

PASSIVATED EMITTERS IN SILICON SOLAR CELLS

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ABSTRACT

In high-efficiency silicon solar cells with low metal contact coverage fractions and high bulk lifetimes, cell performance is often dominated by recombination in the oxide-passivated diffusions on the cell surface. Measurements of the emitter saturation current density, J_0 , of oxide-passivated, boron and phosphorus diffusions are presented, and from these measurements, the dependence of surface recombination velocity on dopant concentration was extracted. The lowest observed values of J_0 which are stable under UV light are given for both boron- and phosphorus-doped, oxide-passivated diffusions, for both textured and untextured surfaces. Contour plots which incorporate the above data were applied to two types of backside-contact solar cells with large area (37.5 cm^2) and one-sun efficiencies up to 22.7%.

INTRODUCTION

The performance of high-efficiency silicon solar cells is becoming increasingly dependent on the properties of oxide-passivated emitters [1,2,3,4,5]. Experimental results for two such cell designs are presented here. The emitter saturation current density, J_0 , was measured for both boron and phosphorus diffusions passivated by oxide, in order to determine how these diffusions may be most effectively used in solar cells. The surface recombination velocity, s , is a critical parameter in the modeling of emitters which are transparent to minority carriers. s was experimentally determined as a function of dopant concentration at the Si/SiO₂ interface from these J_0 measurements. It was found that boron diffusions generally have a higher J_0 than phosphorus diffusions, but that they are stable under the ultraviolet wavelengths found in the solar spectrum. The best J_0 values measured for oxide-passivated diffusions which do not degrade under UV light are given for four cases: phosphorus diffusions with textured and untextured surfaces, and boron diffusions with textured and untextured surfaces. This provides the experimental data necessary to design stable, high-efficiency cells with oxide-passivated emitters, such as backside-contact cells with interdigitated stripe diffusions (stripe IBC cells), p-i-n and n-i-p cells, and n⁺pp⁺ cells.

J_0 MEASUREMENTS

The experimental method used to find J_0 was the contactless measurement of photoconductivity decay in high-lifetime, highly-injected silicon wafers with identical, oxide-passivated diffusions on both sides. This method is described in [6,7,8], and is typically accurate to within 10%. This method measures J_0/n_i^2 directly, and a value of $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$ at 300°K was used to find the J_0 . Boron- and phosphorus-doped SiO₂ deposited by APCVD (atmospheric pressure chemical vapor deposition) was used as the

dopant source. In Fig. 1, the J_0 of each boron-doped, oxide-passivated emitter is shown next to a point which indicates $N_{A,\text{surf}}$, the surface boron concentration of the emitter, and x_j , the emitter thickness at which $N_A = 10^{16} \text{ cm}^{-3}$. The dopant profiles were determined by SIMS (secondary ion mass spectroscopy). The values of J_0 are in units of 10^{-13} A/cm^2 , and the J_0 measurements for samples that have received an FGA (forming gas anneal) are given first, followed by the measured J_0 for samples with no FGA enclosed in parentheses. In addition, three surface preparation conditions are shown: one in which the boron was driven in from the APCVD oxide, and the sample was given a short thermal oxidation at 950°C with the APCVD oxide left on the wafer, and two in which the boron was given either a short or a long drive-in, the oxide was stripped, and the surface was reoxidized at 1000°C. The primary feature of this data is that the oxide-passivated J_0 reaches a minimum of $\sim 0.85 \times 10^{-13} \text{ A/cm}^2$ for these oxidation conditions, over a broad range of $N_{A,\text{surf}}$ from about 3×10^{18} to $2 \times 10^{19} \text{ cm}^{-3}$. This contrasts with the corresponding data for oxide-passivated phosphorus emitters, for which the J_0 of forming-gas-annealed samples increases monotonically with $N_{D,\text{surf}}$, and can be as low as $0.060 \times 10^{-13} \text{ A/cm}^2$ [8]. We have found that oxide-passivated phosphorus diffusions formed by POCl₃ liquid-source doping or by doping

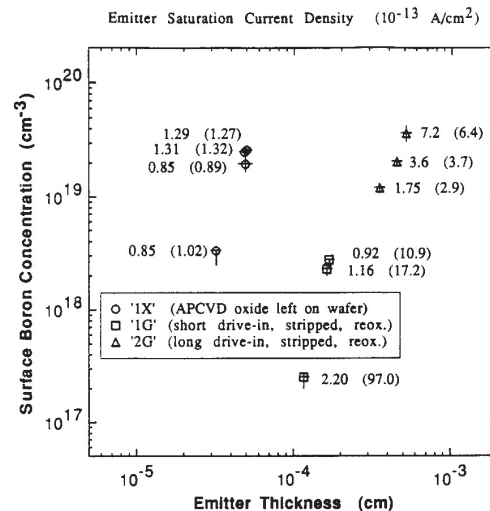


Figure 1. Measured values of the emitter saturation current density, J_0 , for untextured, oxide-passivated boron diffusions. The unbracketed values refer to samples which have received an FGA, and the bracketed values are for samples without an FGA.

