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Selective emitter solar cell through simultaneous laser doping and grooving of silicon followed by self-aligned metal plating

Sisi Wang*, Ly Mai, Alison Wenham, Ziv Hameiri, David Payne, Catherine Chan, Brett Hallam, Adeline Sugianto, Chee Mun Chong, Jingjia Ji, Zhengrong Shi, Stuart Wenham

School of photovoltaic and renewable energy engineering, UNSW, Sydney, NSW 2052, Australia

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ABSTRACT

Both buried contact solar cells (BCSC) and laser doped selective emitter (LDSE) solar cells have achieved considerable success in large-scale manufacturing. Both technologies are based on plated contacts. High metal aspect ratios achieved by BCSC allow low shading loss while the buried metal contacts in the grooves provide good contact adhesion strength. In comparison, although the LDSE cell achieves significantly higher efficiencies and is a much simpler approach for forming the selective emitter region and self-aligned metal plating, the metal adhesion strength falls well short of that achieved by the BCSC. Recent studies show that plated contacts based on the latter can be more durable than screen-printed contacts. This work introduces a new concept of laser doping with grooving to form narrow grooves with heavily doped walls in a simultaneous step, with the self-aligned metal contact subsequently formed by plating. This process capitalizes on the benefits of both BCSC and LDSE cells. The laser-doped grooves are only 3–5 µm wide and 10–15 µm deep; the very steep walls of these grooves remain exposed even after the subsequent deposition of the antireflection coating (ARC). This unique feature significantly reduces the formation of laser-induced defects since the stress due to the thermal expansion mismatch between the ARC and silicon is avoided. Furthermore, the exposed walls allow nucleation of the subsequent metal plating. This novel structure also benefits from greatly enhanced adhesion of the plated contact due to it being buried underneath the silicon surface in the same way as the BCSC. Cell efficiencies over 19% are achieved by using this technology on *p*-type Czochralski (Cz) wafers with a full area aluminum (Al) back surface field (BSF) rear contact. It is expected that much higher voltages and consequently higher efficiencies could be achieved if this technology is combined with a passivated rear approach.

1. Introduction

The buried contact solar cell (BCSC) structure was developed at the University of New South Wales during the 1980s and 1990s [1–6]. This structure is based on laser grooving of the silicon (Si) to form the buried contacts. A range of device performance improvements have been demonstrated using this approach to front side metallization, which enables high aspect ratio with low shading loss, the use of cheap copper (Cu) instead of the more expensive silver, and excellent adhesion strength between plated contacts and the Si beneath them. The suitability of the BCSC for large scale manufacturing was demonstrated in the form of BP Solar's Saturn Technology [7,8]. Although the BCSC have been shown to have superior durability in comparison to screen printed solar cells [9], their manufacturing process is more complicated and thermally expensive, with the laser grooving followed by damage etching, groove diffusion and subsequent preparation for plating.

Another plating-based technology is the laser-doped selective emitter (LDSE) solar cell. Similar to the BCSC, this structure has also been manufactured in large-scale [10–12]. In this method, a spin-on dopant source is applied on to a dielectric layer, that is used as an antireflection coating (ARC), surface passivation layer, and most importantly, as a mask for the subsequent metal plating process [13]. Laser scribing locally melts the regions where metal contact will be formed allowing for the dopant source to be incorporated into the Si. In this way, selective emitters are formed together with a self-aligned plating mask [13]. Despite the success of the conventional LDSE structure, it has a few drawbacks. The main two have been identified to be laser-induced defects caused by the thermal expansion mismatch between the Si and the overlaying dielectric layer [14], and the relatively weak adhesion of the metal contacts, which may peel off during module production [14–16].

In this work, a novel laser-doping process has been developed. The

* Corresponding author.
E-mail address: sisi.wang@unsw.edu.au (S. Wang).

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new method simultaneously forms grooves while heavily doping the groove walls. It capitalizes on the benefits of the BCSC, such as metallization of high aspect ratio, low shading loss, and strong metal adhesion strength, but with the simplicity of the LDSE solar cells [17]. A modified laser doping process has been developed: in a single step, narrow-width grooves with heavily doped walls are formed. Importantly, the narrow width of the grooves allows the dielectric layer to be deposited after the laser doping process, leaving the groove walls relatively exposed to enable metal nucleation in the subsequent plating process. By applying the dielectric layer after the laser-grooving step, thermal expansion mismatch between the Si and the dielectric layer during the laser process is avoided. This minimizes laser-induced defects. Since the metal contact is buried under the Si surface, the adhesion of the contacts is significantly improved compared to the standard LDSE solar cell. This paper illustrates that a single-step laser-doped and grooved selective emitter can be formed with a range of geometries. Lifetime test structures were fabricated to study the impact of the laser grooving process on the induced damage. The light-induced plated (LIP) metal contacts showed excellent adhesion strength in comparison with LDSE and standard screen-printed contacts. Laser-doped and grooved cells with full area Al-BSF rear contacts have been fabricated, achieving over 19% cell efficiency, but with the potential to achieve much higher voltages with improved rear surface passivation also demonstrated.

