ABSTRACT:
A novel technique for imaging the recombination current pre-factor $J_0$ of heavily doped surface regions, ubiquitous to mainstream silicon solar cells, is introduced. This technique utilises photoluminescence in a low injection regime, allowing measurement of test structures with low resistivities, which are unattainable by the conventional Kane and Swanson method [1]. The procedure is fast and simple requiring only one photoluminescence image and no photoconductance measurement (after an initial calibration). The potential of the technique is demonstrated on surface-passivated phosphorus diffuse regions with sheet resistances in the range of $\sim 15 - 120 \, \Omega/sq$. A comparison is made with both high and low injection photoconductance decay (PCD) measurements and a recently proposed high injection $J_0$ imaging technique (based on Kane and Swanson theory) [2, 3].

Keywords: Photoluminescence, calibration, qualification and testing.

1 INTRODUCTION
The recombination current pre-factor $J_0$, is a useful metric in solar cell characterisation. It provides, after multiplication with the normalised electron hole (np) product, the recombination current flowing into a particular region of, or throughout, a solar cell. As such, $J_0$ acts as an injection-independent representation of solar cell recombination.

Each individual solar cell can be described in terms of a number of regional $J_0$ values, representing individual recombination currents in heavily-doped or base-doped regions, and a global $J_0$ which represents recombination across the entire cell. The heavily doped surface regions of solar cells are of particular importance to their efficacy and generally exhibit large recombination currents. In these regions the recombination current pre-factors can be represented by $J_{0n^+}$ or $J_{0p^+}$ depending on the doping type.

1D measurements of $J_{0n^+}$ and $J_{0p^+}$ have proven invaluable in cell characterisation and optimisation. 2D imaging of $J_{0n^+}$ and $J_{0p^+}$ could provide further benefit in analysing spatial variation across a solar cell. Such an imaging technique would ideally be contactless, non-destructive, applicable to industry doping and have a high accuracy, resolution and throughput. Further benefit could be attained from a process which remains valid when imaging both mono- and multi-crystalline material.

Recently, a number of research groups have developed techniques for imaging of recombination current pre-factors using microwave photogeneration (μPC), electroluminescence (EL) and photoluminescence (PL) (PL). However, as of yet these techniques do not satisfy all of the criteria mentioned above, especially with regard to speed of acquisition.

This work introduces a fast and simple $J_{0n^+}$ imaging method which utilises PL in a low injection regime. Although only the recombination current pre-factors of heavily doped phosphorus surface regions are analysed, the theory and technique remains applicable to heavily doped p-type regions and hence could be used to acquire images of $J_{0p^+}$ regions under similar conditions. A comparison is made with an adapted high-injection Kane and Swanson [9] method recently demonstrated by both Muller et al. [7] and Muller et al. [4, 3]. Average $J_{0n^+}$ values obtained from these techniques are compared to single $J_{0n^+}$ values obtained from high [7] and low [10, 11] injection photoconductance decay (PCD) measurements.

2 THEORY

2.1 Principle of low injection PL $J_{0n^+}$ imaging
PL intensity $I_{PL}$ shares a proportionality to np-$n_i^2$ with most of the recombination components found in silicon solar cells. Under certain conditions this linked proportionality allows the removal of injection level $\Delta n$ consideration when obtaining recombination characteristics, for example $J_{0n^+}$ from $I_{PL}$.

In steady state conditions, the continuity equation of a symmetrically phosphorus-diffused p-type silicon test structure (Structure 1, Figure 1) can be thought of as a simple generation $G$ – recombination $\bar{U}$ balance,

$$G = U_{diffusion} + U_{bulk,SRH} + U_{bulk,RAD} + U_{bulk,AUG}$$  

(1)

When considering the above recombination mechanisms only Auger recombination in the bulk does not exhibit proportionality to np – $n_i^2$ [10]. By restricting this scenario to low injection conditions and assuming an approximately constant $\Delta n$ profile we can isolate a common dependence on $\Delta n_{av}$, given by

$$\frac{I_{ph}}{q} = \frac{2N_D J_{0n^+}}{q n_i^2} \frac{W}{\tau_n} + WBN_A + WC_p N_A^{1.65} \Delta n_{av}$$  

(2)

where $I_{ph}$ is the photon flux density into the base, $N_A$ the base doping, $n_i$ the intrinsic carrier concentration and $q$ the carrier charge. $B$ and $C_p$ in the above equation are the radiative recombination coefficient and the Auger hole coefficient, both of which are independent of $\Delta n$ in low injection [10, 11]. $\tau_n$ is the Shockley Read Hall electron lifetime.

