18% LARGE AREA SCREEN-PRINTED SOLAR CELLS ON TEXTURED MCZ SILICON WITH HIGH SHEET RESISTANCE EMITTER

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ABSTRACT

In this paper we report on high efficiency screen-printed 49 cm^2 solar cells fabricated on randomly textured float zone (1.2 Ω-cm) and magnetic Czochralski (MCz) silicon with resistivities of 1.2 and 4.8 Ω-cm, respectively. A simple process involving $POCl_3$ diffused emitters, low frequency PECVD silicon nitride deposition, Al back contact print, Ag front grid print followed by co-firing of the contacts and forming gas anneal produced efficiencies of 17.6% on 1.2 Ω-cm textured float zone Si, 17.9% on 1.2 Ω-cm MCz Si and 18.0% on 4.8 Ω-cm MCz Si. A combination of high sheet resistance emitter (~95 Ω-/□) and the surface texturing resulted in a short circuit current density of 37.8 mA/cm^2 in the 4.8 Ω-cm MCz cell, 37.0 mA/cm^2 in the 1.2 Ω-cm^2 MCz cell and 36.5 mA/cm^2 in the 1.2 Ω-cm^2 float zone cell. The open circuit voltages were consistent with the base resistivities of the two materials. The fill factors were in the range of 0.760-0.770 indicating there is considerable room for improvement. Detailed modeling and analysis is performed to explain the cell performance and provide guidelines for achieving 20% efficient screen-printed cells on MCZ Si.

INTRODUCTION

High sheet resistance emitter for high-efficiency cells can be implemented in two ways: the selective emitter with heavy doping only beneath the grid and 70-100 Ω/□ sheet resistance between the grid, or a homogeneously diffused high sheet resistance (70-100 Ω/□) emitter. The former enables the recombination under the metal contacts to be decoupled, resulting in a reduction of the overall saturation current density . The former 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 later requires the modification of the front contact paste composition and firing of the screen-printed contacts in IR or RTP furnace. On a 0.6 Ω-cm textured float zone Si, substrate, Hilali et al [6] demonstrated a 19% efficient 4-cm^2 screen-printed solar cell using a developmental front silver paste. The average cell efficiency of nine-cells on a wafer was 18.6% with minimum and maximum efficiencies of 17.9% and 19%, respectively.

We have also reported earlier [7] on homogeneous high sheet resistance emitter 4-cm^2 cells on textured magnetically-stabilized CZ (MCZ) with a peak efficiency of 18.4%, average efficiency of 17.5% and minimum of 13.7%. The large variation in cell performance on the same wafer with high sheet resistance emitter is primarily due to the high series resistance, which often dominates the fill factor. Non-uniformity in high sheet resistance emitter cells is a major challenge that needs to be addressed for large area cells. In this study we investigated the non-uniformity of high sheet resistance cells through (a) the use of two different Ag pastes and (b) a novel four-cell pattern, which can be tested as one 49-cm^2 cell or four 12.25 cm^2 cells (Fig. 1).

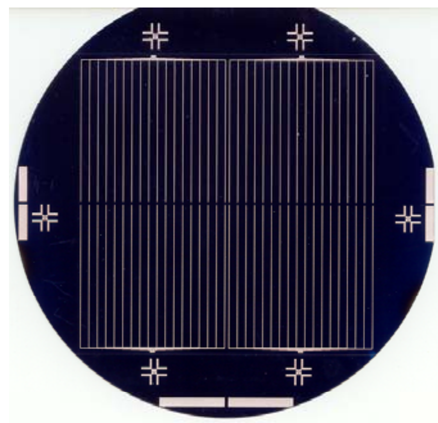

Fig. 1: 49 cm^2 solar cell patern used in this study that can be tested as a single cell or four 12.25 cm^2 cells.

