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Evaluating Crystalline Silicon Solar Cells at Low Light Intensities Using Intensity-Dependent Analysis of *I–V* Parameters

Karola Rühle, Mattias K. Juhl, Malcolm D. Abbott, and Martin Kasemann

***Abstract*—This paper discusses the influence of different solar cell loss mechanisms at low light intensities and presents a simple method for the analysis of solar cell performance under various illumination intensities below 1 sun. Suns–PL and $\mathrm{Suns}-V_{\mathrm{oc}}$ are used to measure the intensity-dependent pseudo *I–V* curves of symmetric test structures and of finished silicon solar cells in an intensity range between 1 sun and 10^{-3} suns. The solar cell parameters from the pseudo *I–V* curves are compared with the parameters evaluated by intensity-dependent measurements of the whole *I–V* curve. The pseudo efficiency and pseudo fill factor are found to be in good agreement with the real values at low intensities as the influence of the series resistance vanishes. Based on this finding, we compare the passivation quality of silicon dioxide and silicon nitride in combination with emitter windows on test structures. Above 0.1 suns, both passivation layers show similar performance. Below 0.1 suns, the pseudo fill factors and pseudo efficiencies of the silicon nitride passivated sample are strongly reduced compared with the sample with silicon dioxide. The open-circuit voltage starts differing below 0.01 suns.**

***Index Terms*—Emitter windows, intensity dependence, low light intensities, pseudo *I–V* curve, suns–PL, suns-$\mathrm{V_{oc}}$.**

I. Introduction

THE evaluation of solar cell parameters is typically performed at an intensity of 1 sun (100 mW/cm^2). For indoor and versatile outdoor applications of solar cells, however, the intensity can be as low as 10^{-3} suns. Cell measurements at 1 sun are not an accurate predictor of the performance at such low light intensities. Many of these applications also require the use of small solar cells with an area of a few cm^2, for example, as a power supply in self-sufficient sensors [1] or in other devices with product integrated photovoltaics [2]. For the design of these small-area low-light solar cells, it is important to reevaluate the impact of the various recombination mechanisms.

Until now, the characterization of low-light solar cells has been done by measuring *I–V* curves at different illumination levels [3]–[7]. A reduction in the illumination intensity was achieved by gray filters as an intensity reduction via the voltage supply of the light source was not possible with the equipment used. The use of filters results is both a time-consuming measurement and the necessity of a large number of filters to investigate a large injection-dependent range. On the other hand, there has also been a lot of substantial work on the influence of parasitic recombination at the cell edges impacting on the global current–voltage (*I–V*) characteristics of a solar cell [8]–[12]. Although those analyses have mostly been limited to the understanding of the 1-sun performance or have been used for the interpretation of the shapes of lifetime curves at low injection levels [13]–[16], the results are very important for the improvement of low-light small-area solar cells operated at low light intensities. In addition, there are characterization techniques that apply a variation in light intensities to characterize solar cell performance by measuring the intensity-dependent (implied) open-circuit voltage. Suns-V_{oc} [17], [18] measures the intensity-dependent cell voltage with a voltage probe, and Suns–Photoluminescence (Suns–PL) [19], [20] measures the emitted photoluminescence that relates to the junction voltage in dependence of the light intensity. Again, those techniques have not yet been applied for a systematic investigation of the low-light performance of solar cells.

In this paper, we start by using the equivalent circuit models of a solar cell to identify the parameters that are expected to be crucial to the *I–V* performance at low light intensities. We then apply the simple Suns-V_{oc} technique to small solar cells to determine the behavior of the open-circuit voltage, the pseudo fill factor, and the resulting pseudo efficiency in an intensity range between 1 sun and 10^{-3} suns. The results are compared with the values obtained from full *I–V* curves taken at different intensities. The pseudo efficiency and pseudo fill factor are found to be in good agreement with the real values at low intensities as the influence of the series resistance vanishes. In addition, we compare the passivation quality of silicon dioxide and silicon nitride in combination with emitter windows on test structures. Emitter windows are a means to isolate the main part of the cell from the highly recombination-active edges. Above 0.1 suns, both passivation layers show a similar performance. Below 0.1 suns, the passivation from the silicon nitride is much lower than from the silicon dioxide.

II. Theoretical Intensity-Dependent Performance of a Silicon Solar Cell

The *I–V* characteristics of a solar cell were first described in analogy to the characteristics of a diode by Shockley and

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Queisser [21] with a dark saturation current density J_0 and an ideality factor n. In the low-level injection range, the defect recombination in the quasi-neutral region in the bulk has the same current–voltage behavior as the radiative recombination with an ideality factor equal to 1 (n_1). This recombination that is comparably strong in silicon adds to the radiative recombination in J_{01}. Defect recombination in the space charge region is typically described by a second diode with a dark saturation current density J_{02} and an ideality factor equal to 2 (n_2), assuming defects with energy states in the middle of the bandgap. The discussion of the realistic values of the ideality factor [22] is beyond the scope of this paper. It has been shown that the recombination in the space charge region is unlikely to reduce the efficiency of bulk-crystalline silicon solar cells [10], while recombination due to an unpassivated edge leads to an enhanced J_{02} recombination.

