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## Analysis and optimization of the bulk and rear recombination of screen-printed PERC solar cells

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### Abstract

In this paper, we investigate the impact of the rear surface passivation, the silicon base material and the local aluminum contacts applied to rear side passivated solar cells with a homogeneously doped emitter at the front. We compare different dielectric surface passivation layers ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiN}_x$ ) on a high-efficiency level using  $125 \times 125 \text{ mm}^2$  and  $156 \times 156 \text{ mm}^2$  *p*-type Cz silicon wafers. It turns out that applying an  $\text{Al}_2\text{O}_3/\text{SiN}_x$  layer stack outperforms all other surface passivation layers due to its excellent surface passivation as well as optical properties. We determine the impact of the light induced degradation depending on the used Cz base material. We measure an efficiency drop between 0.0 % (Ga-doped) and 0.8 % abs. (B-doped) after 8 hours of illumination under 0.5 Suns. We measure the surface recombination velocity of local screen-printed Al contacts with varying the metallisation fraction  $f_{\text{rear}}$  with the dynamic infrared lifetime mapping technique (dyn-ILM) on lifetime samples. We measure a decrease in contact recombination velocity from above 1100 cm/s for small  $f_{\text{rear}}$  to 400 cm/s for large  $f_{\text{rear}}$  on 1.5  $\Omega\text{cm}$  *p*-type FZ-silicon. Microscopy investigations show that this is due to an improved local Al-BSF formation when using higher  $f_{\text{rear}}$ .

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### 1. Introduction

Industrial crystalline Si solar cells typically feature a full-area aluminum (Al) back surface field (BSF) at the rear. It provides a good ohmic contact and a moderate rear side passivation with effective rear

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surface recombination velocities  $S_{\text{rear}}$  ranging from 200 to 600 cm/s on 2-4  $\Omega\text{cm}$   $p$ -type silicon [1,2]. In order to increase the cell efficiency, the passivation quality at the rear has to be improved. A dielectric layer at the rear also improves the internal reflectivity and hence the infrared light absorption of the solar cell.

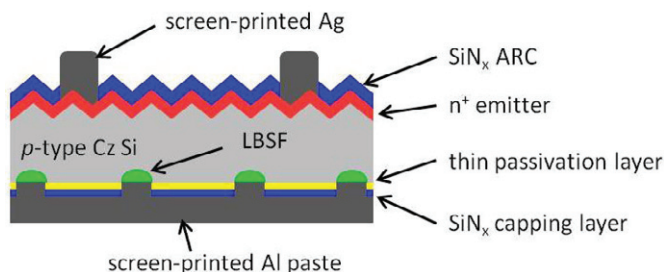


Fig. 1. Schematic of PERC solar cells with screen-printed Ag front and Al rear contacts. We analyse different passivation layers,  $p$ -type Cz-Si base materials and the impact of the rear local contact opening width.

This paper compares different rear passivation layers such as  $\text{SiO}_2/\text{SiN}_x$ ,  $\text{Al}_2\text{O}_3/\text{SiN}_x$ ,  $\text{SiN}_x$ . The light-induced degradation is investigated depending on dopant type. The formation of local Al screen-printed contacts in the passivation layer and its impact on the recombination velocity of the contacts  $S_{\text{met}}$  have been investigated before [3]. In contrast to Ref. 3 we do observe a significant influence of the metallisation fraction  $f_{\text{rear}}$  on  $S_{\text{met}}$ . The  $f_{\text{rear}}$  is in this paper defined as the fraction between metallised line width after firing and pitch  $p$ . We observe a correlation between  $S_{\text{met}}$  and the contact broadening during firing.

## 2. Investigation of rear surface passivation layers

Tab. 1. Solar cell parameters measured under standard testing conditions using  $\sim 180 \mu\text{m}$ -thick,  $p$ -type Cz-silicon, PERC design with identical rear side contact structure and  $f_{\text{rear}} \approx 10\%$  (No. 1-3, 5) using boron-doped  $\rho = 2.1 \Omega\text{cm}$  (No. 1-4) and Ga-doped  $\rho = 0.7 \Omega\text{cm}$  Cz-Si (No. 5).

