

18% Efficient Silicon Photovoltaic Devices by Rapid Thermal Diffusion and Oxidation

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Abstract—For the first time, cells formed by rapid thermal processing (RTP) have resulted in 18%-efficient 1 and 4 cm² single-crystal silicon solar cells. Front surface passivation by rapid thermal oxidation (RTO) significantly enhanced the short wavelength response and decreased the effective front surface recombination velocity (including contact effects) from 7.5×10^5 to about 2×10^4 cm/s. This improvement resulted in an increase of about 1% (absolute) in energy conversion efficiency, up to 20 mV in V_{oc} , and about 1 mA/cm² in J_{sc} . These RTO-induced enhancements are shown to be consistent with model calculations. Since only 3 to 4 min are required to simultaneously form the phosphorus emitter and aluminum back-surface-field (BSF) and 5 to 6 min are required for growing the RTO, this RTP/RTO process represents the fastest technology for diffusing and oxidizing $\geq 18\%$ -efficient solar cells. Both cycles incorporate an *in situ* anneal lasting about 1.5 min to preserve the minority carrier lifetime of lower quality materials such as dendritic-web and multicrystalline silicon. These high-efficiency cells confirmed that RTP results in equivalent performance to cells fabricated by conventional furnace processing (CFP). Detailed characterization and modeling reveals that because of RTO passivation of the front surface (which reduced J_{oe} by nearly a factor of ten), these RTP/RTO cells have become base dominated ($J_{ob} \gg J_{oe}$), and further improvement in cell efficiency is possible by a reduction in back surface recombination velocity (BSRV). Based upon model calculations, decreasing the BSRV to 200 cm/s is expected to give 20%-efficient RTP/RTO cells.

Index Terms—Diffusion, oxidation, photovoltaics, rapid thermal processing, solar cells.

I. INTRODUCTION

LOW COST and high efficiency are the keys to large-scale acceptability of photovoltaic (PV) systems. Since PV modules cost about four dollars per watt, which can produce electricity at a rate of about 25 cents per kilowatt-hour, a factor of two to three in cost reduction is required to make PV attractive for peak load applications. This can be done by reducing manufacturing costs and increasing production output to employ the advantages of economies of scale. Reference [1] emphasizes that to meet the production output of 25 MW/yr close to 50 000 cells (each producing 1.5 W) must be produced per day. This translates into one cell every 1.7 s. To meet the goals of 50 or 100 MW/yr it is important to reduce the overall cell processing time. In industry, the emitter diffusion and BSF formation (if employed) steps frequently bottleneck the cell fabrication process. Most PV

Manuscript received March 26, 1997; revised January 17, 1998. The review of this paper was arranged by Editor P. N. Panayotatos. This research was supported by Sandia National Laboratories under Subcontract AA-1638.

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Publisher Item Identifier S 0018-9383(98)05260-5.

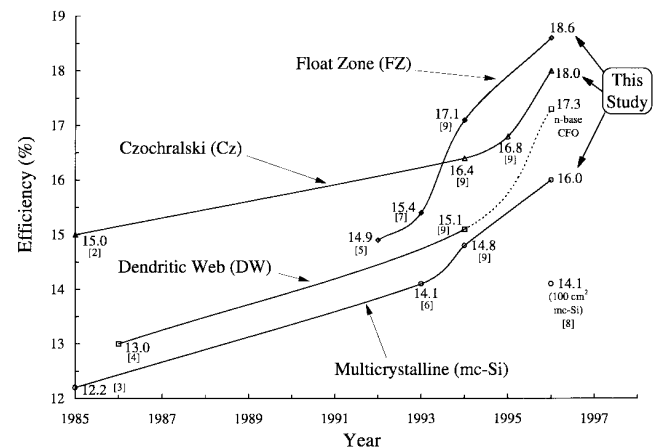


Fig. 1. Progress of RTP-diffused solar cells on various silicon materials. All cells were formed without any high-temperature furnace processing (except for 17.3% dendritic web cell which had a CFP). The number in brackets represent the reference number.

manufacturers do not even employ oxide passivation since the addition of lengthy oxidation steps in a furnace would only retard the throughput further. Rapid thermal processing (RTP) directly addresses these issues since the processing time for diffusion and oxidation is reduced from hours to only minutes or seconds. In addition, an emitter and BSF can be formed simultaneously without cross-contamination in a cold-wall RTP system. It is important to note, that transfer of RTP technology to industry will require the development of high-throughput RTP machines, however, several groups are pursuing this goal and multiwafer RTP machines have recently been built [2].

