

High efficiency *n*-type Si solar cells on Al₂O₃-passivated boron emitters

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In order to utilize the full potential of solar cells fabricated on *n*-type silicon, it is necessary to achieve an excellent passivation on B-doped emitters. Experimental studies on test structures and theoretical considerations have shown that a negatively charged dielectric layer would be ideally suited for this purpose. Thus, in this work the negative-charge dielectric Al₂O₃ was applied as surface passivation layer on high-efficiency *n*-type silicon solar cells. With this front surface passivation layer, a confirmed conversion efficiency of 23.2% was achieved. For the open-circuit voltage V_{oc} of 703.6 mV, the upper limit for the emitter saturation current density J_{0e} , including the metalized area, has been evaluated to be 29 fA/cm². This clearly shows that an excellent passivation of highly doped *p*-type *c*-Si can be obtained at the device level by applying Al₂O₃. © 2008 American Institute of Physics. [DOI: 10.1063/1.2945287]

n-type silicon has an enormous potential for widescale application in the photovoltaics industry. Its relative tolerance to common impurities (e.g. Fe)¹ potentially results in higher minority carrier diffusion lengths compared to *p*-type *c*-Si substrates with a similar impurity concentration. Furthermore *n*-type *c*-Si does not suffer from the boron-oxygen related light-induced degradation (LID), which is known to cause the LID for *c*-Si solar cells based on *p*-type Czochralski *c*-Si.²

In order to benefit from these advantages of the *c*-Si bulk material, a technology for adequate passivation of the B-doped emitters is essential. However, at the device level the excellent passivation quality as achieved for highly doped *n*-type emitters has not been realized so far for highly B-doped *p*-type *c*-Si. SiO₂, the most effective passivation for highly doped *n*-type surfaces,³ does not show the same performance on highly B-doped surfaces.^{4–7} The high boron solubility⁸ combined with the presence of a small fixed positive charge density⁹ contribute to this gap in performance. *a*-SiN_x:H, the second standard passivation layer for *n*⁺-doped surfaces, does not passivate highly doped *p*-type surfaces effectively due to the high concentration of built-in positive charges.^{6,10,11} Nevertheless, Chen *et al.* have shown *a*-SiN_x:H passivation on highly doped *p*-type surfaces with J_{0e} values below 10 fA/cm² for sheet resistivities above 100 Ω/sq.¹² However, no *n*-type cells have been fabricated using this approach which would demonstrate the potential of this technology at the device level. Alternative passivation layers under investigation for highly doped *p*-type surfaces are *a*-Si:H and *a*-SiC_x:H. With *a*-Si:H J_{0e} values below 30 fA/cm² have been reached for sheet resistivities above 100 Ω/sq.^{6,13} *a*-SiC_x:H shows only poor passivation properties so far, with $J_{0e} > 400$ fA/cm² on highly doped *p*-type surfaces ($R_{sheet} = 100$ Ω/sq).¹⁴ Apart from SiO₂, all other layers, especially those rich in Si, show a considerable absorption for photons with a wavelength <600 nm which is undesirable for the application as antireflection coating.

For passivation of highly doped *p*-type *c*-Si, a dielectric containing a fixed negative-charge density without any absorption in the visible part of the solar spectrum would be ideal. One dielectric layer meeting these specifications is the negative-charge dielectric Al₂O₃, which can be fabricated in a low temperature process.

Hoex *et al.* measured emitter saturation currents below 10 fA/cm² on highly doped *p*-type *c*-Si surfaces of unmetallized lifetime samples coated with Al₂O₃ synthesized by atomic layer deposition (ALD).¹⁵ The high density of fixed negative charges (up to $\sim 10^{13}$ cm⁻²) within this layer provides an effective field effect passivation on highly *p*-type doped surfaces.¹⁶ The excellent passivation of lightly doped *p*-type *c*-Si by Al₂O₃ has already been demonstrated at the rear of a diffused emitter *p*-type *c*-Si solar cell.¹⁷ In this paper, it will be proven that the excellent surface passivation of highly doped *p*-type *c*-Si by Al₂O₃ can be accomplished at the device level by achieving very high energy conversion efficiencies.