2. Characterization method

A diode pumped Q-switched 532 nm laser was used in this work. Measured average laser power was used to determine the laser power. To study the laser-doped groove geometry and the quality of the laser-induced junction, cross sections of the wafers were examined using scanning electron microscopy (SEM) and electron beam induced current (EBIC) imaging [18]. The recombination in the samples was characterized by measurement of the effective lifetime as a function of excess minority carrier density using a photo conductance based lifetime tester (WCT-120, Sinton Instruments) and analyzing the measured data using the generalized method [19]. Photoluminescence (PL) imaging [20] was used to identify spatial effects. And a stylus-based adhesion tester [21] was used to evaluate the adhesion strength of the plated metal contacts.

3. Laser doping and grooving

Commercial grade Czochralski (Cz) *p*-type wafers of 1.6 Ω cm resistivity were used to study the groove geometry and quality of the formed junction by SEM and EBIC. The wafers were textured before phosphorous acid was spun onto their surface, following which they were scribed by the 532 nm Q-switched laser to form the doped and grooved selective emitter.

Fig. 1 presents an SEM image of a representative groove cross-section. The measured laser beam diameter is in the range of 10–15 µm. It can be seen that a portion of the melted Si is pushed above the original wafer surface, leaving insufficient silicon beneath the surface to fill the region that became molten, resulting in a narrow gap during the epitaxial re-solidification. The groove is 3–5 µm wide and 10–15 µm deep. The narrow opening ensures that the subsequent dielectric layer deposition will mainly cover the top surface of the wafer, leaving most of the groove walls exposed to allow nucleation of the plated metal. The pyramids adjacent to the melted region are clearly visible, indicating that the laser induced stress and any resulting defects are apparently kept to a minimum level. Fig. 2 illustrates the flexibility of the proposed technology to create different groove geometries; it also demonstrates a continuous doping along the groove wall, even with grooves that are as deep as 30 µm and only 3–5 µm wide. A large range of laser settings could be used to reliably form grooves with desired geometry of 8–13 µm depth and 3–5 µm width. Such a groove geometry has numerous benefits as it ensures that the grooves are: 1) Sufficiently deep to provide good metal contact adhesion without causing significant damage to the Si; 2) narrow enough to prevent the dielectric layer from being significantly deposited inside the groove; and 3) wide enough to allow easy nucleation during plating.

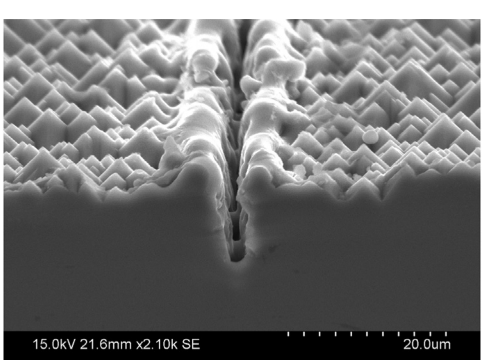

Fig. 1. Cross section SEM image of a typical laser-doped groove.

Fig. 2 shows SEM and EBIC images of four typical grooves. The third column shows the EBIC images superimposed on the SEM images. When the groove is very deep, although the heavy doping along the groove wall is continuous, there does not appear to be enough junction depth to electrically isolate the high recombination velocity surfaces within the grooves from the active regions of the cell. This decreases cell voltage due to an increase in dark saturation current. The second and third groove profiles are the preferred structures. In this case, the widths of the grooves are very narrow and yet the junctions are quite deep within the groove walls as revealed by the EBIC scans. These deeper junctions have been shown to achieve significantly higher voltages by reducing the dark-saturation current. If too much silicon is lost from the molten region, the groove opening becomes too wide, and again, the junction will be too shallow. The grooves with wide opening will also have additional silicon nitride (SiN_x) deposited into the groove therefore necessitating some etching back of the SiN_x to expose the silicon surface and allow nucleation for subsequent plating.

It is shown thus far that the laser-doping and grooving process can simultaneously create grooves and form a continuous, heavily doped selective emitter region along the groove walls. Laser conditions were optimized to form the required geometries. The following section describes the study of laser induced damage and dark saturation current contributions from the laser-doped regions by using lifetime structures.

4. Minimizing laser induced damage

Based on results from the study of groove geometry, two scribing speeds (50 mm/s and 100 mm/s) that could produce the desired geometry were chosen to make lifetime test-structures to investigate laser-induced damage. Since the laser-doping and grooving process can be completed before the deposition of a dielectric layer, it can also be completed before or after the emitter diffusion. To test the optimum sequence the 50 mm/s samples were scribed before and after the emitter diffusion, while the 100 mm/s samples were scribed only before the diffusion process to compare with the 50 mm/s group.

To investigate laser induced damage as a function of laser power, three groups of lifetime samples were fabricated, each processed at four laser power levels ranging from 610 to 770 mW. Control samples (i.e. no laser processing) were included in each group. Industrial grade 1.6 Ω cm *p*-type Cz wafers were used for this experiment. All samples underwent standard alkaline texturing at the same time. After spinning on phosphorus acid onto one side of each sample in group I and II, group I was laser scribed at 50 mm/s, and group II scribed at 100 mm/s to form the grooved selective emitter, a light emitter diffusion was then performed (130–150 Ω/sq). Group III was diffused at the same time as