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ANALYZING BACK CONTACTS OF SILICON SOLAR CELLS BY SUNS-VOC-MEASUREMENTS AT HIGH ILLUMINATION DENSITIES

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ABSTRACT: This work demonstrates the feasibility and usefulness of a new method to analyse the quality of the rear contact of silicon solar cells separated from other ohmic loss channels as e.g. the resistive loss in the front contact grid. The measurement is based on SunsVoc data at high illumination densities between 1 and 1000 suns. Generally the rear contacts can be described as a Schottky diode with a shunt resistor in parallel. At 1 sun operation conditions the back contact is fully dominated by the shunt showing an ohmic behaviour. However, at high illumination densities the Schottky diode can not be shunted completely anymore resulting in an increasing voltage which is opposed to the *pn* junction voltage. Finally a reversal point in the SunsVoc characteristics can be observed, i.e. the voltage decreases with increasing illumination density. The evaluation of this characteristic behaviour is used to extract physical parameters like the barrier height of the contact. Additionally the contact quality is assessed for different contact types and base doping concentrations. The predicted contact quality is in good correlation with the measured fill factors of the cells.

Keywords: Silicon, Contact, Characterisation

1. INTRODUCTION

I_{sc}-V_{oc} curves measured by the SunsVoc method [1] are a versatile tool to investigate the physics of silicon solar cells. Since I_{sc}-V_{oc} curves are unaffected by the series resistance, R_S can be determined by a comparison to the standard *IV* curve [2]. The series-resistance-free pseudo fill factor of the I_{sc}-V_{oc} curve is an excellent measure for the diode quality determined by shunts and junction recombination. It is the upper limit when optimizing the contact quality of silicon solar cells. Combining the SunsVoc method with a spectrally resolved illumination makes it possible to determine recombination parameters comparable to quantum efficiency measurements [3,4].

Cuevas and Sinton have described the observation of a Suns Voc measurement with a reversal point [1]. For illumination densities above this reversal point, the voltage is *decreasing* with *increasing* illumination densities. They attributed this effect to an imperfect contact formation and briefly outlined the use of the Suns-Voc method to analyse contacts [1,5].

In this paper we have used the SunsVoc method [1] to analyse the back contacts of silicon solar cells based on this effect. The reversal of the voltage curve (see Figure 5) is modelled quantitatively and physical parameters as the barrier height of the metal semiconductor system have been extracted. Using this method it is possible to assess the technological quality of different contact structures as PERC [6], LFC [7] and PERL/LBSF [8,9] on different base doping concentrations.

2. GENERAL DESCRIPTION OF CONTACTS

The back contact of *p*-type solar cells is assumed to be an ohmic contact in most simulation models. A more physical description would be based on a Schottky diode with a low barrier height. However the contact resistance of sintered aluminium contacts, the most common metal used for laboratory (PERC, LFC techniques) and industrial cells, is lower than that calculated from the basic Schottky model using published data for the Al/Si barrier height. Thus, Green *et al.* [10] have proposed a more realistic description by a parallel connection of a Schottky diode and shunt resistance (see Fig.1).

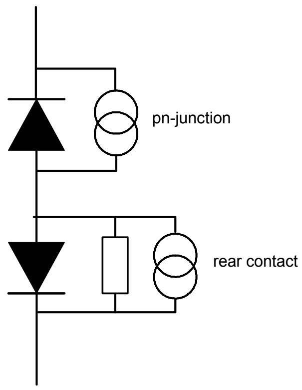

Figure 1: Description of the rear contact by a Schottky diode and a shunt resistor in parallel.

Since the diode at the rear contact is opposed to the junction diode, it can in principle reduce the overall voltage of the solar cell. However, at 1-sun conditions the performance of the back contact is usually fully dominated by the shunt resistance.

While performing J_{sc}-V_{oc} experiments with PERC cells fabricated on lowly doped silicon, Sproul *et al.* [11] have observed such a negative contribution of the back contact diode to the overall voltage already at medium illumination conditions. However, in their experiment they still observed an increasing overall voltage with increasing illumination, i.e. no reversal point.