The effect of built-in charges on the passivation quality for highly doped *p*- and *n*-type surfaces is shown in Fig. 1. For this experiment, symmetrical *p*⁺/*n*/*p*⁺ and *n*⁺/*p*/*n*⁺ lifetime samples (1 Ω cm *n*- or *p*-type *c*-Si) were passivated by a 105 nm thick thermal SiO₂ and subsequently a charge density in the range between -4 and 4×10^{12} cm⁻² was applied on both sides of the samples by means of corona charging.⁹ The quasi-steady-state photoconductance (QSSPC) method¹⁸ is used to measure effective lifetime τ_{eff} . The implied V_{oc} was extracted from the QSSPC data as proposed by Sinton:¹⁹

$$\text{implied } V_{oc} = \frac{kT(\Delta n + N_{dop})\Delta n}{q n_i^2}, \quad (1)$$

where Δn is the excess carrier density, k the Boltzmann constant, T the temperature, q the elementary charge, N_{dop} the bulk doping concentration, and n_i the intrinsic carrier density.

The observed detrimental effect of positive charge on the passivation of highly doped *p*-type surfaces can be explained by the surface depletion of the majority carriers (i.e., the holes) induced by these positive charges. The surface depletion

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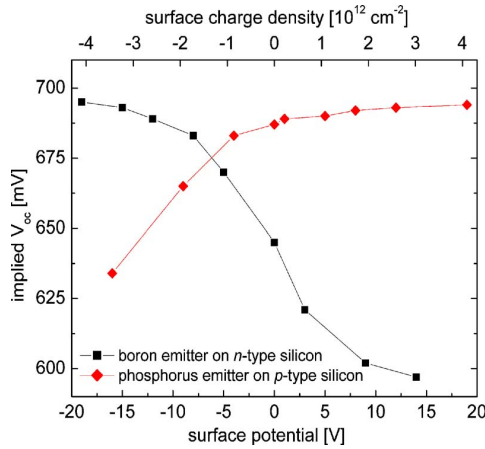


FIG. 1. (Color online) The effect of surface charge density on surface passivation quality. Both the B and P emitters have comparable sheet resistivities of approximately $140 \Omega/\text{sq}$ with surface doping concentrations of $6 \times 10^{18} \text{ cm}^{-3}$ for the B and $8 \times 10^{18} \text{ cm}^{-3}$ for the P emitter. Both emitters are passivated by a 105 nm thick thermal SiO_2 .

tion enhances the minority carrier (i.e., the electron) concentration at the surface, leading to an enhanced surface recombination. The opposite effect occurs when a negative-charge density is applied. In this case, an accumulation layer is induced, providing an effective field effect passivation at the p -type surface. By applying a negative-charge density of $-4 \times 10^{12} \text{ cm}^{-2}$, the implied V_{oc} is increased from below 650 mV (without surface charging) to approximately 690 mV. An analogous effect, but with opposite polarities, can be observed for highly n -type doped surfaces.

In order to investigate the excellent level of surface passivation of highly doped p -type c -Si surfaces by Al_2O_3 at the device level, n -type passivated emitter with rear locally diffused³ (PERL) solar cells (as shown in Fig. 2) were fabricated on (100) $1 \Omega \text{ cm}$, FZ, n -type c -Si wafers with a thickness of $250 \mu\text{m}$. These cells ($A=4 \text{ cm}^2$) feature a front surface with inverted pyramids and evaporated Al/Ti/Pd/Ag front contacts which are thickened by electroplating. The rear surface exhibits a local P diffusion ($R_{\text{sheet}} \approx 20 \Omega/\text{sq}$) and is covered with a 100 nm thick thermally grown SiO_2 and a $2 \mu\text{m}$ thick aluminum layer. BBr₃ diffusion at 890°C

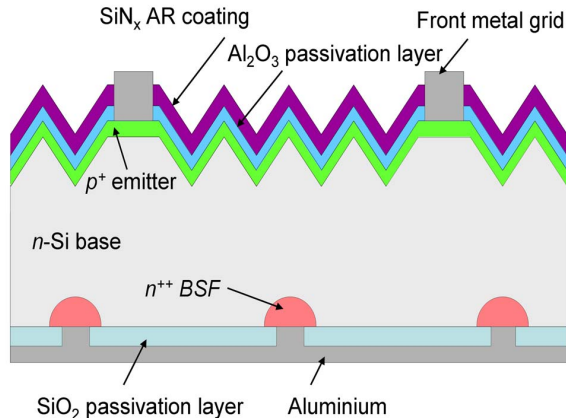


FIG. 2. (Color online) PERL solar cell structure on n -type silicon. Note that this structure has a homogeneous emitter in contrast to the two-step emitter in the original PERL structure.

