

Comprehensive Study of Rapid, Low-Cost Silicon Surface Passivation Technologies

A. Rohatgi, *Fellow, IEEE*, P. Doshi, J. Moschner, T. Lauinger, A. G. Aberle, and D. S. Ruby

Abstract—A comprehensive and systematic investigation of low-cost surface passivation technologies is presented for achieving high-performance silicon devices such as solar cells. Most commercial solar cells today lack adequate surface passivation, while laboratory cells use conventional furnace oxides (CFO) for high-quality surface passivation involving an expensive and lengthy high-temperature step. This investigation tries to bridge the gap between commercial and laboratory cells by providing fast, low-cost methods for effective surface passivation. This paper demonstrates for the first time, the efficacy of TiO_2 , thin (<10 nm) rapid thermal oxide (RTO), and PECVD SiN individually and in combination for (phosphorus diffused) emitter and (undiffused) back surface passivation. The effects of emitter sheet resistance, surface texture, and three different SiN depositions (two direct PECVD systems and one remote plasma system) were investigated. The effects of post-growth/deposition treatments such as forming gas anneal (FGA) and firing of screen-printed contacts were also examined. This study reveals that the optimum passivation scheme consisting of a thin RTO with a SiN cap followed by a very short 730 °C anneal can 1) reduce the emitter saturation current density, J_{0e} , by a factor of >15 for a 90 Ω/sq . emitter, 2) reduce J_{0e} by a factor of >3 for a 40 Ω/sq . emitter, and 3) reduce S_{back} below 20 cm/s on 1.3 Ωcm p-Si. Furthermore, this double-layer RTO+SiN passivation is relatively independent of the deposition conditions (direct or remote) of the SiN film and is more stable under heat treatment than SiN or RTO alone. Model calculations are also performed to show that the RTO+SiN surface passivation scheme may lead to 17%-efficient thin screen-printed cells even with a low bulk lifetime of 20 μs .

Index Terms—Passivation, rapid thermal oxide, silicon, silicon nitride, surface, solar cells.

I. INTRODUCTION

MINIMIZING recombination of minority-carriers at the surfaces of silicon is crucial for the performance of many Si devices including solar cells, BJT's, CCD's, and power devices. The objective of this paper is to provide a comprehensive and systematic study of different surface passivation technologies available for diffused and nondiffused silicon, planar (flat) and chemically textured surfaces. The information is immedi-

ately applicable for junction devices such as solar cells, which typically have a n^+p structure. For such devices, surface passivation is the key to higher performance especially because the trend is toward thinner substrates, which bring the surface closer to the collecting junction.

The passivation schemes investigated include evaporated films of TiO_2 , thin SiO_2 films grown in a conventional furnace (CFO) and in a rapid thermal processor (RTO), plasma-deposited (PECVD) SiN, and selected combinations of RTO, TiO_2 , and SiN. RTO films are of particular interest because thin 8–10 nm films can be grown in an extremely short time. Films like TiO_2 and SiN are investigated because they provide good antireflection properties for silicon, which are essential for photovoltaic devices. Since the properties of SiN depend strongly upon deposition conditions and the type of PECVD equipment used, SiN films from three different sources were compared.

In this study, emphasis is placed on rapid, low-cost technologies like RTO and PECVD SiN that can provide effective surface passivation in short time and with a much lower thermal budget than a CFO. Individually, their effectiveness for solar cell passivation has been demonstrated previously [1]–[3]. However, their combined effect and their ability to withstand subsequent thermal treatments necessary for complete solar cell fabrication has never been studied. Therefore, the impact of solar cell fabrication steps like forming gas anneal (FGA) and screen-printed contact firing on the surface passivation quality of individual and double-layer stacks of dielectrics has also been quantified.

To address the issue of throughput of RTP and PECVD, several manufacturers and researchers are pursuing the goal of multiwafer RTP machines [4] and high-throughput PECVD systems [5]. Additionally, ASE Americas, Inc. has already employed PECVD dielectrics in commercial cells [6]. Thus, some of these promising schemes are currently available for mass production and continued effort is expected to deliver higher throughput.

II. EXPERIMENTAL

To assess the surface passivation of p-type silicon, effective minority carrier lifetime (τ_{eff}) measurements were performed on 1.3 Ωcm p-type $\langle 100 \rangle$ FZ silicon wafers coated with various passivating films. The investigation of n^+ -emitter passivation was performed by J_{0e} measurements by the photoconductance decay (PCD) technique on phosphorus diffused, high-resistivity (750 Ωcm), high bulk lifetime (>1 ms) FZ Si wafers. Some of the wafers were subjected to a chemical random surface texturing before processing. Surface texturing is commonly used in solar cells for reducing reflection losses and optically confining (trapping) light. Samples for the emitter passivation ex-

Manuscript received March 8, 1999. The review of this paper was arranged by Editor P. N. Panayiotatos.

A. Rohatgi is with the University Center of Excellence for Photovoltaics Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250, USA (e-mail: ajeet.rohatgi@ece.gatech.edu).

