HIGH EFFICIENCY SCREEN-PRINTED PLANAR SOLAR CELLS ON SINGLE CRYSTALLINE SILICON MATERIALS

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ABSTRACT

In this paper we report on the fabrication, characterization and analysis of high efficiency planar screen-printed solar cells with high sheet resistance emitter ~ 100 Ω/square. Three single crystalline materials were used in this study including; boron doped magnetically stabilized Cz (MCz), gallium-doped Cz (GaCz) and float zone (FZ). For these three materials, a wide range of resistivities was investigated including Fz - 0.6-4.1 Ω-cm, MCz - 1.2-5.3 Ω-cm and Ga-Cz 2.6-33 Ω-cm. Energy conversion efficiencies of 17.7% were achieved on both Fz (0.6-Ω-cm) and MCz (1.2-Ω-cm) while 16.9% was obtained on GaCz silicon material. The 17.7% efficiency achieved on these two materials is the highest energy conversion efficiency reported on a planar screen-printed silicon solar cell. These results demonstrate the importance of high sheet resistance emitter in achieving high efficiency manufacturable solar cells.

INTRODUCTION

Screen-printing is a simple, rapid, and cost-effective method for forming contacts for solar cells. The majority of commercial silicon solar cells today are made by screen-printed contacts on 30-55 Ω/sq. emitters, rather than on 90-100 Ω/sq. shallow emitters, to avoid high contact resistance and junction shunting. Heavy doping in the emitter results in reduced short-wavelength response and higher emitter saturation current density (J_{oe}), which reduces the cell performance. However, the cell performance can be enhanced by the use of a higher sheet-resistance emitter, provided an effective emitter-surface-passivation is achieved. PC1D model calculations reveal that high sheet resistance emitter induced performance enhancement is a function of base resistivity, front and back surface recombination velocities, and bulk lifetime. For example, if the front surface recombination velocity (FSRV) is very high (>1×10^5 cm/s), then the high sheet resistance emitter under-performs the conventional low sheet resistance homogeneous emitter cell.

The use of high sheet resistance emitter for high-efficiency cells can be performed in two ways; the selective emitter with heavy doping only beneath the grid and 70-100 Ω/sq sheet resistance between the grid, and the homogeneously diffused high sheet resistance (70-100 Ω/sq) emitter. The former decouples the recombination under the metal contacts and results in a reduction of the overall saturation current density (J_o) of the cell. This can be implemented by (i) selectively printing a phosphorus diffusion paste [1, 2], (ii) self-aligned plasma-etch back using screen-printed gridlines as masks [3] and (iii) self-aligned screen printed gridlines using self-doping Ag paste [4-5].

The use of homogeneously diffused high sheet resistance emitter (70 -100 Ω/sq) requires the modification of the front contact paste composition and fast firing of the screen-printed contacts in IR or RTP furnaces. Hilali et al. [6-8], demonstrated, for the first time a 4 cm^2, textured screen-printed solar cells with efficiency >18% on homogeneously diffused 100 Ω/sq. emitter. The >16% EFG reported by Rohatgi et al [9] and >17% on Ga-doped Cz, textured, [10] screen-printed solar cells with 100 Ω/sq emitter used the optimized firing scheme as in [6]. In this study we (i) investigate the impact of base resistivity on the performance of screen-printed planar solar cells in conjunction with high and low sheet resistance emitters, and (ii) quantify the contribution of high sheet resistance emitter to efficiency enhancement through analysis of light and dark I-V, and internal quantum efficiency.

EXPERIMENTS

In this study, the screen-printed n^+-p-p^+ cells (4 cm^2) were fabricated on single-crystalline silicon using Ag paste (CN33-455 from Ferro Corporation) and optimized firing condition [5] on 100 Ω/sq. emitters as well as 45 Ω/sq emitters widely used. P-type 0.6 - 33 Ω-cm, 300-μm-thick (100) float-zone, B-doped magnetic Cz and Ga-doped Cz substrates were used for all the experiments. The wafers were chemically cleaned followed by $POCl_3$ diffusion to form the n^+ (100 Ω/sq) emitters. The diffusion temperature used for the 45 Ω/sq emitter was 877°C while that for the 100 Ω/sq emitter was 842°C. After the phosphorus glass removal and post diffusion clean, the low frequency (50 KHz) PECVD SiNx AR coating was deposited on the emitters. Next, the Al paste was screen-printed on the backside and dried at 200°C. The Ag grid was then screen-printed on top of the SiNx film and Ag and Al contacts were co-fired in a lamp-heated belt furnace. The cells were then isolated using a dicing saw and annealed in forming gas at 400°C for ~20 min. No surface texturing was used in these cells. In addition to the 100 Ω/sq emitter cells, conventional cells with 45 Ω/sq emitter were also fabricated using the same co-firing scheme for the Ag and Al contacts.

