SIMPLIFIED PERC SOLAR CELLS PASSIVATED WITH PECVD SILICON NITRIDE

M.J. Kerr, J. Schmidt, C. Samundsett and A. Cuevas
Centre for Sustainable Energy Systems
Department of Engineering, The Australian National University, Canberra ACT 0200, Australia,
Email: Mark.Kerr@faceng.anu.edu.au, Phone: (+61) 2 6249 0078, Fax: (+61) 2 6249 0506

ABSTRACT: Stoichiometric plasma enhanced chemical vapor deposited silicon nitride films have been used to passivate the front and rear surface of simplified PERC silicon solar cells. These films have the distinctive properties that they can provide excellent surface passivation, are easily patterned using photolithography and wet chemical etching, and are compatible with aluminium layers for a back surface optical reflector. Cells with planar surfaces and random pyramid texturing have been fabricated. Open circuit voltages up to 667mV have been measured on float-zone substrates and 655mV on multicrystalline material, proving the outstanding surface passivation provided by the silicon nitride films. Conversion efficiencies of 18.5% and 16.1% have been obtained respectively.
Keywords: Silicon-Nitride - 1: Passivation - 2: c-Si - 3

1. INTRODUCTION

Solar cells with high open circuit voltage (V_{oc}) rely on surface passivation schemes to minimize the amount of recombination occurring within the cell. The outstanding passivation qualities of plasma enhanced chemical vapor deposited (PECVD) silicon nitride (SiN) films, particularly on p-type silicon surfaces, are well known [1-4]. The implementation of PECVD SiN films into cell designs that can produce high open circuit voltages has been demonstrated by a number of researchers [5, 6].

The highest V_{oc} for silicon solar cells passivated with SiN films at the front and rear (all-SiN cells) appears to be 649mV as achieved by Hübner et al. [5]. They applied **Si-rich** remote-PECVD SiN films to the front and rear of bifacial solar cells fabricated on 1.5 Ωcm FZ material. The high silicon content of the SiN films used by Hübner et al. make them relatively difficult to etch however [7]. Further, it has not been demonstrated that the excellent passivation obtained with these Si-rich SiN films can be maintained in the presence of a metal capping layer. Thus, the use of Si-rich SiN films for rear surface passivation may exclude the fabrication of the high efficiency PERC, PERL and PERT type structures, which all have rear point contacts through a passivating dielectric layer with an overlying aluminium layer.

The purpose of this work is to demonstrate that **stoichiometric** SiN films can be used to passivate the front and **rear surfaces** of PERC cells and maintain high open circuit voltages. In addition, we exploit the low thermal budget of these films to fabricate multicrystalline silicon cells with high open circuit voltages.

2. STOICHIOMETRIC SiN FILMS

Optimised deposition parameters for stoichiometric SiN films on 1 Ωcm p-type silicon have been recently reported [8]. Surface recombination velocities (SRVs) below 10cm/s were measured and the injection level dependence of the SRV was found to be quite weak. The same deposition parameters have subsequently been found to be optimal for SiN on low resistivity p-type silicon (0.3 Ωcm). Figure 1 shows the effective SRV (S_{eff}) as a function of carrier injection level (Δn) for stoichiometric SiN passivated 0.3 Ωcm p-type float zone (FZ) silicon. SRVs below 25cm/s were measured and again, the injection level dependence of the SRV is quite weak.

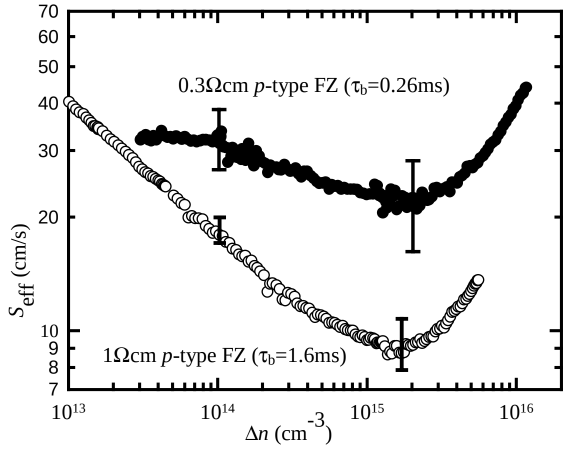

Figure 1: Measured effective SRV for 1.0 Ωcm and 0.3 Ωcm p-type FZ silicon passivated with stoichiometric SiN.

