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Surface recombination velocity of local Al-contacts of PERC solar cells determined from LBIC measurements and 2D simulation

Renate Horbelt[a]*, Gabriel Micard[a], Philipp Keller[a], Reinhart Job[b], Giso Hahn[a], Barbara Terheiden[a]

[a]*University of Konstanz, Department of Physics, 78457 Konstanz, Germany*
[b]*Münster University of Applied Sciences, Dept. of El. Engineering and Computer Science, 48565 Steinfurt, Germany*

Abstract

Industrial production volumes of passivated emitter and rear contact (PERC) solar cells increase due to significantly higher cell efficiencies compared to full area back surface field (BSF) solar cells at similar costs. The main features of PERC cells are dielectric surface passivation of the rear and local contact formation with Al leading to a p^+p junction beneath the Al/eutectic. For non-optimized process conditions, the eutectic in the local Al contact area does not form and so-called voids result. Since it is known that there are voids causing high or low recombination activity, a determination of the surface recombination velocity (SRV) is necessary for identification of the potential for process optimization. The passivation quality of the BSF, locally formed in the rear side contacts, is studied in detail via local internal quantum efficiency (IQE) measured by high resolution light beam induced current (LBIC). The significant spreading of the IQE values is attributed to a variation in local BSF layer thickness at different areas. The SRV of the local contact is determined by fitting the LBIC measurements of voids by 2D simulations. These simulations are based on a detailed modeling of SRV in local contact areas involving a non-uniform SRV in the void's vicinity. The non-uniform SRV in voids is traced back to laser induced damage nearby the local contact opening in the dielectric layer. Additionally the existence of laser damaged areas close to filled contacts is demonstrated in this work.

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Keywords: PERC; voids; surface recombination velocity; simulation; LBIC

* Corresponding author. Tel+49 7531 882079 fax: +49 7531 883895.
E-mail address: renate.horbelt@uni-konstanz.de

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1. Introduction

Void formation in PERC solar cells was first investigated and discussed in more detail by Urrejola *et al*. [1]. In most studies scanning electron microscopy (SEM) has been used to analyze local contact structures after the co-firing process. However, cross-sectional images obtained by this method give very locally restricted information concerning the contact structure. Dressler *et al*. demonstrated that the application of scanning acoustic microscopy (SAM) is a reliable technique to detect voids in PERC solar cells [2]. Additionally, this non-destructive method allows a spatially resolved detection of voids on large cell areas in a short time. The studies of Dressler *et al*. – combining SAM and electroluminescence measurements - gave a first hint that cell efficiency is not necessarily affected by a high amount of voids [2]. Detailed studies concerning the thickness of the local back surface field (LBSF) in voids and filled contacts revealed in general a thinner LBSF or completely missing LBSF for voids compared to filled contacts by applying identical process parameters [3]. According to Lölgen, a reduction of the surface recombination velocity (SRV) is achieved by the application of a BSF [4]. Hence, one crucial factor of voids concerning their negative impact on the electrical solar cell parameters is a sufficiently low SRV, implying a sufficiently thick LBSF formation [5, 6, 7, 8, 9].

Within this work a combination of high resolution LBIC measurements and SAM measurements allow the comparison of the electrical characteristics of voids and filled contacts. It has already been demonstrated by applying a 2D simulation that voids feature a non-uniform SRV, which is attributed to laser damaged areas nearby the local contact structure [10]. One key aspect of this work is the transfer of these findings to filled contacts.

2. Experimental

2.1. Device configuration

The investigated PERC solar cells are processed from p-type Czochralski (Cz) Si wafers (125 x 125 mm^2, thickness around 170 µm), with resistivity of 2-3 Ωcm. The n^+-type emitter (R_{sheet} = 60 Ω/sq) on the front side is coated with a stack of thermal oxide / SiN_X:H and contacted by screen-printed Ag. The rear side of the solar cell is covered by a stack of an Al_2O_3 layer (10 nm, atomic layer deposition) and a SiN_X:H layer (120 nm, remote PECVD). Local openings in this dielectric stack (geometry: opening width of 40 µm, line shape, constant pitch of 1 mm) are achieved by laser ablation (picosecond pulsed laser, 532 nm wavelength, Gaussian profile). A commercially available Al paste is used to form the local contacts on the rear side.