RESULTS AND DISCUSSION

Efficiency dependence on sheet resistance emitter and material resistivity

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Fig. 1 shows the efficiencies of solar cells fabricated with high and low sheet resistance emitters on the three (Fz, MCz and GaCz) single crystalline silicon materials. For these three materials, a wide range of resistivities was used including Fz, MCz and GaCz. On all the three materials, the cell efficiencies with high sheet resistance emitters out perform those cells fabricated with low sheet resistance emitters. This efficiency advantage for the cells fabricated with high sheet resistance emitters is due to 0.2-1.6 mA/cm^2 boosts in J_{sc}, which is due to better blue response and improved surface passivation on the 100 Ω/sq.

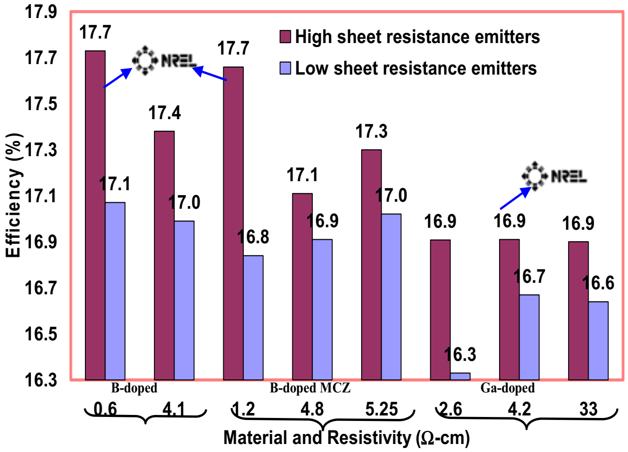


Fig. 1: Comparison of efficiency on cells with high and low sheet resistance emitters as a function of material and resistivity

PC1D model calculations reveal that high sheet resistance emitter induced performance enhancement is a function of base resistivity, front and back surface recombination velocities, and bulk lifetime. For example, if the front surface recombination velocity (FSRV) is very high (>1x10^5 cm/s), then the high sheet resistance emitter under-performs the conventional low sheet resistance homogeneous emitter cell. However, if the FSRV is approximately 10000 cm/s the high sheet resistance emitter gives at least a 0.6% (absolute) increase in cell efficiency. The efficiency difference of 0.6-0.9% between the high and low sheet resistance emitter cells fabricated on Fz (0.6 Ω-cm) and MCz (1.2-Ω-cm) very well match this theoretical prediction.

Short circuit current density as a function of emitter sheet resistance and resistivity

Fig. 2 shows the short circuit current density as a function of the materials resistivity with respect to emitter sheet resistance. The short circuit current density in each group of materials depends on the base resistivity as well as the emitter sheet resistance. The higher the base resistivity and emitter sheet resistance, the higher the short-circuit current density. This dependence can be attributed to lower FSRV (recombination in the emitter or J_{oe}) values as the emitter sheet resistance increases.

Open circuit voltage as a function of sheet resistance emitter and material resistivity.

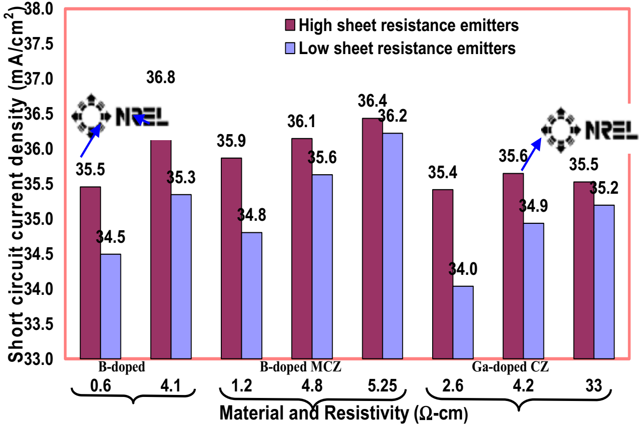


Fig. 2: The short circuit current density on cells with high and low sheet resistance emitters versus material and resistivity.