P. Doshi is with Hewlett-Packard, Atlanta, GA 30319 USA.

J. Moschner and T. Lauinger are with the Institut für Solarenergieforschung GmbH, D-31860 Emmerthal, Germany.

A. G. Aberle is with Photovoltaics Special Research Centre, University of New South Wales, Sydney NSW 2052, Australia.

D. S. Ruby is with Sandia National Laboratories, Albuquerque, NM 87185-0752 USA.

Publisher Item Identifier S 0018-9383(00)02741-6.

periment were diffused on both sides in an RTP system using spin-on dopant sources. Emitters with sheet resistances of 40 and 90 $\Omega/\square$, which correspond to emitters that can accommodate screen-printed and evaporated contacts, respectively, were investigated.

The RTP emitter depth profiles were characterized by spreading resistance analysis. The 90 $\Omega/\square$ diffusion had a surface concentration (C_s) of about $1 \times 10^{20} \text{ cm}^{-3}$ and junction depth (x_j) of 0.18 μm [7]. The profile is modified slightly after an RTO cycle (discussed in the following paragraph). C_s reduced to about 6×10^{19} and x_j increased to about 0.25 μm . It is important to note that this modest change in profile due to RTO did not appreciably alter J_{0e} for the same passivation scheme [7]. Similarly, the 40 $\Omega/\square$ diffusion had a C_s of $2.5 \times 10^{20} \text{ cm}^{-3}$ and junction depth of 0.37 μm which modified to $C_s = 2.1 \times 10^{20}$ and $x_j = 0.4 \mu\text{m}$ after a subsequent RTO cycle.

After removal of the residual phosphosilicate glass, part of the diffused and nondiffused p-type samples were oxidized in the same RTP system used for the diffusions. This rapid thermal oxidation at 900 $^\circ\text{C}$ for 150 s resulted in an oxide thickness of approximately 8–10 nm on diffused surfaces and about 6 nm on nondiffused 1 $\Omega\text{-cm}$ p-Si. The oxidized low-resistivity samples were then annealed in forming gas at 400 $^\circ\text{C}$ for 15 min. After this, deposition of SiN was performed in three different laboratories. The thickness of these films was approximately that of an antireflection (AR) coating ($\sim 60 \text{ nm}$). The refractive indices of these films measured at 632.8 nm were between 2.15 and 2.27, which is in the optimum range for single-layer AR coatings under glass, or the first film (directly in contact with silicon) of double-layer AR coatings in air [8].

Although its passivation is known to be poor, TiO_2 films are also compared for completeness because it is by far the dielectric most commonly employed dielectric by the PV industry as an AR coating. The deposition of TiO_2 was performed by evaporating titanium in an oxygen atmosphere under a low pressure of 15 mPa. For the deposition of SiN, three different PECVD systems were used. Two of these systems have a parallel plate reactor and high frequency excitation, with deposition temperatures of 300 $^\circ\text{C}$ and 350 $^\circ\text{C}$, respectively. The third system is a remote PECVD system with microwave excitation and a deposition temperature of 400 $^\circ\text{C}$ [9]. Table I summarizes the differences in key parameters of these systems. The plasma deposition systems differ in a number of other aspects, such as the reactor geometry, and the plasma power and pressure. However, all three SiN films are used as a standard in the respective laboratories.

After film deposition, the effective minority carrier lifetime (τ_{eff}) was measured on all samples. Subsequently, a forming gas anneal (FGA) at 400 $^\circ\text{C}$ was performed on all samples. As a final step, the samples were subjected to a short (30 s) temperature cycle with a maximum temperature of 730 $^\circ\text{C}$, which is typically used as a firing cycle for screen-printed contacts. This step was performed in a beltline furnace with tungsten-halogen lamp heating in a compressed air ambient.

The minority carrier lifetime was measured after each step using a commercially available inductively-coupled PCD tester. From these data, the emitter saturation current J_{0e} (for diffused

TABLE I
PLASMA DEPOSITIONS USED IN THIS
INVESTIGATION

System No.	Excitation mode	Deposition Temp. [$^\circ\text{C}$]	Gases
SiN1	direct, HF (13.6 MHz)	300	SiH_4 , N_2 , NH_3
SiN2	direct, HF (13.6 MHz)	350	SiH_4 (5%) in He, N_2 , NH_3
SiN3	remote, 2.45 GHz	400	SiH_4 , NH_3

samples) and the surface recombination velocity S_{eff} were calculated. The PCD measurement of J_{0e} is discussed in Kane and Swanson [10] and S_{eff} was calculated from the measured τ_{eff} value using the following two equations [11]:

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_b} + \beta^2 \cdot D_n \quad (1)$$

$$\tan\left(\frac{\beta \cdot W}{2}\right) = \frac{S_{\text{eff}}}{\beta \cdot D_n} \quad (2)$$

In this study, an infinite bulk lifetime ($\tau_b \rightarrow \infty$) was assumed for high-quality 1.3 $\Omega\text{-cm}$ FZ wafers so the calculated S_{eff} actually represents the worst-case (maximum) value.