DEVICE FABRICATION

In this study, 1.2 Ω-cm FZ and 1.2 and 4.8 Ω-cm MCZ silicon were textured on both sides, and cleaned in 1:1:2 H_2SO_4:H_2O_2:H_2O for 5 minutes, followed by a 3 min rinse in de-ionized (DI) water. This was followed by a clean in 1:1:2 HCl:H_2O_2:H_2O for 5 minutes and a 3 min rinse in DI water. Next the wafers were dipped in 10% HF for 2 minutes, followed by a 30 second rinse in DI water. The wafers were loaded in a $POCl_3$ diffusion furnace for the n^+ emitter formation. A diffusion temperature of 843^{o}C was used to obtain a 100-Ω/□ emitters. After phosphorus glass removal and another clean, a PECVD SiNx AR coating was deposited on the emitter. Next, an Al paste from Cermet Materials was screen-printed on the backside and dried at 200^{o}C. The Ag grid was then screen-printed on top of the SiNx film, dried at 200^{o}C and then the Ag and Al contacts were co-fired in a lamp-heated three-zone infrared belt furnace. The samples were edge isolated using a dicing saw before a forming gas treatment for 18 minutes. The cells were characterized by light I-V as well as the internal quantum efficiency (IQE) measurements.

The IQE data was used in conjunction with PC1D to calculate the front and back surface recombination velocities and back surface reflectance.

RESULTS AND DISCUSSION

Effect of Ag paste on cell performance

The glass frit transition temperature, silver particle size and other additives in the front Ag paste determine the quality of the screen-printed contacts. For a homogeneous high sheet resistance emitter solar cell, the print uniformity is critical because any localized high contact resistance, especially on large area cells, can lead to low overall cell efficiency. To determine the appropriate paste that will give uniform cell efficiency distribution, we investigated two front Ag pastes A and B from Dupont and Ferro Corporation, respectively. Figs. 2 and 3 show a typical efficiency distribution of solar cells fabricated with high sheet resistance emitters on FZ silicon using Ag pastes A and B for the front grid.

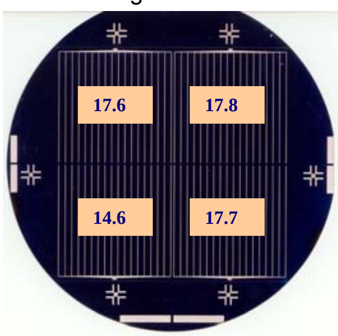

Fig. 2: Cell efficiency distribution for paste A – 14.6% as 49-cm^2 cell.

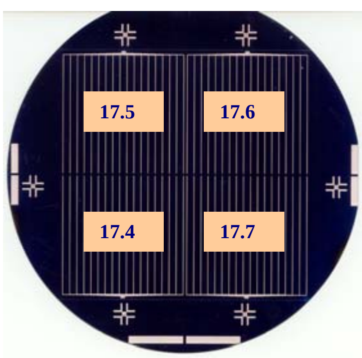

Fig. 3: Cell efficiency distribution for paste B – 17.4% as 49-cm^2 cell.

Each cell was first measured as a 49-cm^2 before cutting into four of 12.25-cm^2 cells. An efficiency of 14.6% with fill factor of 0.577 and series resistance of 7.519 Ω-cm^2 were measured for a 49 cm^2 cell printed with Ag paste A. However, when measured as four 12.25 cm^2 cells, the efficiencies were distributed as shown in Fig. 2. The cell fabricated with Ag paste B resulted in 17.4% efficiency with 0.756 fill factor and a series resistance of 1.234 Ω-cm^2. The cell was cut into four 12.25 cm^2 cells and tested. Figure 3 shows the efficiency distribution for the cell fabricated with Ag paste B with minimum efficiency of 17.4%. In both cases the lowest efficiency in the distribution dictates the efficiency of the large area cell. The lowest efficiency was dominated by the series resistance, which can be caused by localized high contact resistance.