3. EXPERIMENT

Fig. 2 shows a SunsVoc measurement using the generalized analysis [12] of a LFC cell with non-optimal LFC laser parameters at high illumination densities. Due to the non-optimal formation of the back contacts, the fill factor of this cell is only 37.6%. Above 1 sun the SunsVoc measurements shows an unusual behaviour: a decreasing voltage for increasing illumination density.

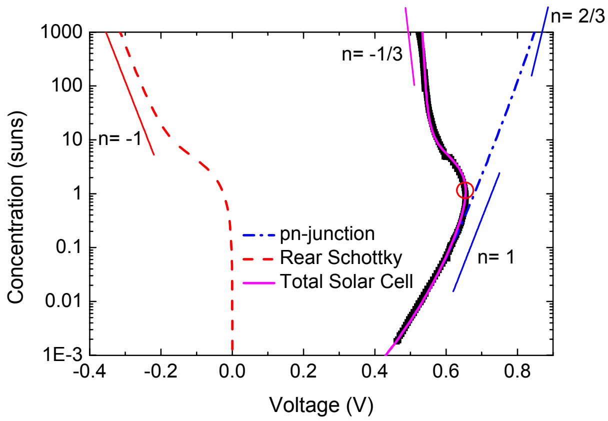

Figure 2: SunsVoc measurement of a LFC cell with non-optimal contact formation (*FF*= 37.6%). The solid line is calculated using the model described in section 3.

The following regions can be distinguished:

- **n ≥ 1:** Below one sun the cell is dominated by the front junction (dash-dotted curve) while the rear contact (dashed curve) is still ohmic and does not contribute significantly to the overall voltage.
- **n ≈ 0:** Around one sun the rear ohmic resistance is not low enough to shunt the rear Schottky junction completely. Therefore the rear voltage which is opposed to the junction voltage increases and the overall voltage does not increase as expected ($n < 1$). A characteristic point is where the voltage increase of both junctions is identical, called the "n=0" point (circle in Fig. 2). Note that for a typical cell with acceptable fill factor this “n=0” point is reached for illumination densities around 100 suns (see examples in Figs. 4 and 5).
- **n < 0**: Above 10 suns the voltage increase of the rear junction is greater than the one of the *pn*-junction, resulting in a *reduction* of the overall voltage.
- **n = -1/3**: At high illumination densities of more than 100 suns the *pn*-junction works already in high injection and is thus limited by Auger recombination (ideality factor $n = 2/3$). The ideality factor n of the Schottky diode is -1, thus the development of the overall voltage can be described by an ideality factor of -1/3.

Using such a measurement it is possible to obtain interesting aspects about the quality and physics of the back contact.

4. MODELLING THE REAR SCHOTTKY DIODE

The modelling performed in this work is based on the Schottky diode equation of the thermionic emission theory [13,14]:

$$\begin{aligned} I_s &= A\left[A^{*}T^{2}\exp\left(-\frac{q\Phi_B}{kT}\right)\right]\left[\exp\left(\frac{qV}{kT}\right)-1\right] \\ &= A\,J_{0S}\left[\exp\left(\frac{qV}{kT}\right)-1\right] \end{aligned} \tag{1}$$

where A is the area of the Schottky diode, A^* the Richardson constant (= 32 A/(cm^2 K^2) for *p*-type silicon [13]) and Φ_B the barrier height (see Figure 3). Other more sophisticated models for the description of Schottky diodes are available [14] but we found the equation above to be sufficient to describe our data.

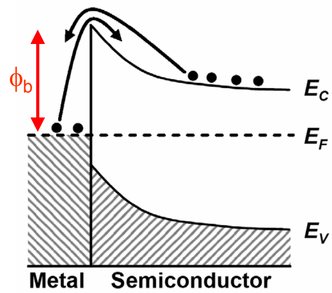

Figure 3: Band diagram of a Schottky diode on *n-type* silicon.