In a parallel work [9], we have optimised the PECVD deposition parameters of stoichiometric SiN to obtain excellent passivation of phosphorus-diffused emitters. For example, the emitter saturation current (J_{oe}) for our standard 100 Ω/☐ diffusion passivated with stoichiometric SiN is approximately 35fA/cm^2 and 65fA/cm^2 for planar and random pyramid (RP) textured surfaces respectively.

In addition to their outstanding electronic qualities, these stoichiometric SiN films have properties that are useful for high V_{oc} and high efficiency solar cells:

i) Optimum refractive index for single layer anti-reflection coating on non-encapsulated cells (n≈1.9).
ii) No absorption in the UV range of the solar spectrum.
iii) Easily patterned using photolithography and wet chemical etching.
iv) Good insulator and thus compatible with aluminium layers for a back surface reflector.
v) Low temperature processing.

3. CELL DESIGN AND FABRICATION

3.1 Cell Design

The PERC cell structure was originally introduced by Blakers et al in 1989 [10]. Various simplified versions of the PERC structure with reduced processing requirements have since been investigated [11-13]. Despite the reduced processing, these simplified PERC structures have demonstrated high open circuit voltages (>670mV) and excellent conversion efficiencies (up to 21.6%). Simplified PERC structures were chosen for this work because:

i) They are suitable for demonstrating the high V_{oc} potential of stoichiometric PECVD SiN films with reduced cell processing.

ii) The requirements on the rear passivating layer of PERC, PERL and PERT cells are similar.

A schematic of the cell structures used in this work is shown in Figure 2. The cell structure differs from the original PERC cell structure in three main ways:

i) The front surface is not textured with inverted pyramids.

ii) A single step emitter is used rather than a selective emitter.

iii) Low temperature (400°C) PECVD SiN is used as a surface passivating, anti-reflection coating on the front and for surface passivation on the rear, rather than high temperature thermal oxides.

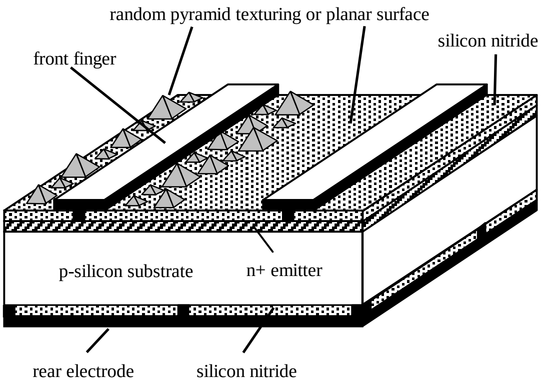

Figure 2: Schematic of the simplified PERC cell structures used in this work.

We have investigated both planar cells and cells textured with random pyramids. Planar cells were of interest as they are indicative of the maximum potential for this cell structure on multicrystalline silicon, while textured cells were expected to give higher conversion efficiency.

3.2 Cell Fabrication

Most cells were fabricated using the sequence shown in Figure 3 on 300µm thick, <100> oriented, 0.3 Ωcm p-type float zone silicon wafers. The wafers were given a standard RCA clean before processing. The n^+ diffusion was performed in a quartz tube at temperatures between 860°C and 880°C using liquid $POCl_3$ as the dopant source. After removing the phosphorus glass, the diffusion was driven-in for 30mins at 900°C for the planar cells and for 35mins at 1050°C for the textured cells. Following drive-in, the sheet resistance was measured to be in the range of 100-130Ω/☐ for the planar cells and 60-70 Ω/☐ for the textured cells. The SiN films were deposited in a high frequency direct plasma reactor (Oxford Plasma Technology, Plasmalab 80+) using ammonia and a 4.5% silane in nitrogen mixture as the process gases. The front SiN was patterned to form a metal grid by the lift-off technique. The front metallization scheme involved evaporating Ti/Pd/Ag and subsequent Ag plating. The rear SiN was patterned and aluminium evaporated onto it. The aluminium layer has the dual role of making local ohmic contact to the p-type base and forming an efficient back surface reflector in conjunction with the SiN film. The rear contact area is approximately 4%. The cells were sintered in forming gas at 400°C to ensure a good ohmic contact and the nominal cell area is $4cm^2$.

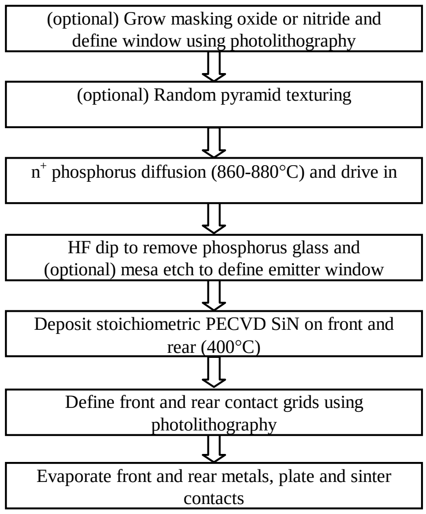

Figure 3: Processing sequence for simplified PERC cells passivated with stoichiometric PECVD SiN.