2.2. Local contact structure

Fig. 1, left and center, shows the cross-sectional views of a “void” and a “filled contact” achieved by SEM imaging. The images reveal a contact width of ~ 70 µm, an increase of about 30 µm compared to the opening width in the dielectric layer directly after laser ablation (40 µm). This widening is attributed to the co-firing process, including the dissolution of silicon [5, 6, 11, 12, 13, 14, 15]. In the void, the eutectic is missing. However, both local contacts are characterized by a uniform LBSF formation.

In order to obtain information about the spatial distribution of voids in the device, SAM measurements were carried out. The method is based on the detection of ultrasonic signals, emitted by a transducer and reflected and scattered by different materials and surfaces within the solar cell. In the end, a grey-scale image of the scanned area is achieved. A more detailed description of the measurement principle is given in [1, 15]. An image of such a SAM measurement (area ~ 50 x 60 mm^2) is shown in Fig. 1, right. For a better separation of the signals, the front side fingers (thin horizontal lines) run perpendicular to the rear side contacts. Voids appear as dark vertical lines. Obviously, this section features a high amount of voids within the local rear contacts.

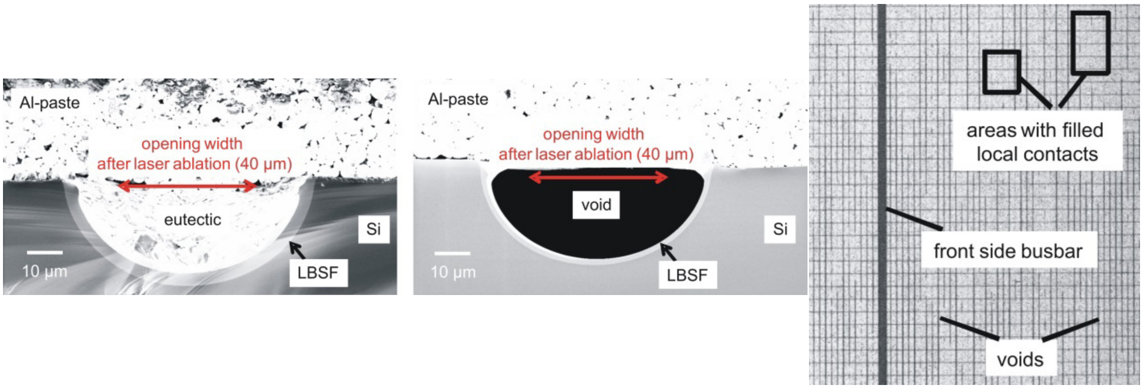

Fig. 1. SEM images of a "filled contact" (left) and a "void" (center). The widening of the contacts during co-firing process is symbolized by the arrow in red, indicating the opening width in the dielectric layer directly after laser ablation. Right: image of the SAM measurement. Thin horizontal lines indicate the front side fingers, running perpendicular to the local rear side contacts. Dark horizontal lines correspond to voids within the local contact area on the rear.

2.3. Determination of spatially resolved internal quantum efficiency (IQE) at local contacts

The main features of the in-house built LBIC measurement set-up are a moveable xy-stage and three different lasers with wavelengths of 833, 910 and 980 nm [16]. These wavelengths correspond to penetrations depths of 15, 36 and 103 µm in Si, respectively. A short circuit current is generated by the laser spots in the solar cell. A step width of 2 µm allows a high resolution and spatially resolved mapping of the short circuit current. For determination of the spatially resolved IQE, the following steps are needed: a calibration of the light intensity with a reference cell, the measurement of the reflected fraction of the incident light and a reflection calibration. Results of the 980 nm laser are shown in Fig. 2 (left) for a "filled contact" and a "void". Note the different scaling of the IQE values. The local contacts can be easily distinguished from the passivated area. While the filled contact reveals an IQE value in the range of the passivated area, a significant drop is detectable for the void. Line scans in x-direction allow plotting the value of each pixel as a function of the position and are shown in Fig. 2, right. The lower IQE value of 0.85 for the void in the passivated cell area compared to that of the filled contact (0.9) is caused by taking the measurements on different solar cells. However, the passivation quality of both solar cells is not at the possible maximum. The IQE in the void is only 0.7 whereas the IQE of the filled contact with 0.88 is nearly as high as the adjacent passivated cell area. Based on the results of such line scans the quantification of the surface recombination velocity (SRV) is realized by 2D simulation solving the relevant partial differential equations with the software flexPDE [17].

