Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 92 (2016) 336 – 340

Energy Procedia

6th International Conference on Silicon Photovoltaics, SiliconPV 2016

Corona field effect surface passivation of n-type IBC cells

Ruy S Bonilla[a*], Christian Reichel[b], Martin Hermle[b], Peter R Wilshaw[a]

[a]Department of Materials, Parks Rd, Oxford, OX1 3PH, United Kingdom,
[b]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, Freiburg, 79110, Germany

Abstract

Passivation of silicon surfaces is an important requirement in achieving high energy conversion efficiencies in interdigitated back contact cells. Surface passivation, commonly achieved by dielectric coatings, can be greatly improved by extrinsic addition of chemical and field effect components. In particular, cell performance is strongly dependent on front surface passivation. In this work device modelling is used to show that 200% relatively better performance can be achieved using charge extrinsically added to a passivation coating without the need for a front surface field. Research scale cells have been tested as a function of front surface corona charge. On average an absolute improvement in efficiency of 0.3% ±0.3 and 0.13% ±0.12 has been observed on cells without and with a front surface field. These results show that extrinsic field effect passivation can produce significant improvements in cell efficiency.

Peer review by the scientific conference committee of SiliconPV 2016 under responsibility of PSE AG.

Keywords: Silicon; surface passivation; corona discharge; dielectric films; IBC solar cells.

1. Introduction

Silicon solar cells exceeding 25% efficiency are now possible thanks to innovative geometries and very precise fabrication processes [1]. The highest efficiency is normally demonstrated in cells with sophisticated and optimised processing steps, which are often only carried out at research scale rather than commercially. The challenge remains to develop industrially compatible processes in such a way that they are implemented and improve the production cost and/or performance of commercial solar cells. Minimising surface recombination losses is a key requirement in

* Corresponding author. Tel.: +44 1865 283097 ; fax: +44 1865 273789.
E-mail address: sebastian.bonilla@materials.ox.ac.uk

Peer review by the scientific conference committee of SiliconPV 2016 under responsibility of PSE AG.
doi:10.1016/j.egypro.2016.07.091

the fabrication of high efficiency (>20%) silicon solar cells. For this, effective passivation coatings have been devised by exploiting the chemical and field effect properties of dielectric materials like SiO_2 [2], SiN_x [3] and AlO_x [4]. It was recently reported that post-deposition processing techniques, termed extrinsic processes, can significantly improve the quality of the passivation coating [5,6]. Furthermore outstanding passivation of silicon surfaces [7] and improvement in solar cell performance [8] was demonstrated using extrinsic field effect passivation provided by corona charging of dielectric coatings. Previous reports [9] [10] have suggested that up to 0.5% (absolute) gain in efficiency could be obtained from improving front surface passivation in screen-printed front contact solar cells, and over 2% gain from improving the rear surface. Most studies coincidently report absolute increments between 0.5 and 1% from enhanced front side passivation, and 1 to 3% from rear side passivation in solar cells with efficiencies exceeding 18% [9,11–14]. Additionally, it has been shown that for thinner solar cells the V_{oc} and η depend more strongly on front surface recombination velocity [15]. These studies, however, did not separately assess the *field effect* component of passivation, nor did they study the more efficient back-contact solar cell geometry. A previous report by the present authors studied the extent to which extrinsic passivation can improve the overall passivation quality of silicon dioxide on silicon [16]. This manuscript furthers such studies by providing a modelling analysis and experimental measurements of the influence of extrinsic field effect passivation (FEP) on the performance of interdigitated back-contact (IBC) silicon solar cells. These results demonstrate that new and inexpensive methodologies can be applied to enhance front surface passivation and thus improve the performance of back contacted silicon solar cells.