Fig. 1 shows that several researchers have fabricated RTP-diffused solar cells [3]–[9]. Although fair progress in RTP cell efficiency has evolved over the years, until now, these efficiencies were lower than those made by their furnace counterpart. In previous studies, we demonstrated high-efficiency RTP cells of 17.1, 16.8, 14.8, and 15.1% on FZ, Cz, multicrystalline, and dendritic web silicon, respectively [10]. These cells were formed by rapid, simultaneous diffusion of a phosphorus emitter on the front and formation of an aluminum BSF on the back. No high-temperature furnace processes were employed. To maintain a high minority-carrier bulk lifetime a short *in-situ* anneal or slow-cool was utilized in the simultaneous RTP diffusion cycle for materials such as dendritic-web and multicrystalline silicon (mc-Si) which are susceptible to quenching-induced lifetime degradation [11]. When compared with cells made by conventional furnace processing (CFP),

RTP cells matched CFP cells in the long wavelength internal quantum efficiency (IQE) response [12]; however, in the short wavelengths, RTP cells suffered from a lack of adequate front surface passivation and heavy doping effects (Auger recombination and bandgap narrowing) in the emitter. In this paper, we present substantial enhancements in the short wavelength response by growing a front passivating oxide by rapid thermal processing (RTO) on lower doped RTP emitters.

The use of an RTO for PV devices was discussed by Schindler *et al.* [8]. An RTO-passivated cell with an efficiency of 16.6% was fabricated, however a CFP emitter was employed. Recently, Sivothythaman *et al.* [9] fabricated fully RTP-processed 100 cm² cells on mc-Si, which utilized an RTO to achieve efficiencies up to 14.1%. Considering the large area of the device, this result is practical except that (as in this study) photolithographically-defined evaporated contacts were used to permit a lowly doped emitter. Compared with screen-printed contacts, evaporated contacts give nearly 2% greater cell efficiency because of very low grid shading, superior contact quality, and better short wavelength response [13]. In addition, since RTP cooling rates were not controlled, Sivothythaman's mc-Si cells may have been susceptible to quenching-induced lifetime degradation.

This paper shows that high-throughput RTP cells fabricated with an RTO deliver the same performance as cells with a conventional furnace oxide (CFO). We have been able to bridge the efficiency gap between RTP and CFP cells we had reported earlier [12]. By implementing RTO passivation, RTP cells have for the first time reached efficiencies above 18%—making the RTP/RTO process one of the fastest technologies to fabricate high-efficiency photovoltaic devices.

II. EXPERIMENTAL

Before fabricating RTP cells with front oxides, a passivation study involving emitter saturation current density (J_{oe}) measurements of SiO₂ and SiN-passivated RTP emitters was conducted. J_{oe} was measured by the PCD technique [14] on samples simultaneously diffused on both sides by phosphorus spin-on dopants. The CFO was formed by inserting wafers into the furnace at 850 °C, allowing 5 min for temperature stabilization, growing a 10–15 nm thick oxide for 10 min, ramping down to 400 °C at 5 °C/s for 90 min, and annealing in forming gas for 30 min [see Fig. 2(a)]. The SiN films were deposited to a thickness of 65–70 nm in a PECVD system operating at 13.6 MHz. Deposition conditions included a temperature of 300 °C, RF power of ~30 W, pressure of 0.9 torr, and SiH₄/NH₃ flowrate ratio adjusted to give a SiN refractive index of 2.14–2.17 (measured at 632.8 nm).

Simple n⁺pp⁺ cells were also fabricated. After initial wafer cleaning, aluminum evaporated onto the back and phosphorus dopants (with a concentration of 10²⁰ cm⁻³) spun onto the front were RTP diffused to simultaneously form the emitter and BSF. Next, a CFO or RTO was grown followed by evaporation of back and front contacts, which were defined by photolithography. The simultaneous RTP diffusion was done at about 890 °C for only 30 s to achieve an emitter sheet resistance of 90–120 Ω/sq.; and RTO was done at 900 °C/165 s [see Fig. 2(b)] to grow a 12- to 13-nm oxide.