No.	Rear passivation	Area [ $\text{cm}^2$ ]	$f_{\text{rear}}$ [%]	Dopant	$V_{\text{oc}}$ [mV]	$J_{\text{sc}}$ [ $\text{mA}/\text{cm}^2$ ]	FF [%]	$\eta$ [%]	$\eta_{\text{illuminated}}$ (%)
1	$\text{SiO}_2/\text{SiN}_x$	233	10	boron	652	38.3	77.2	19.3	18.5
2	$\text{Al}_2\text{O}_3/\text{SiN}_x$	149	10	boron	646	39.0	77.2	19.5	
3	$\text{SiN}_x$	149	10	boron	642	38.3	77.4	19.1	
4	Al-BSF	147	100	boron	632	37.1	79.8	18.7	
5	$\text{SiO}_2/\text{SiN}_x$	233	10	gallium	657	37.6	77.3	19.1	19.1

We apply different passivation layers to our PERC solar cell process with a homogeneous emitter and Ag screen-printed front contacts [4]. We compare on the basis of solar cell results three types of industrially relevant passivation layers: a thermally-grown  $\text{SiO}_2$  capped with plasma enhanced chemical vapour deposited (PECVD)  $\text{SiN}_x$ , a stack of plasma-assisted (PA) ALD- $\text{Al}_2\text{O}_3/\text{SiN}_x$  and a  $\text{SiN}_x$  single layer. The passivation layer thickness is in the range of 5-30 nm, the  $\text{SiN}_x$  layer thickness is in the range of 100-250 nm. On  $p$ -type FZ-Silicon test wafers with  $\rho = 1.5 \Omega\text{cm}$ , these passivation layers show a surface recombination velocity  $S_{\text{pass}} \leq 10 \text{ cm/s}$  for  $\text{SiO}_2/\text{SiN}_x$  [5] and ALD- $\text{Al}_2\text{O}_3/\text{SiN}_x$  [6,7] at injection densities relevant for solar cell application ( $\Delta n = 10^{13} - 10^{15} \text{ cm}^{-3}$ ). A  $\text{SiN}_x$  single layer shows a  $S_{\text{pass}} \approx 50 \text{ cm/s}$  after firing for  $\Delta n = 10^{15} \text{ cm}^{-3}$  [8]. They are therefore promising candidates for the rear side passivation of screen-printed PERC solar cells. Conventional solar cells with a full area Al-BSF are

processed as reference. Table 1 shows the measured cell parameters of PERC solar cells with  $\text{SiO}_2/\text{SiN}_x$  (No. 1), PA ALD- $\text{Al}_2\text{O}_3/\text{SiN}_x$  (No. 2) and  $\text{SiN}_x$  rear side passivation (No. 3). A conventional solar cell with a full area Al-BSF is shown as reference (No. 4). Considering No. 1-3, solar cells with identical rear contact geometry are compared, which explains the similar  $FF$ . The impact of the passivation layers can be observed in the open-circuit voltage  $V_{oc}$  and the short-circuit current density  $J_{sc}$ . In order to compare the  $J_{sc}$  variation, the reflectivity  $R$  and the internal quantum efficiency (IQE) are measured as shown in Fig. 2.

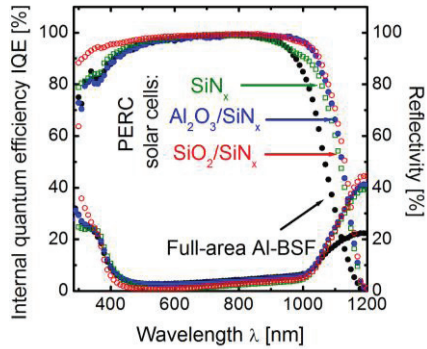


Fig. 2. Internal quantum efficiency (IQE) and reflectivity of screen-printed PERC solar cells with  $\text{SiO}_2/\text{SiN}_x$  (red), ALD- $\text{Al}_2\text{O}_3/\text{SiN}_x$  (blue) and  $\text{SiN}_x$  (green) rear side passivation compared to a conventional solar cell with full area Al-BSF (black).