Fig. 1(a)–(c) illustrates the influence of different J_{01} and J_{02} values on the intensity dependence of the solar cell parameters. Obviously, the two diodes have different dependences on the intensity because of the two different ideality factors. In general, the n_1 diode is limiting toward high intensities, while the n_2 diode is limiting the efficiency toward low intensities. The same tendency is true for the open-circuit voltage and the fill factor.

Further losses are described by a shunt resistance and a series resistance. It is well known that the shunt resistance R_{sh} limits the efficiency of a solar cell toward low illumination intensities [see Fig. 1(d)–(f)], while the series resistance R_{s} is limiting toward high light intensities [4]. For small shunt values, the characteristic of a solar cell becomes linear, which results in a limiting fill factor of 25% as indicated in Fig. 1(f) for $R_{\mathrm{sh}} = 10^3$ $\Omega\cdot\mathrm{cm}^2$. For shunt resistances below 10^4 $\Omega\cdot\mathrm{cm}^2$, the fill factor decreases stronger than the open-circuit voltage toward low intensities. The series resistance reduces the fill factor and, thus, the efficiency at high intensities, while the measurements of the open-circuit voltage are unaffected by the series resistance. This causes an overestimation of solar cell performance, when evaluating the pseudo *I–V* curves from Suns-V_{oc} or Suns-PL measurements. Obviously, this overestimation increases with an increased effect of series resistances, i.e., increases with increasing series resistance and decreases with decreasing current and hence illumination intensities. For series resistances below 5 $\Omega\cdot\mathrm{cm}^2$, the relative difference in efficiency and pseudo efficiency is less than 4% for intensities below 0.1 suns for the J_{01} and J_{02} values considered here.

For small solar cells with an area of a few cm^2, edge recombination was observed at an intensity of 1 sun [10]. Thereby, the recombination rate at the edge itself and the resistive path to the edge were found to influence the performance of the solar cell. This resistance-limited recombination [9], [23] can be modeled in an equivalent circuit when including an additional diode J_{H} and resistor R_{H}. The influence of J_{H} and R_{H} are shown in Fig. 1(g)–(i). We simulated a high edge recombination with a J_{H} value of 10^6 A/cm^2 and with an ideality factor equal to 2. The edge recombination does not influence the performance in case of a very large resistance. With decreasing resistance, the performance of the solar cell is strongly reduced toward low intensities, while the 1-sun performance is almost unaffected. At intermediate intensity levels, the performance of the solar cell shows similar characteristics as observable in case of a shunt resistance. However, the fill factor does not approach the minimum value as given in Fig. 1(f), but instead rises owing to the limiting diode J_{H}. The parameter variations were calculated using the equivalent-circuit calculator on PV Lighthouse [24].

Edge recombination losses can be avoided by a proper edge isolation, e.g., with laser doping [15] or by the formation of emitter windows [25], [26]. Emitter windows consist of a locally diffused emitter that does not extend to the edge of the sample. Outside the emitter window, a passivation layer ensures a reduced surface recombination. In the following, we apply emitter windows as edge passivation and show the intensity-dependent influence of the passivation layer outside the emitter window on the cell performance with a simple evaluation method.

III. Intensity-Dependent Evaluation of Silicon Solar Cells and Test Structures

A. Experimental Setup

Intensity-dependent measurements of the *I–V* curve and Suns-V_{oc} measurements of the pseudo *I–V* curve were performed on solar cells, allowing direct comparison between the two measurement techniques. The *I–V* measurements were performed with a Wacom sun simulator, and the incident light intensity was reduced using filters. The Suns-V_{oc} measurements were performed with a Sinton Instruments Suns-V_{oc} stage. The included flash lamp allowed for measurements in an intensity range down to approximately 0.01 suns. For the measurements below 0.01 suns, an LED array with a wavelength of 625 nm was used. For the evaluation of the Suns-V_{oc} measurements, it was assumed that the voltage does not change with the incident spectrum. Suns-PL measurements were unable to be performed on these devices owing to our system using a rear PL detection system, and the devices having a full metallized rear.