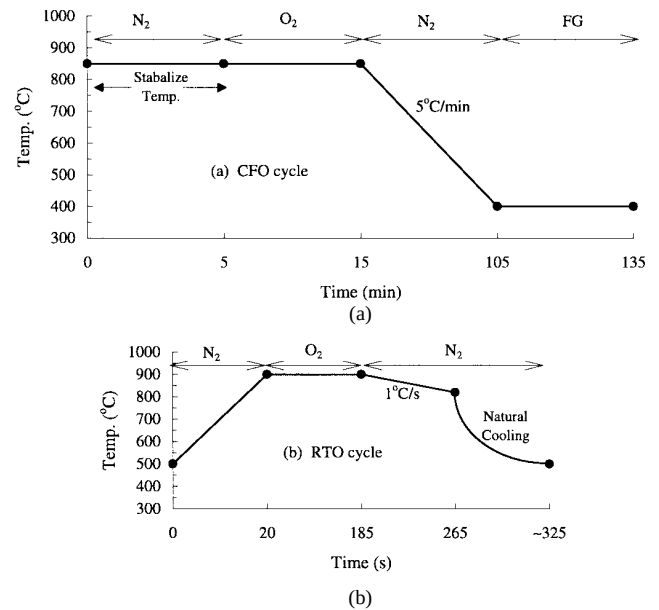


Fig. 2. Temperature cycle for growing (a) conventional furnace oxide (CFO) and (b) rapid thermal oxide (RTO).

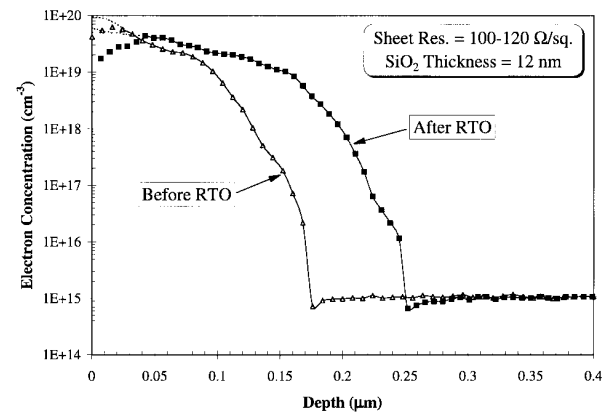


Fig. 3. Spreading resistance profiles of diffused emitters before and after the RTO cycle.

The RTO cycle serves not only to form a high-quality oxide in a total time of 5 min instead of over 2 h, but also to reduce the surface concentration (N_s) and increase the junction depth (x_j) as depicted by the spreading resistance profiles shown in Fig. 3. In the past, our RTP emitters were made by a heavier doped phosphorus spin-on concentration of 10²¹ cm⁻³ [12], [15] resulting in emitters with $N_s \cong 2 \times 10^{20}$ cm⁻³ and $x_j \cong 0.14$ μm, whereas the emitters in this study were made by the 10²⁰ cm⁻³ spin-on resulting in lower $N_s \leq 10^{20}$ cm⁻³ and a deeper x_j in the 0.18–0.26 μm range [see Fig. 3]. The decrease in surface concentration is beneficial (provided good surface passivation is obtained) because it results in reduced front-surface-recombination-velocity (FSRV) for oxide passivated emitters [16]. Cell fabrication was finally completed with the evaporation of a ZnS/MgF₂ antireflection coating and 15 min contact anneal at 400 °C. Unlike our previous work [12], in this study, PECVD AR coatings were not used so that parasitic absorption within SiN [17] would

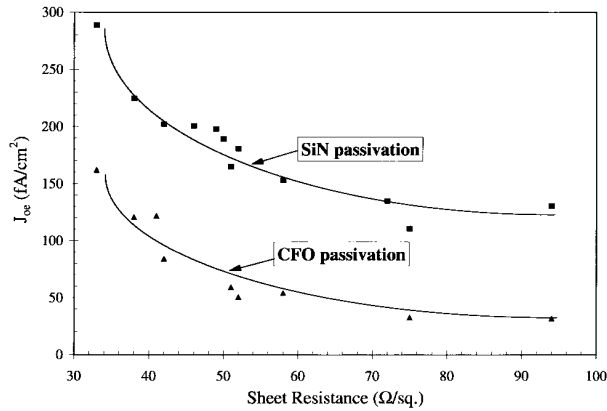


Fig. 4. Emitter component of reverse saturation current density (J_{oe}) as a function of RTP emitter sheet resistance and surface passivation. J_{oe} was measured by the PCD technique.

not perturb short wavelength IQE response. Details of the fabrication of CFP cells has been discussed elsewhere [12].