The recombination current density of the *pn*-diode can be described by the combination of three diodes and a shunt resistor:

$$\begin{aligned} J_{pn}(V) &= J_{01}(e^{qV/kT}-1)+J_{02}(e^{qV/(2kT)}-1) \\ &\quad +J_{0,hli}(e^{3qV/(2kT)}-1)+V/R_{p,pn} \end{aligned} \tag{2}$$

with J_{01} being the dark saturation current of base and emitter (n_1=1), J_{02} the dark saturation current of the space charge region of the *pn*-junction (n_2=2) and $J_{0,hli}$ the dark saturation current in high level injection, dominated by Auger recombination (n_{Auger}=2/3):

$$J_{o,hli} = q\,W\,C_A n_i^3 \tag{3}$$

C_A is the ambipolar Auger coefficient and W the thickness of the cell. $R_{p,pn}$ is the shunt of the *pn*-junction. A series resistance should not be included since SunsVoc measurements are not affected by R_S.

The performance of the back contact including Schottky diode and shunt $R_{p,S}$ is described by

$$J_s = J_{S0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]-V/R_{p,S} \tag{4}$$

Figure 2 shows that the description using equations (2) and (4) leads to a good agreement with the measured data over 6 decades of illumination density (see solid line in Figure 2). It is especially convincing that the ideality factor of the measured data of about 1/3 at high illumination densities is in good agreement with the one expected from the combination of (2) and (4):

$$V_{oc}(C) \overset{C\to\infty}{=} n_{Auger}\frac{kT}{q}\ln\left(\frac{J_{sc,pn}}{J_{0,hli}}\right) - \frac{kT}{q}\ln\left(\frac{J_{sc,S}}{J_{S0}}\right)$$
$$= n_{Auger}\frac{kT}{q}\left[\ln(C) + \ln\left(\frac{J_{sc,pn,1sun}}{J_{0,hli}}\right)\right]$$
$$-\frac{kT}{q}\left[\ln(C) + \ln\left(\frac{J_{sc,S,1sun}}{J_{S0}}\right)\right] \quad (5)$$
$$= (n_{Auger} - 1)\times\frac{kT}{q}\ln(C)$$
$$+ n_{Auger}\ln\left(\frac{J_{sc,pn,1sun}}{J_{0,hli}}\right) - \ln\left(\frac{J_{sc,S,1sun}}{J_{S0}}\right)$$

$$\Rightarrow V_{oc}(C) \propto -\frac{1}{3}\frac{kT}{q}\ln(C) \quad (6)$$

with C being the illumination concentration in suns and $J_{SC,pn}$ and $J_{sc,S}$ the short-circuit currents of the *pn*- and Schottky-diode.

After the successful description of the measured data it was our aim to extract the barrier height Φ_B of the metal semiconductor system. Although we can extract the *total* current of the Schottky diode I_{os} of our cells (see Figure 2), it is difficult to determine the current *density* J_{0S} since the area A of the rear contact points is not easily measured. Additionally, $J_{sc,S}$ is not exactly known. Therefore it is not accurate to determine the barrier height from one single measurement. Thus, we decided to measure the SunsVoc characteristics at two temperatures (see Figure 4).

For the description of the *pn*-diode at different temperatures it is necessary to include a temperature dependence of n_i as e.g. given by Wasserab [11,15].

$$n_i = 5.71\times10^{19}\left(\frac{T}{300}\right)^{2.365}\exp\left(\frac{-6733}{T}\right)\mathrm{cm}^{-3} \quad (7)$$

For the description of the Schottky diode the same $R_{p,s}$ value for both temperatures was used while two individual J_S-values were fitted for T_1 and T_2. Although only this value was adapted the fit quality is excellent for both measurements (see Figure 4).

From the ratio of these two dark saturation currents, it is possible to determine the barrier height:

$$\Phi_B = \left(\frac{q}{kT_1} - \frac{q}{kT_2}\right)^{-1} \times \ln\left(\frac{I_{S0}(T_2)}{I_{S0}(T_1)}\frac{T_1^2}{T_2^2}\right) \quad (8)$$

The Φ_B value for the measurement shown in Figure 4 is 0.38 V. This is in good agreement with literature values [16] although the barrier height is strongly dependent on surface preparation and subsequent heat treatments. Other samples with better contact performance have shown lower values in the range 0.2 – 0.3 V. Thus, this method seems to be suitable for a more comprehensive study of barrier heights of contacts with different process technologies.