TABLE I. Results of n -type PERL solar cells passivated by Al_2O_3 (AM1.5G, $100 \text{ mW}/\text{cm}^2$, 25°C).

	V_{oc} (mV)	j_{sc} (mA/cm^2)	FF (%)	η (%)
Average (28 cells)	696.9 ± 5.6	40.9 ± 0.3	78.8 ± 1.8	22.5 ± 0.7
Best	703.6	41.2	80.2	23.2 ^a

^aIndependently confirmed by Fraunhofer ISE CalLab.

followed by a drive-in oxidation at 1050°C result in a homogeneous B emitter with a sheet resistance of $140 \Omega/\text{sq}$ ($6 \times 10^{18} \text{ cm}^{-3}$ surface doping concentration, $1.5 \mu\text{m}$ depth). This front side B emitter is passivated by a stack consisting of a 30 nm Al_2O_3 film followed by a 40 nm thick SiN_x . The deposition of the Al_2O_3 was performed by plasma-assisted ALD (on an Oxford Instruments FlexALTM setup) at a temperature of 200°C .¹⁶ The plasma-assisted chemical vapor deposition SiN_x was deposited at 400°C (SINA XS, Roth & Rau AG).

The one-sun parameters of the PERL solar cells featuring the Al_2O_3 front side passivation are summarized in Table I. The best cell exhibits a V_{oc} of 703.6 mV, a J_{sc} of $41.2 \text{ mA}/\text{cm}^2$, and a FF of 80.2% resulting in an independently certified solar cell efficiency of 23.2% (aperture area measurement). The exceptional high values for V_{oc} , despite the lack of a two-step emitter, prove the outstanding ability of Al_2O_3 for the passivation of highly doped p -type surfaces in the solar cell devices.

To gain a deeper insight into the front surface passivation, an upper limit of the emitter saturation current J_{0e} can be determined from the open-circuit voltage V_{oc} and the saturation current density $J_0 = J_{0b} + J_{0e}$ by employing the one-diode equation:

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{J_{sc}}{J_{0b} + J_{0e}} + 1 \right). \quad (2)$$

The V_{oc} is determined by the saturation current densities of both the emitter J_{0e} and the base J_{0b} . Thus, to obtain an upper limit for J_{0e} , a reasonable J_{0b} has to be derived. The saturation density of the base, which also includes recombination in the bulk and at the rear side, can be calculated by

$$J_{0b} = \frac{qn_i^2 D_p}{LN_D} \cdot \frac{S_{\text{rear,eff}} \cosh(W/L) + D_p/L \sinh(W/L)}{D_p/L \cosh(W/L) + S_{\text{rear,eff}} \sinh(W/L)}. \quad (3)$$

The effective surface recombination velocity (SRV) of a point contacted rear is given by²⁰

$$S_{\text{rear,eff}} = \frac{D_p}{W} \left[\frac{p}{2W\sqrt{\pi f}} \arctan \left(\frac{2W}{p} \sqrt{\frac{\pi}{f}} \right) - \exp \left(-\frac{W}{p} \right) + \frac{D_p}{fWS_{\text{cont}}} \right]^{-1} + \frac{S_{\text{pass}}}{1-f}, \quad (4)$$

where $D_p = 11.6 \text{ cm}^2/\text{s}$ is the hole diffusion coefficient, $W = 250 \mu\text{m}$ the wafer thickness, $p = 135 \mu\text{m}$ the contact pitch, $f = 5\%$ the metallization fraction, and S_{cont} and S_{pass} the SRVs of the metalized and the passivated sections of the rear side, respectively. S_{cont} has been calculated by numerical modeling in PC1D (Ref. 21) on an idealized cell structure with intrinsic bulk lifetime, assuming $S_{\text{front}} = 0 \text{ cm}/\text{s}$. A strong P back surface field is present beneath the contacts. In this case, S_{cont} is independent of the actual SRV of the metal-Si interface,