Suns-PL measurements were performed on symmetric test structures with a modified Sinton Instruments WCT-120 stage. The stage was modified through the addition of a photodiode within the photoconductance (PC) coil, allowing simultaneous measurement of PC and PL from the same area of the wafer [27]. The combination of flash lamp and LED enabled a measurement over a wide intensity range. The method used for calibration of the PL signal is outlined elsewhere [15], [27], [28]. The measurements were taken with full-area illumination of the wafer to avoid an impact of nonilluminated areas on the sample lifetime [15]. Underneath the sample, we used an aperture made of a material that does not emit luminescence in the range of 900–1200 nm to ensure that solely the PL signal from a defined region was measured. Implied voltage measurements from PC [29] were not able to be used at low injection levels owing to the PC signal being dominated by artifacts [30], [31].

The pseudo *I–V* curve can be derived from the intensity-dependent (implied) voltage measured with Suns-V_{oc} or Suns-PL by relating the illumination intensity to the photogenerated current [32]. This implicitly assumes a linear dependence between the light-generated current and the generation rate. It

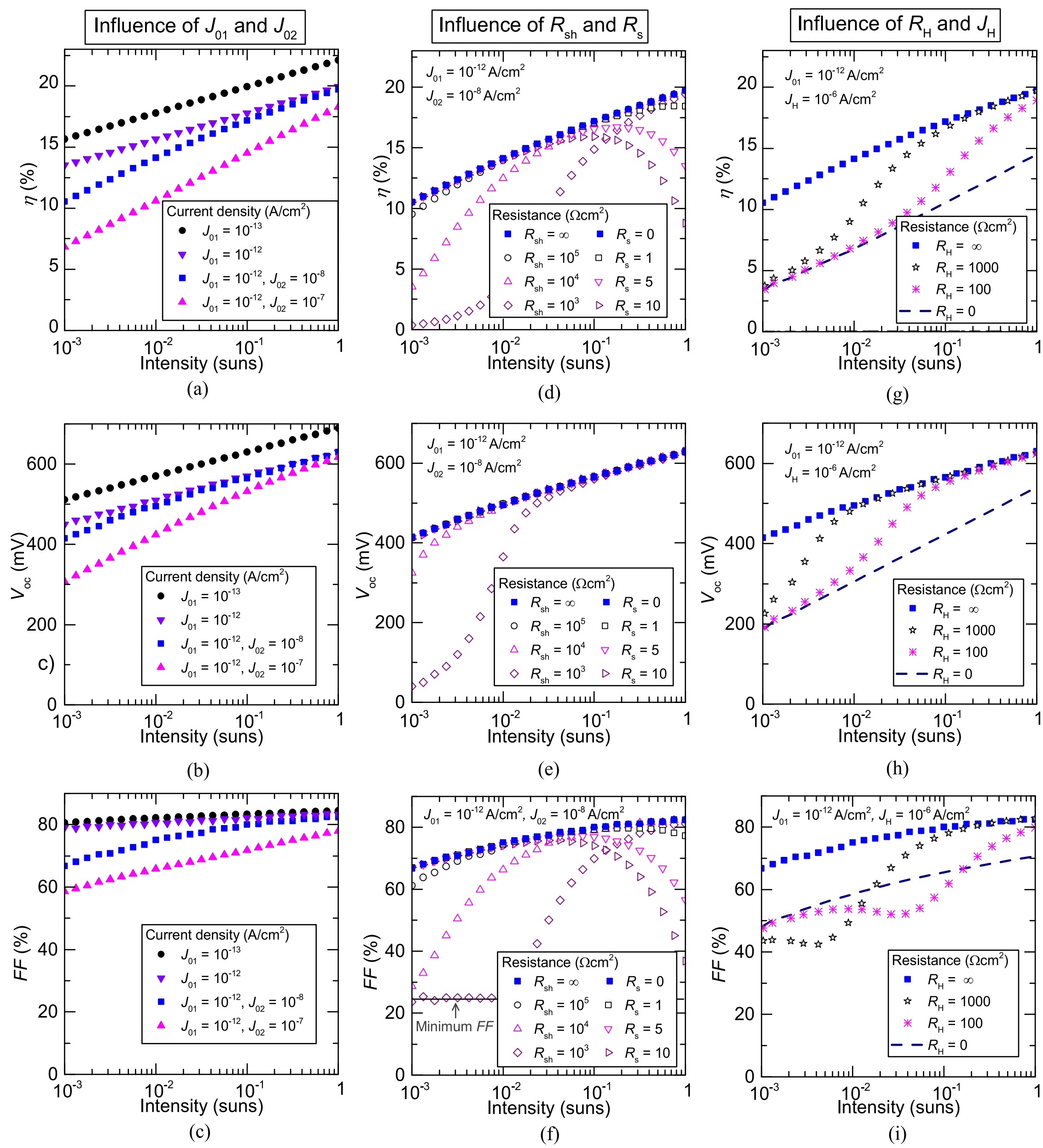

Fig. 1. Influence of varying J_{01} and J_{02} values on the intensity dependence of (a) η, (b) $V_{\rm oc}$, and (c) *FF*. Furthermore, the influence of a varying $R_{\rm sh}$ and R_s on (d) η, (e) $V_{\rm oc}$, and (f) *FF* and the influence of $J_{\rm H}$ and $R_{\rm H}$ on (g) η, (h) $V_{\rm oc}$, and (i) *FF* are shown.