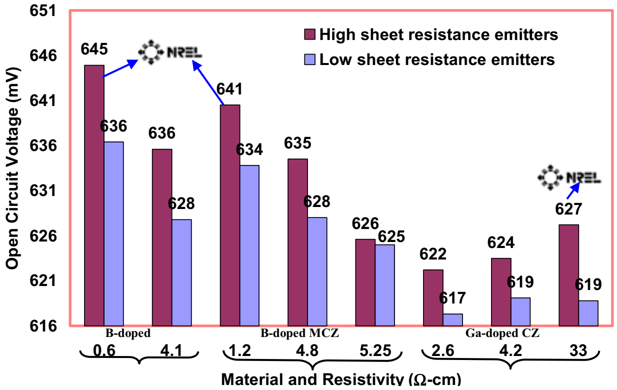
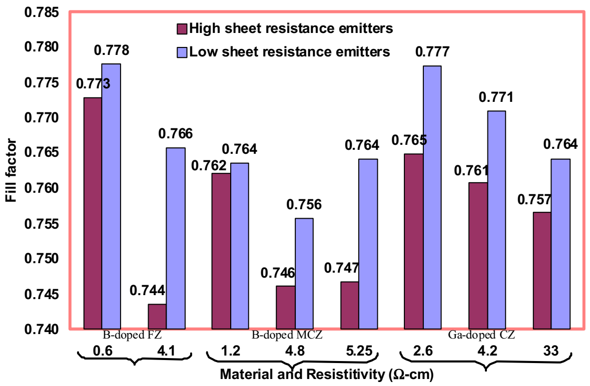


Fig. 3: The open circuit voltage on cells with high and low sheet resistance emitters versus material and resistivity.

The open circuit voltage is lower in higher resistivity (Fig. 3) materials than in materials with lower resistivity. This trend, however, is reversed in GaCz material. From PC1D calculation, the J_{ob} (base leakage current density) for the 2.6 and 4.2 Ω-cm Ga-doped materials should be about the same and higher for resistivities >10 Ω-cm. Furthermore, there is a 5-9 mV difference in open circuit voltage difference between cells with high and low sheet resistance emitters. This V_{oc} improvement on is attributed to the lower values of the saturation current density in the cells with high sheet resistance emitters.

Fill factor dependence on material resistivity and emitter sheet resistance.

Fig. 4 compares the fill factors on the cells with low sheet high sheet resistance emitters. Cells with low sheet resistance emitters give higher fill factors than cells with high sheet resistance emitters. This indicates that the silver paste used to fabricate these two set of cells requires further optimization in order to obtain low contact resistance on both set of sheet resistance emitters with a single firing step. Also, the fill factor decreases as the emitter sheet resistance and the material resistivity increase.



Internal Quantum efficiency analysis

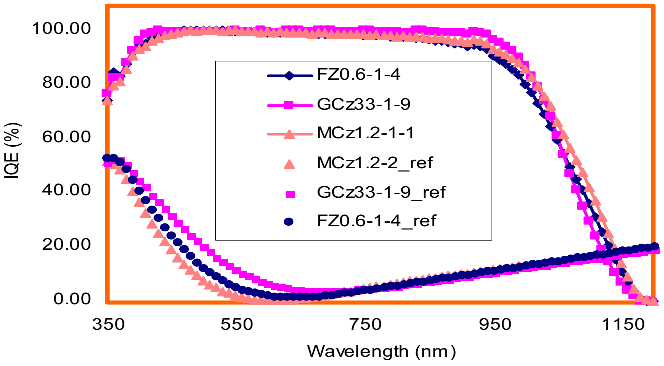
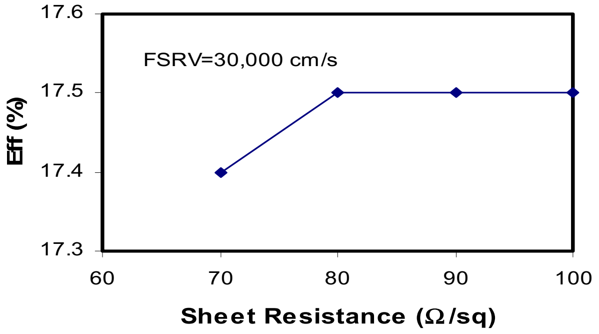


Fig. 5: Internal quantum efficiency of the three highest efficiency planar screen-printed solar cells with high sheet resistance emitters.