4. CELL RESULTS

4.1 Planar Float-Zone Cells

The I-V curve at standard testing conditions for one of the best all-SiN passivated, planar cells is given in Figure 4. The measured open circuit voltage is 667mV, confirming the excellent front and rear surface passivation provided by the SiN films. This V_{oc} is a significant improvement over the previous record for all-SiN passivated cells of 649mV [5]. Importantly, the rear aluminium layer does not appear to have altered the quality of the rear surface passivation.

Spectral response and reflectivity measurements are given in Figure 5. They indicate that the internal quantum efficiency (IQE) between the wavelengths 350-650nm is approximately 100%, which gives additional proof of the excellent front surface passivation.

The short circuit current density (J_{sc}) of $33.1mA/cm^2$ is reasonable for a single layer anti-reflection coating on a planar surface. The short and long wavelength EQE are relatively low however, and clearly this cell would benefit from reduced reflection at these wavelength. Further, the long wavelength IQE is relatively low and so the inclusion of light trapping features would also be beneficial.

A fill factor of 80.7% and a conversion efficiency of 17.8% were achieved. This fill factor is reasonable for PERC cells where series resistance due to the widely spaced rear metal contacts tends to soften the fill factor.

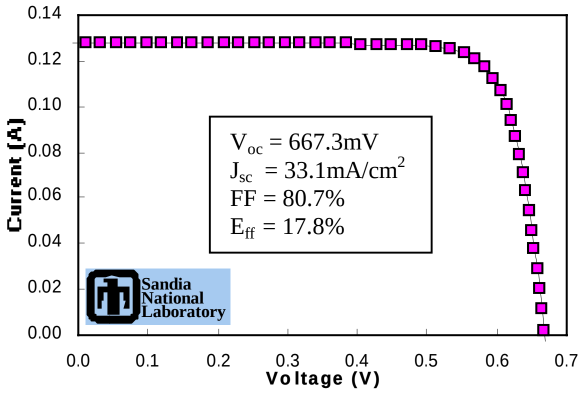

Figure 4: Independently measured I-V curve for a planar, all-SiN passivated, simplified PERC cell.

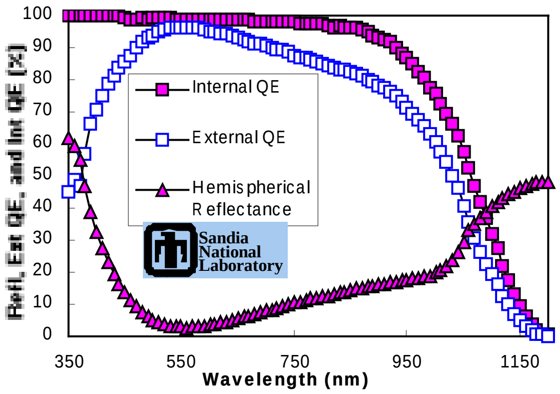

Figure 5: Spectral response and hemispherical reflectivity for a planar, all-SiN passivated, simplified PERC cell.

In-house measurements for other planar, all-SiN passivated, simplified PERC cells are given in Table I (measured relative to the above independently calibrated cell). These results are for cells where the diffusion window was not defined using a masking oxide, but by mesa etching the cells after the diffusion. It can be seen that the results for mesa etched cells are comparable to those using a masking oxide. Further, there appears to be little difference between mesa etched cells fabricated on 0.3 Ωcm substrates and on 0.7 Ωcm substrates.

Table I: Calibrated measurements of other planar, all-SiN passivated PERC cells fabricated by mesa etching.

	Cell 1*	Cell 2	Cell 3
Base Resistivity	0.3Ωcm	0.3Ωcm	0.7Ωcm
Diffusion window	masking oxide	mesa etched	mesa etched
Voc (mV)	667.3	671	668
Jsc (mA/cm^2)	33.1	32.5	33.6
FF (%)	80.7	81.5	77.8
η (%)	17.8	17.8	17.5

* Independently confirmed at Sandia National Laboratories

4.2 Random Pyramid Textured Float-Zone Cells

The results in the previous section suggest that high efficiency solar cells (efficiency >20%) can be produced by incorporating a front surface texture into the cell fabrication. This should boost the short circuit current density by reducing front surface reflection and improving the light trapping features of the cells.