The  $\text{Al}_2\text{O}_3/\text{SiN}_x$  (blue) and  $\text{SiN}_x$  (green) passivated PERC cells have a similar emitter doping profile and  $\text{SiN}_x$  front surface passivation as the full area Al-BSF solar cell (black). Therefore, both the IQE and reflectivity almost coincide in the short wavelength region. In contrast, the PERC solar cell with  $\text{SiO}_2/\text{SiN}_x$  rear and front passivation (red) show a deviation in the short wavelength reflectivity. Due to the fact that for both solar cells  $R$  and IQE almost coincide in the long wavelength region, we conclude that the difference in the front side antireflection coating contribute to a lower short circuit current density for  $\text{SiO}_2/\text{SiN}_x$  ( $J_{sc} = 38.3 \text{ mA/cm}^2$ ) compared to  $\text{Al}_2\text{O}_3/\text{SiN}_x$  ( $J_{sc} = 39.0 \text{ mA/cm}^2$ ) passivated PERC solar cells. Only a part of the losses ( $\leq 0.3 \text{ mA/cm}^2$ ) can be explained by the slightly higher front side shading at the  $156 \times 156 \text{ mm}^2$  solar cell No.1. However the IQE data which are adjusted for reflectivity show for the  $\text{SiO}_2/\text{SiN}_x$  passivation in the short wavelength region an increase. It results from a significantly lower phosphorus concentration at the surface caused by the thermal oxidation as shown in Ref. [9]. This explains the improved open-circuit voltage of cell No. 1 compared to cell 2 and 3 in Tab. 1.

In the long-wavelength region, the strong improvement of  $R$  and IQE are clearly shown to be due to the dielectric rear surface passivation. Using an IQE evaluation program from Fischer [10], based on models from Basore [11] and Brendel and Rau [12], the internal reflectance  $R_b$  and the effective rear surface recombination velocity  $S_{\text{rear}}$  are extracted from the wavelength region between 850 nm and 1000 nm. We assume a bulk lifetime  $\tau_b = 800 \text{ } \mu\text{s}$ , which we obtained on Cz  $p$ -type test samples in the regenerated state. The investigated layers show a  $R_b$  of about 90 %. The full area Al-BSF solar cell shows a  $S_{\text{rear}} = (450 \pm 100) \text{ cm/s}$ . All applied dielectric passivation layers show a decreased recombination at the rear. While  $S_{\text{rear}} = (70 \pm 30) \text{ cm/s}$  for  $\text{Al}_2\text{O}_3/\text{SiN}_x$  and  $S_{\text{rear}} = (90 \pm 30) \text{ cm/s}$  for  $\text{SiO}_2/\text{SiN}_x$  passivated solar cells, it is  $S_{\text{rear}} = (300 \pm 80) \text{ cm/s}$  for the  $\text{SiN}_x$  passivated PERC solar cell. Applying  $\text{SiN}_x$  passivation (cell No. 3 in Tab. 1) results therefore not only in a moderate  $V_{oc} = 642 \text{ mV}$  but also in a moderate  $J_{sc} = 38.3 \text{ mA/cm}^2$  compared to  $V_{oc} = 646 \text{ mV}$  and  $J_{sc} = 39.0 \text{ mA/cm}^2$  for the PERC solar cell with  $\text{Al}_2\text{O}_3/\text{SiN}_x$  passivation (No. 2). Thereby the increased  $S_{\text{rear}}$  is caused by the high injection dependency of the  $\text{SiN}_x$  surface passivation with  $S_{\text{pass}} \geq 100 \text{ cm/s}$  for  $\Delta n = 10^{13} \text{ cm}^{-3}$  on  $1.5 \text{ } \Omega\text{cm}$   $p$ -type FZ-Si wafers. In contrast, the  $\text{SiO}_2/\text{SiN}_x$  and  $\text{Al}_2\text{O}_3/\text{SiN}_x$  passivation layers do not depend on  $\Delta n$  in the relevant range  $10^{13} \text{--} 10^{15} \text{ cm}^{-3}$ .