To insure high accuracy from the PCD measurements, each data point reported is an average of at least four raw measurements made over different regions of each sample. Each passivation was applied to half of a 4-in diameter wafer and the four measurements were made evenly across the half-wafer. In some cases, such as the unpassivated and RTO passivated samples, as many as twelve measurements were averaged because three samples were prepared for the three different SiN films used in this study. Excluding the infrequent data significantly above or below the average, these multiple PCD τ_{eff} measurements on a sample showed 5–25% variation. This variation represents the combined effects of errors in instrumentation and nonuniformity in surface passivation, sheet resistance, and texturing. J_{0e} measurements, especially over the 40 $\Omega/\square$ diffusion were quite uniform because this emitter is less sensitive to surface passivation variation.

III. RESULTS AND DISCUSSION

A. Passivation of Heavily Doped Emitter Surfaces

The passivation of solar cell front surfaces was investigated on both 40 $\Omega/\square$ and 90 $\Omega/\square$ emitters. On a relatively opaque 40 $\Omega/\square$ emitter (which is generally needed to accommodate screen-printed contacts), the surface is largely decoupled from the emitter bulk, because of the high surface doping concentration and depth of the doping profile. Thus, the introduction of RTO or SiN passivation resulted in a moderate decrease in J_{0e} of about a factor of two to three, as can be seen from Fig. 1. While TiO_2 showed hardly any passivation, SiN1 was clearly inferior to RTO or SiN3, which, in combination, resulted in the best passivation. Note that the high-temperature treatment during RTO growth changed the doping profile and lead to a lower surface doping concentration, which allowed for better surface passivation. The J_{0e} values for textured samples were about 1.5 to 2

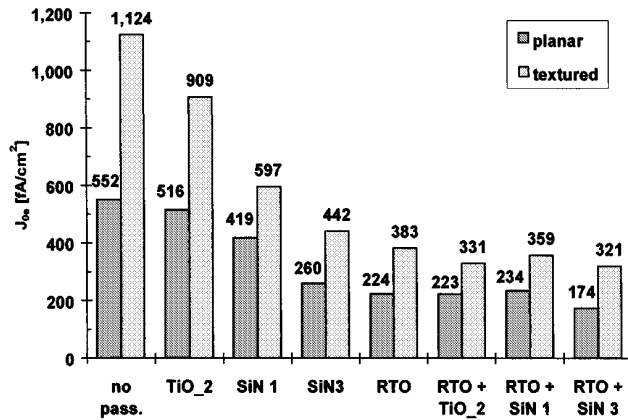


Fig. 1. Emitter saturation current densities for different passivation schemes on 40 Ω/□ RTP emitters.

times higher than those for planar surfaces, which resembles the 1.73 times increase in surface area resulting from regular pyramidal texturing.

On the relatively transparent 90 Ω/□ emitters, (which are generally used for evaporated or photolithographically-defined contacts) the difference in the degree of passivation for various schemes was more apparent, as shown in Fig. 2. Again, TiO₂ does not provide any appreciable reduction in J_{0e} . For the planar surface, RTO growth reduced J_{0e} by more than a factor of ten to below 100 fA/cm², as does the deposition of SiN₃. However, on the textured surface, RTO is not as effective, resulting in a moderate J_{0e} value of 400 fA/cm². Here, SiN₃ and the RTO+SiN double layers were clearly superior resulting in J_{0e} values in the range of 60–215 fA/cm².

As-deposited double layers of RTO and SiN were better than the nitrides alone in all cases, resulting in low J_{0e} values of 50 fA/cm² for planar and 100 fA/cm² for textured emitter surfaces (see Fig. 2). A subsequent forming gas anneal did not change the surface passivation appreciably. The same applies for the contact firing cycle (730 °C-30 s) on the 40 Ω/□ emitters. This indicates that double layer passivation with a SiN cap preserves the passivation quality of heavily-doped silicon during contact firing. For comparison, thin conventional furnace oxides (CFO's) and double layers of CFO and SiN were grown on the same emitters. This passivation resulted in identical or only slightly lower J_{0e} values than the RTO-based schemes.

B. Passivation of Undiffused (1 Ωcm p-Si) Surfaces

As discussed earlier, this study also focused on evaluating the passivation of undiffused 1.3 Ωcm p-type silicon surfaces. The maximum S_{eff} resulting from the many passivation schemes is shown in Fig. 3. (Note that S_{eff} values above 10⁴ cm/s could not be measured reliably by the method used in this study.) The impact of the subsequent FGA is also included in Fig. 3. Similar to the heavily-doped surface passivation, TiO₂ again gave no measurable surface passivation. The lack of passivation was also evident for the as-grown RTO, however, unlike TiO₂ it improved considerably after FGA. Similar behavior was observed for CFO passivation [3]. This indicates that very thin oxides rely upon hydrogen to improve surface passivation. Our previous capacitance–voltage (C–V) measurements of thin RTO

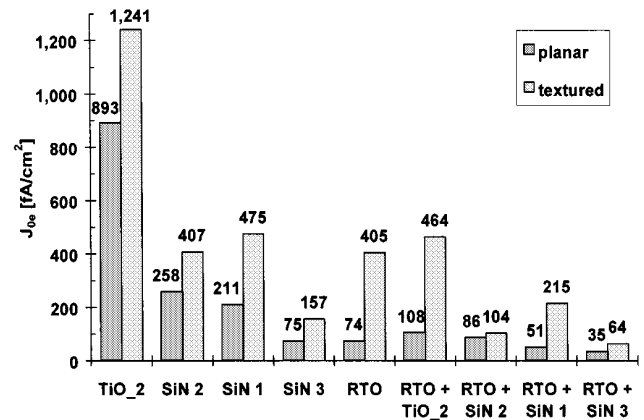


Fig. 2. Emitter saturation current densities for 90 Ω/□ RTP emitters.

