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High efficiency *n*-type Si solar cells on Al_2O_3-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 Al_2O_3 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/cm^2. This clearly shows that an excellent passivation of highly doped *p*-type *c*-Si can be obtained at the device level by applying Al_2O_3. © *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. SiO_2, 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 solubility[8] combined with the presence of a small fixed positive charge density[9] 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/cm^2 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/cm^2 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/cm^2 on highly doped *p*-type surfaces ($R_{sheet}=100$ Ω/sq).[14] Apart from SiO_2, 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 Al_2O_3, which can be fabricated in a low temperature process.

Hoex *et al.* measured emitter saturation currents below 10 fA/cm^2 on highly doped *p*-type *c*-Si surfaces of unmetalized lifetime samples coated with Al_2O_3 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 Al_2O_3 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 Al_2O_3 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 SiO_2 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) method[18] is used to measure effective lifetime τ_{eff}. The implied V_{oc} was extracted from the QSSPC data as proposed by Sinton:[19]

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

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 deple-

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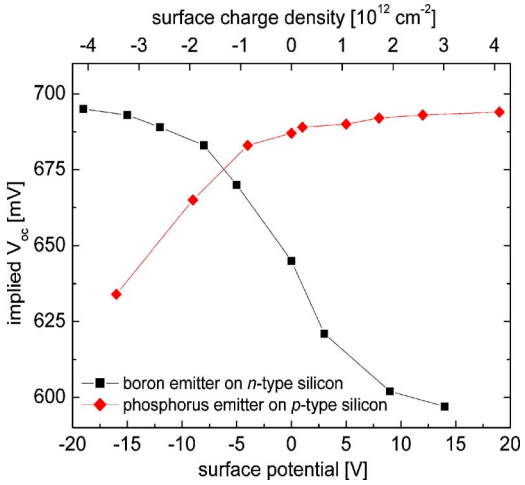

FIG. 1. (Color online) The effect of surface charge density on surface passivation quality. Both the B and P emitters have comparable sheet resistivities of approximately 140 Ω/sq with surface doping concentrations of 6×10^{18} cm^{-3} for the B and 8×10^{18} cm^{-3} for the P emitter. Both emitters 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 -4×10^{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_2O_3 at the device level, *n*-type passivated emitter with rear locally diffused[3] (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 ($A=4$ 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 ($R_{sheet}\approx20$ Ω/sq) and is covered with a 100 nm thick thermally grown SiO_2 and a 2 μm thick aluminum layer. BBr_3 diffusion at 890 °C

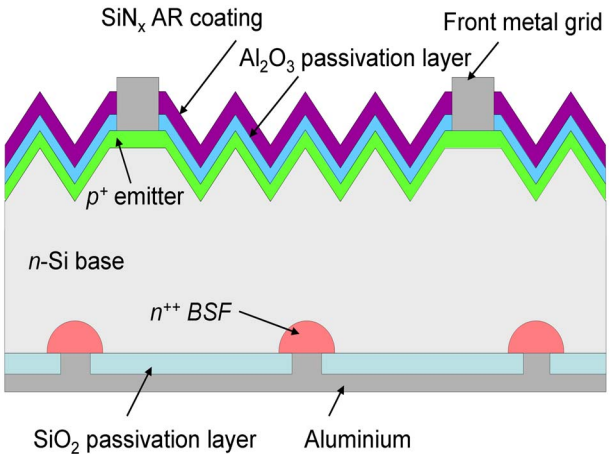

FIG. 2. (Color online) PERL solar cell structure on *n*-type silicon. Note that this structure has a homogeneous emitter in contrast to the two-step emitter in the original PERL structure.

TABLE I. Results of *n*-type PERL solar cells passivated by Al_2O_3 (AM1.5G, 100 mW/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]

[a]Independently 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 Ω/sq (6×10^{18} cm^{-3} surface doping concentration, 1.5 μm 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 FlexAL™ 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 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_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:

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

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

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

The effective surface recombination velocity (SRV) of a point contacted rear is given by[20]

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

where $D_p=11.6$ cm^2/s is the hole diffusion coefficient, $W=250$ μm the wafer thickness, $p=135$ μm 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,

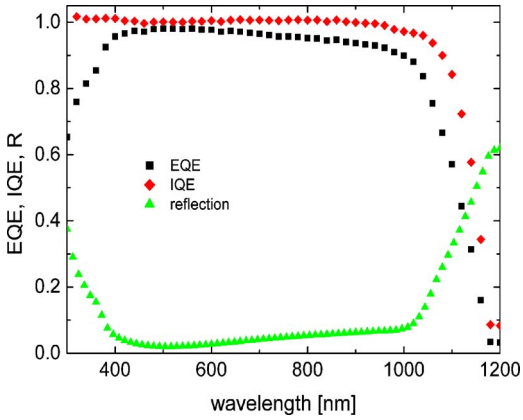

FIG. 3. (Color online) EQE, IQE, and reflection of an Al_2O_3-passivated PERL solar cell.

leading to $S_{cont} \sim 55$ cm/s. Applying Eqs. (2) and (3), the upper limit for the total dark emitter saturation currents $J_{0e,total}$ are 45 fA/cm^2 for $S_{pass}=0$ cm/s ($J_{0b}=10$ fA/cm^2) and 29 fA/cm^2 for a more realistic but still very good $S_{pass}=5$ cm/s ($J_{0b}=25$ fA/cm^2), including the recombination in the contacted and passivated areas of the emitter. To estimate the impact of the contacted area on $J_{0e,total}$, using PC1D and a S_{cont} of 10^6 cm/s, we have calculated the dark saturation current in the contacted region, $J_{0e,cont}$, to be 1800 fA/cm^2. This results in an area-weighted dark saturation current for this region, $f_{cont} \times J_{0e,cont}$, of 20.3 fA/cm^2 (contacted area $f_{cont}=1.1\%$). The area-weighted value for the passivated region has been calculated, $(1-f_{cont}) \times J_{0e,pass}=9.9$ fA/cm^2, using the J_{0e} value of ~ 10 fA/cm^2 extracted by Hoex *et al.* on nonmetalized lifetime test structures with a comparable B emitter.[15] This leads to a $J_{0e,total}$ 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 ($S_{pass}=5$ 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_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 cell[22] 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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