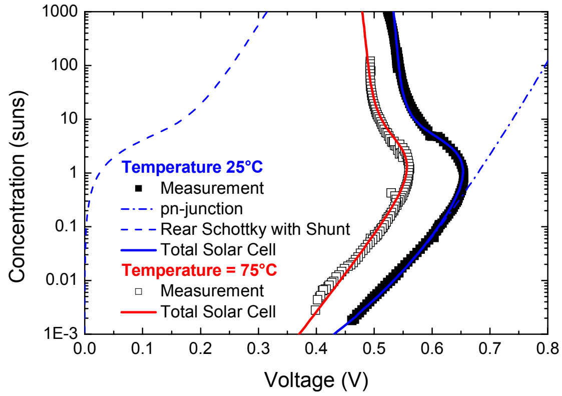

Figure 4: Measurement and simulation of two SunsVoc measurements at 25°C and 75°C.

5. ANALYSIS OF DIFFERENT REAR CONTACT STRUCTURES

For technological assessment of the contact quality solar cells with different rear structures were compared (see Figure 5). We have used cells with the following rear structures:

- PERC: Evaporated Al point contacts annealed at 425° for 25 min, no additional doping under contacts.
- LFC: 2 µm Al fired through 105 nm thermal oxide, aluminium p^+-doping due to laser fire process under the contact [17].
- Boron PERL: Al point contacts with additional high boron p^+-diffusion under contacts.

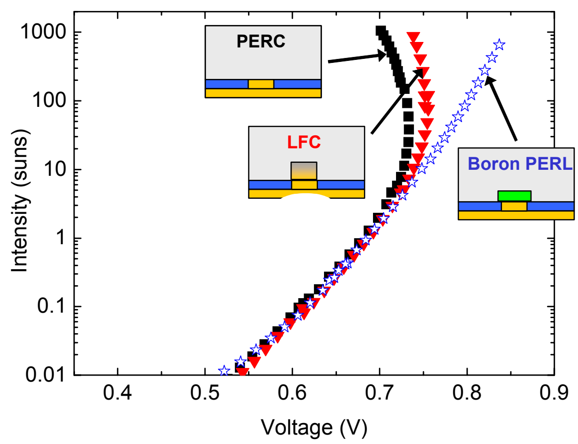

Figure 5: Suns-Voc measurement of cells with different rear contact structures.

It can be seen that with increasing contact quality the influence of the rear Schottky diode is reduced and the illumination for which the "n=0" point is reached increases. As expected the LFC back contacts have a higher contact quality compared to a simple PERC contact due to the additional Al doping under the contact [17]. The best quality is achieved by cells with local boron BSF where the p^+-doping concentration is significantly higher than for LFC cells. In this case no significant effect of the back contact can be observed up to 1000 suns.

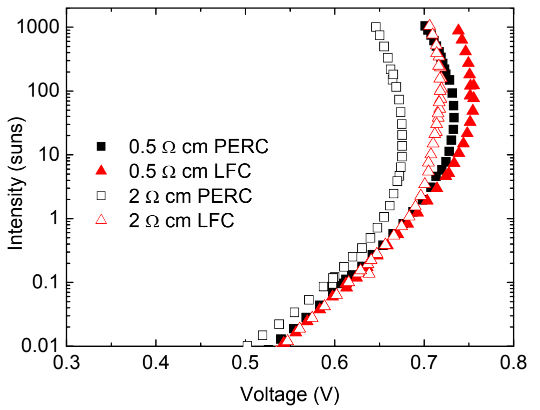

Figure 6: Suns-Voc measurement of PERC and LFC cells with different base doping concentrations.

In Figure 6 additional measurements of LFC and PERC cells with different base doping concentration are shown. It is well known that the contact resistance is reduced with increasing base doping concentration. The same dependence is also observed in our measurements. The influence of the rear Schottky diode is lower for higher base doping concentration.

Figure 7 shows a more quantitative analysis of the "n=0" point as a function of base doping concentration for PERC and LFC cells. The quality of the PERC contacts increases strongly with increasing doping concentration, while the quality of LFC contacts is nearly independent of the base doping concentration.[1] This is due to the Al doping induced by the laser firing process which makes the contact resistance nearly independent of the base doping concentration.