has been shown that the Suns-PL agrees well with Suns-$V_{\rm oc}$ measurements [20], [33] unless the assumption that the average carrier density throughout the bulk is equal to the carrier density at the junction edge fails as can occur in situations such as extreme shunting of an emitter [34].

An example for the calculation of the pseudo *I–V* curve from a Suns-PL measurement is shown in Fig. 2. The intensity values in suns (*y*-axis) are converted into the photogenerated current density *J*, resulting in the series-resistance-free pseudo *I–V* curve [see Fig. 2(b)]. Here, a short-circuit current density of 37.7 mA/cm^2 was used for the calibration of the pseudo *I–V* curve at 1 sun as it was measured on finished solar cells. This evaluation of the 1-sun pseudo *I–V* curve from a Suns-$V_{\rm oc}$ or Suns-PL measurement is by no means new and has been presented in earlier publications [32], [35]–[37]. So far, the pseudo *I–V* curve has always been evaluated at 1 sun, although the pseudo *I–V* curve can be evaluated for various illumination intensities. We extended the evaluation of the pseudo *I–V* curve to the intensity range below 1 sun. This is shown in Fig. 2(c) for an intensity of 0.05 suns. The short-circuit current density at 0.05 suns was approximately 1.9 mA/cm^2 due to the linear intensity dependence. In the following, the series-resistance-free fill factor and efficiency of the pseudo *I–V* curve are called pseudo fill factor *pFF* and pseudo efficiency $\eta_{\rm p}$ to avoid confusion with the fill factor *FF* and efficiency η obtained by an *I–V* measurement.

B. Samples

Solar cells, shown in Fig. 3, were fabricated on 1-Ω·cm p-type float-zone silicon with a thickness of approximately 230 μm.

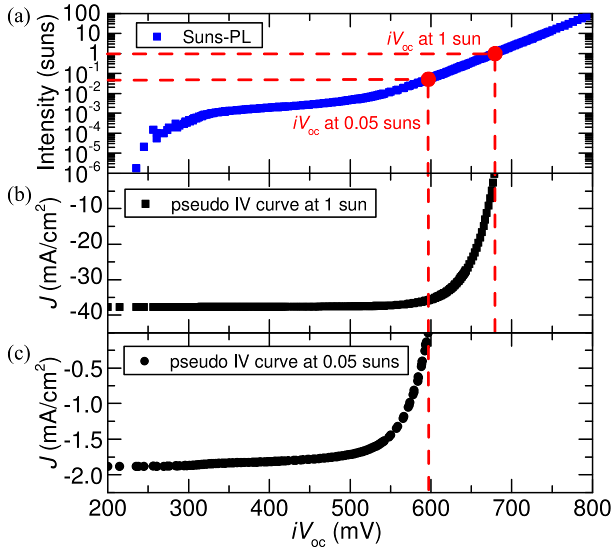

Fig. 2. Comparison of (a) a Suns-PL curve with the resulting pseudo *I–V* curve at (b) 1 sun and (c) 0.05 suns. Note the different scaling of the *y*-axis.

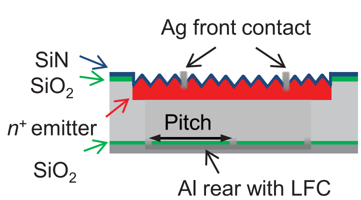

Fig. 3. Schematic cross section of the solar cell with silicon dioxide (SiO_2) as passivation layer outside of the emitter window.

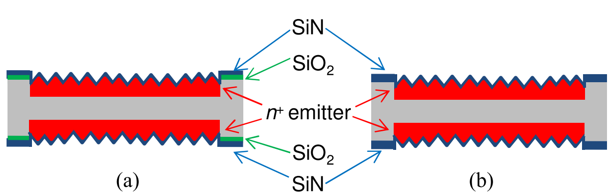

Fig. 4. Schematic cross sections of the symmetric test structures with (a) silicon dioxide and (b) silicon nitride as passivation layer outside of the emitter window. The passivation layer of the emitter is silicon nitride for both samples.