Dopant	Surface Texture	$\rho_{\square}$ ($\Omega/\square$)	N_{surf} (cm^{-3})	x_j (μm)	Stable J_o at 300°K After UV Exposure (10^{-13} A/cm ^{2})
phos.	untex.	175	7.4×10^{18}	1.1	0.28
phos.	tex.	157	8.6×10^{18} *	1.2 *	0.71
boron	untex.	158	5.0×10^{18}	1.4	0.58
boron	tex.	132	7.0×10^{18} *	2.1 *	2.9

* From measurements made on identically processed, untextured samples.

Table 1. Dopant diffusions shown to have stable values of J_o under the ultraviolet wavelengths found in sunlight, at concentrations of 100 to 200 suns.

from APCVD oxide have comparable values of measured J_o . So the recombination in phosphorus diffusions seems to depend primarily on the dopant profile and on the oxidation and anneal conditions, not on the specific source of the phosphorus.

Stability

It has been observed previously that oxide-passivated phosphorus diffusions are more resistant to degradation by ultraviolet light than are undoped Si/SiO $_2$ interfaces [9,10]. In fact, if the surface phosphorus concentration is high enough, the J_o of the diffusion is stable when exposed to the UV wavelengths found in sunlight. Since the J_o of phosphorus diffusions increases with increasing $N_{D,\text{surf}}$, it is desirable to use the diffusion with the lowest $N_{D,\text{surf}}$ which yields a stable emitter. It was found here that boron diffusions do not degrade when exposed to the UV wavelengths found in the solar spectrum. This result was predicted earlier, based on the hypothesis that degradation is caused by electron injection into the SiO $_2$ conduction band [10]. UV photons with energies of ~ 4.8 eV or higher can still cause degradation at the p-type Si/SiO $_2$ interface by injecting holes into the SiO $_2$ valence band, but such high-energy photons are virtually non-existent in sunlight.

Table 1 lists the lowest stable J_o values that have been observed for textured and untextured, boron and phosphorus diffusions with oxide passivation. The boron samples listed are also the samples with the lowest J_o before UV exposure, so no trade-off between J_o and stability is required for boron as it is for phosphorus. However, even the lowest J_o achievable on textured, boron-doped surfaces is still 2.9×10^{-13} A/cm ^{2} , much higher than the 0.71×10^{-13} A/cm ^{2} possible for textured, phosphorus-doped surfaces. Using this data on the lowest, stable J_o values observed for oxide-passivated emitters, realistic predictions of the achievable efficiencies of p-i-n, n-i-p, and stripe IBC cells may be made [11].

The emitters in Table 1 were exposed using a xenon arc lamp, at an incident intensity of 10 to 20 W/cm ^{2} . The spectrum of this lamp is very UV-rich compared to the solar spectrum, so that the degradation it produces occurs at a much faster rate than in natural sunlight. Since hole injection is thought to be the dominant mechanism for the boron-doped Si/SiO $_2$ interfaces, they were exposed behind filters which eliminate photons with energies greater than 4.8 eV, which occur in the lamp spectrum but not in the solar spectrum. Lightly-doped phosphorus control diffusions degraded about 0.4 times as fast behind the filters as when the filters were not present, demonstrating that UV wavelengths which are damaging to phosphorus diffusions are still present in the spectrum used to expose the boron samples.

EXTRACTED EMITTER PARAMETERS

The recombination in passivated emitters is often dominated by the surface recombination velocity, s , at the Si/SiO $_2$ interface. In emitter modeling studies, s has frequently been given an assumed value, partly because it is a very process dependent parameter, and because the relationship between s and surface dopant concentration was not known. Although s can be strongly affected by oxide growth conditions, anneal conditions, surface roughness, and contamination, we have found that surface recombination velocities which are low, stable, and repeatable can be obtained using dry oxidation with no trichloroethane (TCA), followed by a forming gas anneal. The dependence of s at the Si/SiO $_2$ interface on phosphorus and boron concentration was extracted from J_o measurements of transparent emitters, for which the J_o was strongly dependent on surface recombination. This extraction was performed by solving the carrier transport equations numerically, using the measured SIMS profiles of the diffusions, along with the dependence of bandgap narrowing [12], minority carrier mobility [12,13,14], and bulk lifetime [12,15,16] on dopant concentration. The SIMS profiles were checked both by using reference samples and by comparing the measured and predicted values of sheet resistance.