2. PC2D simulation of FEP in IBC cells

Back contacted solar cells have been shown to perform substantially better than front contacted ones thanks to the reduction in shading and resistive losses. A commercial IBC solar cell was simulated in PC2D [17] to quantify the improvements available when extrinsic FEP is applied via corona discharge. The cell schematic is illustrated in Fig. 1 where the simulation domain has been defined using 20 x 20 elements. The cell area was 1 cm^2 and its parameters were chosen to be similar to those of IBC cells fabricated by Fraunhofer ISE [18]. The surface recombination in PC2D is characterized by the dark saturation current density J_0. The J_0 metric includes recombination occurring in the doped (bent band) region near the surface, for example in front and back surface fields, or at ohmic contacts. Here, J_0 was found using a simulation method recommended by Cabanas-Holmen and Basore [19]. This involved simulating a diode comprising a moderately doped base and the highly doped surface layer such as that proposed for the n+ front surface field (FSF) in an IBC cell using an complementary error function profile with n_{peak}=5 x 10^{18} cm^{-3}, 1.4 µm junction and a R_s=148 Ω/sq. This simulation was executed for a varying concentration of surface charge and for a front surface both diffused and un-diffused with the FSF.

Fig. 2 illustrates the performance of a model IBC solar cell with and without an n+ FSF of R_s =148 Ω/sq. When the FSF is present positive charge deposited on the top surface improved η, J_{sc} and V_{oc} by 0.51%, 0.6 mA/cm^2 and 5 mV, respectively. Negative charge, on the other hand, produced a reduction in the performance of the cell. In the absence of a FSF, recombination at the front surface reduces by over 3 orders of magnitude when FEP is applied. This is evident from the decrease in dark saturation current in Fig. 2.b. η, J_{sc} and V_{oc} are seen to improve by 12%, 20 mA/cm^2 and 60 mV, respectively, when front surface charge increases from 10^9 to 10^{13} q/cm^2. This is an astounding improvement in cell efficiency only due to front surface field effect passivation.

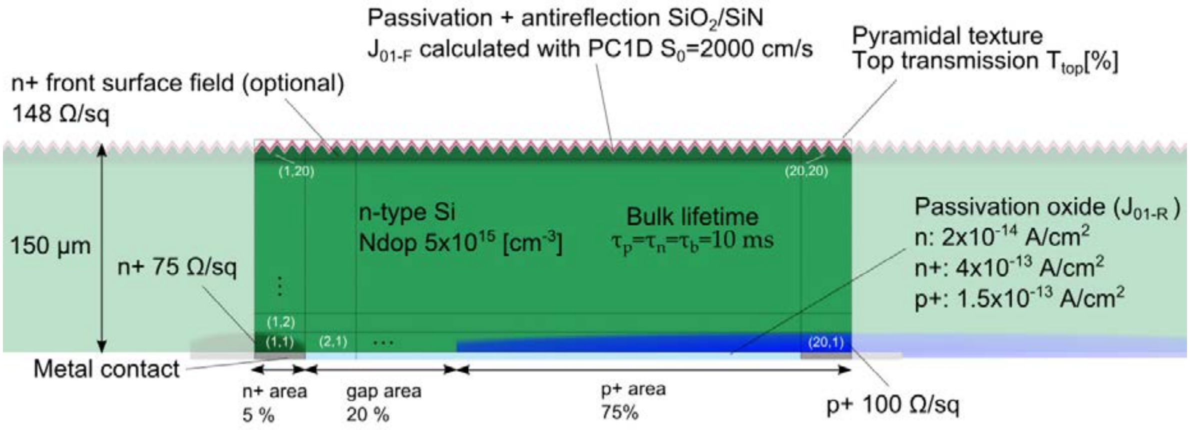

Fig. 1. Simulation domain and definition of regions for the IBC cell modelled in PC2D.