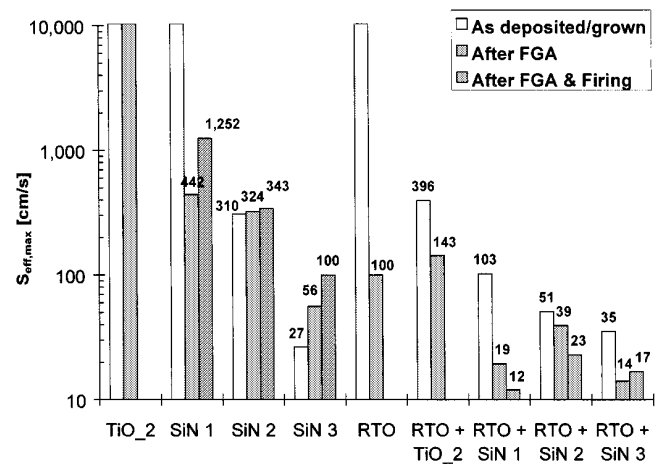


Fig. 3. Maximum surface recombination velocities and the effect of subsequent heat treatments for different passivation schemes on planar surfaces.

films showed an order of magnitude reduction in the density of interface states at midgap (D_{it}) following FGA [3].

Like the RTO, SiN₁ initially gave very poor passivation but improved after the FGA. In contrast, as-deposited SiN₃ gave very good passivation, but degraded slightly after the FGA. The superiority of as-deposited SiN₃ compared with the other as-deposited SiN films can be due to the many differences in deposition parameters, chamber geometry, etc. that can exist between different PECVD systems. However, major differences are the completely damage-free deposition and the higher deposition temperature of 400 °C for SiN₃. SiN₁ and SiN₂ were deposited at lower temperatures because of constraints of individual PECVD systems. Studies have shown that under proper conditions, SiN can result in quite good passivation when deposited by either direct high-frequency (HF) or remote plasma systems; however, temperatures up to 400 °C are required for the best passivation [12]. Thus, SiN₁ improved after the FGA because it was deposited at only 300 °C and the additional 400 °C heat treatment served to deliver the hydrogen more efficiently to the Si/SiN interface.

Better results were obtained by double layer combinations of RTO with any of the three nitrides (see Fig. 3). Here, the presence of SiN on top of the RTO gives the dual benefit of positive

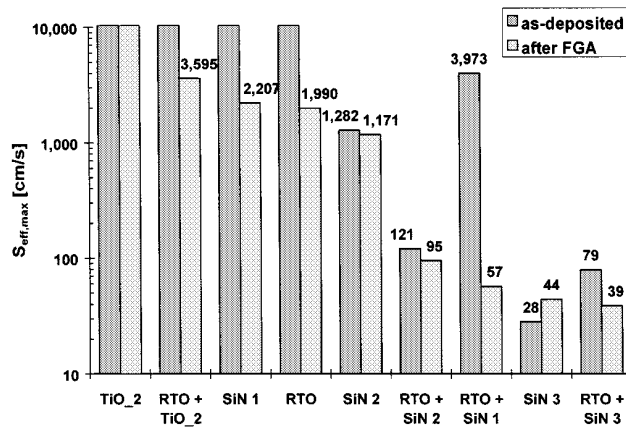


Fig. 4. Maximum surface recombination velocities for textured surfaces.

charge [13] and possible hydrogenation during PECVD [14]. The RTO+SiN3 initially gives the best passivation because of the better hydrogenation during the 400 °C deposition. However, after the 400 °C FGA, S_{eff} values below 50 cm/s are observed for all RTO+SiN combinations. As a result, all three double-layer passivations are fairly similar in their quality after the anneal. This improvement is attributed to the annealing-induced release of hydrogen from the SiN that reaches the interface and reduces D_{it} .

Fig. 4 shows that the same trend was observed for textured surfaces, with SiN3 giving considerably better passivation than the other nitrides. After FGA, all RTO+SiN double layers showed good passivation, resulting in a very low S_{eff} value of 39 cm/s for RTO+SiN3. This shows that RTO+SiN passivation can be maintained even on textured surfaces.