For boron emitters, it was found that when the bandgap narrowing, $\Delta E_g(N_A)$, given by Slotboom and de Graaff in [17] was used, the predicted J_o values were higher than the measured values even when a surface recombination velocity of zero was assumed. This is the classic study of bandgap narrowing in silicon. To resolve this dilemma, the bandgap narrowing in boron-doped silicon was independently determined by comparing the measured J_o of thick and thin emitters with a very high surface recombination velocity due to the presence of metal deposited on the surface [18]. The bandgap narrowing found in this way was

$$\Delta E_g = (0.0178 \text{ eV}) \ln \left(\frac{N_A}{2.3 \times 10^{17} \text{ cm}^{-3}} \right),$$

for $N_A \geq 2.3 \times 10^{17} \text{ cm}^{-3}$. The uncertainty in ΔE_g is ~ 4 meV. This is the dependence of ΔE_g on N_A which was used to extract s from J_o measurements of boron-doped emitters. The bandgap narrowing found here is ~ 16 meV lower than the fit given by Slotboom and de Graaff, for all boron concentrations, resulting in a predicted J_o that is nearly two times lower for a given value of s .

In Fig. 2, surface recombination velocity is plotted versus surface boron concentration for the Si/SiO $_2$ interface. For three of the processing conditions shown, s is constant with respect to $N_{A,\text{surf}}$, and has an average value of 1640 cm/s. The value of s for the stripped, reoxidized emitters

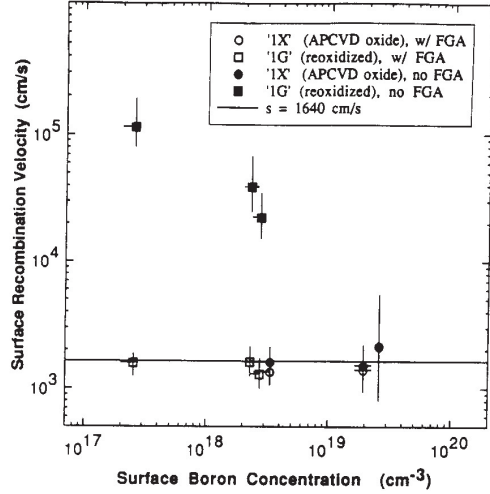


Figure 2. Surface recombination velocity, s , extracted from measurements of J_0 on oxide-passivated boron diffusions.

with no FGA is more than 10 times higher. The reason for this is unknown. For the most lightly doped emitter, with $N_{A,surf} = 2.5 \times 10^{17} \text{ cm}^{-3}$, s was found to decrease with increasing injection level. The value of s plotted for this emitter applies when the pn -product is less than $\sim 10^{31} \text{ cm}^6$ (when the fermi-level splitting is less than $\sim 0.640 \text{ V}$), in which case s is independent of injection level.

The presence of a conductive layer above the oxide can have a strong effect on s . In solar cells, the conductive layer is usually metal which is electrically connected to the underlying diffusion over some fraction of its area. So to first order, the fermi level in the metal is the same as in the diffusion beneath the oxide. When the gate metal is Al, and the doped layer is n-type, this tends to accumulate the surface slightly, which could decrease s to a small degree. For p-type Si, however, the metal tends to cause depletion or inversion at the silicon surface, which can change s dramatically. There are many situations in which $N_{A,surf}$ is large enough or the oxide is thick enough that the metal layer does not affect the surface potential significantly, but the values of s in Fig. 2 should be applied with caution beneath a conductive layer.

Figure 3 shows the dependence of s on $N_{D,surf}$ for the phosphorus-doped Si/SiO₂ interface for comparison [8]. The surface recombination velocity is a strong function of surface phosphorus concentration, so that the assumption of a value of s which is constant with respect to $N_{D,surf}$ could lead to predicted J_0 values which are different from experimental values by more than an order of magnitude.

