the SEM images of parts (a) and (b).