It is important to note that, at its highest point, the efficiency obtained for a cell *without* the expensive FSF exceeds that obtained in a cell with a FSF and no dielectric charge. This is due to a reduction in intrinsic Auger and radiative recombination in the heavily doped surface region which is required to produce a FSF. When charge is present in both the FSF and no-FSF cells the efficiency of the no-FSF cell exceeds that of a FSF cell by 0.03% absolute, with the extrinsically deposited charge being a potentially much lower cost approach. This indicates that regardless of the presence of a FSF, the cell efficiency is largely governed by the passivation quality of the front surface, and that extrinsic FEP alone can provide excellent passivation and thus cell performance.

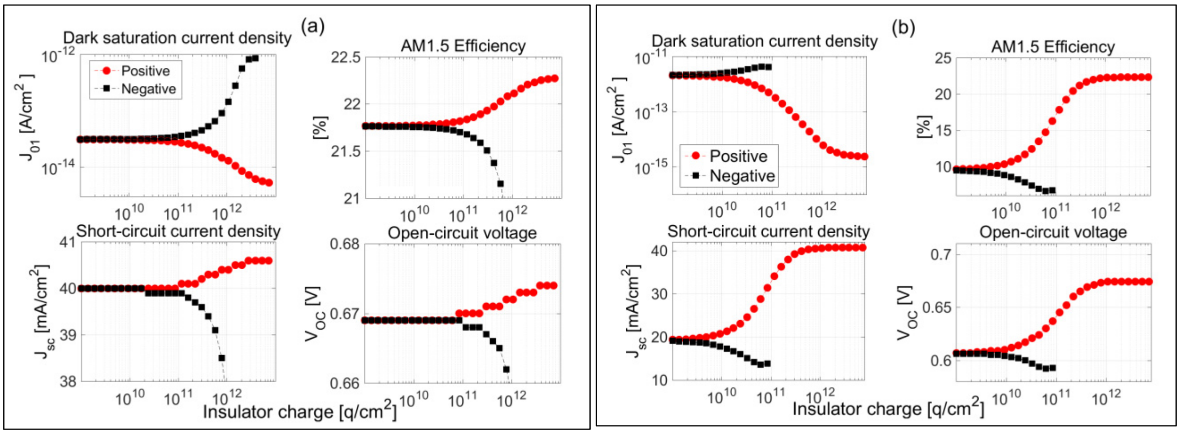

Fig. 2. Dark saturation current in a model diode simulated in PC1D and cell performance simulated in PC2D when front surface charge is modified for a. an n-type IBC cell that includes a 148 **Ω**/sq FSF for passivation, and b. an n-type IBC cell without a FSF.

3. Influence of FEP on research scale IBC cells

Fourteen 2 x 2 cm^2 IBC cells were fabricated at Fraunhofer ISE including cells with and without a FSF (cells of Type A and C in reference [18]). These were tested to determine the effect of extrinsic FEP using an ISO calibrated solar simulator at Fraunhofer ISE. The cells were charged for a period of time and then directly taken to the solar simulator for characterisation. The corona discharge was a point to plane configuration with a distance of 8 cm, and 8 kV applied to the point electrode. Fig. 3 illustrates the aggregate and normalised results for the change in cell performance (V_{oc}, J_{sc} and η) under AM1.5 illumination as corona charge is deposited on the front surface of both groups of cells. The IV characteristics were acquired several times on each cell to account for experimental error in the handling and measuring procedures. It was observed that excessive deposition of corona charge resulted in a degradation of the cell performance due to dielectric breakdown. This is not included in Fig. 3 as only the optimal corona charge measurements are illustrated for meaningful comparison. These results show that regardless of the presence of a FSF a substantial improvement in cell performance is available when positive charge is added to the front surface of IBC cells. Only in one cell did extrinsic FEP not improve cell performance. Thirteen different cells showed a level of improvement in efficiency, ranging from 0.01 to 0.7% absolute. For cells without (with) a FSF a 0.9% (0.5%) relative improvement in efficiency was produced. J_{sc} improved by 0.1% (0.02%), while V_{oc} remained largely constant. This demonstrates that extrinsic FEP can be used controllably to enhance the passivation properties of IBC cells and therefore improve their performance.