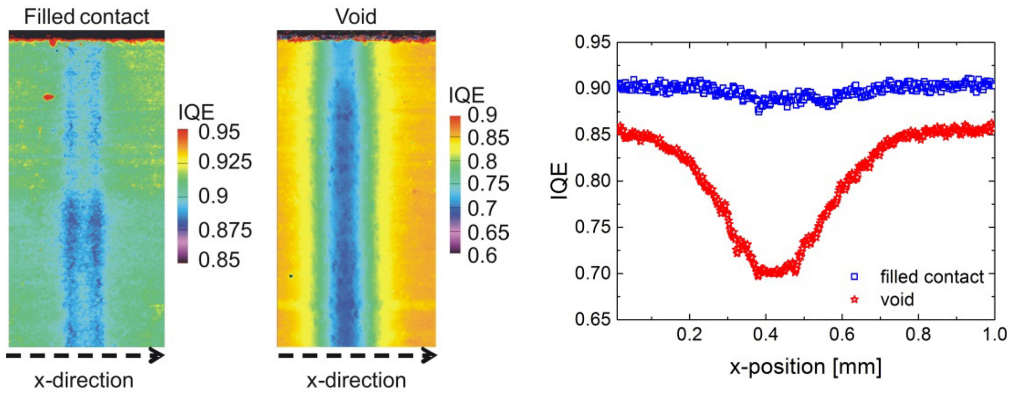

Fig. 2. Left: high resolution IQE mappings of a filled contact and a void (λ=980 nm, 1x2 mm²). The dark lines on top of the images are the front side fingers used to localize the regions of interest. Note the different scaling. Right: line scans in x-direction across the local contacts.

2.4. Quantification of SRV in voids

Micard *et al*. established a procedure to obtain the SRV of grain boundaries in multicrystalline Si [18, 19]. For this purpose the corresponding line scans of LBIC measurements were fitted by solving the 2D minority carrier diffusion equation. The method was adapted from its original application characterizing grain boundaries to the requirements of local contacts in PERC solar cells and turned out as an important tool to analyze local contacts in more detail [15]. The left diagram in Fig. 3 shows the line scans of the IQE measurement data obtained from illumination with lasers of wavelengths of 833, 910 and 980 nm.

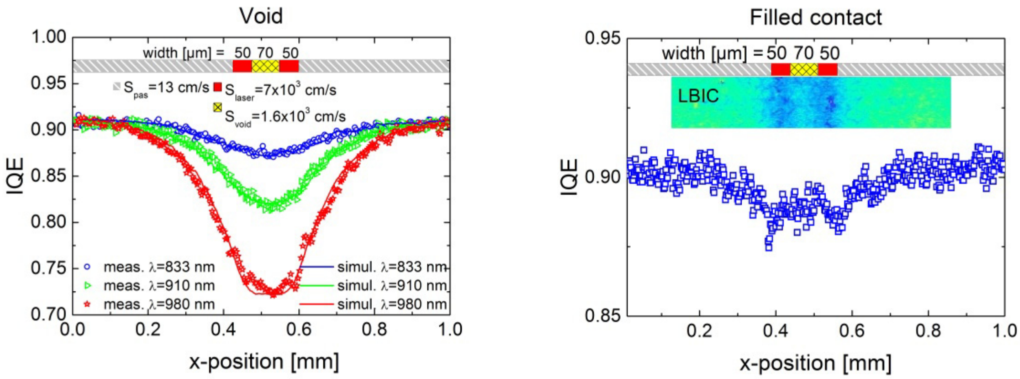

Fig. 3. Left: measured IQE profiles of a void for three laser wavelengths and the corresponding simulated profiles, considering a non-uniform SRV in the void as indicated in the sketch incorporated in the diagram. Right: measured IQE profile of a filled contact, including the corresponding LBIC map (λ=980 nm). The measurement fit well to the finding of a non-uniform SRV in the contact area.