III. RESULTS

The passivation characteristics of SiO_2 and PECVD SiN were first studied by J_{oe} measurements. To be relevant to any contact scheme including screen printing, the study was carried out on a wide range of emitter sheet resistances from 30 to 100 Ω/sq . Fig. 4 shows the measured J_{oe} as a function of the RTP emitter sheet resistance. The furnace grown oxide (CFO) gave a factor of two to four times lower J_{oe} (depending upon the sheet resistance) than SiN passivation on the same emitter. At 90 Ω/sq , J_{oe} was reduced significantly from 130 fA/cm^2 for SiN passivation down to 30 fA/cm^2 for CFO passivation. At 40 Ω/sq . (which can accommodate screen-printed contacts [13]), the reduction was less impressive decreasing J_{oe} from only 200 fA/cm^2 for SiN to 100 fA/cm^2 for CFO. It is important to note that the true J_{oe} of the cell will be greater since the effect of contacts are not present in the PCD measurements. It is better, therefore, to judge the impact of front surface passivation by short wavelength IQE measurements as will be shown in the next section. To demonstrate the effectiveness of front oxides on RTP cells, the well-established CFO technology was first applied to RTP cells. Fig. 5 shows that CFO passivation of RTP cells produces virtually the same results as cells fabricated entirely by CFP. These RTP/CFO cells eliminated the huge loss in short wavelength IQE response we had observed in the past [12] and gave virtually the same cell performance.

Use of a CFO, however, mitigates the attractiveness of an RTP process because it requires a lengthy furnace process as shown in Fig. 2(a), whereas growth of an oxide by RTP maintains the high-throughput nature of the entire RTP processing sequence. Thus, an RTO cycle was developed to provide the same high-quality oxide as a CFO but in a time of only 5–6 min as shown in Fig. 2(b). Cells fabricated according to this RTP/RTO process gave efficiencies up to 18.6% which represents the highest reported efficiency for any RTP-diffused cell. Table I shows that numerous RTP cells employing an RTO near or above 18% efficiency have been fabricated. Average of (at least) fourteen 1 cm^2 cells on each wafer give above

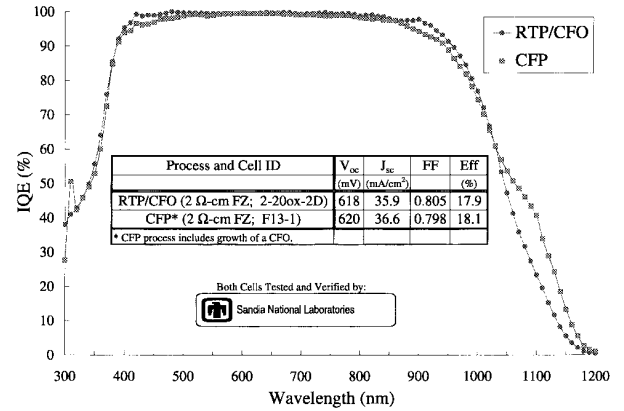


Fig. 5. Comparison between RTP and CFP cells both passivated by a CFO. Nearly identical performance is achieved by both processes because of CFO passivation.

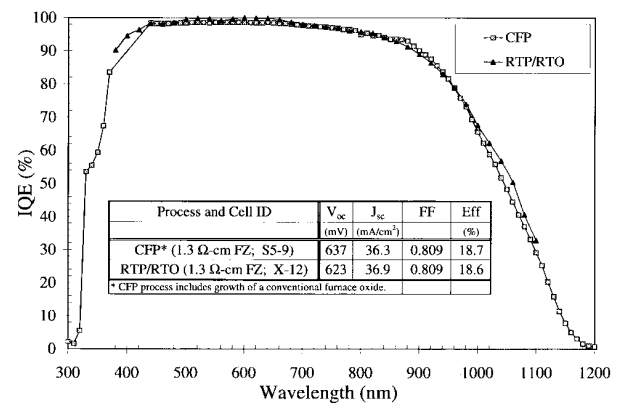


Fig. 6. Highest efficiency RTP/RTO cell compared to CFP cell (both) fabricated on 1.3 $\Omega\text{-cm}$ FZ silicon. Comparable short wavelength response between both types of cells indicates similar quality of RTO and CFO surface passivation.

18% for FZ and 17.5% for Cz silicon. Figs. 6 and 7 show that virtually identical performance is achieved by the RTP/RTO process compared with lengthy CFP (which includes growth of a CFO) on both FZ and Cz substrates. In comparison with cells without an RTO, these figures also depict the large increase in the short wavelength IQE response because of improved front surface passivation and reduced heavy doping effects, resulting in performance improvements of about 1 mA/cm^2 in J_{sc} and 1% in absolute efficiency. These enhancements were found to be consistent with model predictions, as will be shown in the following PC-1D simulations.

