Performance improved by point-contact electrodes and SiO_2/SiN_X layers at rear

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The rear point-contact fabricated through the laser-opening technique for mass production was applied on the photovoltaic cells. Laser opening, different layers for passivation (SiO_2) and protection (SiN_X) were employed to investigate their impact on the performances of solar cells. The SiN_X layer protects the SiO_2 layer from being burnt through by aluminium paste at the co-firing step. A conversion efficiency (η) of 16.91% with an open-circuit voltage of 628 mV was obtained for the optimal cell, a stack structure with SiO_2 and SiN_X layers, which also achieves a lower contact resistance of 6.66 mΩ·cm^2 and a higher light-beam-induced current of 80.77 mA/cm^2. The optimal cell also showed longer lifetime and 3–4% increased quantum efficiency in the visible wavelength range. Therefore, the developed process has simplicity and reliability, is fast and cost-effective and could be applied to industrial applications.

Introduction: Silicon solar cells with rear contacts (electrodes) have shown outstanding performance, providing a cost-effective process for p-type silicon solar cells [1]. The rear point-contact (PC) located in an array can decrease the contact coverage fraction and further increase reflectivity at the bottom, thus increasing light absorption and conversion efficiency. The major advantage of restricting contact coverage to small points is that it significantly increases the output voltage of cells [2]. In a typical application, a back side field (BSF) with full-area aluminium (Al) formed at the rear contacts behave like a p–n junction. This Al-BSF provides an ohmic contact and a moderate rear passivation, thus effectively reducing the recombination velocities at the rear surface and improving the collection probability of minority carriers. The passivation of the rear dielectric layer also improves the internal reflectivity, which reduces absorption losses caused by the rear-Al electrodes. Dielectric layers such as SiO_2, SiN_X, SiC, SiO_X and Al_2O_3 are favourable candidates [3]. To increase the efficiency of rear PC solar cells, the quality of passivation combined with reflectivity at the rear ought to be improved. A SiO_2/Al rear contact guarantees a low surface recombination on the rear side [4].

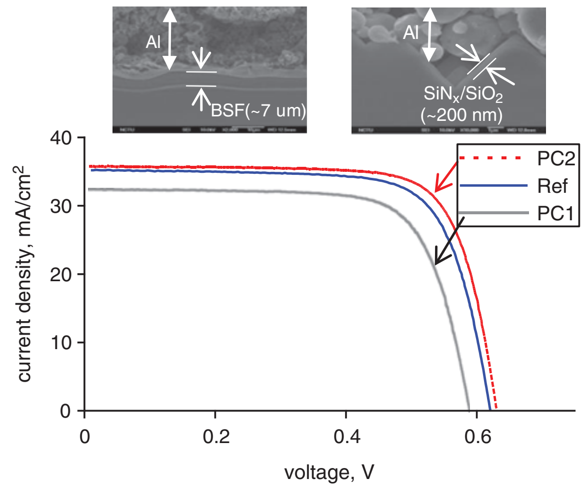
The aim of this research was to improve the solar-cell performance using different rear PC processes. Following our previous study of the laser-opening technique [5], we developed two fabrication methods for single-crystalline silicon (sc-Si) solar cells with rear electrodes and compared the characteristics of different PC processes. The first, designated as PC1, involves alloying the silicon wafer with Al paste to significantly change the local contact configuration. The second, designated as PC2, utilises stack layers of SiO_2/SiN_X and laser opening replacing the photolithography process to ablate the dielectric layers stack in specific PC schemes. Lastly, we applied Al screen-printing techniques to form the rear electrodes.