The textured emitter region was limited to an area of 2×2 cm^2, defining the emitter window. The planar region outside the emitter window and the rear side were passivated with a thermal dioxide. A silicon nitride was deposited on the front side by plasma-enhanced chemical vapor deposition (PECVD) to reduce reflectance. The emitter was contacted by a screen printed silver grid. The rear side was contacted by laser fired contacts (LFC) and screen-printed aluminum paste. The pitch size between the LFCs was 480 μm.

Furthermore, two sets of symmetric test samples were fabricated with similar performance at 1 sun but different responses at low illumination intensities by using two different passivation layers outside the emitter window, namely silicon dioxide [see Fig. 4(a)] and silicon nitride [see Fig. 4(b)]. Silicon nitride is known to induce an inversion layer on p-type silicon due to its fixed positive charges which reduce the lifetime at low injections [38] while silicon dioxide results in a better lifetime. The symmetric test samples were fabricated on the same material as the solar cells. One sample was processed in analogy to the solar cell with silicon dioxide and silicon nitride as passivation layer outside of the emitter window. The second sample was passivated solely with silicon nitride outside of the emitter region. For both sample sets, the emitter was passivated by PECVD silicon nitride. The samples were subject to an anneal step at 820 °C to simulate the thermal treatment of a firing step used on a standard cell.

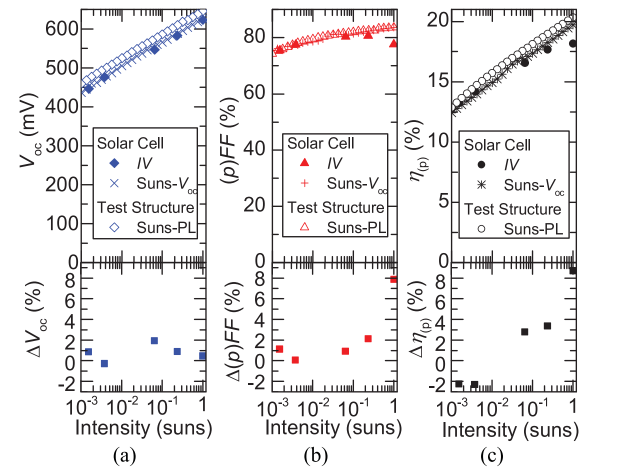

Fig. 5. Comparison of the solar cell parameters from pseudo *I–V* curves gained by Suns-V_{oc} measurements and the parameters of intensity-dependent *I–V* measurements: (a) open-circuit voltage, (b) (pseudo) fill factor, and (c) (pseudo) efficiency. The relative deviation of the Suns-V_{oc} evaluation from the *I–V* measurements is shown in the lower part.

C. Comparison of Pseudo I–V and Light I–V Evaluation of Finished Solar Cells

Fig. 5 shows the intensity-dependent open-circuit voltages, the (pseudo) fill factors, and the (pseudo) efficiencies from the evaluation of the light *I–V* and the pseudo *I–V* measurements of the finished solar cells. The relative deviation of the pseudo *I–V* parameters from the *I–V* parameters is shown in the lower part of Fig. 5. The measurements were performed on three identically processed samples, and the measurements of the three samples were averaged. The averaged measured short-circuit current density of 37.7 mA/cm^2 from the *I–V* measurement at 1 sun was used for the calculation of the pseudo *I–V* curves from the Suns-V_{oc} measurements.

The maximum deviation of the open-circuit voltage measured by the Suns-V_{oc} setup from the one measured with the sun simulator is 2%. The difference between the fill factor and the pseudo fill factor is approximately 8% at 1 sun due to the influence of series resistance. Thus, the efficiency differs from the pseudo efficiency by also approximately 8%. Since the influence of the series resistance vanishes toward low intensities, the difference between pseudo and real fill factor, and thus between pseudo and real efficiency, vanishes as predicted by the simulations in Fig. 1. For intensities of 0.2 suns and below, the deviation is less than 4%.

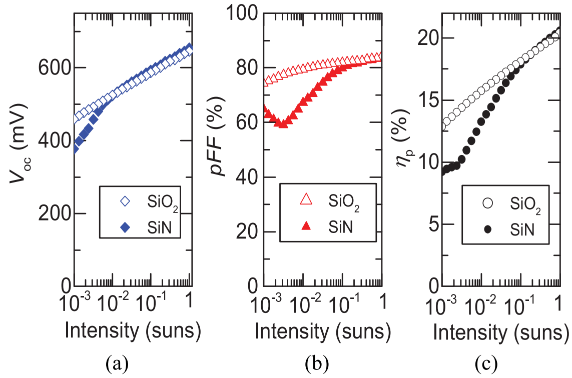

Fig. 6. Evaluation results of the symmetric test structures with emitter windows passivated with silicon dioxide (SiO_2) and silicon nitride (SiN). (a) Implied open-circuit voltage, (b) pseudo fill factor, and (c) pseudo efficiency.