CONTOUR PLOTS FOR SOLAR CELL DESIGN

To facilitate the design of high-efficiency silicon solar cells, contour plots were generated which give the J_0 of gaussian, boron or phosphorus diffusions with oxide passivation, as a function of both the surface dopant concentration and emitter depth (Figs. 4 and 5). J_0 contour plots are also given for metal-contacted diffusions. (Figs. 6 and 7). For boron-doped Si surfaces contacted by 99% Al/1% Si, s was measured to be $\sim 1.65 \times 10^5 \text{ cm/s}$ [18]. For phosphorus-doped, metal-contacted surfaces, s is taken to be $v_{th}/4 \approx 3 \times 10^6 \text{ cm/s}$, where v_{th} is the thermal velocity of electrons imping-

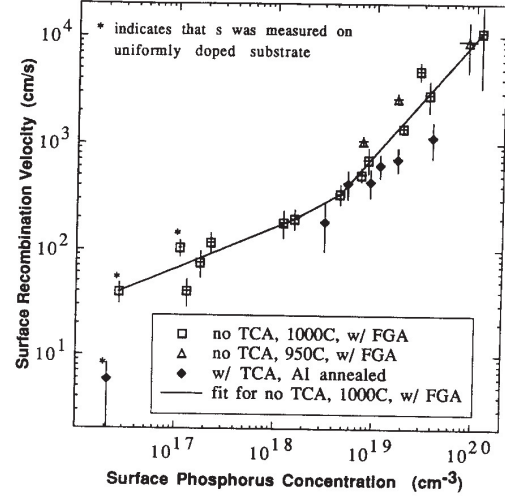


Figure 3. Surface recombination velocity, s , extracted from measurements of J_0 on oxide-passivated phosphorus diffusions.

ing on the surface. Another important parameter for the solar cell designer is J_{lost} , defined to be the current density photogenerated in the emitter on the sunward surface of a solar cell, minus the useful current density that flows out of the emitter into the substrate. So J_{lost} is related to the quantum efficiency of the cell. Contour plots of J_{lost} were also calculated for oxide-passivated, boron and phosphorus emitters (Figs. 8 and 9). J_{lost} was calculated for the SERI AM1.5 direct normal solar spectrum incident on the cell [19], normalized to have an incident intensity of 0.100 W/cm^2 (one sun). The photogenerated current density in 0.1 cm of silicon is 0.0415 A/cm^2 for this spectrum. Although Figs. 8 and 9 were calculated for untextured surfaces, they may have some applicability for grooved surfaces if the longer average path length of the light through the surface diffusion is taken into account. It would be useful to have an equivalent pair of J_{lost} contour plots for textured surfaces, but due to the complicated paths of the light rays in the texturing pyramids, and unknown doping non-uniformities over the pyramid surface, this is a difficult case to model. Empirical measurements are probably a simpler and more accurate method of determining J_{lost} on the textured surface. Contour plots of sheet resistance, $\rho_{\square}$, for boron- and phosphorus-doped emitters are provided to help correlate measured $\rho_{\square}$ with the preceding contour plots (Figs. 10 and 11).

Consider a front-gridded cell with the stable, textured, phosphorus diffusion listed in Table 1 on the sunward surface. Most of the front and back surfaces should be passivated with oxide to reduce recombination in the cell. A typical value of the metal-to-silicon contact area is $\sim 1\%$ of the total area. This value of $N_{D,surf} = 8.6 \times 10^{18} \text{ cm}^{-3}$ is too low to ensure an adequately low contact resistance to Al/Si. A textured phosphorus diffusion with $N_{D,surf}$ over $2 \times 10^{19} \text{ cm}^{-3}$, such as the one in [8] with $x_j = 1.49 \mu\text{m}$, $N_{D,surf} = 2.79 \times 10^{19} \text{ cm}^{-3}$, and $J_0 = 2.8 \times 10^{-13} \text{ A/cm}^2$ would also be stable and would solve the contact resistance problem, but at the cost of a higher front J_0 . The unpassivated regions where metal contacts the silicon will have a J_0 of $\sim 9 \times 10^{-13} \text{ A/cm}^2$ from Fig. 7 for this choice of dopant profile. An alternative that comes at the expense

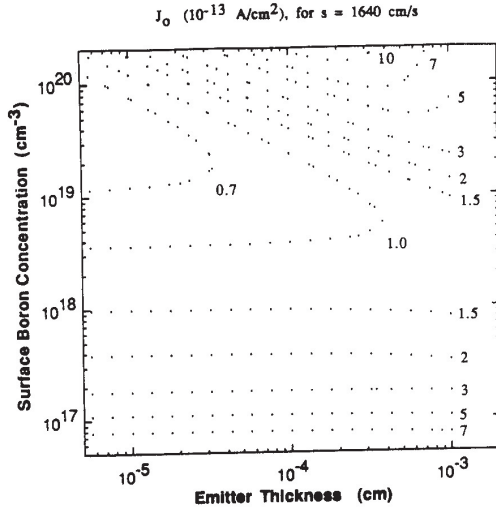


Figure 4. Contours of constant J_0 for untextured, oxide-passivated emitters with a gaussian boron profile, using experimental values of surface recombination velocity after FGA.