The relationship between PL intensity and $\Delta n_{av}$ [12] in low injection can also be written in a similar manner as
where $A_i$ is a linear scaling factor. This factor is a ratio between the amount of photons collected by the detector and the total PL events occurring within the substrate. It is sensitive to the $\Delta n(x)$ profile and the specific measurement setup. $A_i$ can be easily obtained using Equation 3 in conjunction with PL and $\Delta n$ images from a Quasi-steady-state PC-calibrated PL imager. From Equation 2 we can derive the proportionality between recombination characteristics and PL intensity given by

$$I_{||} = A_iB \left[ \frac{J_{ph}}{2 J_{on}^+ + 2WqB + WqC_pN_d^{0.65}} \right]$$

The extraction of $J_{on}^+$ from the above equation requires an approximation of the SRH electron lifetime which is often hard to obtain accurately. Two levels of simplification which can be applied when warranted are the assumption of an intrinsic bulk (only Auger and radiative recombination are significant) or recombination dominance of the heavily doped region (making bulk recombination comparatively negligible). These assumptions produce

$$I_{||} = A_iB \left[ \frac{J_{ph}n_i^2}{2J_{on}^+ + WqB + WqC_pN_d^{0.65}} \right]$$

and

$$I_{||} = A_iB \left[ \frac{J_{ph}n_i^2}{2N_dJ_{on}^+} \right]$$

respectively. In instances when the above approximations are not warranted the obtained $J_{on}^+$ value is representative of an upper limit.

The assumption of no significant bulk recombination can be increased in accuracy, albeit sacrificing some signal intensity, by introducing a single-side diffused structure (Structure 2, Figure 1) with a back surface of “infinite” surface recombination velocity $S$. The previous assumption of constant $\Delta n(x)$ is no longer valid and a simple constant-gradient profile is assumed where $\Delta n_{\text{back}}$ is approximately 0 and $\Delta n_{\text{grad}} = 1/2\Delta n_{\text{front}}$. This assumption requires that the base diffusion length is much greater than $W$. Recombination at the back surface will be limited by the diffusion coefficient of electrons $D_n$, which can be assumed constant in low injection [13], the G-U balance can be written in this instance as

$$J_{ph} = \left[ \frac{N_dD_n^{1/2} + D_n}{qW} \right] \Delta n_{\text{front}}.$$  

Hence we derive

$$I_{||} = A_iB \left[ \frac{J_{ph}^{1/2}}{2J_{on}^+ + qD_n/N_dW} \right]$$

Figure 1: Cross-sectional diagrams of test structures 1-3, used for $J_{on}^+$ imaging techniques in this paper.

2.2 Comparison to detailed modelling

An analysis of the validity of the simple theory proposed in Equations 5 and 8 is made by comparison with the more complex model for recombination and photoluminescence employed in QSSModelV5 [14]. Structures 1 and 2 with widths of 300µm and base resistivities of 0.5, 1 and 2 Ω-cm, are used for the simulations. Bulk SRH recombination is removed and a monochromatic illumination source with a wavelength of 809nm is used to mimic the PL laser source and ensure the majority of generation occurs at the front side. The simulated photoluminescence intensity is monitored whilst front and back $J_{on}^+$ values are simultaneously increased in structure 1 and the front $J_{on}^+$ value is increased in structure 2 (whilst the back is fixed at an $S$ of approximately $10^7$ cm/s). $I_{||}$ is then used as a proxy for an “experimental input” to Equations 5 and 8 in order to determine $J_{on}^+$. The results of this exercise are shown in Figure 1. They reflect a high degree of correlation between $J_{on}^+$ values in the 10-1000 fA/cm² range for both structures 1 and 2, proving that in principle a low injection PL method based on either structure should work.