IV. PC-1D SIMULATIONS AND DISCUSSION

In order to improve the understanding of these record-high-efficiency (1 and 4 cm^2) RTP/RTO cells and provide guidelines for further improvements, it was necessary to perform model calculations. *PC-1D for Windows* [18] was used to solve the one-dimensional semiconductor transport equations and compute solar cell performance using the default material recombination parameters set by *PC-1D*. (These include the intrinsic carrier concentration $n_i = 1 \times 10^{10} \text{ cm}^{-3}$, the band gap narrowing model of Klaassen *et al.* [19], mobility model used in Cuevas *et al.* [20], and Auger coefficient $C_{nA} = 2.2 \times 10^{-31}$

TABLE I
HIGH-EFFICIENCY RTP/RTO SILICON SOLAR CELLS

ID	Res. (Ω -cm)	Material	Area (cm ²)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF	Eff. (%)
9631\X-12	1.3	FZ	1	623	36.9	0.809	18.6
15 cell average on 9631\X	1.3	FZ	1	619	36.6	0.801	18.2
9631\C-2*	2.8	Cz	1	607	37.5	0.790	18.0
14 cell average on 9631\C	2.8	Cz	1	608	37.3	0.772	17.5
9631\HS-2	0.9	HEM mc-Si	1	593	34.1	0.790	16.0
9615\RO2-3*	0.6	FZ	4	633	35.9	0.789	17.9
9615\RO2-6*	0.6	FZ	4	633	35.7	0.793	17.9
9611\PR-7*	1.3	FZ	4	623	36.4	0.780	17.7
5 cell average on 9611\PR	1.3	FZ	4	623	36.6	0.776	17.7

*Tested and verified by Sandia National Laboratories.

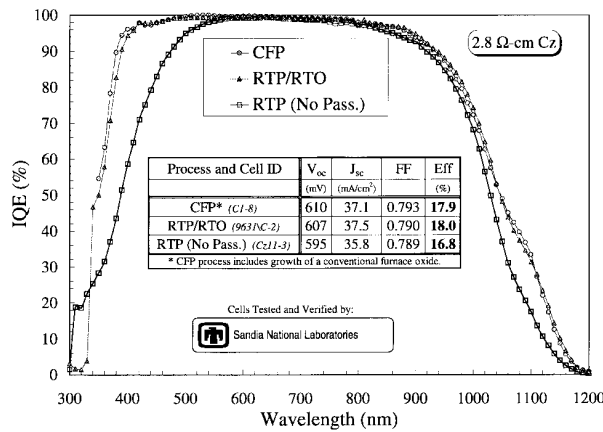


Fig. 7. Highest efficiency RTP/RTO cell compared to CFP cell (both fabricated on 2.8 Ω -cm Cz silicon).

of Wang *et al.* [21]) The purpose of the PC-1D simulations was threefold: 1) quantitatively assess the impact of RTO passivation on reducing the FSRV of cells fabricated in this study; 2) using the estimated change in FSRV values, show that the enhanced cell performance resulting from RTO passivation is consistent with the model calculations; and 3) provide guidelines for further improvement of RTP/RTO devices.

A. Estimation of Front Surface Recombination Velocity for RTP Cells

To analyze the short wavelength behavior of RTP cells and calculate performance improvements resulting from RTO passivation, it is necessary to first assess FSRV values. This is generally difficult because the actual FSRV that dictates short wavelength response is affected by the presence of contacts. Therefore, we decided to assess the FSRV with and without contacts by a combination of IQE and J_{oe} measurements. In order to obtain the effective FSRV with the contacts, the

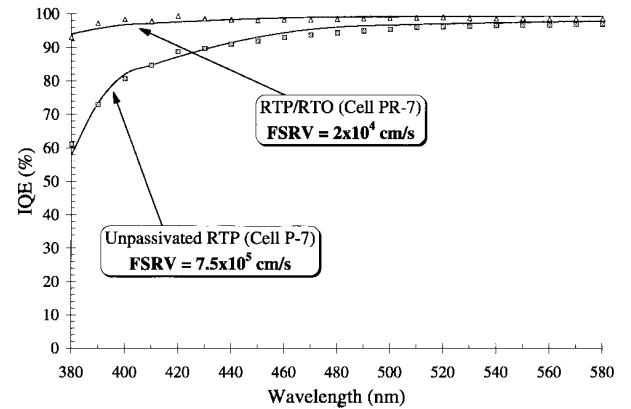


Fig. 8. Matching of measured (data points) and PC-1D calculated (solid curve) short wavelength IQE response to estimate the *spatially-averaged* front surface recombination velocity (FSRV).

measured short wavelength IQE response was matched with PC-1D-calculated IQE using the measured emitter profiles in Fig. 3. Fig. 8 shows that using the “after RTO” profile from Fig. 3 and matching the short wavelength response of the RTO cell gave a best-fit effective FSRV value of about 20 000 cm/s. It is important to note that any value between 15 000 and 25 000 matched the data with little error. Matching the significantly lower short wavelength IQE response of the unpassivated cell in Fig. 8 (using the “before RTO” profile in Fig. 3) gave an effective FSRV value of about 7.5×10^5 cm/s.