### 3. Investigation of different Si bulk materials on light induced degradation

The PERC solar cell No. 1 in Tab. 1 is illuminated for 8 hours with white light, which typically suffices to activate all recombination active boron-oxygen-complexes. Thus we measure a cell efficiency degradation of 0.8 % abs. to 18.5 % for the boron-doped Cz-Si. The effect of light induced degradation for boron-doped Cz-Si wafer is shown in Fig. 3. As shown in Fig. 3 a) the IQE and  $R$  are agreeing for small wavelengths  $\lambda$ , one can recognize in Fig. 3 b) that the data for  $\lambda > 850$  nm differ during white light illumination. Using the software LASSIE [10,13] we extract from the IQE data for  $\lambda > 850$  nm the effective surface recombination velocity  $S_{\text{rear}}$ , and the bulk diffusion length  $L_b$ . While for both the  $S_{\text{rear}}$  is supposed to be constant at  $(90 \pm 30)$  cm/s, the extracted  $L_b$  decreases from 1940  $\mu\text{m}$  (regenerated) to 490  $\mu\text{m}$  (degraded). This corresponds to a bulk lifetime degradation from 1200  $\mu\text{s}$  to 80  $\mu\text{s}$  and fits well with obtained bulk lifetime on our test wafers of  $\tau_b = 800$   $\mu\text{s}$  in the regenerated state compared to  $\tau_b = 100$   $\mu\text{s}$  in the degraded state. For comparison purposes a solar cell was made with the same  $\text{SiO}_2/\text{SiN}_x$  passivation and the same screen-printing Al-paste applying a Ga-doped Cz-Si wafer with a base resistivity  $\rho = 0.7$   $\Omega\text{cm}$  (cell No. 5 in Tab. 1). It suffers from a lower  $J_{\text{sc}} = 37.6$   $\text{mA}/\text{cm}^2$  at about the same  $FF = 77.3$  % and slightly increased  $V_{\text{oc}} = 657$  mV resulting in  $\eta = 19.1$  %. However, this PERC solar cell does not show any degradation during illumination. Therefore the IQE of the Ga-doped Cz-Si PERC solar cell does not alter at all during illumination. From the IQE data in the long wavelength region we extract  $S_{\text{rear}} = (200 \pm 50)$  cm/s and  $L_b = (1150 \pm 200)$   $\mu\text{m}$  corresponding to a bulk lifetime  $\tau_b = 490$   $\mu\text{s}$ . This fits very well with measured  $\tau_b = 450$   $\mu\text{s}$  on test wafers before and after illuminating with white light.