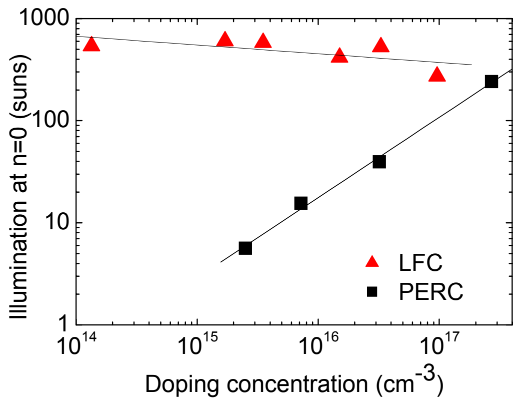

Figure 7: Illumination at the "n=0" point for different rear contact structures as a function of the base doping concentration.

[1] Note: The small shift of n=0 to lower illumination values with increasing doping concentration can be attributed due to the lower dark saturation current of cells with higher doping concentration.

6. OPTIMIZATION OF PROCESS PARAMETERS

This technique also allows to optimize the process parameters of the contact formation. Figure 8 shows the measurement of two LFC cells processed with identical cell structure but different LFC laser parameters. The "n=0"-point appears at lower illumination densities for parameter set B. Thus we can predict a lower contact quality for set B. Although the Schottky diode does not influence the voltage of both cells at 1 sun illumination, the effect of lower quality of the contact is reflected by the lower fill factor of cell B. Using this method, departures from ideal behaviour can be even seen before they result in a yield loss due to low efficiency.

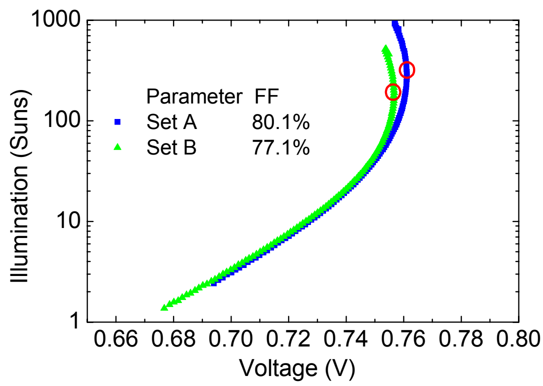

Figure 8: SunsVoc measurement of two LFC cells with identical cell structure (contact pitch, etc.) but different laser parameter for the LFC process.

Figure 9 shows the n=0 points for LFC cells processed with laser parameters A and B on different doping concentration. As can be seen cells processed with the "bad" laser parameter set B show consistently a lower "n=0" point.

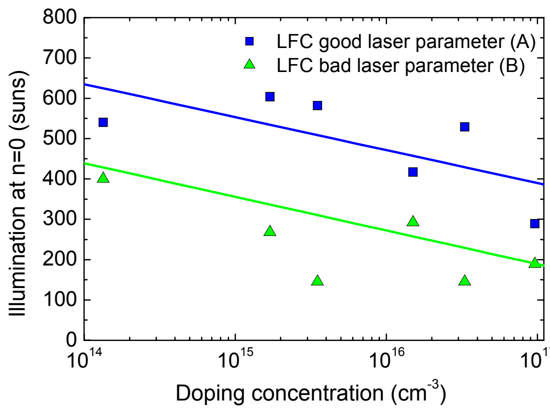

Figure 9: Comparison of the "n=0" points of LFC cells processed with laser parameters A and B (see Figure 8) with different doping concentration.

This difference in contact quality is strongly supported by the measured fill factors of these cells (see Figure 10).

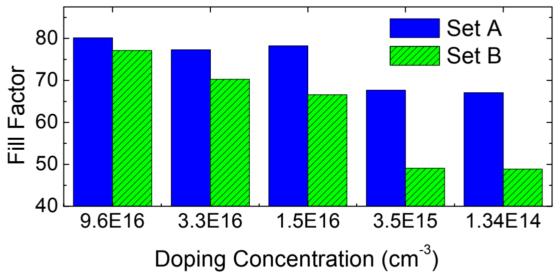

Figure 10: Measured fill factors of the cells shown in Figure 9.

An extreme example with very bad laser parameters is shown in Figure 2. In this case not only the fill factor suffers (FF = 37.6 %) but also the open-circuit voltage is reduced from ideally 689 mV (blue dotted line at 1 sun) to 655 mV (measurement at one sun).