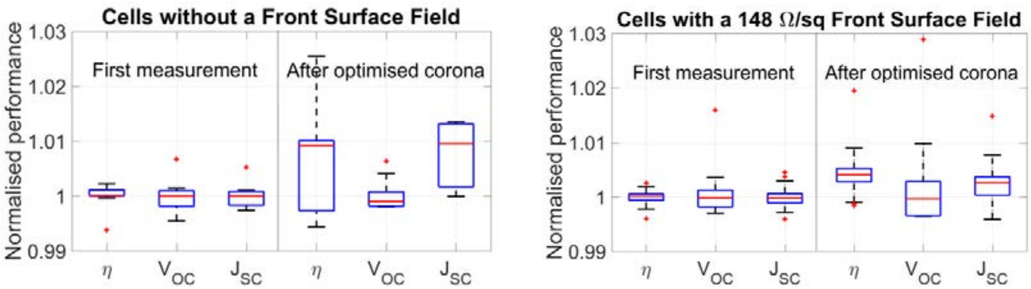

Fig. 3. Normalised performance of 5 IBC solar cells without a FSF and 8 with a FSF, before and after corona discharge has been deposited to an optimal passivation level. Plot box illustrates media, 95% confidence interval and standard deviations. Outliers are illustrated as red crosses.

4. Conclusions

Simulations showed that up to 200% relatively better performance of IBC solar cells may be achieved by using extrinsic passivation without the need for a FSF. A cell which uses a passivating FSF also benefits from extrinsic FEP, however the need for such FSF is eliminated since for the same dielectric charge, IBC cells without the FSF are predicted to perform better. This important finding translates into cost-reduction in the production line of IBC cells, since no lengthy high temperature diffusions are required on the front surface to produce the FSF when dielectric films can withstand enough charge.

Research scale IBC cells have been characterised as a function of improved FEP produced using corona charge. On average, four IBC solar cells lacking a FSF were seen to have an absolute improvement in efficiency of 0.3% $\pm$0.3, while eight IBC cells with a FSF improved by 0.13% $\pm$0.12. This indicates that the improvements achieved varied widely, yet extrinsic FEP produces a higher improvement in efficiency for cells that do not have a FSF, as predicted from simulations.

Acknowledgements

RS Bonilla is the recipient of an EPSRC (UK) Postdoctoral Research Fellowship, EP/M022196/1. PR Wilshaw acknowledges the support from EPSRC grant EP/M024911/1. Data published in this article can be downloaded from http://ora.ox.ac.uk.

References

[1] Panasonic Corporation, Panasonic HIT Solar Cell Achieves World's Highest Energy Conversion Efficiency of 25.6% at Research Level, URL: panasonic.co.jp/corp/news/, 2014.
[2] M.J. Kerr, A. Cuevas, Very low bulk and surface recombination in oxidized silicon wafers, Semicond. Sci. Technol. 17 (2002) 35–38. doi:10.1088/0268-1242/17/1/306.