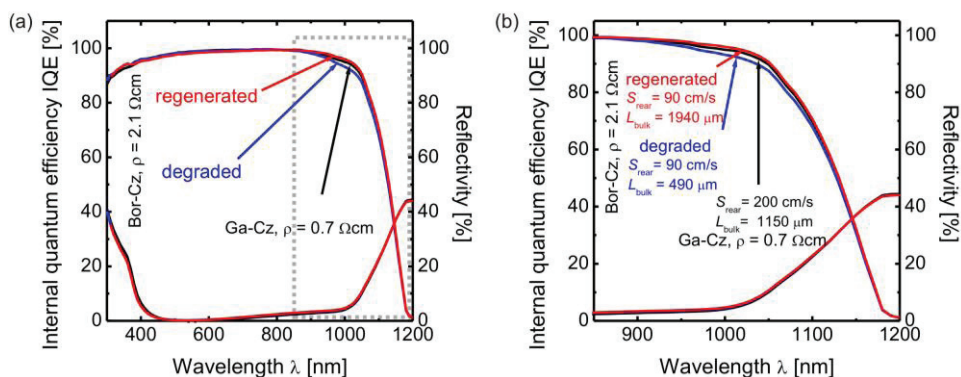


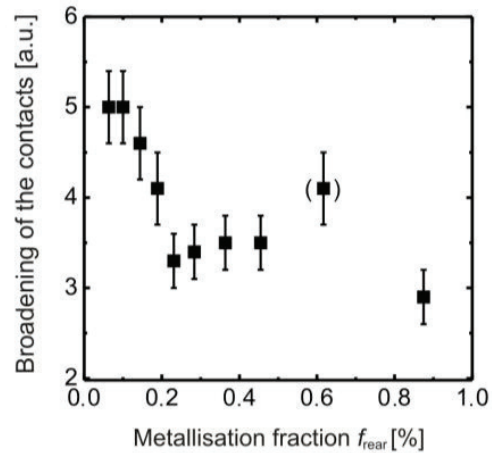
Fig. 3. a) Internal quantum efficiency (IQE) and reflectivity curves of  $\text{SiO}_2/\text{SiN}_x$ -passivated PERC solar cells on  $p$ -type Cz silicon. Applying Boron dopants results in different IQE curves depending on degraded (red) or regenerated status (blue). In contrast, the IQE curve of PERC solar cells applying Ga dopants does not change during annealing. b) Zoom-in to the wavelength range where  $S_{\text{rear}}$  and  $L_b$  are extracted using the software LASSIE [10,13].

### 4. Structural investigations of local Al-BSF and its influence on the surface recombination velocity

We study the formation of the solar cell rear contacts, which are fabricated by local laser ablation of the passivation stack followed by full-area Al screen-printing and firing. We measure the contact recombination velocity performing lifetime measurements on test samples. For this purpose we use 290  $\mu\text{m}$ -thick, 125 mm  $\times$  125 mm  $p$ -type, boron-doped and shiny-etched Float-Zone silicon wafers with a resistivity of 1.5  $\Omega\text{cm}$ . The wafers are cleaned in a wet chemical RCA process. A dry thermal oxidation is carried out resulting in a 10 nm-thick  $\text{SiO}_2$  layer on both surfaces. Afterwards we deposit symmetrically  $\text{SiN}_x$  layers with an in-line microwave PECVD system. At one side, the  $\text{SiO}_2/\text{SiN}_x$  passivation stacks are locally ablated by a 532 nm laser with pulse lengths of 10 picoseconds (Laser Contact Openings). We

vary the metallisation fraction at the rear  $f_{\text{rear}}$  by varying the local LCO area as well as the pitch  $p$ . The metallisation is realized by full-area Al screen-printing using the same Al paste as for the cells in Tab. 1. The samples are fired in a belt furnace at a nominal peak set temperature between 870°C and 930 °C and a belt velocity of 5.9 m/min.

Fig. 4. Structural investigations of the screen-printed local Al BSF contact formation to the base: broadening of the contact width as a function of the metallisation fraction  $f_{\text{rear}}$ .



Due to the local alloying process of Si and Al in local contacts a broadening of the screen-printed contact geometry compared to the dielectric ablated geometry has been reported before [14]. Fig. 4 plots the broadening of the contact structure as a function of the  $f_{\text{rear}}$ . It is provided by comparing the LCO fraction  $f_{\text{LCO}}$  after laser ablation with the metallisation fraction  $f_{\text{rear}}$  after firing. The  $f_{\text{LCO}}$  is determined by measuring the local LCO area using optical microscope images after the laser ablation. The  $f_{\text{rear}}$  is determined by measuring the width of the contact cross section using scanning electron microscopy images. There is a steep decrease of the broadening up to  $f_{\text{rear}} = 0.2$  % and thus to a certain contact opening width. By a further increase of the contact opening structure, the contact broadening saturates.