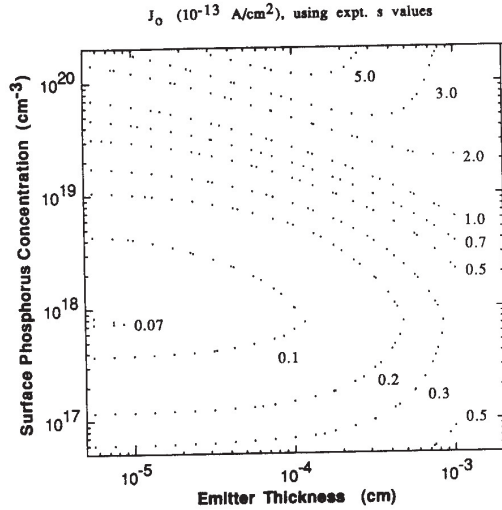


Figure 5. Contours of constant J_0 for untextured, oxide-passivated emitters with a gaussian phosphorus profile, using experimental values of surface recombination velocity after FGA.

of greater processing complexity is to use the more lightly-doped, textured, phosphorus diffusion in Table 1, and introduce heavier n-type doping directly beneath the contacts. This results in a stable sunward surface, low contact resistance, a passivated J_0 of 0.71×10^{-13} A/cm², and an unpassivated J_0 of $\sim 4 \times 10^{-13}$ A/cm² in the contact areas, for a total sunward side J_0 of only $\sim 0.75 \times 10^{-13}$ A/cm².

CELL RESULTS

Two recent experimental cell results indicate a direct application of this data. First, consider point-diffusion, backside-contact cells with 37.5 cm² area for one-sun applications. This design has n- and p-type point diffusions on the otherwise undoped back side [22], and an oxide-passivated, un-

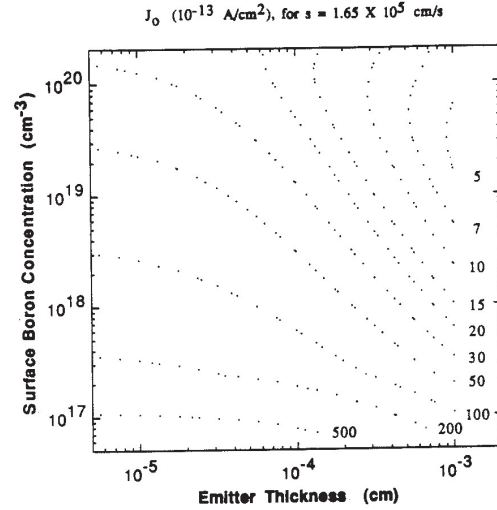


Figure 6. Contours of constant J_0 for metal-contacted boron emitters with a gaussian profile. The value of s used was 1.65×10^5 cm/s.

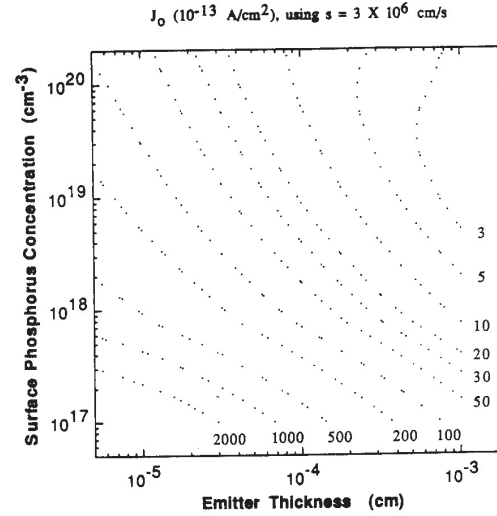


Figure 7. Contours of constant J_0 for metal-contacted phosphorus emitters with a gaussian profile. The value of s used was 3×10^6 cm/s.

contacted, phosphorus diffusion on the textured sunward surface [4,23]. The metal-contacted point diffusions have a 1.5% coverage fraction for each dopant type, and the remainder of the back is passivated with oxide. The oxidized front surface was Al annealed by depositing a thin layer of Al, heating the cell to 330°C, and stripping off the Al. From the contour plots for metal-contacted diffusions, the n-type J_0 is about 4×10^{-13} A/cm² and the p-type J_0 is about 9×10^{-13} A/cm², for a total backside J_0 of $\sim 0.2 \times 10^{-13}$ A/cm². Based on measurements made on untextured wafers that went through the same processing steps, the sunward side diffusion has $\rho_{\square} = 115 \Omega/\square$, $x_j \approx 0.36 \mu\text{m}$, and $N_{D,\text{surf}} \approx 3.5 \times 10^{19} \text{ cm}^{-3}$. An Al annealed, textured emitter with approximately the same phosphorus