Due to the high penetration depth of long wavelength light in Si, information about the recombination mechanisms on the rear side affected by the passivation quality is obtained. Fitting the less penetrative wavelengths (833 and 910 nm) confirms the validity of the evaluated model for the top and middle part of the Si bulk. Parameters incorporated in the model are the SRV of the passivated areas in between the local contacts of $S_{pas} = 13\ cms^{-1}$, a contact width of 70 µm as determined by SEM and a SRV within the void of $S_{void} = 1.6 \times 10^3\ cms^{-1}$. In addition, a relevant input parameter is the existence of a laser damaged area along the void. A width of 50 µm each and a SRV of $S_{laser} = 7 \times 10^3\ cms^{-1}$ is obtained for reliable fits of IQE line scans of all three wavelengths. Hence, voids are characterized by a non-uniform SRV in the contact area. The laser damaged areas are explained by the Gaussian laser beam used for the ablation process of the dielectric layer. A decline in pulse energy from the center to the edge of the beam leads to a damage of the dielectric layer and the silicon bulk beneath this layer while the pulse energy is not sufficiently high for the ablation process itself.

Taking these laser damaged areas into account conclusions concerning a phenomena detected at filled contacts can be drawn. The IQE mapping of a filled contact in Fig. 2 (left) is characterized by the two vertical lines of lower IQE on both edges of the local contact. A comparison of the corresponding line scan with the aforementioned model is in good agreement, as indicated in Fig. 3 on the right. Note the small band width of the IQE from 0.85 to 0.95. The small drop of IQE at the edges of the filled local contact fits well with the dimension of the laser damaged areas. Hence, the passivation quality of the LBSF in filled local contacts is affected by these laser damaged areas too.

3. Conclusion

High resolution LBIC measurements in combination with SAM measurements permit a detailed characterization of local contacts in PERC solar cells and an accurate comparison of the electrical characteristics of voids and filled contacts in particular. The experimental results reveal a large variation of IQE values for voids and a small reduction of IQE for filled contacts only.

2D simulations were used for the determination of the SRV in a void. The x-line scan of the IQE data and the simulation fit well providing a non-uniform SRV in the void. The void area can be subdivided in a 70 µm wide area with an SRV of $S_{void} = 1.6 \times 10^3$ cms^{-1} surrounded by two areas with a SRV of $S_{laser} = 7 \times 10^3$ cms^{-1} and a width of 50 µm each. These areas are attributed to the laser ablation process, where a laser with a Gaussian beam is used. At the outer regions of the laser beam the pulse energy is not sufficiently high for a complete ablation of the dielectric layer. However, the dielectric layer and the Si substrate are damaged.

Within this work a transfer of the results obtained from voids to filled contacts was carried out. Filled contacts are characterized by two lines with lower IQE at the outer edges of the local contact. These findings are in good agreement with the fact of a non-uniform SRV detected in voids. Thus, laser damaged areas affect the passivation quality of the LBSF in filled local contacts.

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References

[1] Urrejola E, Peter K, Plagwitz H, Schubert G. Silicon diffusion in aluminum for rear passivated solar cells. Appl Phys Lett 2011;**98**:153508.

[2] Dressler K, Dauwe S, Droste T, Rossa J, Meidel R, Schünemann K, Ramspeck K, Gassenbauer Y, Metz A. Characterisation of rear local contacts including BSF formation using RAMAN and scanning acoustic microscopy. Proc. 27th EU PVSEC, Frankfurt 2012, p. 755-8

[3] Horbelt R, Herguth A, Hahn G, Job R, Terheiden B. Temperature dependence of void formation in PERC cells and their spatially resolved detection by combining scanning acoustic microscopy and electroluminescence measurements. Proc. 29th EUPVSEC, Amsterdam 2014, p. 427-32

[4] Lölgen P. Surface and volume recombination in silicon solar cells. PhD Thesis, University of Utrecht (1995), ISBN: 90-393-0548-X.