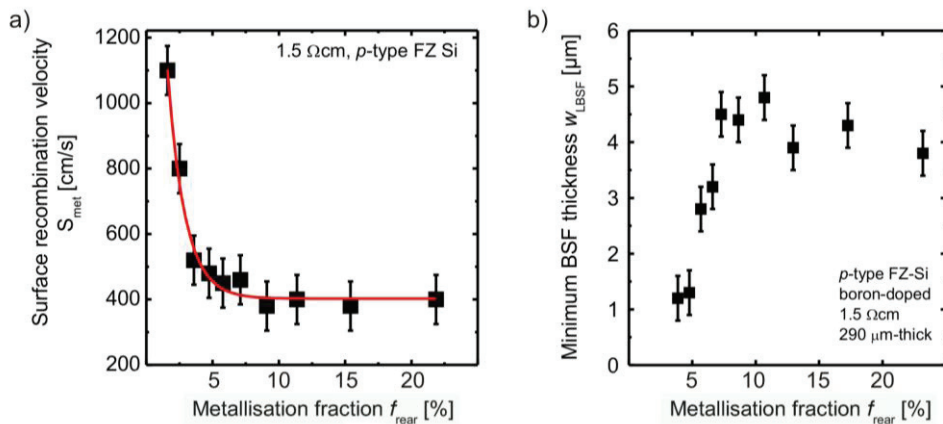


Fig. 5. a) Decreased surface recombination velocity of the metallised contacts  $S_{\text{met}}$  with increased metallisation fraction up to  $f_{\text{rear}} = 5$  % following by a saturation in  $S_{\text{met}} = (400 \pm 75)$  cm/s. b) The minimum BSF thickness strongly depends on  $f_{\text{rear}}$  for  $f_{\text{rear}} \leq 7$  % and saturates at about 4  $\mu\text{m}$  for  $f_{\text{rear}} > 7\mu\text{m}$ .

Applying the calibration-free dynamic infrared carrier lifetime mapping (dyn-ILM) technique [15] we obtain mappings of the effective lifetime  $\tau_{\text{eff}}$ . Using the approach in Ref. [16] we obtain an upper limit for



the area-averaged rear surface recombination velocity  $S_{\text{rear}}$  for each single contact geometry window. In order to determine the surface recombination velocity in the metallised areas  $S_{\text{met}}$  we use the equation developed by Fischer [10,17,18] that describes the area-averaged  $S_{\text{rear}}$  as a function of  $S_{\text{met}}$  and  $S_{\text{pass}}$  which is the surface recombination velocity in the passivated areas. As shown in Figure 5 a) a decrease of  $S_{\text{met}}$  from  $(1100 \pm 100)$  cm/s down to  $(400 \pm 75)$  cm/s is observed with increased metallisation fraction up to  $f_{\text{rear}} = 5\%$ , whereby the pitch between the line contacts remains constant. The constant  $S_{\text{met}}$  for  $f_{\text{rear}} > 5\%$  demonstrates that the contact opening matters only up to a certain limit. Figure 4 b) shows the minimum Al-BSF width  $w_{\text{LBSF}}$  as a function of  $f_{\text{rear}}$ . The  $w_{\text{LBSF}}$  is the smallest Al  $p^+$ -doped thickness in the local contact, mostly measured at the contact edges. It is determined by means of secondary electron microscopy measurements. While  $w_{\text{LBSF}}$  is around  $1 \mu\text{m}$  for small  $f_{\text{rear}}$ , it increases significantly with increasing  $f_{\text{rear}}$  and saturates at about  $4 \mu\text{m}$  for  $f_{\text{rear}} > 7\%$ .