Although the method of matching short wavelength IQE to estimate FSRV places significant dependence on the accuracy of IQE measurements, it has advantages over more traditional means such as calculating FSRV from J_{oe} measurements from PCD techniques. Difficulty in calculating FSRV from J_{oe} arises because PCD samples, diffused and passivated on both sides without the grid, do not account for the effect of front contacts which is the true condition of a finished device. To

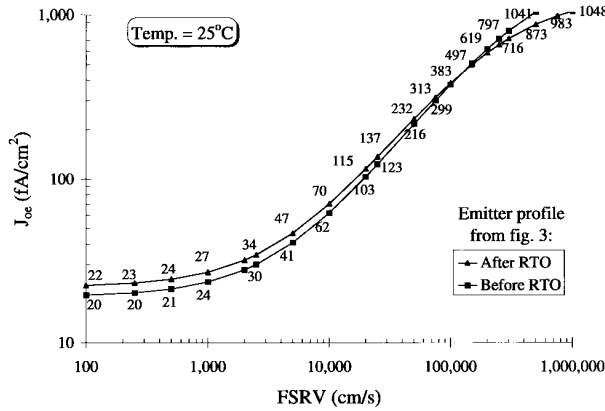


Fig. 9. J_{oe} computed using (1) and the measured emitter profiles in Fig. 3. predict FSRV from the measured J_{oe} , PC-1D is used to vary FSRV until the calculated J_{oe} (1) matches the measured J_{oe}

$$J_{oe} = \frac{J_p(x_{je})}{\exp(qV/kT) - 1}. \quad (1)$$

In the PC-1D simulation, the cell is biased to any voltage, V in the dark, and the minority hole current, J_p is calculated at the edge of the depletion region on the emitter side (x_{je}) using the measured emitter profile. Since J_p is a function of FSRV, (1) can be iterated until the measured J_{oe} is obtained. Fig. 9 shows the calculated J_{oe} (without the metal grid) as a function of FSRV determined by (1) for the profiles studied in this paper. For an oxide-passivated RTP emitter with a sheet resistance of 90 $\Omega/\text{sq.}$, Fig. 4 showed that J_{oe} is about 30 fA/cm^2 which translates into an FSRV of about 2000 cm/s . Although this value is in good agreement with published values of FSRV obtained from PCD analysis [20], [22], it is significantly lower than the effective FSRV value of about 20 000 cm/s which agreed with the measured short wavelength IQE. The 7.5×10^5 cm/s obtained by matching the IQE of the unpassivated cell is also greater than the value of 2×10^5 cm/s based upon J_{oe} measurements of bare silicon samples reported by Cuevas *et al.* [16]. Thus, matching the short wavelength IQE gives an estimate of the *spatially-averaged* (or effective) FSRV which accounts for the variation in FSRV between the passivated and contacted regions. The fact that the spatially-averaged FSRV was found to be greater than the FSRV of the passivated region is also consistent with the successful PCD measurements on grid covered samples by ISFH in Germany [23]. According to Fig. 9, the spatially-averaged FSRV values of 20 000 and 7.5×10^5 cm/s for RTP emitters correspond to spatially-averaged J_{oe} values of 115 fA/cm^2 for RTO passivation and about 1000 fA/cm^2 for the unpassivated case.

B. Comparison Between Measured and Simulated RTO-Induced Enhancements in Cell Parameters

To study the effect of emitter design on RTP cell performance and explain the observed RTO-induced improvement in cell performance, devices were modeled as a function of surface doping concentration (N_s), junction depth (x_j), and FSRV. The sheet resistance (ρ_s) was held constant at 100 $\Omega/\text{sq.}$ and a Gaussian profile was assumed for modeling purposes.

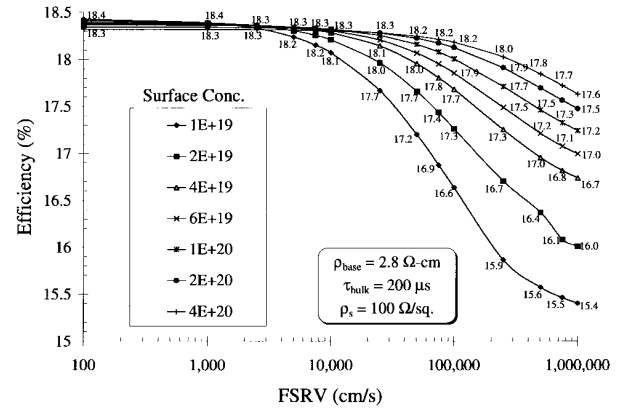


Fig. 10. PC-1D simulations for the 2.8 $\Omega\text{-cm}$ Cz cells showing the effect of emitter profiles and FSRV on cell performance. (The sheet resistance was fixed at 100 $\Omega/\text{sq.}$)