[5] Müller J, Bothe K, Gatz S, Plagwitz H, Schubert G, Brendel R. Recombination at local aluminum-alloyed silicon solar cell base contacts by dynamic infrared lifetime mapping. En Proc 2011;8:337-42.

[6] Gatz S, Bothe K, Müller J, Dullweber T, Brendel R. Analysis of local Al-doped back surface fields for high efficiency screen-printed solar cells. En Proc 2011;8:318–23.

[7] Chen Y, Altermatt P, Dong J, Zhang S, Liu J, Chen D, Deng W, Jiang Y, Liu B, Xiao W, Zhu H, Chen H, Jiao H, Pan X, Zhong M, Wang D, Sheng J, Zhang Y, Shen H, Feng Z, Verlinden P J. Al-Alloyed local contacts for industrial PERC cells by local printing. Proc. 40th IEEE PVSC, Colorado, USA, 2014, p. 3322-5

[8] Chen Y, Shen H, Altermatt P. Analysis of recombination losses in screen-printed aluminum-alloyed back surface fields of silicon solar cells by numerical device simulation. Sol En Mat Solar Cells 2014;120:356-62.
[9] Chen D, Yang Y, Li Z, Liang Z, Feng Z, Verlinden P, Shen H. Analysis of morphologies and distribution of Al-doped local back surface field for screen printed i-PERC solar cells. Proc. 27th EUPVSEC, Frankfurt 2012, p. 1303-6
[10] Horbelt R, Micard G, Keller P, Hahn G, Job R, Terheiden B. Characterization of local Al-contacts by light beam induced current measurements and their verification by 2D simulation using flexPDE. Phys. Status Solidi A. DOI:10.1002/pssa.201532753(2016).
[11] Agostinelli G, Szlufcick J, Choulat P, Beaucarne G. Local contact structures for industrial PERC-type solar cells. Proc. 20th EUPVSEC, Barcelona 2005, p. 942–5
[12] Grasso F S, Gautero L, Rentsch J, Preu R, Lanzafame R. Characterisation of local Al-BSF formation for PERC solar cell structures, Proc. 25th EUPVSEC, Valencia 2010, p. 371–4
[13] Bähr M, Heinrich G, Doll O, Köhler I, Maier C, Lawerenz A. Differences of rear-contact area formation between laser ablation and etching paste for PERC solar cells, Proc. 26th EUPVSEC, Hamburg 2011, p. 1203–9
[14] Großer S, Mayerhofer R, Theobald J. Microstructure study of laser-opened rear contacts on PERC solar cells, Proc. 29th EUPVSEC, Amsterdam 2014, p. 1395–8
[15] Horbelt R, Hahn G, Job R, Terheiden B. Void formation on PERC solar cells and their impact on the electrical cell parameters verified by luminescence and scanning acoustic microscope measurements. En Proc 2015;84:47-55.
[16] Pernau T, Spiegel M, Fath P, BucherE. High-speed and high accuracy IQE and L_{eff}-mapping - a tool for advanced quality control in the PV-industry. Proc. 17th EUPVSEC, Munich 2001, p. 702-705
[17] FlexPDE 6.2, PDE Solutions Inc, 9408 E. Holman Rd., Spokane Valley, WA 99206, USA (http://www.pdesolutions.com).
[18] Micard G, Hahn G, Zuschlag A, Seren S, Terheiden B. Quantitative evaluation of grain boundary activity in multicrystalline semiconductors by light beam induced current: an advanced model. J Appl Phys 2010;108:034516.
[19] Micard G. Quantitative investigation of grain boundary recombination activity in multicrystalline silicon using light beam induced current contrast profiles - analytical models and applications. PhD thesis University Konstanz 2011.