Advanced selective emitter structures by laser opening technique for industrial mc-Si solar cells

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A laser opening technique is employed as the photolithography process to form selective emitter (SE) structures on multi-crystalline silicon (mc-Si) substrates for the large-area (156 × 156 mm^2) solar-cell industry. The best efficiency of 16.35% is obtained with the developed SE structure after a damage removal process with optimisation of heavily and lightly doped dopants, which yields a gain of 0.88% absolute compared with that of a reference cell. Significantly, the SE mc-Si solar cell without the damage removal process can also reach a gain of 0.48% absolute. The developed SE process has simplicity, reliability, is fast, cost-effective, and could be effectively applied to mass production in industrial applications.

Introduction: The common crystalline-silicon (C-Si) solar cell for commercial application is about 40–50 Ω/sq with homogeneous doping in the emitter region. This method can reduce contact resistance in the metal–semiconductor interface. However, it would increase surface recombination velocity, thus decreasing the performance of cells [1]. To overcome these disadvantages, a trade-off compromise could be obtained by a selective emitter (SE) structure [2, 3], which has heavily doped dopants (HDDs) underneath the contact metal, and lightly doped dopants (LDDs) in the illuminated area. This leads to reduced contact resistance as well as lower surface recombination velocity, thus resulting in the improved performance of cells.

Recently, much effort has been made to prepare large-area SE solar cells by many approaches, such as etching paste [2], laser doping [3] and etching back [4]. In the case of etching paste, it has the advantages of being fast, simple and of reliable process. Furthermore, it is possible to achieve a low-cost production concept. But the etching paste method has some disadvantages, such as dilation of line-width in the opening region, and leads to an increase of the HDD region, thus increasing the surface recombination velocity. In the case of laser doping, the remaining phosphosilicate glass (PSG) on the wafer serves as a dopant source. The laser selectively melts the Si and locally increases the amount of phosphorus (P) in the emitter as well as driving it deeper into the wafer, thus lowering the emitter sheet resistance underneath the metal contact. However, this laser doping process leads to reduction of open-circuit voltage (Voc) and filled factor (FF) owing to laser-induced damage. In addition, etch-back techniques are based on the selective etching of the homogeneous emitter using the metallisation scheme to form an SE. The SE was obtained by etching-back non-protected regions in an acidic etch bath of HF/HNO_3 until it reached the appropriate sheet resistance. This drawback is that the etching solution is hard to set accurately, thus lowering the reproducibility in industrial applications. Laser processing as a photolithography step is an important tool for C-Si solar cell fabrication. Recently, many processing technologies have utilised lasers in C-Si solar cell fabrication, such as edge isolation, laser-fired back contacts, laser texturing. These processes all demonstrate the benefits of versatility, simplicity, reliability, speed, cost-effectiveness and increasing the use of lasers in industrial applications. As the formation of the selective emitter usually involves patterning of diffusion barrier layers, laser opening can be successfully used for this purpose, avoiding the photolithography step. In this Letter, the SE mc-Si solar cell by means of the laser opening process is investigated without the disadvantages of etching paste, laser doping and the etching-back process, and thus can be effectively introduced into industrial large-area production.

Experiment: For the fabrication of multi-crystalline silicon (mc-Si) solar cells as described previously [5], a 1 Ωcm *p*-type (100)-oriented Si with size of 15.6 × 15.6 cm^2 (6 inch) was used. This wafer thickness is about 200 μm. An Nd:YAG laser (λ = 532 nm) with a pulse duration of 30 ns melts the wafer surface in order to form an SE structure. In the first fabrication step, texturisation of the mc-Si is carried out by an HF/HNO_3 solution. Then, the silicon dioxide (SiO_2) as the diffusion barrier layer is grown by wet oxidation. The laser ablation is next used to open a barrier in order to have HDD under the contact metal with interdigitated fingers followed by deeper $POCl_3$ diffusion. Afterwards, the SiO_2 barrier is removed by an HF-dip in order to form the second P diffusion with an 80–90 Ω/sq shallow emitter. The passivation and antireflection (AR) is formed by a plasma enhanced chemical vapour deposition (PECVD) SiN on the front surface. Screen printing is applied to the solar cells to form metallic contacts. Finally, laser edge isolation is used to avoid shutting at the front and the rear side.