Figure 6 shows the correlation between the measured  $S_{\text{met}}$  from Fig. 5 a) and the measured minimum Al-BSF thickness  $w_{\text{LBSF}}$  in Fig. 5 b). The data clearly indicate that small  $w_{\text{LBSF}}$  lead to high contact recombination velocities  $S_{\text{met}}$ . According to the method introduced in Ref. [19], we perform a numerical simulation to verify the measured change in the recombination properties at specific contact schemes as a function of the Al-BSF layer thickness. The input parameters for the simulations are the base resistivity of  $1.5 \Omega\text{cm}$ , the bulk lifetime in the Al- $p^+$  layer  $\tau_{\text{bulk}} = 130 \text{ ns}$  [20] and the rear surface recombination velocity  $S_{\text{cell, rear}} = 10^7 \text{ cm/s}$ . We use a depth dependent Al doping profile

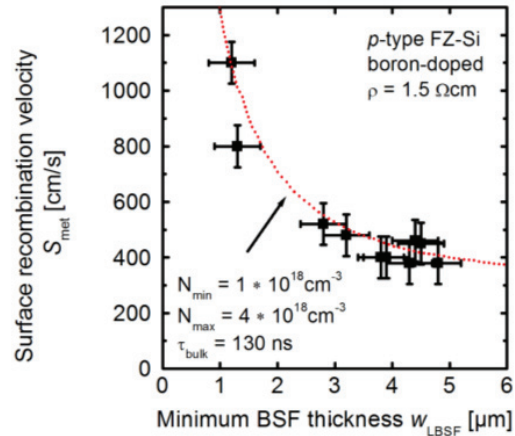


Fig. 6. Decreased surface recombination velocity  $S_{\text{met}}$  at the contacts with increased minimum BSF thickness  $w_{\text{LBSF}}$  corresponds to simulations (red dotted line)

$$N_{\text{Al}}(z) = N_{\text{min}} \exp\left(\frac{z}{w_{\text{LBSF}}} \ln\left(\frac{N_{\text{max}}}{N_{\text{min}}}\right)\right) \quad (1)$$

in the Al- $p^+$  region of thickness  $w_{\text{LBSF}}$  with  $N_{\text{min}} = 1 \times 10^{18} \text{ cm}^{-3}$  and  $N_{\text{max}} = 4 \times 10^{18} \text{ cm}^{-3}$ , which is comparable to previously measured doping profiles of full area Al- $p^+$  layers [20]. The results of the simulations in Fig. 6 clearly confirm the experimental finding.

## 5. Conclusions

We have demonstrated an excellent optical and surface passivation performance of  $\text{Al}_2\text{O}_3/\text{SiN}_x$  layers at the rear side of fully screen-printed PERC solar cells with homogeneous phosphorus-doped front side emitter. The investigated alternative dielectric layers suffer either from a moderate rear surface passivation ( $\text{SiN}_x$ ) or from an increased reflection on the solar cell front ( $\text{SiO}_2/\text{SiN}_x$ ). In an investigation regarding the base material we observed a degradation of the efficiency during illumination of 0.8 % absolute using boron-doped Cz-Si. In contrast Ga-doped Cz-Si does not show any degradation resulting in an energy conversion efficiency of 19.1 % before and after illuminating. The influence of the

metallisation fraction  $f_{\text{rear}}$  on the surface recombination velocity below the metal contacts  $S_{\text{met}}$  is investigated in detail. We demonstrated  $S_{\text{met}} < 500$  cm/s for large  $f_{\text{rear}}$  on lifetime samples with  $\rho = 1.5$   $\Omega\text{cm}$ . The application of the improved rear contact geometry and  $\text{Al}_2\text{O}_3/\text{SiN}_x$  rear surface passivation contributes to a PERC solar cell efficiency of 20.1 %, with  $J_{\text{sc}} = 39.0$  mA/cm<sup>2</sup>,  $V_{\text{oc}} = 655$  mV and  $FF = 78.8$  % [21,22].

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