Experiment: The solar cells were fabricated as described previously [5, 6]. The samples were sc-Si substrates of large area (~125 × 125 mm^2), (100)-oriented p-type Czochralski (Cz) Si wafers of resistivity (~0.5–3 Ω·cm) with a thickness of 200 µm after saw-damage etching in KOH. In the first step, the substrate was texturised using an HF/HNO_3 solution. Subsequently, SiO_2 was grown as a diffusion barrier layer through wet oxidation. Next, the front metallisation of the diffused sc-Si wafers was achieved using standard Ag paste for the screen-printed metallisation, following which the wafers were baked and co-fired at 750°C. The cells were fabricated with rear electrodes using different PC processes (PC1 and PC2) and one device without PC as a reference (Ref). An Nd:YAG laser (532 nm wavelength and 30 ns pulse duration) was then used to drill an array of holes at the rear of PC2 to form the PC structure.

The PC1 sample was fabricated without laser opening in a two-step process: first, screen-printing the point Al paste and co-firing; then screen-printing the full-area Al paste and once again co-firing, to produce PC and Al-BSF (SiO_2 layer) at the rear electrode. During the fabrication of PC1, the full-area Al paste at a high co-firing temperature (~760°C) burns through the SiO_2, likely resulting in high resistance. To overcome this problem, the geometry of the PC2 rear contacts was designed to have a stack structure of a SiO_2/SiN_X layer (thickness = 200 nm), with SiO_2 thermally grown at 900°C for 1200 s and SiN_X deposited by plasma-enhance chemical vapour deposition on top of the SiO_2 for 1500 s. The SiN_X layer protects the SiO_2 layer from penetrating by Al paste in the area outside the hole drilled by laser opening. Finally, the solar cells were edge-isolated using a dicing saw.

The current density–voltage (J–V) curves of the developed devices were measured under the air mass (AM1.5) of the solar simulator (Wacom, WXS-220S-L2) illuminated at 1000 W/m^2 on a Keithley 4200 instrument. The surface passivation quality was assessed by lifetime measurements (Semilab, WT-2000). The quantum efficiency (QE) was measured by a spectral measurement system (photovoltaic (PV) measurement, C-995). In addition, the contact resistance and the light-beam-induced current (LBIC) were measured using a CoRRescan instrument (MRN-061).

Results and discussion: Fig. 1 shows the J–V characteristics of the sc-Si solar cells (PC1, PC2 and Ref) with different rear-electrode fabrication processes under standard measuring conditions (AM1.5 spectra, 1000 W/m^2, 25°C). The main PV parameters of the solar cells processing with different rear electrodes are listed in Fig. 1. Among the processes, PC2 shows optimal solar-cell performance with the open-circuit voltage (V_{OC}) = 0.628 V, short-circuit current density (J_{SC}) = 35.996 mA/cm^2, conversion efficiency (η) = 16.91% and series resistance (R_S) = 6.66 mΩ·cm^2. Significantly, this optimal η value shows an absolute gain of 3.93% compared with the Ref cell. These improvements are attributed directly to a reduced rear recombination and an improved rear reflectance caused by the passivation layer (SiO_2) [3] and indirectly to the protection layer (SiN_X) deposited on the SiO_2 layer, thus reducing damage to the passivation layer during the laser opening and co-firing after screen-printing of Al paste on the rear electrode. In the scanning electron microscopy (SEM) photos (Fig. 1, top), the Ref cell (left image) shows the cross-section of the BSF, which is ~7 µm in thickness. The PC2 cell (right image) shows the cross-section of the SiN_X/SiO_2 layers (~200 nm thickness). The disappearance of the BSF layer in the PC2 cell is due to the SiN_X/SiO_2 layer insulating the rear-Al electrode, thus lowering the fill factor (FF) value of 74.7% as compared with that of the Ref cell, as shown in Fig. 1. One reason for this result is the increased R_S for the locally contacted cell of PC2 in contrast to the Ref cell [7].