In the work reported in this Letter, we used three SE kinds of different process schemes for comparison purposes. The SE1 cell is not a damage removal process and the SE2 cell has damage removal by KOH for 4 min. Both SE1 and SE2 have the same sheet resistance with 50 Ω/sq underneath the metal contact, and 80 Ω/sq in the illuminated area. For SE3, in order to achieve the optimum condition of HDD and LDD in emitter sheet resistance, we use 40 Ω/sq underneath the contact metal and 90 Ω/sq in the illuminated area. In addition, this SE3 cell has damage removal process by KOH for 4 min. On the other hand, the reference (Ref) cell is 50 Ω/sq with homogeneous doping in the emitter region.

For simplification of terrestrial solar-cell characterisation, the induced current density-voltage (*J-V*) curves of the developed devices were measured under the air mass (AM1.5) of the solar simulator (Wacom, Model: WXS-220S-L2) illumination at 1000 W/m^2 on a Keithley 4200 instrument. The quality of the surface passivation is revealed by lifetime measurements, which are obtained by a Semilab WT-2000. We also measured the sample's quantum efficiency (QE) by PV Measurement (Model: QEX7). In addition, the contact resistance and the light beam-induced current (LBIC) scan were measured by CoRRescan instrument (Model: MRN-061).

Results and discussion: To remove thermal oxide as the diffusion barrier layer, the developed laser-opening process needs to melt the Si surface because of the low light absorption of the thermal SiO_2. In the SEM photos (insets of Fig. 1), the left image shows laser damage in the opening region. Obviously in the same opening region, the right image appears as the random pyramid structure after laser damage is removed by KOH solution. Meanwhile, Fig. 1 illustrates the *J-V* characteristics of SE mc-Si solar cells with different process schemes under standard measuring condition (AM 1.5 spectra, 1000 W/m^2, 25°C). The best performance of the SE3 solar cell shows the highest Voc (0.621 V), short-circuit current density (Jsc = 34.55 mA/cm^2) and conversion efficiency (CE = 16.35%) and yielded a gain of 0.88%absolute compared to the reference cell. Significantly, the SE mc-Si solar cell without damage removal process for the SE1 cell can also yield a gain of 0.48%absolute compared to the reference cell. Furthermore, the mc-Si solar cells with the SE structure show a relatively lower FF than that of a Ref cell owing to minority carriers crowding at the lateral junction [6].

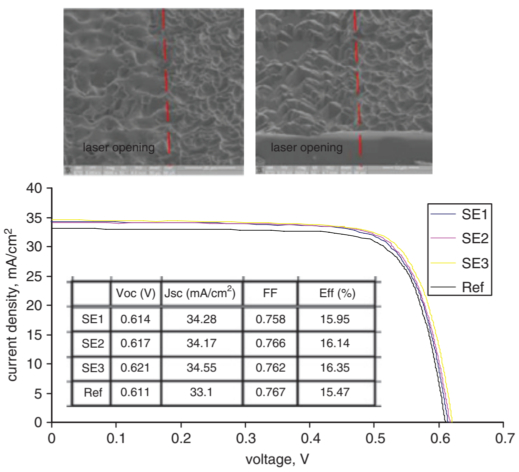

Fig. 1 *Current density-voltage (J-V) characteristics of selective emitter (SE) multi-crystalline silicon (mc-Si) solar cells with different process schemes*

Insets: SEM images before (left) and after (right) laser-opening process. Performance of mc-Si solar cells by different developed SE structures shown in bottom inset