At higher $J_{on}^+$ values the proposed method decreases in accuracy as the assumption of constant gradient $\Delta n(x)$ becomes invalid due to “bending” of the $\Delta n(x)$ profile from recombination in the surface diffused regions. At lower $J_{on}^+$ values such contribution to recombination becomes minute and care should be taken in interpreting results, as a higher weight is placed on the accuracy of parameterisations used to quantify the intrinsic bulk lifetime and the diffusivity.

In the above simulations a new $A_i$ is calculated for every $J_{on}^+$ input. It would be beneficial in an industrial quality control system to treat this factor as constant.
removing the need for an inductive coil in the system and reducing the time required to acquire images. Alike simulations performed with a constant \( A_i \) reveal a reduction in the valid range for the symmetrically diffused structure (structure 1) to \( \sim 10^{-50} \) fA/cm\(^2\). No appreciable reduction in the range of validity was seen with single-side diffused (structure 2) simulations.

The two test structures and accompanying equations described above allow the acquisition of \( J_{on^+} \) images by fast, simple, linear scaling of a single \( I_{d} \) image using known test structure characteristics and constants. This method requires no contacts and can be conducted on test structures with low bulk resistivities, representative of industrial solar cells – a possibility sometimes unattainable by the Kane and Swanson PCD technique. Further, structure 2 resembles a solar cell precursor, hence this technique could be applied as part of an inline quality control system.

One drawback of these techniques is that the \( J_{on^+} \) image depends heavily on the accuracy of test structure width, doping and optical property measurements as well as parameterisations of Auger, radiative and diffusion coefficients.

2.3 High injection PL \( J_{on^+} \) imaging

The method of \( J_{on^+} \) extraction pioneered by Kane and Swanston using PCD forms the basis for high injection \( J_{on^+} \) imaging used in this paper. Adapting Equation 1 into an effective lifetime \( \tau_{eff} \) form yields

\[
\frac{1}{\tau_{eff}} = \frac{2J_{on^+}(\Delta n_{avg} + N_A)}{qWn_i^2} + \frac{1}{\tau_{bulk,SRH}} + \frac{1}{\tau_{bulk,RAD}} + \frac{1}{\tau_{bulk,AUG}}
\]

assuming a uniform \( \Delta n(x) \) and identical front and rear diffusions. The intrinsic bulk recombination components are eliminated using appropriate parameterisations of Kerr et al. [10] creating a corrected lifetime \( \tau_{corr} \). The separation of recombination components from the heavily doped region and bulk (only SRH) is achieved by their difference in \( \Delta n \) dependence in high injection. This can be utilised by plotting \( 1/\tau_{corr} \) against \( \Delta n \) and deriving \( J_{on^+} \) by a simple scaling of the gradient. In this manner multiple high injection PC-calibrated PL \( \tau_{eff} \) and \( \Delta n \) image sets can be used to calculate a \( J_{on^+} \) value at each pixel location. In practice at least four, preferably more, PL image sets are taken at different illumination intensities (to produce different \( \Delta n \) densities) to acquire sufficient data for reliable \( J_{on^+} \) images.

As this method inherits from the Kane and Swanson technique it is subject to the same measurement range limitations and inaccuracies. It is also worth noting that significant computational power is required to perform linear regression at every pixel – this is especially relevant to high resolution imaging.