As a last step, the SiN and RTO+SiN double layers was subjected to a screen-printed contact firing cycle with a maximum temperature of 730 °C for about 30 s to test for thermal stability (see Fig. 3). In general, the nitrides alone failed to maintain good passivation. This may be the result of hydrogen escaping from the interface and the SiN films. However, the RTO+SiN double layers not only withstood the firing, they usually improved after firing. This annealing-induced improvement in RTO+SiN passivation is attributed to the release in hydrogen from the SiN film coupled with the passivation of the RTO/Si interface underneath. This is supported by FTIR measurements, which show a significant reduction in the hydrogen content of the RTO+SiN films after high-temperature anneals [15], [16]. Fig. 3 shows that exceptionally low S_{eff} values below 25 cm/s resulted regardless of the type of nitride used. RTO+SiN1, resulted in the lowest S_{eff} value of 12 cm/s on a planar surface. Note that this value gives the same value as the record low S_{eff} value of 4 cm/s resulting from SiN3 passivation [9] which was calculated using a bulk lifetime of 1.7 ms. Instead, all calculations in this study assumed an *infinite* bulk lifetime, which results in the higher value of 12 cm/s corresponding to the worst-case or *maximum* S_{eff} as reported in Fig. 3. Thus, the combination of RTO, SiN, and the standard high-temperature firing (already common in commercial cell manufacturing) results in exceptional surface passivation that is virtually independent of different SiN deposition conditions.

TABLE II
SURFACE RECOMBINATION VELOCITIES USED FOR THE CALCULATIONS IN FIG. 5. (NOTE: J_{0e} AND S_b OBTAINED FROM FIGS. 1 AND 3, RESPECTIVELY. S_f WAS CALCULATED AS IN [7])

Film	J_{0e} (fA/cm ²)	S_f (cm/s)	S_b (cm/s)
TiO ₂	516	350,000	Not used
SiN1	419	200,000	1,250
SiN3	260	55,000	100
RTO+SiN1	234	35,000	12
RTO+SiN3	174	5,000	Not used

C. Impact of Surface Passivation on Photovoltaic Device Performance

Model calculations were performed to predict the impact of the various promising surface passivation schemes on the energy conversion efficiency of photovoltaic devices. *PC-1D for Windows* [17] version 5.1 was used to solve the one-dimensional semiconductor transport equations and compute cell performance. The default material recombination parameters set by *PC-1D* were used. (These include the intrinsic carrier concentration $n_i = 1 \times 10^{10}$ cm⁻³, the band gap narrowing model of Klaassen, et al. [18], mobility model used in Cuevas, et al. [19], and Auger coefficient $C_{nA} = 2.2 \times 10^{-31}$ of Wang, et al. [20]). Other parameters held constant for all calculations include a front internal reflectance of 92% (specular), back surface reflectance of 70% (diffuse), bulk resistivity of 1.3 Ωcm, measured 40 Ω/□ emitter profile, series resistance of 0.6 Ωcm², shunt resistance of 10 kΩcm², J_{02} of 5 nA/cm², n_2 of 1.7, and grid shading (broadband reflectance) of 6%. The latter values are consistent with the parameters typically obtained for screen-printed cells and result in an FF of about 0.77–0.78. All calculations assumed a planar (flat) surface and an optimized double layer antireflection coating.

Fig. 5 shows the calculated cell efficiencies as a function of measured front and/or back surface passivation (J_{0e} and $S_{eff,max}$) for two different values of cell thickness ($W = 100$ or 300 μm) and bulk lifetime ($\tau_b = 20\mu s$ or 200 μs). Table II shows the values of front and back surface recombination velocities (S_f and S_b , respectively) used for the simulations. S_f was calculated using the measured J_{0e} and 40 Ω/sq. emitter profile as done in [7]. Some of the best commercial screen-printed cells are about 14–15% efficient today and do not usually have front or back surface passivation. Fig. 5 shows that up to about 0.5% (absolute) gain in efficiency can be derived from improving just the front surface passivation. An even greater improvement can be gained by employing the high quality passivation schemes on the back surface as well. The calculations show that >17%-efficient screen-printed cells are possible with RTO+SiN front and back surface passivation even on materials with a bulk lifetime of only 20 μs.

It is important to note that the calculations assumed negligible contact recombination, which may not be valid especially for gridded back contacts. One solution for limiting con-