SEM cross sections of the contact interface in good and bad cells fabriacated with paste A were conducted to elucidate the non-uniform efficiency distribution. Fig. 4 shows a cross section of the front Ag grid for a good cell with low series resistance and acceptable fill factor. In this case, the Ag crystallites are clearly seen and are separated from the grid by a thin glass layer. The contact interface for the poor cell, which had a high series resistance and low fill factor, exhibited a thick glass layer between the bulk silver and the crystallites as shown in Fig. 5. This thick glass layer is believed to impede the tunneling of the carriers from the crystallites to the bulk silver and resulting in a high contact resistance, which lowers the fill factor.

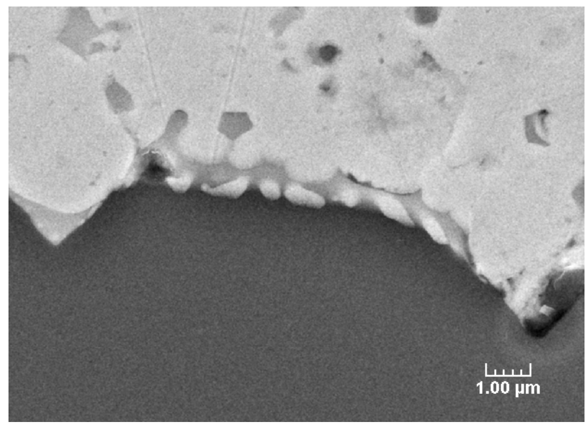

Fig. 4: Cross-section for paste B for cell with good fill factor and low series resistance

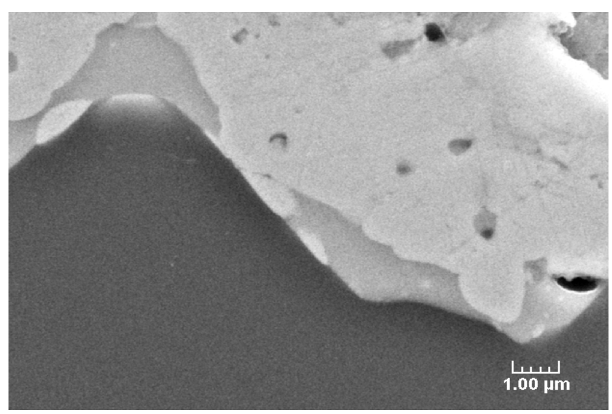

Fig. 5: Cross-section for paste B for cell with good fill factor and high series resistance

From the above SEM analysis and the cell efficiency distribution in Figs. 2 and 3, it is appears that the non-uniformity in cell performance is due to the non-uniform glass distribution at the interface between the Ag crystallites and the silver grid. Since paste A produced a lower efficiency on 49 cm^2 than paste B, we chose paste B for the remainder of this study.

Light I-V characteization of large area, high efficiency MCZ silicon solar cells

Table 1: NREL confirmed 49-cm^2 high efficiency screen-printed solar cells with high sheet resistance emitters fabricated on FZ and MCZ.

Cell ID	Material	Resistivity (Ω-cm)	Voc (mV)	Jsc (mA/cm^2)	FF (%)	η (%)
3-2	MCZ	1.2	632	37.0	76.4	17.9
4-2	**MCZ**	**4.8**	**619**	**37.8**	**76.9**	**18.0**
1-4	FZ	1.2	634	36.5	76.0	17.6

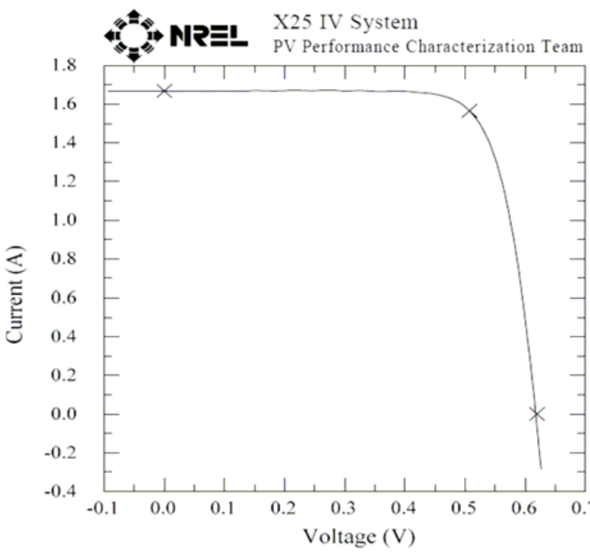

Fig. 6: I-V measurements by NREL for the 18%, 49-cm^2, textured front and back 100 Ω/sq emitter cell on 4.8 Ω-cm MCZ silicon.