The constant sheet resistance (ρ_s) of 100 $\Omega/\text{sq.}$ was chosen because model calculations show little gain in increasing ρ_s beyond this value. (We have also found empirically in numerous experiments in our laboratory that 100 ± 20 $\Omega/\text{sq.}$ gives optimal performance for homogeneous emitters prepared for evaporated contacts.) Three different base resistivities are analyzed since cells fabricated on FZ and Cz were 1.3 and 2.8 $\Omega\text{-cm}$, respectively; and 0.2 $\Omega\text{-cm}$ was included to exhibit the case where the emitter strongly affects cell performance (i.e. low J_{ob}). All other parameters for the base region were fixed with a bulk lifetime of 200 μs and back-surface-recombination-velocity of 10 000 cm/s (which is applicable to a relatively poor BSF such as the 1 mm evaporated aluminum BSF used in this study).

Figs. 10 and 11 show all possible combinations of FSRV and (Gaussian 100 $\Omega/\text{sq.}$) emitter profile on cell performance. These figures can be used to explain the observed enhancements in cell performance resulting from RTO passivation. For samples with and without RTO passivation, N_s is about 6×10^{19} and 1×10^{20} cm^{-3} , respectively (when the profiles in Fig. 3 are extrapolated to the surface). As stated earlier, N_s decreases following RTO because of the additional diffusion during the RTO cycle and slight consumption of the surface region to grow the SiO_2 . Fig. 10 shows that in the case of 2.8 $\Omega\text{-cm}$ Cz material, using the $N_s = 1 \times 10^{20}$ curve with FSRV = 7.5×10^5 cm/s for the unpassivated cell and $N_s = 6 \times 10^{19}$ curve with FSRV = 20 000 cm/s for the RTO passivated cell, the calculated efficiency increases by 1% (absolute). Table II shows that this is in good agreement with the I-V measurements on 2.8 $\Omega\text{-cm}$ Cz cells. Also, notice that the measured increase of 12 mV in V_{oc} is consistent with the simulations.

Fig. 11 depicts the simulation for the 1.3 $\Omega\text{-cm}$ FZ cells. Using the appropriate curves in Fig. 11 and the same decrease in FSRV because of RTO passivation, an increase of about 1.2% is predicted for the FZ cells. Table III shows that the 18 mV increase in V_{oc} and 1.0 mA/cm^2 increase in J_{sc} are in excellent agreement with the calculated predictions. The calculated gain of 1.2% for 1.3 $\Omega\text{-cm}$ cells is slightly greater than the 1.0% predicted for 2.8 $\Omega\text{-cm}$ cells because higher base doping reduces the J_{ob} component of the total $J_o = J_{oe} + J_{ob}$, and results in a greater increase in V_{oc}

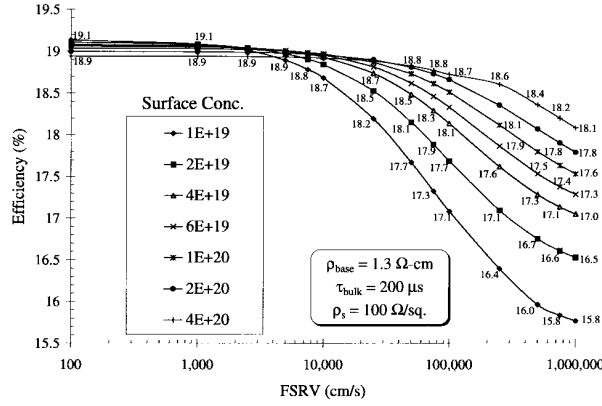


Fig. 11. PC-1D simulations for the 1.3 Ω -cm FZ cells showing the effect of emitter profiles and FSRV on cell performance. (The sheet resistance was fixed at 100 Ω /sq.)