Additionally, Fig. 5 shows the pseudo *I–V* evaluation from Suns-PL measurement of the symmetric test structure [see Fig. 4(a)], allowing a direct comparison of the metallized and nonmetallized sample. The reduction of the open-circuit voltage compared to the implied open-circuit voltage of the nonmetallized sample is approximately 24 mV ($\pm$2 mV) and shows no dependence on the intensity. This voltage difference is most likely caused by an enhanced recombination due to the metal contacts. The fill factor is in very good agreement. Thus, it is possible to estimate the performance of the solar cell from the pseudo *I–V* evaluation of symmetric lifetime samples.

D. Application to Symmetric Test Structures With Emitter Windows

The intensity-dependent parameters derived from Suns-PL measurements on the symmetric test structures are shown in Fig. 6. The pseudo efficiencies were calculated with an assumed short-circuit current density of 37.7 mA/cm^2 at 1 sun, as measured on the finished solar cell.

Above 0.1 suns, the silicon nitride passivated sample results in similar pseudo *I–V* parameters as the silicon dioxide passivated sample. Below 0.1 suns, the pseudo fill factors and pseudo efficiencies are strongly reduced compared with the sample with silicon dioxide, while the open-circuit voltage starts differing below 0.01 suns. Below an intensity of 3×10^{-3} suns, the fill factor of the silicon nitride passivated sample starts increasing again. This behavior is shown in the simulation of resistance-limited recombination (see Fig. 1). Thus, the inversion layer of the silicon nitride is most likely reducing the resistance $R_{\rm H}$ yielding in a resistance-limited performance.

IV. Discussion and Conclusion

This paper reevaluated the recombination mechanisms influencing the solar cell performance at intensities well below 1 sun. Especially in the case of small solar cells, edge recombination losses are hardly limiting at 1 sun, while they strongly influence the low-intensity performance. Toward low intensities, the influence of the series resistance is vanishing. This enables the evaluation of pseudo *I–V* curves from intensity-dependent open-circuit voltage measurements for the estimation of solar cell performance at low intensities. For values of series resistances below 5 $\Omega\cdot$cm^2, the relative deviation of pseudo *I–V* parameters from the real *I–V* parameters is less than 4% for intensities below 0.1 suns. This facilitates the characterization of low-light solar cells, which is nowadays performed with intensity-dependent measurements of the whole *I–V* curve. For optimization of low-intensity solar cells, it is thus not necessary to measure complete *I–V* curves for a whole range of intensities. A single Suns-$V_{\rm oc}$ or Suns-PL curve is sufficient because the series resistance does not significantly impact the fill factor of the *I–V* curve. Furthermore, the evaluation of pseudo *I–V* curves can be performed even on solar cell test structures, providing significant reduction in processing.

Regarding the processing technology for low-light solar cells, we analyzed the quality of silicon dioxide and silicon nitride passivation layers outside the emitter windows. The emitter itself was passivated with silicon nitride in both cases. For intensities above 0.1 suns, both passivation types show similar performance. Below 0.1 suns, the performance of the silicon nitride sample falls substantially compared with the silicon dioxide passivated sample. The reason is that silicon nitride induces an inversion layer resulting in an intensity-dependent lifetime. The evaluation indicates that the inversion layer induced by silicon nitride causes a resistance-limited recombination. Such a recombination is avoided by the silicon dioxide passivation layer. These results suggest that resistance-limited recombination could be avoided with an aluminum oxide passivation layer outside of the emitter window due to its negative fixed charges, inducing depletion on p-type silicon.

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References

[1] W. S. Wang, T. O'Donnell, N. Wang, M. Hayes, B. O'Flynn, and C. O'Mathuna, "Design considerations of sub-mW indoor light energy harvesting for wireless sensor systems," *ACM J. Emerg. Technol. Comput. Syst.*, vol. 6, no. 2, pp. 1–26, Jun. 2010.

[2] N. H. Reich, "On the design of product integrated photovoltaic systems," Ph.D. dissertation, Center for Photovoltaic Engineering, Utrecht Univ., Utrecht, The Netherlands, 2010.

[3] J. F. Randall and J. Jacot, "Is AM1.5 applicable in practice? Modelling eight photovoltaic materials with respect to light intensity and two spectra," *Renew. Energy*, vol. 28, no. 12, pp. 1851–1864, Oct. 2003.

[4] N. H. Reich, W. G. J. H. M. van Sark, E. A. Alsema, R. W. Lof, R. E. I. Schropp, W. C. Sinke, and W. C. Turkenburg, "Crystalline silicon cell performance at low light intensities," *Sol. Energy Mater. Sol. Cells*, vol. 93, no. 9, pp. 1471–1481, Sep. 2009.