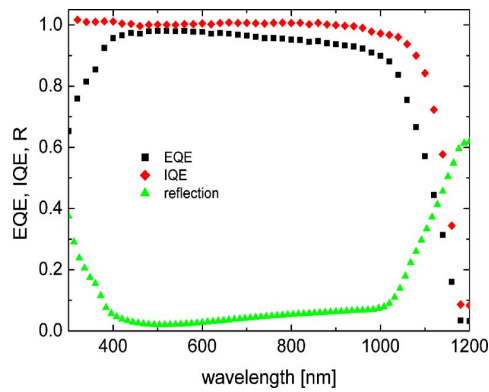


FIG. 3. (Color online) EQE, IQE, and reflection of an Al_2O_3 -passivated PERL solar cell.

leading to $S_{\text{cont}} \sim 55 \text{ cm/s}$. Applying Eqs. (2) and (3), the upper limit for the total dark emitter saturation currents $J_{0e,\text{total}}$ are 45 fA/cm^2 for $S_{\text{pass}} = 0 \text{ cm/s}$ ($J_{0b} = 10 \text{ fA/cm}^2$) and 29 fA/cm^2 for a more realistic but still very good $S_{\text{pass}} = 5 \text{ cm/s}$ ($J_{0b} = 25 \text{ fA/cm}^2$), including the recombination in the contacted and passivated areas of the emitter. To estimate the impact of the contacted area on $J_{0e,\text{total}}$, using PC1D and a S_{cont} of 10^6 cm/s , we have calculated the dark saturation current in the contacted region, $J_{0e,\text{cont}}$, to be 1800 fA/cm^2 . This results in an area-weighted dark saturation current for this region, $f_{\text{cont}} \times J_{0e,\text{cont}}$, of 20.3 fA/cm^2 (contacted area $f_{\text{cont}} = 1.1\%$). The area-weighted value for the passivated region has been calculated, $(1 - f_{\text{cont}}) \times J_{0e,\text{pass}} = 9.9 \text{ fA/cm}^2$, using the J_{0e} value of $\sim 10 \text{ fA/cm}^2$ extracted by Hoex *et al.* on nonmetalized lifetime test structures with a comparable B emitter.¹⁵ This leads to a $J_{0e,\text{total}}$ of 30.2 fA/cm^2 which is in good agreement to our previous calculation of 29 fA/cm^2 . A V_{oc} of 702 mV agreeing very well with the measured V_{oc} of the cells has been obtained, taking into account a J_{0b} of 25 fA/cm^2 ($S_{\text{pass}} = 5 \text{ cm/s}$) from Eq. (3). This calculation shows that about 66% of the recombination in the emitter is due to the contacted area.

The high internal quantum efficiency (IQE) in Fig. 3 also shows the effective front side passivation. These very high IQE values of $\sim 100\%$ in the $300\text{--}600 \text{ nm}$ range clearly demonstrate that the negative-charge dielectric Al_2O_3 is an excellent front surface passivation layer on B-doped emitters. Not only an excellent passivation quality has been reached on highly p -doped c -Si by Al_2O_3 resulting in a V_{oc} of 703.6 mV but moreover no additional detrimental effects such as optical absorption or inversion channel shunting are present, which would result in a poor performance at the device level.

In summary, an exceptionally high conversion efficiency of 23.2% for an n -type PERL solar cell with a front side B-doped emitter has been reported in this work. To date the highest reported efficiencies on n -type material were 22.7% (681 mV) on a backside-contact solar cell²² and also 22.7% (702 mV) on a rear emitter PERT solar cell.²³ This study demonstrates the excellent performance of our n -type solar cells and the superior passivation of highly B-doped surfaces by the negative-charge dielectric Al_2O_3 . The passivation of highly doped p -type c -Si has been obtained at the device level achieving the required technology for high-efficiency diffused emitter solar cells on n -type c -Si.

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