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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_s, including the metalized area, has been evaluated to 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-SiNₓ: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.⁶,⁹,¹¹ Nevertheless, Chen et al. have shown a-SiNₓ:H passivation on highly doped p-type surfaces with J_{oc} 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-SiCₓ:H. With a-Si:H J_{oc} values below 30 fA/cm² have been reached for sheet resistivities above 100 Ω/sq.⁶,¹³ a-SiCₓ:H shows only poor passivation properties so far, with J_{oc} > 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).¹³ The high density of fixed negative charges (up to ~10¹³ cm⁻²) within this layer provides an effective field effect passivation on highly p-type doped surfaces.¹⁰ 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 × 10¹² cm⁻² was applied on both sides of the samples by means of corona charging.⁹ The quasi-steady-state photoconductance (QSSPC) method¹⁴ is used to measure effective lifetime τ_{eff}. The implied V_{oc} was extracted from the QSSPC data as proposed by Sinton:¹⁵

\[
\text{implied } V_{oc} = \frac{kT (\Delta n + N_{dop}) \Delta n}{q n_\text{i}^2},
\]

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 deple-
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 in-

In order to investigate the excellent level of surface passivation of highly doped p-type c-Si surfaces by Al2O3 at the device level, n-type passivated emitter with rear locally diffused (PERL) solar cells (as shown in Fig. 2) were fabricated on (100) 1 Ω cm, FZ, n-type c-Si wafers with a thickness of 250 μm. These cells (A=4 cm²) 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 (Rsheet ≈ 20 Ω/sq) and is covered with a 100 nm thick thermally grown SiO2 and a 2 μm thick aluminum layer. BBr3 diffusion at 890 °C followed by a drive-in oxidation at 1050 °C result in a homogeneous B emitter with a sheet resistance of 140 Ω/sq (6 × 1018 cm−3 surface doping concentration, 1.5 μm depth). This front side B emitter is passivated by a stack consisting of a 30 nm Al2O3 film followed by a 40 nm thick SiNc. The deposition of the Al2O3 was performed by plasma-assisted ALD (on an Oxford Instruments FlexAL™ setup) at a temperature of 200 °C.16 The plasma-assisted chemical vapor deposition SiNc was deposited at 400 °C (SINA XS, Roth & Rau AG).

The one-sun parameters of the PERL solar cells featuring the Al2O3 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 mA/cm², 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 Al2O3 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:

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

\[ J_{0b} = \frac{qA^2D_p}{L_{N_p}^3} \frac{S_{rear,eff}\cos(W/L) + D_p/L\sinh(W/L)}{D_p/L\cosh(W/L) + S_{rear,eff}\sin(W/L)}. \] (3)

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

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

where Dp=11.6 cm²/s is the hole diffusion coefficient, W =250 μm the wafer thickness, p=135 μm the contact pitch, f=5% the metallization fraction, and Scont and Spass the SRVs of the metalized and the passivated sections of the rear side, respectively. Scont has been calculated by numerical modeling in PC1D (Ref. 21) on an idealized cell structure with intrinsic bulk lifetime, assuming Sfront=0 cm/s. A strong P back surface field is present beneath the contacts. In this case, Scont is independent of the actual SRV of the metal-Si interface.
leading to \( S_{\text{cont}} \approx 55 \text{ cm/s} \). 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 \( S_{\text{pass}} \approx 0 \text{ cm/s} \) (\( J_{0b} = 10 \text{ fA/cm}^2 \)) and 29 fA/cm\(^2\) for a more realistic but still very good \( S_{\text{pass}} \approx 5 \text{ cm/s} \) (\( J_{0b} = 25 \text{ fA/cm}^2 \)), 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 \( S_{\text{cont}} \) of 10\(^8\) 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.\(^\text{15}\) 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 \( V_{\text{oc}} \) of 702 mV agreeing very well with the measured \( V_{\text{oc}} \) of the cells has been obtained, taking into account a \( J_{0b} \) of 25 fA/cm\(^2\) (\( S_{\text{pass}} \approx 5 \text{ cm/s} \)) 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 300–600 nm range clearly demonstrate that the negative-charge dielectric \( \text{Al}_2\text{O}_3 \) 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 \( \text{Al}_2\text{O}_3 \) resulting in a \( V_{\text{oc}} \) 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 cell\(^\text{22}\) and also 22.7% (702 mV) on a rear emitter PERT solar cell.\(^\text{23}\) 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 \( \text{Al}_2\text{O}_3 \). The passivation of highly \( p \)-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.