Fig. 5 shows the internal quantum efficiency (IQE) for the best cell, one each, from the three groups of materials. The high sheet resistance emitter cells give better short wavelength response compared to the 45 Ω/sq emitter cells. At short wavelength (370 nm) the IQE value of 82% for MCz (1.2-Ω-cm), 84% for FZ (0.6-Ω-cm) and 87% for GaCz (33-Ω-cm) are measured. The long wavelength response at 990 nm is 89% for the MCz (1.2-Ω-cm), 84% for Fz (0.6-Ω-cm) and GaCz (33-Ω-cm) cells with high sheet resistance emitters.

FSRV and BSRV values, for the three cells, were extracted by matching the measured short and long wavelength response with the PC1D calculated response. From this calculation, the front surface recombination velocity (FSRV) and the bulk lifetime are found to be quite similar. However, the back surface recombination velocity was different according to material resistivity. BSRV values of 135 cm/s, 200 cm/s and 640 cm/s were extracted, respectively, for the GaCz, MCz and Fz cells. Although the BSRV for the Fz (0.6-Ω-cm) material is about three times that of the MCz (1.2-Ω-cm) cell, the efficiencies are the same because of the 4 mV V_{oc} and 1% FF advantages.

To ensure that the emitter sheet resistance is not too high, we carried out a PC1D calculation for emitter sheet resistance ranging from 70-100 Ω/sq. Fig. 6 is the results of PC1D model calculation. According to the calculation, going from emitter sheet resistance of 70 Ω/sq to 100 Ω/sq improves the cell efficiency by only 0.1%. This calculation, however, did not take into account the change in FSRV as the emitter sheet resistance changes. More work is required in the emitter sheet resistance optimization where the spreading resistance of the actual emitters is used in PC1D calculation.



CONCLUSION

We have modeled, fabricated and analyzed planar screen-printed solar cells on three single crystalline silicon materials. These three materials include; boron doped magnetically-stabilized Cz (MCz), gallium doped Cz (GaCz) and FZ. A wide range of resistivities was investigated including; Fz with resistivity of 0.6-4.1 Ω-cm, MCz with resistivity of 1.2-5.3 Ω-cm and GaCz with resistivity of 2.6-33 Ω-cm. A simple cell process sequence involving emitter formation using $POCl_3$, Al BSF, PECVD SiNx AR coating, and belt furnace co-firing of front and back screen-printed contacts. This resulted in very high post process lifetimes (>500 µs at 1E15 cm^3 injection level). Both high and low sheet emitter resistance cells were fabricated and their performance compared and contrasted.

The cells fabricated on low resistivity (0.6 Ω-cm) Fz exhibited the highest open circuit voltage of 645 mV while the high resistivity GaCz showed the lowest V_{oc} (627 mV). The fill factors and short-circuit current densities, respectively, ranged from 75.7 to 77.4% and 35.6 to 35.9

mA/cm^2 for the GaCz with resistivity of 33 Ω-cm and MCz with resistivity of 1.2 Ω-cm. Independently confirmed energy conversion efficiencies of 17.7% were achieved on both Fz (0.6-Ω-cm) and MCz (1.2-Ω-cm) while 16.9% was obtained on GaCz silicon material. The 17.7% efficiency, to the best of our knowledge, achieved on these two materials is the highest energy conversion efficiency ever reported on a planar screen-printed silicon solar cell with only single antireflection coating.

IQE data coupled with PC-1D analysis showed a marked difference in the back surface recombination velocity (BSRV) for the three cells: 135 cm/s, 200 cm/s and 640 cm/s, respectively, for GaCz, MCz and Fz. The FSRV values are comparable in all the three cells despite the different base resistivity. This is the evidence of high quality surface passivation which led to short circuit current density of >35 mA/cm^2 on the three cells with high sheet resistance emitters. The results presented in this work demonstrate the importance of high sheet resistance emitter in achieving high efficiency manufacturable solar cells. It should be noted that surface texturing in conjunction with high sheet resistance emitter could enhance this efficiency. The efficiency value as high as 18.8%, independently confirmed by NREL, has been achieved on textured 0.6 and 1.2 Ω-cm float zone silicon. The full report on this is presented in this conference [11].

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