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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 $J_{0e}$, 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,⁷ 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 $J_{0e}$ 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-SiCₓ: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-SiCₓ:H shows only poor passivation properties so far, with $J_{0e}>400$ fA/cm² on highly doped p-type surfaces ($R_{th}=100$ 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.

Kessels 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 $\sim 10^{13}$ 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 $4 \times 10^{12}$ cm⁻² was applied on both sides of the samples by means of corona charging.¹⁹ The quasi-steady-state photoconductance (QSSPC) method¹⁸ is used to measure effective lifetime $\tau_{eff}$. The implied $V_{oc}$ was extracted from the QSSPC data as proposed by Sinton:¹⁶

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

where $\Delta n$ 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-

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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 $-4 \times 10^{12}$ 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 $Al_{2}O_{3}$ 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 $\Omega$ cm, FZ, $n$-type $c$-Si wafers with a thickness of 250 $\mu$m. These cells ($A=4$ 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 ($R_{sheet}=20$ $\Omega$/sq) and is covered with a 100 nm thick thermally grown SiO$_{2}$ and a 2 $\mu$m thick aluminum layer. BBr$_{3}$ 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 $\Omega$/sq (6 $\times$ 10$^{18}$ cm$^{-3}$ surface doping concentration, 1.5 $\mu$m depth). This front side B emitter is passivated by a stack consisting of a 30 nm Al$_{2}$O$_{3}$ film followed by a 40 nm thick SiN$_{x}$. The deposition of the Al$_{2}$O$_{3}$ was performed by plasma-assisted ALD (on an Oxford Instruments FlexAl$^{TM}$ setup) at a temperature of 200 °C. 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$_{2}$O$_{3$ 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 mA/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$_{2}$O$_{3$ 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 $J_{0s}=J_{0b}+J_{0e}$ by employing the one-diode equation:

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

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 $J_{0b}$, 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

$$J_{0b} = \frac{q n_{i}^{2} D_{p} S_{rearr, eff} \cosh(W/L)}{W D_{p} \sinh(W/L)} + \frac{D_{p} S_{rearr, eff} \sinh(W/L)}{W D_{p} \sinh(W/L)}.$$  

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

$$S_{rearr, eff} = \frac{D_{p}}{W} \left[ \frac{p}{2 W \sqrt{\pi f}} \arctan \left( \frac{2 W}{p} \sqrt{\pi f} \right) - \exp \left( - \frac{W}{p} \right) \right]^{-1} + \frac{D_{p}}{f W S_{cont}}.$$  

where $D_{p}=11.6$ cm$^{2}$/s is the hole diffusion coefficient, $W$ =250 $\mu$m the wafer thickness, $p=135$ $\mu$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 $S_{front}=0$ cm/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,
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 $J_{0\text{e,total}}$ are $45 \text{ fA/cm}^2$ for $S_{\text{pass}} = 0 \text{ cm/s}$ ($J_{0\text{b}} = 10 \text{ fA/cm}^2$) and $29 \text{ fA/cm}^2$ for a more realistic but still very good $S_{\text{pass}} = 5 \text{ cm/s}$ ($J_{0\text{b}} = 25 \text{ fA/cm}^2$), including the recombination in the contacted and passivated areas of the emitter. To estimate the impact of the contacted area on $J_{0\text{e,total}}$, using PC1D and a $S_{\text{cont}}$ of $10^{6} \text{ cm/s}$, we have calculated the dark saturation current in the contacted region, $J_{0\text{e,cont}}$, to be 1800 fA/cm$^2$. This results in an area-weighted dark saturation current for this region, $f_{\text{cont}} \times J_{0\text{e,cont}}$, of 20.3 fA/cm$^2$ (contacted area $f_{\text{cont}} = 1.1\%$). The area-weighted value for the passivated region has been calculated, $(1 - f_{\text{cont}}) \times J_{0\text{e,pass}} = 9.9 \text{ fA/cm}^2$, using the $J_{0\text{e}}$ value of $\sim 10 \text{ fA/cm}^2$ extracted by Hoex et al. on nonmetallized lifetime test structures with a comparable B emitter.15 This leads to a $J_{0\text{e,total}}$ 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 $J_{0\text{b}}$ 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 300–600 nm range clearly demonstrate that the negative-charge dielectric Al$_2$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 Al$_2$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 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$_2$O$_3$. 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.