7. CONCLUSION

Using the SunsVoc method at high illumination densities featuring a reversal point in the I_{sc}-V_{oc} characteristics, it is possible to determine physical parameters of the back contacts of silicon solar cells. By using the thermionic Schottky diode model it was possible to describe the measured curves quantitatively. Measurements at different temperatures allowed to extract the barrier height Φ_B of the metal semiconductor system at the back contact points of high-efficiency cells and demonstrated the validity of the physical model. The method was also used to predict the contact quality of different contact types as PERC, LFC and PERL on different base doping concentrations. The predicted contact quality is in good agreement with the measured fill factors of cells which shows that this new method is a versatile tool for solar cell characterisation.

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References

[1] R. A. Sinton and A. Cuevas, "A quasi-steady-state open-circuit voltage method for solar cell characterization", *Proceedings of the 16th European Photovoltaic Solar Energy Conference* (Glasgow, UK), pp. 1152-1155, 2000.

[2] M. Wolf and H. Rauschenbach, "Series resistance effects on solar cell measurements", *Advanced Energy Conversion*, vol. 3, pp. 455-479, 1963.

[3] H. Mäckel and A. Cuevas, "Spectral resolved analysis of the open-circuit voltage", *Solar Energy Materials and Solar Cells*, vol. 1, pp. 225-237, 2004.

[4] H. Mäckel, "Capturing the spectra of solar cells", PhD-Thesis, Australian National University, 2005.

[5] A. Cuevas and R. Sinton, in *Practical Handbook of Photovoltaics: Fundamentals and Applications*, edited by T. Markvart and L. Castaner (Elsevier, Oxford, 2003).

[6] A. W. Blakers, A. Wang, A. M. Milne, J. Zhao, and M. A. Green, "22.8% efficient silicon solar cell", *Applied Physics Letters*, vol. 55, pp. 1363-1365, 1989.

[7] E. Schneiderlöchner, R. Preu, R. Lüdemann, and S. W. Glunz, "Laser-fired rear contacts for crystalline silicon solar cells", *Progress in Photovoltaics: Research and Applications*, vol. 10, pp. 29-34, 2002.

[8] J. Zhao, A. Wang, and M. A. Green, "24% efficient PERL structure silicon solar cells", *Proceedings of the 21st IEEE Photovoltaic Specialists Conference* (Kissimmee, Florida, USA), pp. 333-335, 1990.

[9] J. Knobloch, A. Aberle, W. Warta, and B. Voss, "Starting points for raising the efficiency of practical silicon solar cells", *Proceedings of the 5th International Photovoltaic Science and Engineering Conference* (Kyoto, Japan), pp., 1990.

[10] M. A. Green, A. W. Blakers, J. Zhao, A. M. Milne, A. Wang, and X. Dai, "Characterization of 23-percent efficient silicon solar cells", *IEEE Transactions on Electron Devices*, vol. 37, pp. 331-336, 1990.

[11] A. B. Sproul and M. A. Green, "Improved value for the silicon intrinsic carrier concentration from 275 to 375 K", *Journal of Applied Physics*, vol. 70, pp. 846-854, 1991.

[12] M. J. Kerr, A. Cuevas, and R. A. Sinton, "Generalized analysis of quasi-steady-state and transient decay open circuit voltage measurements", *Journal of Applied Physics*, vol. 91, pp. 399-404, 2002.

[13] D. K. Schroder, *Semiconductor Material and Device Characterization*, John Wiley & Sons, New York, 1990.

[14] E. H. Rhoderick and R. H. Williams, *Metal-semiconductors contacts*, Clarendon Press (University-Press), Oxford, 1988.

[15] T. Wasserab, *Z. Naturforsch. Teil A 32*, pp. 746, 1977.

[16] H. C. Card, "Aluminum-silicon Schottky barriers and ohmic contacts in integrated circuits", *IEEE Transactions on Electron Devices*, vol. ED 23, pp. 538-544, 1976.

[17] S. W. Glunz, E. Schneiderlöchner, D. Kray, A. Grohe, H. Kampwerth, R. Preu, and G. Willeke, "Laser-fired contact solar cells on p- and n-type substrates", *Proceedings of the 19th European Photovoltaic Solar Energy Conference* (Paris, France), pp. 408-411, 2004.