	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	η (%)	R (μΩ·cm²)
Ref	35.188	0.616	75.1	16.27	3.84
PC1	32.392	0.587	72.8	13.86	9.46
PC2	35.996	0.628	74.7	16.91	6.66

Fig. 1 *Current J–V curves of sc-Si solar cells with rear electrodes for PC1, PC2 and Ref*

Cross-sectional SEM images of Ref (left) and PC2 (right) cells are shown above the graph
Table (bottom) is electrical performance of three rear-electrode cells

Fig. 2 shows the internal QE (IQE, left axis) and external QE (EQE, right axis). It should be noted, however, that the EQE and IQE of the PC1 cell are lower than those of the Ref cell for all wavelengths except for the range of 450–540 nm. The high R_S on the rear increases the loss of current flowing through the back electrode. From the view point of the QE, a sharp decrease occurs above the wavelength of 550 nm for the EQE and IQE of PC1. This sharp change is a consequence of the higher R_S at the rear side of PC1. The near unity (100%) of the EQE and IQE of PC2 cells illuminated by short wavelength light (500–600 nm) clearly demonstrates that the fabrication process of PC2 is capable of maintaining excellent lifetime.

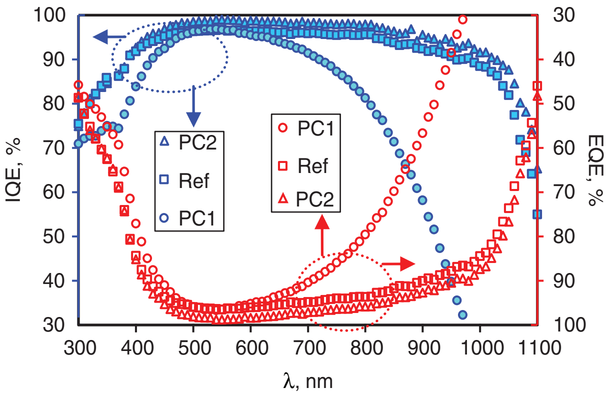


Fig. 2 *Internal (left axis) and external (right axis) QE of different solar-cell rear contacts: PC1, PC2 and Ref*

The PC2 cell shows the best IQE and EQE in the wavelength range from 400 to 1100 nm compared with that of the Ref and PC1 cells. This is mainly due to the minority carrier lifetime increased by rear passivation and to the laser-opening technique improving the contact resistance. In the PV mechanism, the efficiency is strongly related to the generation of electron–hole pairs and their recombination before being delivered to the external circuit at a certain voltage [8].

Fig. 3 demonstrates the contact resistance (R_C, in (mΩ· cm^2)), the lifetime (in μs) (both at the left axis), as well as the average LBIC scans (in mA/cm^2) (at the right axis), compared among the PC1, PC2 and Ref cells.

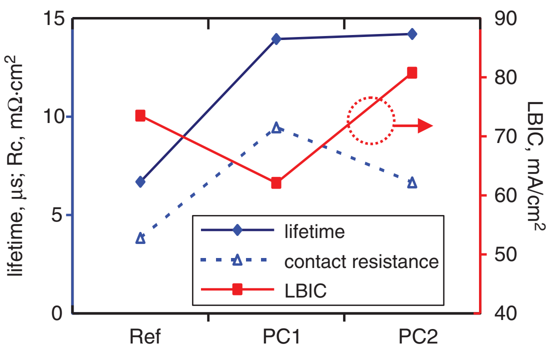


Fig. 3 *Comparison of lifetime (μs), contact resistance (mΩ·cm^2) (both at left axis) and LBIC (mA/cm^2) (at right axis) of PC1, PC2 and Ref processes*

Among these three cells, the PC1 cell showed the highest values of R_C (9.45 mΩ·cm^2) and lowest value of LBIC (62.1 mA/cm^2). Both the R_C and LBIC of PC1 are worse than the values of PC2. This is a consequence of the double screen-printing with co-firing procedures. These burn through the Al paste and passivation (SiO_2) layer, thus lowering the values of η (13.86%) and J_{SC} (32.392 mA/cm^2), as shown in Fig. 1. It is worth noting that the high contact resistance of the PC1 cell could also degrade the solar-cell performance.