TABLE II
COMPARISON BETWEEN MEASURED AND SIMULATED
IMPROVEMENT IN CELL PERFORMANCE RESULTING FROM RTO
PASSIVATION OF 1 cm^2 RTP CELLS ON 2.8 Ω -cm Cz SILICON

ID	Passi- vation	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	Eff. (%)
9631\C-2	RTO	607	37.5	0.790	18.0
Cz11-3	None	595	35.8	0.789	16.8
Actual improvement		12	1.7	0.001	1.2
Calculated improvement		12	1.3	0.001	1.0

TABLE III
COMPARISON BETWEEN MEASURED AND SIMULATED
IMPROVEMENT IN CELL PERFORMANCE RESULTING FROM RTO
PASSIVATION OF 4 cm^2 RTP CELLS ON 1.3 Ω -cm FZ SILICON

ID	Passi- vation	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	Eff. (%)
9611\PR-7	RTO	623	36.4	0.780	17.7
9611\P-7	None	605	35.4	0.787	16.8
Actual improvement		18	1.0	-0.007	0.9
Calculated improvement		19	1.1	0.003	1.2

when J_{oe} is reduced. This effect can be amplified by further reduction in base resistivity, provided sufficient lifetime is preserved. For example, similar calculations revealed that the efficiency of 0.2 Ω -cm cells with a bulk lifetime of 50 μs increases by 1.7% because of RTO passivation of the emitter.

C. Guidelines for Further Improvement of RTP/RTO Cells

To increase the performance of RTP/RTO cells further, it is necessary to determine the efficiency-limiting mechanisms. Detailed IQE analysis of RTP/RTO cells revealed that J_{ob} is much greater than J_{oe} . This was determined by extracting the effective diffusion length (L_{eff}) from the near-infrared (860–980 nm) inverse-IQE response [24] and using the simple formula

$$J_{ob} = q \frac{n_i^2}{N_A} \frac{D_n}{L_{eff}}. \quad (2)$$

For all cells in this study, (2) gave a J_{ob} value greater than 1000 fA/cm^2 which is an order of magnitude greater than the spatially-averaged J_{oe} of about 115 fA/cm^2 for RTO-passivated cells (determined in Section IV-A). (Without the RTO, J_{oe} and J_{ob} are comparable.) Thus, because of high-quality RTO passivation of emitters, RTP/RTO cells now suffer from base recombination.

Further analysis reveals that a high back surface recombination velocity (BSRV) is responsible for the high J_{ob} . By matching the measured long wavelength IQE of RTP/RTO cells (made with a 1- μm evaporated BSF, in this study) to PC-1D calculated IQE, the BSRV was found to be very high ($\geq 10,000$ cm/s). Furthermore, PCD measurements on processed FZ and Cz materials used in this study gave lifetimes greater than 200 μs ($L_{bulk} > 800$ μm). Since this makes the L_{bulk}/W ratio high, these RTP/RTO cells are strongly limited by back surface recombination. Therefore, research is in progress to reduce BSRV by screen-printed aluminum BSF technology which has been shown to reduce BSRV value to 200 cm/s because of the substantially increased depth of the p^+ region [25], [26]. Other possibilities include a boron BSF which is capable of increasing the doping level of the p^+ region [27] or dielectric passivation (via RTO and/or PECVD silicon nitride) in combination with point or grid rear contacts. PC-1D model calculations on 1.3 Ω -cm material, show that screen-printed aluminum BSF's with a BSRV of 200 cm/s could increase RTP/RTO cell efficiencies beyond 19%.

V. CONCLUSIONS

The fabrication, characterization, and analysis of the first $\geq 18\%$ efficient RTP cells was presented. Improved energy conversion efficiencies were attained by RTO passivation of the emitter which significantly enhanced the short wavelength response and decreased the FSRV (including contact effects) from about 7.5×10^5 to 2×10^4 cm/s. As a result, cell efficiency increased by about 1% (absolute) with 10–20 mV increase in V_{oc} (depending upon base resistivity) and about 1 mA/cm^2 increase in J_{sc} . Although less improvement would be expected for standard screen-printed cells (which have heavily doped emitters and depend less on surface passivation), these results are still useful for clever cell designs involving a selective emitter with RTO passivation. The cells presented in this work were diffused and oxidized in a total time of only about 10 min indicating the potential for substantially increasing the throughput of high-temperature processes compared with CFP. Compared with cells made by CFP (which includes growth of a conventional furnace oxide), these RTP/RTO cells gave virtually identical performance using the same cell structure and base material. Detailed modeling and analysis was also performed to show that the RTO-induced enhancements are consistent with PC-1D simulations and to provide guidelines for further improvements. RTO passivation of the emitter has shifted the dominant recombination mechanism to the base ($J_{ob} \gg J_{oe}$), so the next generation of high-efficiency RTP/RTO cells require reducing back surface recombination. Based on model calculations, $>19\%$ -efficient RTP/RTO cells are expected by reducing the BSRV to 200 cm/s on 1.3 Ω -cm silicon.

ACKNOWLEDGMENT

The authors would like to thank D. Ruby *et al.* of Sandia National Laboratories for cell testing and verification and S. Kamra of Georgia Institute of Technology, Atlanta, for help with cell fabrication.

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