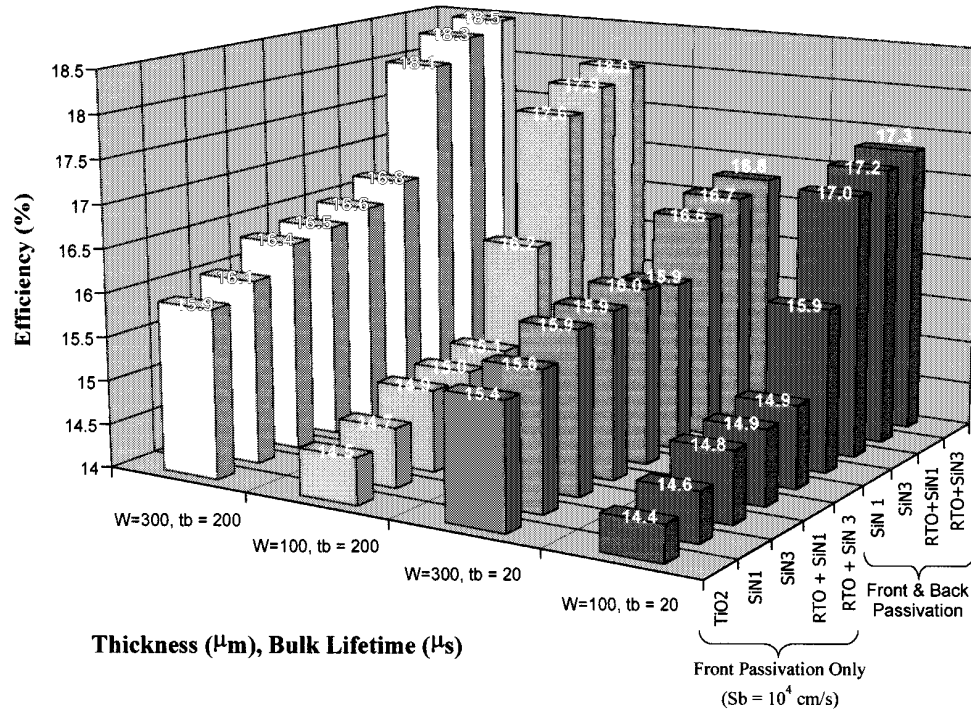


Fig. 5. Impact of front and/or back surface passivation on photovoltaic device performance. All calculations were performed with a $40 \Omega/\square$ emitter, 6% grid shading factor, and fill factor of 0.77–0.78 to be consistent with screen-printed solar cells. See Table II for the calculated S_f and measured S_b corresponding to each passivation.

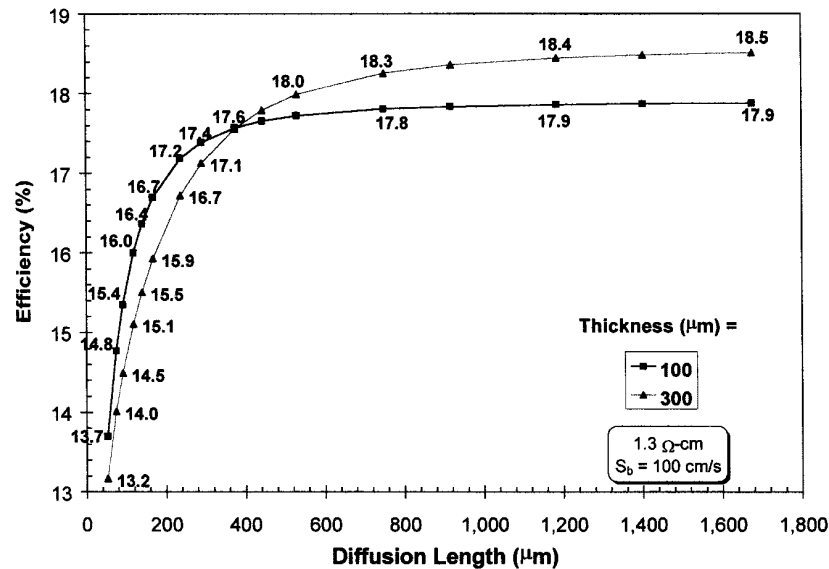


Fig. 6. Impact of thinning cells when S_b is low. In this case, thinner cells are superior to thick cells when the bulk lifetime is below about $50 \mu\text{s}$ ($L_d = 375 \mu\text{m}$).

tact recombination is to employ a highly effective local back surface field (BSF). Several investigators including ourselves [3], [21], [22] have demonstrated S_{pp+} values as low as 200 cm/s using an optimized screen-printed Al BSF. Thus, the combination of high-quality RTO+SiN silicon surface passivation and a gridded (local) BSF to reduce contact recombination may help in realizing the high efficiency cells predicted in Fig. 5. Additionally, this results in a bifacial structure, which offers the possibility of increased power output when rear illumination is made available.

Fig. 5 also illustrates the increased importance of back surface passivation for thinner cells, which consume less silicon and therefore reduce cost. In fact, for the low $\tau_b = 20 \mu\text{s}$ ($L_d = 237 \mu\text{m}$) case, the calculations show that decreasing the cell thickness from $W = 300$ to $100 \mu\text{m}$ actually improves efficiency because of the high-quality back surface passivation. This effect is highlighted in the model calculations shown in Fig. 6. Bringing the well-passivated back surface within a diffusion length of the front collecting junction increases the cell's open-circuit voltage (V_{oc}) because of the reduction in the

volume of recombination. In this case, the short-circuit current density (J_{sc}) does not decrease considerably because the photogenerated carriers absorbed deeper than L_d in the thick device have low collection probability. In contrast, the 300 μm thick cells with a bulk lifetime of 200 μs ($L_d = 750 \mu\text{m}$) have sufficiently long diffusion length to benefit from the good back passivation, and thinning this planar cell degrades the efficiency because of reduced long-wavelength photon absorption and substantial decrease in J_{sc} . (This is, of course, a function of the light trapping properties, i.e., thinning passivated cells can still help if good texturing and back surface reflector are employed.) Thus, if S_b is maintained to the low levels ($\leq 100 \text{ cm/s}$) presented in this study, it is better to have $W < L_d$ especially for materials with low lifetimes. These calculations are encouraging especially since cost limitations are forcing the recent trend to reduced cell thickness with PV grade (defective) silicon.