[5] A. Virtuani, E. Lotter, M. Powalla, U. Rau, and J. H. Werner, "Highly resistive Cu(In,Ga)Se_2 absorbers for improved low-irradiance performance of thin-film solar cells," *Thin Solid Films*, vols. 451/452, pp. 160–165, Mar. 2004.

[6] N. H. Reich, W. van Sark, E. A. Alsema, S. Y. Kan, S. Silvester, A. S. H. van der Heide, R. W. Lof, and R. E. I. Schropp, "Weak light performance and spectral response of different solar cell types," in *Proc. 20th Eur. Photovoltaic Solar Energy Conf. Exhib.*, 2005, vol. 6, pp. 6–10.

[7] A. Sacco, L. Rolle, L. Scaltrito, E. Tresso, and C. F. Pirri, "Characterization of photovoltaic modules for low-power indoor application," *Appl. Energy*, vol. 102, pp. 1295–1302, Feb. 2013.

[8] R. Kuhn, P. Fath, and E. Bucher, "Effects of pn-junctions bordering on surfaces investigated by means of 2D-modeling," in *Proc. 28th IEEE Photovoltaic Spec. Conf.*, 2000, pp. 116–119.

[9] K. R. Mcintosh and C. B. Honsberg, "The influence of edge recombination on a solar cells I-V curve," in *Proc. 16th Eur. Photovoltaic Sol. Energy Conf.*, 2000, pp. 1651–1654.

[10] K. R. McIntosh, "Lumps, humps and bumps: three detrimental effects in the current-voltage curve of silicon solar cells," Ph.D. dissertation, Univ. New South Wales, Sydney, Australia, 2001.

[11] S. Steingrube, O. Breitenstein, K. Ramspeck, S. Glunz, A. Schenk, and P. P. Altermatt, "Explanation of commonly observed shunt currents in c-Si solar cells by means of recombination statistics beyond the Shockley-Read-Hall approximation," *J. Appl. Phys.*, vol. 110, no. 1, pp. 014515-1–014515-10, 2011.

[12] D. Kray, "Modeling, geometric optimization and isolation of the edge region in silicon solar cells," *Sol. Energy Mater. Sol. Cells*, vol. 94, no. 5, pp. 830–835, May 2010.

[13] F. W. Chen, J. E. Cotter, M. D. Abbott, T.-T. A. Li, and K. C. Fisher, "The influence of parasitic effects on injection-level-dependent lifetime data," *IEEE Trans. Electron Devices*, vol. 54, no. 11, pp. 2960–2968, Nov. 2007.

[14] M. Kessler, T. Ohrdes, P. P. Altermatt, and R. Brendel, "The effect of sample edge recombination on the averaged injection-dependent carrier lifetime in silicon," *J. Appl. Phys.*, vol. 111, no. 5, pp. 054508-1–054508-12, 2012.

[15] C. E. Chan, M. D. Abbott, M. K. Juhl, B. J. Hallam, B. Xiao, and S. R. Wenham, "Assessing the performance of surface passivation using low-intensity photoluminescence characterization techniques," *IEEE J. Photovoltaics*, vol. 4, no. 1, pp. 100–106, Jan. 2014.

[16] B. Veith, T. Ohrdes, F. Werner, R. Brendel, P. P. Altermatt, N.-P. Harder, and J. Schmidt, "Injection dependence of the effective lifetime of n-type Si passivated by Al_2O_3: An edge effect?" *Sol. Energy Mater. Sol. Cells*, vol. 120, pp. 436–440, Jan. 2014.

[17] R. Sinton and A. Cuevas, "A quasi-steady-state open-circuit voltage method for solar cell characterization," in *Proc. 16th Eur. Photovoltaic Solar Energy Conf.*, May 2000, pp. 1–4.

[18] M. Wolf and H. Rauschenbach, "Series resistance effects on solar cell measurements," *Adv. Energy Convers.*, vol. 3, no. 2, pp. 455–479, Apr. 1963.

[19] L. Ferraioli, P. Maddalena, A. Parretta, A. Wang, and J. Zhao, "Current-voltage characteristics of high-efficiency silicon solar cells from photoluminescence," *Appl. Phys. Lett.*, vol. 85, no. 18, pp. 4222–4224, 2004.

[20] T. Trupke, R. A. Bardos, M. D. Abbott, and J. E. Cotter, "Suns-photoluminescence: Contactless determination of current-voltage characteristics of silicon wafers," *Appl. Phys. Lett.*, vol. 87, no. 9, pp. 093503-1–093503-3, Aug. 2005.

[21] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells," *J. Appl. Phys.*, vol. 32, no. 3, pp. 510–519, Mar. 1961.