Experiments with random pyramid textured substrates are underway. The texturing was performed into either oxide or nitride masked windows using a mixture of KOH and Isopropanol. This produces texture features which are approximately 10µm in size.

The I-V curve for an all-SiN passivated RP-PERC cell is given in Figure 6. The measured open circuit voltage was 655mV, which demonstrates that a high V_{oc} can also be achieved despite the more challenging front surface.

The short circuit current density was 36.8mA/cm^2 and represents a relative boost of 11% in the J_{sc} compared to planar cells. Some loss in J_{sc} is expected due to the emitter being relatively deep and heavily doped (≈60Ω/□).

The most disappointing result is the fill factor of only 76.9%. Given that the rear surface is identical to those of the planar cells, the fill factor loss is thought to originate at the front of the cell. These cells may benefit from pyramid rounding, an improved emitter design to boost J_{sc} and fill factor, and possibly improved photolithography for metallization on the front surface.

The conversion efficiency for the RP-PERC cells is 18.5% at this time. Unfortunately, this is only marginally better than for the planar cells with the gains in J_{sc} being lost in both V_{oc} and fill factor.

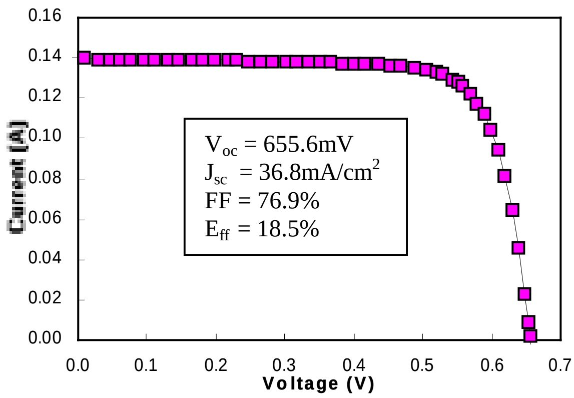

Figure 6: Independently measured I-V curve for a random pyramid textured, all-SiN passivated, simplified PERC cell. Measured at NREL.

4.3 Multicrystalline Silicon Cells

The mesa-etched cells described in section 4.1 were fabricated with only one high temperature step (the phosphorus diffusion). Such a process is thus suitable for fabricating high V_{oc} multicrystalline solar cells, as it would minimise any degradation of the minority carrier lifetime from thermal processing.

We fabricated mesa-etched cells on 200µm thick, gettered 0.2 Ωcm multicrystalline substrates from Eurosolare. The cell area was 4cm^2 and the I-V curve for one of the best all-SiN passivated multicrystalline cells is given in Figure 7. A V_{oc} of 655mV was obtained, amongst the highest ever recorded for multicrystalline silicon. This high V_{oc} results from the high bulk lifetime of the gettered multicrystalline substrates (>20µs) and the ability of the cell fabrication to maintain this high lifetime and provide excellent surface passivation. The potential for bulk defect passivation by atomic hydrogen in the PECVD SiN films could also contribute to the high V_{oc}.

Spectral response and reflectivity measurements for the multicrystalline cell are given in Figure 8. As before, the internal quantum efficiency (IQE) between the wavelengths 350-650nm is approximately 100%, an outcome of the excellent front surface passivation.

The long wavelength reflectance data for the multicrystalline cell are quite high compared to the data for the FZ cell of Figure 4. This is partly due to the multicrystalline substrate being thinner, but it demonstrates that a significant amount of the long wavelength light is being reflected from the rear surface of the cell. Thus, the rear aluminium reflector is operating effectively.

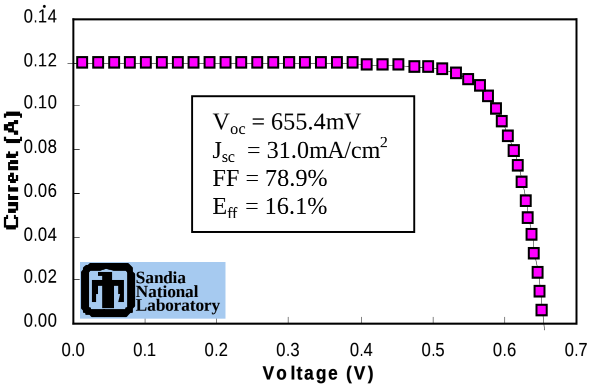

Figure 7: Independently measured I-V curve for a planar, all-SiN passivated, multicrystalline PERC cell.