IV. CONCLUSION

This study provides a thorough investigation of silicon surface passivation by RTO, TiO_2 , different PECVD silicon nitrides, and double-layer oxide/nitride combinations of these films. The deposition or growth of these films can be performed in a matter of minutes, and all of the passivation schemes used in this study provide or allow for near-optimum antireflection properties. Thus, they can enhance the performance of current industrial solar cells significantly. We have found that both RTO and silicon nitride films can individually reduce surface recombination substantially. However, double-layers of RTO+SiN can improve the surface passivation even further, resulting in exceptionally low J_{0e} values below 50 fA/cm^2 on 90 $\Omega/\square$ emitters, 200 fA/cm^2 on 40 $\Omega/\square$ emitters, and maximum S_{eff} values approaching 10 cm/s on a planar 1.3 Ωcm Si surface. The combination of RTO and SiN also reduces the gap in passivation quality between the different nitrides allowing for a high degree of freedom in the SiN deposition conditions. Furthermore, this combination has been shown to enhance the stability of the surface passivation under thermal treatments such as screen-printed contact firing. Textured surfaces revealed a similar trend as planar surfaces but showed an expected greater amount of surface recombination. Therefore, effective RTO+SiN passivation is even more essential for textured surfaces since surface recombination can frequently limit performance. Finally, model calculations showed that the combination of RTO+SiN double-layer passivation and standard screen-printed contact firing anneal can result in significant improvement of current industrial cells. Calculations show that this passivation on the front and back may lead to 17%-efficient screen-printed cells on thinner substrates (100 μm) with low bulk lifetimes (20 μs), resulting in considerable cost reduction of photovoltaic cells.

REFERENCES

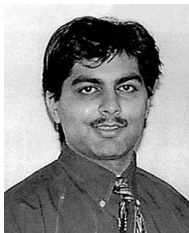
- [1] S. Sivoththaman *et al.*, "Rapid thermal processing of conventionally and electromagnetically cast 100 cm^2 multicrystalline silicon," in *Rec. 25th IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1996, pp. 621–624.
- [2] B. Lenkeit, R. Auer, A. G. Aberle, and R. Hezel, "Bifacial silicon solar cells with screen-printed rear contacts," in *Proc. 14th Eur. Commission Photovoltaic Solar Energy Conf.*, Bedford, MA, 1997, pp. 853–856.
- [3] P. Doshi *et al.*, "Characterization and application of rapid thermal oxide surface passivation for the highest efficiency RTP silicon solar cells," in *Rec. 26th IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1997, pp. 87–90.
- [4] M. Lefrancois, "Product information regarding the "RTP solar cell furnace," and "High-throughput RTP solar cell processor model VS2400," Vortek Ind., Vancouver, B.C., Canada.
- [5] A. G. Aberle, J. Moschner, and R. Hezel, "PECVD deposition of silicon nitride: Fundamentals and prospects for industrial application," in *Proc. 8th Workshop on Crystalline Silicon Solar Cell Materials and Processes*, Copper Mountain, CO, 1998, pp. 77–84.
- [6] R. Gonsiorowski and G. Czernienko, "Method of fabricating solar cells with silicon nitride coating," U.S. Patent 4 751 191, assigned to Mobil Solar Energy Corp., June 14, 1988.
- [7] P. Doshi and A. Rohatgi, "18% efficient silicon photovoltaic devices by rapid thermal diffusion and oxidation," *IEEE Trans. Electron. Devices*, vol. 45, pp. 1710–1716, Aug. 1998.
- [8] P. Doshi, G. E. Jellison, and A. Rohatgi, "Characterization and optimization of absorbing PECVD antireflection coatings for silicon photovoltaics," *Appl. Opt.*, vol. 36, pp. 7826–7837, Oct. 20, 1997.
- [9] J. Schmidt, T. Lauinger, A. G. Aberle, and R. Hezel, "Record low surface recombination velocities on low-resistivity silicon solar cell substrates," in *Rec. 25th IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1996, pp. 413–416.
- [10] D. E. Kane and R. M. Swanson, "Measurement of the emitter saturation current by a contactless photoconductivity decay method," in *Rec. 18th IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1985, pp. 578–583.
- [11] D. K. Schroder, *Semiconductor Material and Device Characterization*. New York: Wiley, 1990, ch. 8.
- [12] T. Lauinger, A. G. Aberle, and R. Hezel, "Comparison of direct and remote PECVD silicon nitride films for low-temperature surface passivation of p -type crystalline silicon," in *Proc. 14th Eur. Commission Photovoltaic Solar Energy Conf.*, Bedford, MA, 1997, pp. 853–856.
- [13] R. Hezel, "High charge densities in Si-nitride and their effect on the inversion layer mobility of silicon MIS/IL solar cells," in *Rec. 16th IEEE Photovoltaic Specialists Conf.*, New York, NY, 1982, p. 1237.
- [14] —, "Silicon nitride for the improvement of silicon inversion layer solar cells," *Solid-State Electron.*, vol. 24, pp. 863–868, 1981.
- [15] A. Rohatgi *et al.*, "Improved understanding and optimization of RTP and PECVD processes for high-efficiency silicon solar cells," in *Proc. 13th Eur. Commission Photovoltaic Solar Energy Conf.*, Nice, France, Oct. 23–27, 1995, pp. 413–416.
- [16] L. Cai and A. Rohatgi, "Effect of post-PECVD photo-assisted anneal on multicrystalline silicon solar cells," *IEEE Trans. Electron. Devices*, vol. 44, pp. 97–103, Jan. 1997.
- [17] P. Basore and D. Clugston, "PC1D version 4 for windows: From analysis to design," in *Rec. 25th IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1996, pp. 377–381.
- [18] D. Klaassen, J. Slotboom, and H. C. de Graaf, "Unified apparent bandgap narrowing in n - and p -type silicon," *Solid-State Electron.*, vol. 35, pp. 125–129, 1992.
- [19] A. Cuevas *et al.*, "Extraction of surface recombination velocity of passivated phosphorus-doped silicon emitters," in *Rec. 24th IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1994, pp. 1446–1449.
- [20] C. Wang and A. Neugroschel, "Minority-carrier transport parameters in n -type silicon," *IEEE Electron Device Lett.*, vol. 11, pp. 576–578, Dec. 1990.
- [21] P. Lölgen *et al.*, "Aluminum back-surface field doping profiles with surface recombination 2a velocities below 200 cm/s ," in *Rec. 23rd IEEE Photovoltaic Specialists Conf.*, Piscataway, NJ, 1993, pp. 236–242.
- [22] S. Narasimha, J. Mejia, and A. Rohatgi, "Screen printed aluminum back surface fields for silicon solar cells," presented at the *Conf. 6th Workshop on the Role of Impurities and Defects in Silicon Device Processing*, Golden, CO, 1996.