[22] K. McIntosh, P. Altermatt, and G. Heiser, "Depletion-region recombination in silicon solar cells: When does mDR $= 2$," in *Proc. 16th Eur. Photovoltaic Sol. Energy Conf.*, 2000, pp. 251–254.

[23] F. Hernando, R. Gutierrez, G. Bueno, F. Recart, and V. Rodriguez, "Humps, a surface damage explanation," in *Proc. 2nd World Conf. Photovoltaic Sol. Energy Convers.*, 1998, pp. 1321–1323.

[24] P. Lighthouse. (2014). Equivalent-circuit calculator. [Online]. Available: http://www.pvlighthouse.com.au/calculators/ECcalculator/ECcalculator.aspx

[25] S. W. Glunz, J. Dicker, M. Esterle, M. Hermle, J. Isenberg, F. J. Kamerewerd, J. Knobloch, D. Kray, A. Leimenstoll, F. Lutz, D. Osswald, R. Preu, S. Rein, E. Schaffer, C. Schetter, H. Schmidhuber, H. Schmidt, M. Steuder, C. Vorgrimler, and G. Willeke, "High-efficiency silicon solar cells for low-illumination applications," in *Proc. 29th IEEE Photovoltaic Spec. Conf.*, 2002, pp. 450–453.

[26] M. Hermle, J. Dicker, W. Warta, S. W. Glunz, and G. Willeke, "Analysis of edge recombination for high-efficiency solar cells at low illumination densities," in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, 2003, vol. 2, pp. 1009–1012.

[27] Z. Hameiri, N. Gao, B. Hallam, R. A. Sinton, J. W. Weber, and T. Trupke, "Effective doping density obtained from combined photoconductance and photoluminescence measurements," in *Proc. 26th Eur. Photovoltaic Solar Energy Conf.*, 2011, pp. 117–121.

[28] Z. Hameiri, T. Trupke, N. Gao, R. A. Sinton, and J. W. Weber, "Effective bulk doping concentration of diffused and undiffused silicon wafers obtained from combined photoconductance and photoluminescence measurements," *Prog. Photovoltaics Res. Appl.*, vol. 21, pp. 942–949, 2013.

[29] R. A. Sinton, A. Cuevas, and M. Stuckings, "Quasi-steady-state photoconductance, a new method for solar cell material and device characterization," in *Proc. 25th IEEE Photovoltaic Spec. Conf.*, 1996, pp. 457–460.

[30] D. Macdonald and A. Cuevas, "Trapping of minority carriers in multicrystalline silicon," *Appl. Phys. Lett.*, vol. 74, no. 12, pp. 1710–1712, 1999.

[31] D.-H. Neuhaus, P. J. Cousins, and A. G. Aberle, "Trapping and junction-related perturbations of the effective excess carrier lifetime," in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, 2003, vol. 1, pp. 91–94.

[32] M. J. Kerr, A. Cuevas, and R. A. Sinton, "Generalized analysis of quasi-steady-state and transient decay open circuit voltage measurements," *J. Appl. Phys.*, vol. 91, no. 1, pp. 399–404, 2002.

[33] T. Trupke and R. A. Bardos, "Photoluminescence: A surprisingly sensitive lifetime technique," in *Proc. 31st IEEE Photovoltaic Spec. Conf.*, 2005, pp. 903–906.

[34] M. D. Abbott, R. A. Bardos, T. Trupke, K. C. Fisher, and E. Pink, "The effect of diffusion-limited lifetime on implied current voltage curves based on photoluminescence data," *J. Appl. Phys.*, vol. 102, no. 4, pp. 044502-1–044502-7, 2007.

[35] G. Smestad and H. Ries, "Luminescence and current-voltage characteristics of solar cells and optoelectronic devices," *Sol. Energy Mater. Sol. Cells*, vol. 25, nos. 1/2, pp. 51–71, Jan. 1992.

[36] T. Trupke, R. A. Bardos, and M. D. Abbott, "Self-consistent calibration of photoluminescence and photoconductance lifetime measurements," *Appl. Phys. Lett.*, vol. 87, no. 18, pp. 184102-1–184102-3, 2005.

[37] B. Michl, D. Impera, M. Bivour, W. Warta, and M. C. Schubert, "Suns-PLI as a powerful tool for spatially resolved fill factor analysis of solar cells," *Prog. Photovoltaics Res. Appl.*, vol. 22, no. 5, pp. 581–586, May 2012.

[38] S. Dauwe, J. Schmidt, A. Metz, and R. Hezel, "Fixed charge density in silicon nitride films on crystalline silicon surfaces under illumination," in *Proc. 29th IEEE Photovoltaic Spec. Conf.*, 2002, pp. 162–165.

Authors' photographs and biographies not available at the time of publication.