[3] W. Soppe, H. Rieffe, A. Weeber, Bulk and surface passivation of silicon solar cells accomplished by silicon nitride deposited on industrial scale by microwave PECVD, Prog. Photovoltaics. 13 (2005) 551–569.
[4] A. Richter, S.W. Glunz, F. Werner, J. Schmidt, A. Cuevas, Improved quantitative description of Auger recombination in crystalline silicon, Phys. Rev. B. 86 (2012) 165202. doi:10.1103/PhysRevB.86.165202.
[5] R.S. Bonilla, P.R. Wilshaw, A technique for field effect surface passivation for silicon solar cells, Appl. Phys. Lett. 104 (2014) 232903. doi:10.1063/1.4882161.
[6] R.S. Bonilla, K. Collett, L. Rands, G. Martins, R. Lobo, P.R. Wilshaw, Stable, Extrinsic, Field Effect Passivation for Back Contact Silicon Solar Cells, Solid State Phenom. 242 (2015) 67–72. doi:10.4028/www.scientific.net/SSP.242.67.
[7] R.S. Bonilla, F. Woodcock, P.R. Wilshaw, Very low surface recombination velocity in n-type c-Si using extrinsic field effect passivation, J. Appl. Phys. 116 (2014) 054102.
[8] R.S. Bonilla, C. Reichel, M. Hermle, S. Senkader, P.R. Wilshaw, Controlled field effect surface passivation of crystalline n-type silicon and its application to back-contact silicon solar cells, in: Proc. 2014 40th IEEE Photovoltaics Spec. Conf., IEEE, Denver, CO, 2014.
[9] A. Rohatgi, P. Doshi, J. Moschner, T. Lauinger, A.G. Aberle, D.S. Ruby, Comprehensive study of rapid, low-cost silicon surface passivation technologies, IEEE Trans. Electron Devices. 47 (2000) 987–993. doi:10.1109/16.841230.
[10] U. of N.S. Wales, PC1D, (n.d.). http://www.pv.unsw.edu.au/info-about/our-school/products-services/pc1d (accessed August 20, 2012).
[11] P. Doshi, A. Rohatgi, 18% efficient silicon photovoltaic devices by rapid thermal diffusion and oxidation, IEEE Trans. Electron Devices. 45 (1998) 1710–1716. doi:10.1109/16.704369.
[12] O. Schultz, M. Hofmann, S.W. Glunz, G.P. Willeke, Silicon oxide/silicon nitride stack system for 20% efficient silicon solar cells, in: Conf. Rec. Thirty-First IEEE Photovolt. Spec. Conf., IEEE, 2005: pp. 872–876. doi:10.1109/PVSC.2005.1488271.
[13] J. Dupuis, E. Fourmond, V.M.-T. Yen, O. Nichiporuk, M. Greffioz, N. Le Quang, et al., Study of Rear PECVD Dielectric Stacks for Industrial Silicon Solar Cells, in: 24th Eur. Photovolt. Sol. Energy Conf., Hamburg, Germany, 2009: pp. 1623–1627.
[14] A. Das, K. Ryu, A. Rohatgi, 20% Efficient Screen-Printed n-Type Solar Cells Using a Spin-On Source and Thermal Oxide/Silicon Nitride Passivation, IEEE J. Photovoltaics. 1 (2011) 146–152. doi:10.1109/JPHOTOV.2011.2172189.
[15] M. Hofmann, S. Kambor, C. Schmidt, D. Grambole, J. Rentsch, S.W. Glunz, et al., PECVD-ONO: A New Deposited Firing Stable Rear Surface Passivation Layer System for Crystalline Silicon Solar Cells, Adv. Optoelectron. 2008 (2008) 1–10. doi:10.1155/2008/485467.
[16] R.S. Bonilla, C. Reichel, M. Hermle, G. Martins, P.R. Wilshaw, Extrinsic Passivation of Silicon Surfaces for Solar Cells, Energy Procedia. 77 (2015) 774–778. doi:10.1016/j.egypro.2015.07.109.
[17] P.A. Basore, K. Cabanas-Holmen, PC2D: A Circular-Reference Spreadsheet Solar Cell Device Simulator, IEEE J. Photovoltaics. 1 (2011) 72–77. doi:10.1109/JPHOTOV.2011.2166376.
[18] F. Granek, M. Hermle, S.W. Glunz, Analysis of the current linearity at low illumination of high-efficiency back-junction back-contact silicon solar cells, Phys. Status Solidi - Rapid Res. Lett. (2008) 151–153. doi:10.1002/pssr.200802126.
[19] P.A. Basore, K. Cabanas-Holmen, Comparison of 1D and 2D Model Results for Selective Emitter and Interdigitated Back Contact Cells, 27th Eur. Photovolt. Sol. Energy Conf. Exhib. (2012) 1462–1464. doi:10.4229/27thEUPVSEC2012-2BV.5.42.