Ajeet Rohatgi (M'78–SM'86–F'91) received the B.S. degree in electrical engineering from the Indian Institute of Technology, Kanpur, India, in 1971, the M.S. degree in materials engineering from the Virginia Polytechnic Institute and State University, Blacksburg, in 1973, and the Ph.D. degree in metallurgy and material science from Lehigh University, Bethlehem, PA, in 1977.

He joined Westinghouse Research and Development Center, Pittsburgh, PA in 1977, and became a Westinghouse Fellow in 1984. He joined the Electrical Engineering Faculty, Georgia Institute of Technology, Atlanta, in 1985, as an Associate Professor, and was promoted to Full Professor in 1987. He is currently a Regents' Professor and a Georgia Power Distinguished Professor in the School of Electrical Engineering. He is the founding director of the University Center of Excellence for Photovoltaic Research and Education at Georgia Tech. He has made seminal contributions to the fundamental understanding of advanced photovoltaic devices; rapid thermal processing of dielectrics and solar cells; impurities and defects in silicon; science and technology of dielectrics for silicon surface passivation and antireflection coating; and design and fabrication of high efficiency cells on low-cost silicon materials. He has published over 200 technical papers in various journals and proceedings and holds more than ten patents.

Dr. Rohatgi became an IEEE Fellow in 1991, and received the Westinghouse Engineering Achievement Award in 1984 and the Georgia Tech Distinguished Professor Award in 1996 for his sustained contributions to the field of photovoltaics. He is the General Chair for the 28th IEEE Photovoltaic Specialists Conference and co-organizer of the Electrochemical Society Symposium on Photovoltaics for the 21st Century.



P. Doshi received the B.S. and Ph.D. degrees in electrical engineering in 1992 and 1997, respectively, both from the Georgia Institute of Technology, Atlanta.

He is currently a member of the Research Faculty at the University Center of Excellence for Photovoltaics Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology. His research interests include the design, modeling, fabrication, and characterization of silicon photovoltaic devices. His current emphasis

involves the development of cost-effective manufacturing technologies for solar cell fabrication using promising low-cost silicon materials.

Dr. Doshi received the Sigma Xi Best Thesis Award for his research on rapid thermal processing, PECVD, and screen printing of high-efficiency solar cells.

J. Moschner, photograph and biography not available at the time of publication.

T. Lauinger, photograph and biography not available at the time of publication

A. G. Aberle, photograph and biography not available at the time of publication

Douglas S. Ruby received the B.S. degree in physics from the Massachusetts Institute of Technology, Cambridge, in 1978, and the M.S. and Ph.D. degrees in physics from the University of Illinois at Urbana-Champaign in 1980 and 1985, respectively. His dissertation research dealt with the material and defect characterization of GaAs grown by vapor-phase epitaxy.

He is currently a Principal Member of Technical Staff in the Photovoltaic System Components Department, Sandia National Laboratories, Albuquerque NM, where he has conducted research on silicon solar cells since 1985. His research interests include the design, modeling, fabrication, and testing of crystalline silicon and compound semiconductor solar cells for terrestrial power generation. He is the Team Leader of the Sandia PV Cell Development Team, which has emphasized research in the following areas: plasma-enhanced chemical vapor deposition of silicon oxides and nitrides for low-temperature surface and bulk defect passivation, and reactive ion etching of silicon cells for selective-emitter and low-reflectance structure formation. He is also Director of the Crystalline Silicon Research Cooperative—a National Laboratory/Industry/University consortium with representatives from most of the U.S. silicon photovoltaics manufacturing and research communities.