3 TEST STRUCTURE FABRICATION

Test structures implemented in this study were fabricated from float zone (FZ), p-type, (100) silicon substrates. Resistivities of 100 and 0.5 Ω-cm were used to ensure that high and low injection conditions were attainable. Following Si-etching and RCA cleaning samples were subjected to one of six (D1-D6) different symmetrical phosphorus-diffusion and thermal oxide drive-in procedures (phosphorus glass was deglazed and samples re-cleaned between diffusion and oxidation/drive-in steps). Precursors of structures 1-3 were included in each of these six procedures to ensure comparable dopant diffusions. The profiles and sheet resistances (single-side) of the diffusions produced by the six procedures were determined by electrochemical capacitance-voltage (ECV) and contactless conductance measurements, these are shown in Figure 3. Simulated sheet resistances were also obtained from the measured diffusion profile and are included as a comparison in Table 1. The final fabrication step for test structures 1 and 3 was a 30 minute forming gas anneal (FGA) at 400°C, known to improve the surface passivation quality of thermal SiO\(_2\). In addition to this, structure 2 required the etching of both the oxide and diffusion from one side. Reactive ion etching (RIE) was used for this process as it is known to result in a surface with an approximately

Figure 2: Comparison of \( J_{on^+} - I_{d} \) proportionality of the simplified theory in this paper (hollow markers) and the QSSModelV5 [14] (lines). Simulations are shown for symmetrical structure 1 (a.) and asymmetrical structure 2 (b.).
“infinite” SRV.

$J_{on^+}$ values for structures 1 and 3 were obtained for accuracy comparison using low [10, 11] and high injection [7] PCD measurements (using a Sinton WCT 120 lifetime tester). Quasi-steady-state PC and transient PCD were used to make the low and high injection measurements respectively. Accurate determination of test structure width, doping and optical properties required for $J_{on^+}$ calculation were obtained by digital micrometre callipers, Sinton conductive instrument and a spectrophotometer with an integrated-sphere, respectively.

![Graph](image)

**Figure 3:** Diffusion profiles and measured sheet resistances (single side) from diffusion processes 1-6.

4 $J_{on}$ IMAGING

All PL imaging is performed with a BT-Imaging LIS-R1 QSSPC calibrated PL imager. Low injection $J_{on^+}$ images of structure sets 1 and 2 are obtained by first finding the relevant $J_0$ values (using $I_{ll}$ and $Dn$ images in conjunction with Equation 3), following which $J_{on^+}$ images can be obtained by a simple scaling of the $I_{ll}$ image in accordance with Equations 5, 6 or 8. The $Dn$ region in which PL measurements are made must be both in low injection and free of lifetime overestimation artefacts like trapping in multi-crystalline silicon and depletion region modulation in mono-crystalline silicon. In this instance the $5 \times 10^{14} - 1 \times 10^{15}$ cm$^{-2}$ region was seen to avoid such effects. An acquisition time of less than 0.5 seconds is required to take images. Example images for structure sets 1 and 2 are shown in Figure 4 with diffusions D2, D4 and D6.

For the high-injection imaging, five high-injection (> $1.3 \times 10^{15}$ cm$^{-2}$) $\tau_{eff}$ and $Dn$ images are taken of structure set 3 at increasing incident photon flux. $J_{on^+}$ images are prepared using the simple but computationally-intensive process described in the theory section above. Example high injection $J_{on^+}$ images are also included in Figure 4 for diffusions D2, D4 and D6.

Some degree of correlation is seen between analogous images collected from the three different techniques. Images acquired by the high injection technique produce $J_{on^+}$ values consistently lower than those generated via the low injection techniques. This difference is discussed in the PCD comparison section below.

Aside from general differences in magnitude, the images generated by the high injection technique appear more uniform than those produced by the low injection techniques. The greater uniformity is possibly a consequence of the averaging involved in the high injection measurement method, as images are generated from linear regression performed on 5 image sets (5 $\tau_{eff}$ and $5 Dn$ images). The slightly deeper position of the $n$-$p$ junction in the high resistivity structures as compared to the low resistivity ones could also increase the uniformity. In addition to this, a longer fabrication procedure was required for structure 2, accounting for some of the very high $J_{on^+}$ regions seen in these images.

Worth noting is that on some of the images taken with the low injection techniques, especially on the asymmetrical samples, faint lines following the contour of the outer edge of the test structure are visible. This is not to be confused with the clear ring like structure, seen in almost all images, caused by the underlying inductive coil and housing. These are believed to be caused by deviations in dopant densities arising during the crystal growth procedure [17]. These deviations affect both the diffusivity and PL signal resulting in slight differences in the measured $J_{on^+}$.