The PC2 process achieved lower contact resistance (R_C = 6.66 mΩ·cm^2) and the highest LBIC (80.77 mA/cm^2) due to the SiN_X/SiO_2stack layers. This coincided with a reverse trend of FF (see Fig. 1). The PC2 cell also showed the highest conversion efficiency (η = 16.91%) and current density (J_{SC} = 35.996 mA/cm^2). The lifetime of the PC2 cell is similar to that of the PC1 and both are better than that of the Ref cell. PC2 results in a lifetime increased by nearly 7.51 μs, a contact resistance increased by 3 mΩ·cm^2, as well as a LBIC that is higher by 7 mA/cm^2 in comparison with those of the Ref cell.

Conclusions: We have evaluated the performance of the three sc-Si solar cells. PC2 shows the optimal solar cell characteristics with V_{OC} of 0.628 V, J_{SC} of 35.996 mA/cm^2, η of 16.91%, R_S of 6.66 mΩ·cm^2 and the highest LBIC of 80.77 mA/cm^2. Compared with that of a Ref cell, the improved PV properties and QE of the PC2 cell is attributed to the stack structure of the SiO_2/SiN_X layer reducing damage to the passivation layer owing to the high thermal budget during the co-firing process after screen-printing of Al paste. This was also proved by the EQE and IQE measurements. The laser-opening technique is simple, reliable, fast and cost-effective and has no drawback of etching paste, thus enabling the possibility of being introduced into industrial production applications.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Fellmeth, T., Mack, S., Bartsch, J., Erath, D., Jäger, U., Preu, R., Clement, F., and Biro, D.: '20.1% efficient silicon solar cell with aluminium back surface field', *IEEE Electron Device Lett.*, 2011, **32**, (8), pp. 1101–1103, doi: 10.1109/LED.2011.2157656

2 Guo, J.H., and Cotter, J.: 'Laser-grooved backside contact solar cells with 680 mV open-circuit voltage', *IEEE Trans. Electron Devices*, 2004, **51**, (12), pp. 2186–2192, doi: 10.1109/TED.2004.839870

3 Gatz, S., Bothe, K., Müller, J., Dullweber, T., and Brendel, R.: 'Analysis of local Al-doped back surface fields for high efficiency screen-printed solar cells', *Energy Procedia*, 2011, **8**, pp. 318–323, doi: 10.1016/j.egypro. 2011.06.143

4 Eisele, S., Roder, T., Ametowobla, M., Bilge1, G., Kohler, J.R., and Werner, J.H.: '18.9% efficient silicon solar cell with laser doped emitter'. IEEE Photovoltaic Specialists Conf., Philadelphia, PA, USA, June 2009, pp. 883–885, doi: 10.1109/PVSC.2009.5411148

5 Ho, J.J., Cheng, Y.T., Liou, J.J., Lin, C.H., Dimitrov, D.Z., Tsai, S.Y., Wang, C.K., Lee, W., and Wang, K.L.: 'Advanced selective emitter structures by laser opening technique for industrial mc-Si solar cells', *Electron. Lett.*, 2010, **46**, (23), pp. 1559–1561, doi: 10.1049/el.2010.2471

6 Cheng, Y.T., Ho, J.J., Wang, C.K., Lee, W., Lu, C.C., Yau, B.S., Nain, J. L., Chang, S.H., Chang, C.C., and Wang, K.L.: 'Improvement of organic solar cells by flexible substrate and ITO side treatments', *Appl. Surf. Sci.*, 2010, **256**, pp. 7606–7611, doi: 10.1016/j.apsusc.2010.06.011

7 Lauermann, T., Lüder, T., Scholz, S., Raabe, B., Hahn, G., and Terheiden, B.: 'Enabling dielectric rear side passivation for industrial mass production by developing lean printing-based solar cell processes'. IEEE Photovoltaic Specialists Conf., Honolulu, HI, USA, June 2010, pp. 028–033, doi: 10.1109/ PVSC.2010.5614042

8 Luque, A., and Hegedus, S.: 'Handbook of photovoltaic science and engineering' (Wiley, Chichester, West Sussex, England, 2003)