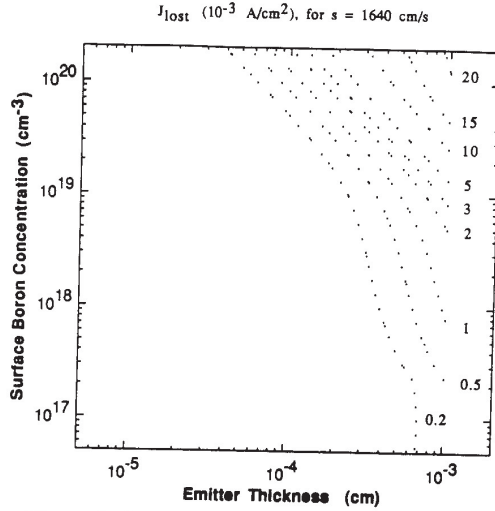


Figure 8. Contours of constant J_{lost} for untextured, oxide-passivated emitters with a gaussian boron profile, using experimental values of surface recombination velocity after FGA.

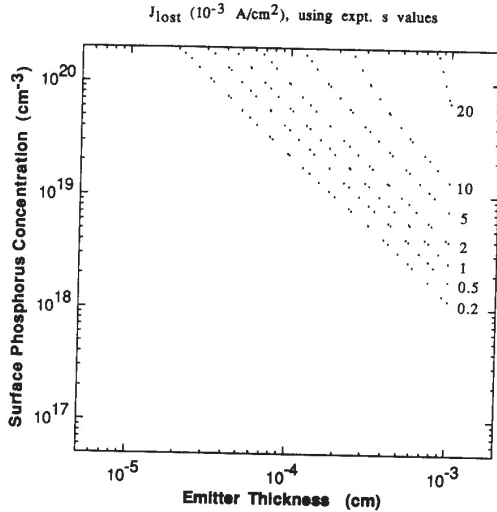


Figure 9. Contours of constant J_{lost} for untextured, oxide-passivated emitters with a gaussian phosphorus profile, using experimental values of surface recombination velocity after FGA.

profile has been measured to have $J_o = 0.68 \times 10^{-13} \text{ A/cm}^2$ [8]. Neglecting the small amount of recombination at the Al annealed, undoped back surface and in the undoped, highly-injected base, the total cell J_o is predicted to be $\sim 0.9 \times 10^{-13} \text{ A/cm}^2$ at 300°K. If J_{sc} is 0.042 A/cm² at one sun, as it is for a good silicon cell with light-trapping, then the predicted V_{oc} of this cell is $\sim 0.696 \text{ V}$ at 300°K. The actual measured parameters of the best cell of this type are: $V_{oc} = 0.698 \text{ V}$, $J_{sc} = 0.0415 \text{ A/cm}^2$, $FF = 0.784$, and $\eta = 22.7\%$ [24]. All cell measurements described here were made at Sandia National Laboratories, at 0.100 W/cm², $T = 25.0 \pm 0.2^\circ\text{C}$, on 5.0 cm $\times$ 7.5 cm cells. The efficiencies include no spectral mismatch correction, but the spectral

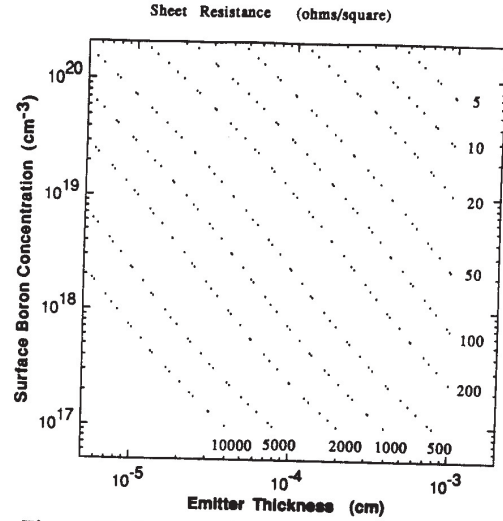


Figure 10. Contours of constant $\rho_{\square}$ for emitters with a gaussian boron profile, using the majority carrier mobility data of Thurber [20].

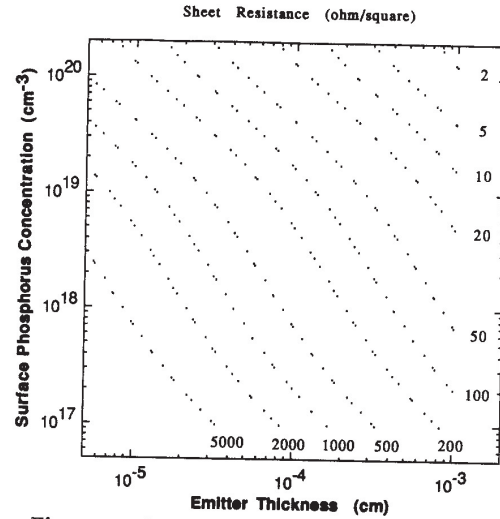


Figure 11. Contours of constant $\rho_{\square}$ for emitters with a gaussian phosphorus profile, using the majority carrier mobility data of Thurber [21].

mismatch correction between the simulated spectrum and the ASTM AM1.5G solar spectrum is typically <1% for this type of light-trapping solar cell.