Table 1 summarizes the electrical parameters of the high efficiency screen-printed cells fabricated on textured MCZ (1.2 and 4.8 Ω-cm) and FZ (1.2 Ω-cm) silicon materials with high sheet resistance emitters. A simple co-firing of the screen-printed Ag front grid and Al back contact produced efficiencies of 17.6% on 1.2 Ω-cm float zone Si, 17.9% on 1.2 Ω-cm MCZ Si and 18% on 4.8 Ω-cm MCZ Si. From Table 1 the 4.8 Ω-cm resistivity cell produced the lowest open circuit voltage, highest short circuit current density, highest fill factor and best efficiency. As expected, the open circuit voltages of the lower resistivity FZ and MCZ silicon were superior; the slightly lower short circuit current density and fill factor impacted the cell efficiency. Fig. 6 shows the I-V data for the best cell achieved on 4.8 Ω-cm MCZ silicon. This was tested and verified by NREL and also represents the highest efficiency fully screen-printed cell on MCZ to date.

PC1D modeling and Internal Quantum efficiency analysis

Table 2: Modeling parameters for the 18.0% textured 100- Ω/sq MCZ cell

Cell Parameters	MCZ Cell
Base Resistivity (Ω-cm)	4.8
R_s (Ω-cm^2)	0.92
R_{sh} (Ω-cm^2)	158,366
n_2	2
J_{o2} (nA/cm^2)	15.7
Emitter sheet resistance (Ω/sq)	100
Surface Concentration (cm^3)	$1.5x10^{20}$
Texture angle (degrees)	54.7
Texture depth (μm)	3
τ_{bulk} (μs)	400
BSRV (cm/s)	220
BSR (%)	66
FSRV (cm/s)	55,000
Grid shading (%)	6.5
Modeled V_{oc} (mV)	622
Modeled J_{sc} (mA/cm^2)	37.9
Modeled FF (%)	76.4
Modeled Efficiency (%)	18.0

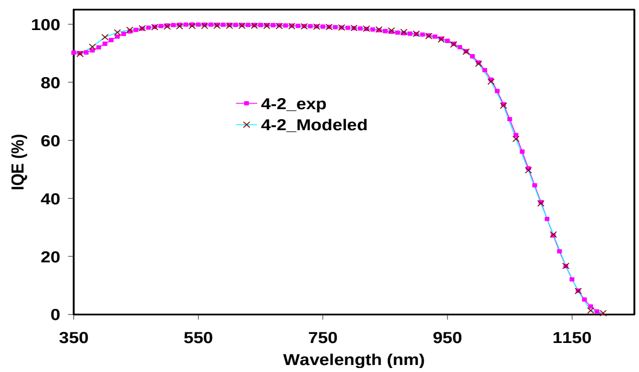

Fig. 7: Measured and simulated IQE for the 18.0% MCZ Si cell.