Fig. 2 plots the external quantum efficiency (EQE on the left axis) and the internal quantum efficiency (IQE on the right axis) for comparison of different processes. The SE1 cell shows slightly lower EQE and IQE in the wavelength range from 700 to 900 nm compared with a Ref cell, which is mainly due to the laser-induced defect (without damage removal) and propagating into the bulk region during the diffusion process [7]. The EQE and IQE for the SE2 cell in the wavelength range are similar to SE3 and higher than those of SE1 and the Ref cell. After the damage removal process, there not only was increased QE for the middle wavelength but also increased QE for the short wavelength range. The best EQE and IQE in the short wavelength are reached for SE3. However, the mc-Si solar cells with an SE structure evidently show higher EQE and IQE compared with a reference cell owing to lower emitter doping in the illuminated region.

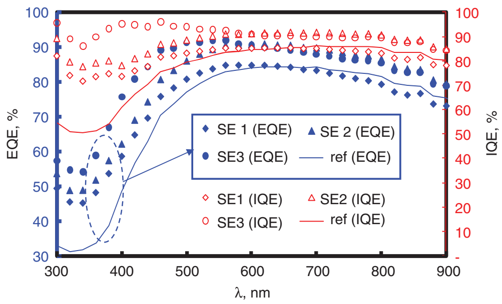

Fig. 2 *Results of external and internal quantum efficiencies (EQE, left; IQE, right) measurements by three different processes on large-size mc-Si solar cells; corresponding data of reference cell also plotted as comparison*

Fig. 3 shows the lifetime, contact resistance and LBIC scan for different process schemes. The average effective minority carrier lifetime (τ_{eff}) is measured by means of microwave-induced photo-conductance decay (MW-PCD) at the injection level of about 10^{16} atoms/cm^3. The SE1 cell shows lower average lifetime, LBIC and contact resistance which is mainly due to the laser-induced defect and increasing minority carrier recombination [8]. It is worth noting that the contact resistance for the SE1 cell could be also affected in this experiment. The optimal average lifetime and LBIC scan for the SE3 cell is obtained. This is mainly due to optimisation of heavy-light doping in the emitter regions and without the laser induced defect. In addition, the contact resistance for the SE3 cell is similar to the SE2 cell.

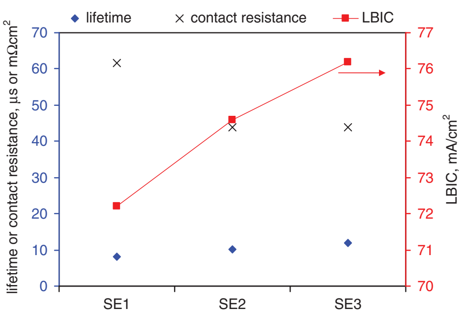

Fig. 3 *Comparison with lifetime (in μs), contact resistance (in mΩ/cm2 both at left axis) and LBIC (in mA/cm2 at right axis) on mc-Si solar cells developed by three different SE processes*

Conclusion: Three types of SE mc-Si solar cells with different laser-opening schemes are evaluated. The best efficiency of 16.35% is performed for the SE3 cell. In addition, we were able to achieve an SE mc-Si solar cell without damage removal process with efficiency of 15.95% and effectively yield a gain of 0.48%absolute compared with those of a Ref cell. Measurements of EQE and IQE show no losses due to less laser-induced damage on the front side for the SE1 cell without the damage removal process. However, this laser opening process has simplicity, reliability, is fast, cost-effective and has not the disadvantages of etching paste, laser doping and the etching-back process, thus it could be effectively introduced into industrial production applications. Moreover, the developed technique is very simple, cheap and suitable for mass production, thus it is promising for large-area mc-Si solar cell manufacturing. In the future, we will focus both on improving the mc-Si texturing quality and on implementing novel process features such as different material coatings to obtain relatively highly efficient solar cells.

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