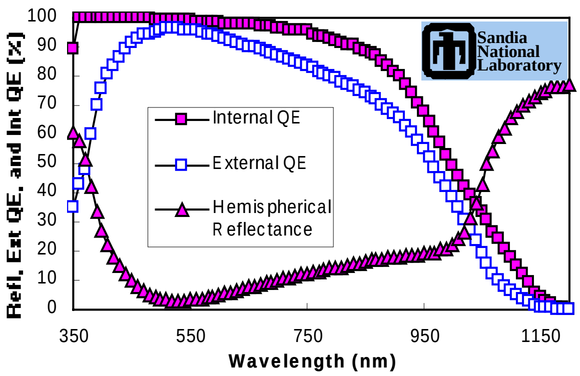

Figure 8: Spectral response and hemispherical reflectivity for a planar, all-SiN passivated, multicrystalline PERC cell.

5. CONCLUSION

Simplified PERC type solar cells involving only PECVD SiN layers for front and rear surface passivation have been fabricated. Planar devices on float zone material have produced open circuit voltages up to 667mV. These high V_{oc}'s confirm the excellent surface passivation of the stoichiometric SiN layers used, even in the presence of a rear aluminium capping layer. These results also suggest that stoichiometric SiN layers are suitable for passivating the rear surface of PERL and PERT type cells

Cells fabricated on gettered, multicrystalline substrates using only one high temperature step have produced open circuit voltages up to 655mV. The simplified PERC cell structure using PECVD SiN films for surface passivation is therefore suited for high efficiency multicrystalline silicon solar cells. Further, with the present commercial trend towards thinner silicon substrates, the passivation properties demonstrated by these stoichiometric SiN films on thin (≈200µm) multicrystalline substrates may be of relevance. While thinner substrates may provide an economic gain, their use places greater demand on achieving adequate surface passivation to maintain and improve cell efficiency. This work supports that PECVD SiN films appear to be an excellent candidate for meeting these passivation requirements

ACKNOWLEGEMENTS

The authors would like to thank C. Jagadish and H. Tan for making it possible to use the PECVD reactor at the Electronic Materials Engineering Department of the ANU. Many thanks go to D.S. Ruby of Sandia National Laboratories and K. Emery of NREL for providing the cell data under standard testing conditions. The multicrystalline substrates were kindly provided by F. Ferrazza of Eurosolare SpA. This work has been supported by funding from the Australian Research Council. One of the authors (J.S.) gratefully acknowledges the support of a Feodor Lynen Fellowship by the German Alexander von Humboldt Foundation.

REFERENCES

[1] A. G. Aberle and R. Hezel, *Prog. Photovolt.*, **5** (1997), 29-50.

[2] C. Leguijt, *et al.*, *Sol. En. Mat. and Sol. Cells*, **34** (1994), 177-181.

[3] B. Lenkeit, T. Lauinger, A. G. Aberle, and R. Hezel, *2nd World Conference on Photovoltaic Energy Conversion*, Vienna (1998), 1434-1437.

[4] J. Schmidt, T. Lauinger, A. G. Aberle, and R. Hezel, *25th IEEE Photovoltaic Specialists Conference*, Washington (1996), 413-416.

[5] A. Hübner, A. G. Aberle, and R. Hezel, *14th European Photovoltaic Solar Energy Conference*, Barcelona (1997), 92-95.

[6] S. Muramatsu, *et al.*, *Technical Digest of the 11th International Photovoltaic Science and Engineering Conference*, Sapporo (1999), 583-584.

[7] T. Lauinger, J. D. Moschner, A. G. Aberle, and R. Hezel, *Journal of Vacuum Science and Technology A*, **16** (1998), 530-543.

[8] J. Schmidt and M. J. Kerr, *Technical Digest of the 11th International Photovoltaic Science and Engineering Conference*, Sapporo (1999), 581-582.

[9] M. J. Kerr, J. Schmidt, and A. Cuevas, *this conference* (2000), .

[10] A. W. Blakers, *et al.*, *Appl. Phys. Lett.*, **55** (1989), 1363-1365.

[11] A. W. Blakers, *et al.*, *4th International Photovoltaic Science and Engineering Conference*, Sydney (1989), 801-806.

[12] A. Hübner, C. Hampe, and A. G. Aberle, *Sol. En. Mat. and Sol. Cells*, **46** (1997), 67-77.

[13] J. Knobloch, *et al.*, *25th IEEE Photovoltaic Specialists Conference*, Washington (1996), 405-408.