Table 2 shows the results of modeling and characterization of the 18.0% efficient 49-cm^2 MCZ cell where a number of measured and extracted input parameters are listed along with the modeled cell efficiency. A front surface recombination velocity (FSRV) of 55,000 cm/s and back surface recombination velocity (BSRV) of 220 cm/s were extracted by matching the measured IQE with the simulated IQE in the short and long wavelength range using the PC1D simulation program. The experimentally measured emitter doping profile, base thickness, base doping and bulk lifetime were also used as inputs for device simulations. The bulk lifetime was found to be ~400 μs by the photoconductance decay (PCD) technique, after etching the cell down to bare Si. A junction leakage current (J_{o2}) of 15.7 nA/cm^2 and second diode ideality factor 1.65 was determined by the Suns-V_{oc} technique. The back surface reflectance (BSR) was found to be 66% using the extended spectral analysis of the cell IQE [8]. With all the above input parameters, the PC1D model predicted a cell efficiency of 18.0% with V_{oc}

of 622 mV, J_{sc} of 37.9% mA/cm^2 and a FF of 0.764 which agreed fairly well with the measured V_{oc} of 619 mV, J_{sc} of 37.8 mA/cm^2, FF of 0.769, and efficiency of 18.0%. Fig. 7 shows a good match between the measured and simulated IQE for the 18.0% cell. From this analysis it is clear that the 18.0% cell fell short in the BSRV and BSR values required for 20% efficiency.

Fig. 8 shows a set of guidelines to raise the efficiency of MCZ silicon cell from 18.0% to 20.0%. First, by improving the screen-printed contacts to loweri the series resistance from 0.92 Ω-cm^2 to 0.6 Ω-cm^2 , the fill factor can be raised to 0.790 and efficiency can reach 18.9%. An improved rear contact with BSRV of 100 cm/s and BSR of 76% can raise the efficiency to >19%. Finally, improving the front contacts to lower the FSRV and shading can increase the MCZ cell efficiency to 20%.

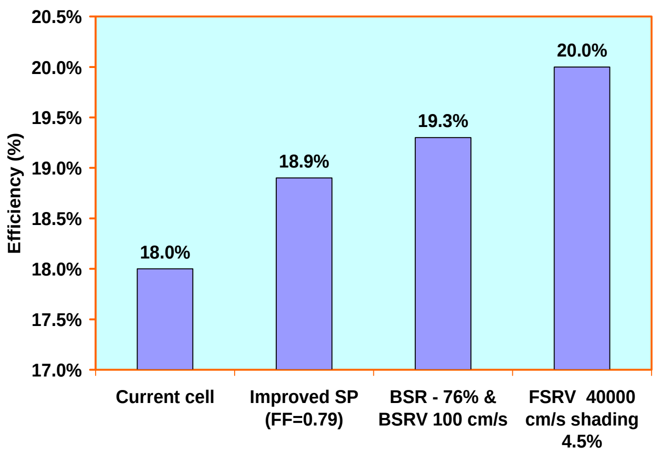

Fig. 8: Guidelines for achieving a 20.0%-efficienct cell on MCZ Si with a 100 Ω/sq emitter.

CONCLUSION

We have investigated the non-uniformity in high sheet resistance emitter cells through the use of two Ag pastes and novel four-cell pattern, which can be tested as one 49-cm^2 cell or four 12.25-cm^2 cells. We found that the cell fabricated with Ag paste B exhibited better uniform efficiency distribution than paste A. The lowest efficiency, which is dominated by high series resistance, dictates the efficiency of a 49-cm^2. The SEM analysis revealed a thin glass layer separating the Ag crystallites from the grid on a good cell and thick glass layer and less Ag crystallite for the worst cell.

We have used Ag paste B to achieve screen-printed 49 cm^2 cell efficiencies of 18.0%, 17.9% and 17.6% on MCZ 4.8 Ω-cm, 1.2 Ω-cm and 1.2 Ω-cm FZ silicon, respectively. An FSRV of 55,000 cm/s and BSRV of 220 cm/s were extracted by matching the measured IQE with the simulated IQE in the short and long wavelength range using PC1D and the measured emitter doping profile, base thickness, base doping and bulk lifetime. Detailed analysis of 18.0% efficient MCZ cell indicates that we need to improve the fill factor from 0.769 to 0.79, FSRV from 55,000 cm/s to 40,000 cm/s and the rear contact technology to improve the BSRV from 220 cm/s to 100 cm/s in order to raise the efficiency from 18.0% to ≥20%.

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