Second, consider a simpler backside-contact cell design in which all the surfaces are doped [5,25]. This type of cell again has an uncontacted, oxide-passivated, n-type diffusion on the textured sunward surface, and has interdigitated n- and p-type stripes on the back, which are contacted by metal over a small fraction of their area. Stripe IBC cells of this type have achieved efficiencies up to 21.9% [5]. This design has demonstrated very good yield: a recent run had 19 cells with an average V_{oc} of $0.665 \text{ mV} \pm 1\%$

and an average J_{sc} of $0.0351 \text{ A/cm}^2 \pm 3\%$ at 0.100 W/cm^2 , out of 19 cells finished. There were only $\sim 400 \text{ \AA}$ of SiO_2 on the textured front surface, which is a very poor AR coating. This is responsible for the low J_{sc} values. Even if no AR coating is applied to these cells, they will regain some current when encapsulated, due to light trapping between the textured surface and the air/glass interface. The oxidation time and temperature were kept low to avoid the high values of J_{lost} that can result from deep, heavily-doped emitters. The sunward emitter can be deep if it has a low surface concentration, but one of the simplifications in this run was that the non-contacted sunward diffusion and the contacted back n-type diffusion were formed in the same step. Since a high $N_{D,surf}$ is needed for good contact resistance on the back, the sunward surface must have a high $N_{D,surf}$ as well.

From measurements on untextured companion wafers, the n-type diffusion had $\rho_D = 60 \text{ } \Omega/\square$, $x_j \approx 0.7 \mu\text{m}$, and $N_{D,surf} \approx 5 \times 10^{19} \text{ cm}^{-3}$. The p-type diffusion on the back had $\rho_D = 100 \text{ } \Omega/\square$, $x_j \approx 0.8 \mu\text{m}$, and $N_{D,surf} \approx 4 \times 10^{19} \text{ cm}^{-3}$. The metal-contacted regions on these cells had a coverage fraction of only 0.1% for each doping type. Therefore, although the J_o of the metal-contacted p-type diffusion is $\sim 25 \times 10^{-13} \text{ A/cm}^2$ and the metal-contacted n-type J_o can be seen to be $\sim 16 \times 10^{-13} \text{ A/cm}^2$ from Figs. 6 and 7, the contribution of the metal-contacted regions to the total backside J_o is a negligible $0.04 \times 10^{-13} \text{ A/cm}^2$. From Figs. 4 and 5, the J_o of the oxide-passivated, untextured boron diffusion covering $\sim 50\%$ of the back is $\sim 1.4 \times 10^{-13} \text{ A/cm}^2$, and the J_o of the back phosphorus diffusion is $\sim 1.8 \times 10^{-13} \text{ A/cm}^2$, for a total backside J_o of $\sim 1.6 \times 10^{-13} \text{ A/cm}^2$. Because the sunside diffusion is more heavily-doped than it needs to be, and has only been forming-gas annealed rather than Al annealed, its J_o is $\sim 2.0 \times 10^{-13} \text{ A/cm}^2$ from [8]. Thus, the total cell J_o is $\sim 3.6 \times 10^{-13} \text{ A/cm}^2$ at 300°K , and the predicted V_{oc} at 300°K for $J_{sc} = 0.042 \text{ A/cm}^2$ is 0.660 V at 300°K . If a slightly more complex process is used to make the sunside diffusion lighter than the contacted diffusion on the back, so that the sunside J_o is $0.71 \times 10^{-13} \text{ A/cm}^2$ as shown in Table 1 for a stable, textured, phosphorus diffusion, then the total cell J_o can be as low as $\sim 2.3 \times 10^{-13} \text{ A/cm}^2$, for a predicted V_{oc} of 0.672 V .

CONCLUSIONS

Measurements of the recombination parameters of oxide-passivated, boron and phosphorus emitters in silicon have been carried out. The surface component of recombination in the emitter was isolated from the bulk component to yield the surface recombination velocity as a function of boron and phosphorus concentration. The best observed emitter saturation current densities are tabulated for boron and phosphorus, textured and untextured, oxide-passivated diffusions which do not degrade under the UV wavelengths present in sunlight. This data can be used to assess the potential performance of a wide variety of high-efficiency cell designs, including one-sun and concentrator cells, and cells with high-level and low-level injection substrates. The data has been compiled in a set of contour plots, and was applied to the design of 37.5 cm^2 one-sun solar cells with up to 22.7% efficiency.