### Table 1: Comparison of average $J_{on^+}$ values obtained from high and low injection imaging techniques to corresponding values obtained by PCD, these results are plotted in Figure 5. The values within the brackets are the standard deviations of the measured area.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Δn regime</th>
<th>Parameter</th>
<th>D1 (Ω/sq)</th>
<th>D2 (Ω/sq)</th>
<th>D3 (Ω/sq)</th>
<th>D4 (Ω/sq)</th>
<th>D5 (Ω/sq)</th>
<th>D6 (Ω/sq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCD Simulation</td>
<td>$R_{Sheet}(Ω/sq)$</td>
<td>115</td>
<td>95</td>
<td>92</td>
<td>44</td>
<td>32</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>PCD</td>
<td>Low Injection</td>
<td>$J_{on^+}(IA/cm²)$</td>
<td>83</td>
<td>115</td>
<td>109</td>
<td>168</td>
<td>180</td>
<td>229</td>
</tr>
<tr>
<td>PL (Structure 1)</td>
<td>High Injection</td>
<td>$J_{on^+}(IA/cm²)$</td>
<td>64 (4)</td>
<td>92 (10)</td>
<td>85 (6)</td>
<td>140 (10)</td>
<td>157 (18)</td>
<td>255 (9)</td>
</tr>
<tr>
<td>PCD</td>
<td>Low Injection</td>
<td>$J_{on^+}(IA/cm²)$</td>
<td>76</td>
<td>103</td>
<td>100</td>
<td>196</td>
<td>209</td>
<td>228</td>
</tr>
<tr>
<td>PL (Structure 2) (Eq.8)</td>
<td>Low Injection</td>
<td>$J_{on^+}(IA/cm²)$</td>
<td>79 (29)</td>
<td>132 (29)</td>
<td>145 (19)</td>
<td>229 (24)</td>
<td>276 (34)</td>
<td>280 (27)</td>
</tr>
<tr>
<td>PL (Structure 1) (Eq.5)</td>
<td>Low Injection</td>
<td>$J_{on^+}(IA/cm²)$</td>
<td>79 (17)</td>
<td>110 (13)</td>
<td>108 (12)</td>
<td>218 (36)</td>
<td>242 (45)</td>
<td>271 (23)</td>
</tr>
<tr>
<td>PL (Structure 1) (Eq.6)</td>
<td>Low Injection</td>
<td>$J_{on^+}(IA/cm²)$</td>
<td>95 (14)</td>
<td>129 (16)</td>
<td>128 (13)</td>
<td>238 (37)</td>
<td>261 (46)</td>
<td>286 (20)</td>
</tr>
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</table>
Table: Structure Comparison

<table>
<thead>
<tr>
<th>Structure 1 (Equation 6)</th>
<th>Structure 2 (Equation 8)</th>
<th>Structure 3 (High Injection Symmetrical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Injection Symmetrical</td>
<td>Low Injection Asymmetrical</td>
<td>High Injection Symmetrical</td>
</tr>
</tbody>
</table>

Figure 4: A small selection of $J_{on}$ images obtained from high (structure 3) and low (structures 1 and 2) injection techniques applied to test structures with equivalent diffusion profiles. The scale on the right has units of fA/cm$^2$.

Figure 5: Comparison of obtained average $J_{on}$ (imaging) and $J_{on}$ values (PCD) as a function of measured sheet resistance. The green data sets are those obtained by high injection methods whilst those in blue and cyan are low injection techniques. Phosphorus diffusions followed by thermal oxide growth and forming gas anneal.

5 COMPARISON WITH PCD

A comparison between average $J_{on}$ values determined via the PL imaging techniques described above, and $J_{on}$ values obtained by well-established PCD techniques on analogous structures needs to be undertaken to assess the validity of the former. Individual image averaging was made over the estimated area and...
location of the coil used in PCD measurements. The results are presented in Table 1 and are plotted in Figure 5. Each data point is further the result of an average of two to four individual wafers. Standard deviations of values around the coils are also included in Table 1 and align with the previous observation of greater uniformity in the images obtained by the high injection technique.

It can be seen that all techniques reveal the same expected dependence of $I_{on}$ on the sheet resistance of the surface-passivated diffusion. That is, a decreasing $I_{on}$ for increasing $R_{sheet}$. A very high degree of correlation is seen between the low and high injection PCD techniques. Of the imaging techniques, the best agreement with standard high injection PCD is exhibited by the high injection PL imaging technique, which utilizes the same theoretical principle at each pixel location. Although consistently lower it remains within 25% of the high injection PCD values across all measurements.

Low injection imaging techniques generally give higher $I_{on}$ values for a given sheet resistance, especially at lower sheet resistances. This is likely potentially due to a number of contributing factors:

Unaccounted for SRH recombination in the base would result in a larger portion of recombination being attributed to the heavily doped region and hence a higher $I_{on}$. This same effect would not be expected using the high injection techniques as the base SRH recombination is separated by its different dependence on $dn$ rather than being subtracted from the recombination total. It is unlikely that the differences seen between the techniques are solely due to this effect as FZ wafers were used and the low injection PCD technique does not exhibit the same high $I_{on}$. In fact, the deviation is seen to increase with lower sheet resistances, where the dominance of the diffused region recombination over base SRH recombination is strongest.

The differences and particularly the increased deviation from the high injection PCD technique seen at lower sheet resistances could also be explained by the different conditions of measurement. As the low injection imaging technique utilises QSS conditions a significant proportion of carriers may be injected into the diffusion region and not reach the base. This would lead to an overestimation of $I_{ph}$ and hence $I_{on}$ for a given PL output. The effect would increase with lower sheet resistances, like the trend seen in Figure 5, as the junction is deeper. However, this same effect is not seen clearly for the low injection PCD measurements and high injection imaging technique, both of which are measured in QSS. The high injection PCD technique is impervious to this effect as it is measured using transient PCD where $I_{ph}$ is not used.

Another potential contribution to the differences is the slightly thinner diffusion region width expected for the lower resistivity structures. The difference in diffusion width could result in a change in $I_{on}$, as the actual base width is now larger (see Equations 5, 6 and 8). However, simulations in EDNA V1.2 [17] of measured diffusion profiles with different background doping suggest that this contribution is very small.

Finally, it is worth noting that as all of the low injection techniques are based around a subtraction of recombination components, a heavy emphasis is placed on the accuracy of parameterisations and test structure measurements.

Even with the above mentioned deviations, the introduced low injection $I_{on}$ imaging techniques show very good agreement with the high injection PCD measurement given the inherent level of error in the experiment. In a separate experiment, a comparison of average $I_{on}$ values of heavily doped regions formed under the same diffusion and drive in conditions revealed deviations of up to 10% which were not factored into this experiment. In addition the error in PCD measurements are not insignificant and could also affect the spread of data and assessment of correlation [15].

7 CONCLUSION

A novel, low injection technique which provides a 2D image of the recombination current pre-factor that characterises the surface diffused region has been introduced. This technique is demonstrated over diffusion profiles with an approximate sheet resistance range of 15 – 120 $\Omega$/sq. The validity range of the proposed theory, estimated by comparison with simulated PL results from QSSModelV5, is found to be appropriate for imaging industrial high efficiency solar cells. A comparison with existing dominant PCD based techniques and a high-injection $I_{on}$ imaging technique indicate reasonable correlation between all techniques. A deviation in correlation of $I_{on}$ values between the new, low injection technique and the comparison techniques is seen at lower sheet resistances. Potential contributing factors to this reduced correlation include an overestimation of $I_{ph}$ using QSS conditions, unaccounted for SRH recombination in the base region and general inaccuracies in test structure measurements and parameterisations.

8 ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided by the Australian Research Council and the Australian Solar Institute.

REFERENCE