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References

- [1] A. W. Blakers and M. A. Green, *Appl. Phys. Lett.*, vol. 47, pp. 818-820, 1985.
- [2] M. A. Green, A. W. Blakers, S. R. Wenham, S. Narayanan, M. R. Willison, M. Taouk, and T. Szpitalak, in *Proc. 18th IEEE PVSC* (Las Vegas, NV), 1985, pp. 39-42.
- [3] M. Spitzer, C. J. Keavney, in *Proc. 18th IEEE PVSC* (Las Vegas, NV), 1985, pp. 43-49.
- [4] R. R. King, R. A. Sinton, and R. M. Swanson, in *Proc. 20th IEEE PVSC* (Las Vegas, NV) 1988.
- [5] R. A. Sinton, R. R. King, and R. M. Swanson, in *Proc. 4th IEEE Photovoltaic Science and Engineering Conf.* (Sydney, Australia) 1989.
- [6] H. W. Curtis and R. L. Verkuil, *Lifetime Factors in Silicon*, ASTM Special Technical Publication 712, American Society for Testing and Materials Symposium (San Diego, CA), Feb. 15-16, 1979, American Society for Testing and Materials, Philadelphia, Pa.
- [7] D. E. Kane and R. M. Swanson, in *Proc. 18th IEEE PVSC* (Las Vegas, NV) 1985, pp. 578-583.
- [8] R. R. King, R. A. Sinton, and R. M. Swanson, *IEEE Trans. on Elect. Dev.*, Vol. 37, No. 2, pp. 365-371, Feb. 1990.
- [9] P. E. Gruenbaum, R. A. Sinton, and R. M. Swanson, in *Proc. 20th IEEE PVSC* (Las Vegas, NV) 1988, pp. 423-428.
- [10] P. E. Gruenbaum, R. R. King, and R. M. Swanson, *Journal of Applied Physics*, Vol. 66, No. 12, pp. 6110-6114, 15 Dec. 1989.
- [11] A. Cuevas, R. A. Sinton, and R. M. Swanson, this conference, *Proc. 21st IEEE PVSC*, 1990.
- [12] J. A. del Alamo, "Minority Carrier Transport in Heavily Doped n-Type Silicon," Ph.D. Dissertation, Elec. Eng. Dept., Stanford University, Nov. 1985.
- [13] J. Dziewior and D. Silber, *Applied Physics Letters*, Vol. 35, No. 2, pp. 170-172, 1977.
- [14] S. E. Swirhun, "Characterization of Majority and Minority Carrier Transport in Heavily Doped Silicon," Ph.D. Dissertation, Elec. Eng. Dept., Stanford University, Stanford, CA, June 1987.
- [15] J. Dziewior and W. Schmid, *Appl. Phys. Lett.*, Vol. 31, No. 5, pp. 346-348, 1 Sept. 1977.
- [16] T. F. Ciszek, *Solar Cells*, Vol. 21, 1987.
- [17] J. W. Slotboom and H. C. de Graaff, *Solid-State Electronics*, Vol. 19, pp. 857-862, 1976.
- [18] R. R. King and R. M. Swanson, "Studies of Diffused Boron Emitters: Saturation Current, Bandgap Narrowing, and Surface Recombination Velocity," to be published.
- [19] R. J. Matson, Keith A. Emery, and Richard E. Bird, *Solar Cells*, vol. 11, pp. 105-145, 1984.
- [20] W. R. Thurber, R. L. Mattis, Y. M. Liu, and J. J. Filliben, *J. Electrochem. Soc.*, vol. 127, no. 10, pp. 2291-2294, October 1980.
- [21] W. R. Thurber, R. L. Mattis, Y. M. Liu, and J. J. Filliben, *J. Electrochem. Soc.*, vol. 127, no. 8, pp. 1807-1812, August 1980.
- [22] R. M. Swanson, *Solar Cells*, Vol. 17, pp. 85-118, 1986.
- [23] R. R. King, R. A. Sinton, and R. M. Swanson, *Appl. Phys. Lett.*, vol. 54, no. 15, pp. 1460-1462, 10 April 1989.
- [24] John D. McBrayer, Sandia National Laboratories, personal communication.
- [25] R. A. Sinton and R. M. Swanson, *IEEE Trans. on Electron Devices*, Vol. 37, No. 2, pp. 348-352, Feb. 1990.