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Imaging of the relative saturation current density and sheet resistance of laser doped regions via photoluminescence

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We present an approach to characterize the relative saturation current density ($J_{sc}$) and sheet resistance ($R_{sh}$) of laser doped regions on silicon wafers based on rapid photoluminescence (PL) imaging. In the absence of surface passivation layers, the $R_{sh}$ of laser doped regions using a wide range of laser parameters is found to be inversely proportional to the PL intensity ($I_{PL}$). We explain the underlying mechanism for this correlation, which reveals that, in principle, $I_{PL}$ is inversely proportional to $J_{sc}$ at any injection level. The validity of this relationship under a wide range of typical experimental conditions is confirmed by numerical simulations. This method allows the optimal laser parameters for achieving low $R_{sh}$ and $J_{sc}$ to be determined from a simple PL image.

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I. INTRODUCTION

The main challenge in today’s silicon solar cells industry is to increase the conversion efficiency and to lower the production costs of cells. A route towards higher efficiency is the application of selective emitter (SE) and local back surface field (LBSF) structures in the solar cells. A SE structure can reduce contact resistance by allowing heavy doping under the metal contacts, while ensuring low recombination in the optically active regions through lighter doping. These improvements result in higher fill factors, open circuit voltages, and a better blue response. A heavily doped LBSF can also increase the fill factor and voltage due to a decreased series resistance and recombination at the rear-side contacts. The world-record high efficiency (25%) passivated emitter, rear locally diffused (PERL) silicon solar cell has such SE and LBSF structures.1

Recently, laser processing has attracted considerable attention as a fast and cost-effective technique in forming SE and LBSF structures for silicon solar cells. Up until now, mainly two different classes of laser doping techniques, dry and wet laser processing, have been developed for high efficiency solar cell fabrication. The commonly used dry laser processing for SE or LBSF formation is based on laser doping from a dopant-containing layer or precursor, such as laser-fired contact,2 laser doping from the phosphosilicate or borosilicate glass (PSG or BSG) layers,3,4 laser transfer doping,5 laser doping from a sputtered precursor layer,6 laser annealing of ion implanted silicon samples,7,8 and so on. The wet laser doping technique is the so-called laser chemical processing (LCP), which can open the passivation layers and form the SE or LBSF doping in a single step.9 The coupling of a laser beam into a dopant-containing liquid (phosphorus acid or alkaline aqueous boron solution) jet enables the formation of local n- or p-type doping to create SE and/or LBSF structures for either p- or n-type solar cells.10,11 Therefore, it is important to develop characterization methods for the optimization of laser doping or laser-activated doping techniques.

Laser doping is generally characterized by the sheet resistance ($R_{sh}$), contact resistance ($R_c$), and the doping profile. The doping profile is measured by secondary ion mass spectroscopy (SIMS) or electrochemical capacitance voltage (ECV), which are relatively time consuming. Secondary electron microscopy dopant contrast image has also been proposed to characterize the doping profile in cross sections of laser-doped lines.12 The $R_{sh}$ and $R_c$ are typically measured using the transfer length measurement (TLM) technique initially developed in the 1980s,13 and further modified for measuring the $R_{sh}$ and $R_c$ of a single laser-doped line.14,15 Up until now, the easiest way to characterize laser doped or annealed regions is to measure the $R_{sh}$ by four point probe (4PP) measurements or sheet resistance imaging (SRI), which is based on the principle of free carrier absorption in combination with a charge-coupled device (CCD) camera sensitive in the infrared.16 However, optimization of laser parameters (e.g., laser fluence, pulse width, pulse overlapping ratio, scanning speed) using above approaches requires a large parameter space to be explored. Usually, the saturation current density ($J_{sc}$) of laser doped regions is measured by the quasi-steady-state photoconductance (QSSPC) technique with double side laser doped and passivated samples, which is also time consuming. In contrast, photoluminescence (PL) imaging is a fast, non-destructive, and spatially resolved measurement technique, which is widely applied for the determination of carrier lifetime,17 interstitial iron concentrations,18 series and shunts resistances,19,20 dopant concentration,21 crystal orientation,22 and so on. Recently, a camera-based technique for the local determination of saturation current density of high doped regions has been developed by using photoconductance calibrated PL imaging. In the absence of surface passivation layers, the $R_{sh}$ of laser doped regions using a wide range of laser parameters is found to be inversely proportional to the PL intensity ($I_{PL}$). We explain the underlying mechanism for this correlation, which reveals that, in principle, $I_{PL}$ is inversely proportional to $J_{sc}$ at any injection level. The validity of this relationship under a wide range of typical experimental conditions is confirmed by numerical simulations. This method allows the optimal laser parameters for achieving low $R_{sh}$ and $J_{sc}$ to be determined from a simple PL image.

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imaging.\textsuperscript{23} Fell et al. have successfully applied a 2D/3D device simulation based method to derive the recombination properties of locally laser processed regions from the average PL signals.\textsuperscript{24} However, both methods involve complicated multidimensional analytical or numerical modelling, and the samples have to be partly passivated. In this study, we demonstrate that PL imaging is also well suited to the characterization of the relative $R_{SH}$ and $J_{sc}$ of laser doped regions without passivation, which shows similar recombination properties of the metal contacted emitters.\textsuperscript{25} No passivation and numerical simulations, and only small laser doped regions are needed for the application of this technique, which provides a rapid means of optimizing laser doping parameters.

II. EXPERIMENTAL

The laser doping or activation processes were carried out on (100)-oriented silicon wafers with high base resistivity (>$100$ $\Omega$-cm), in order to measure the sheet resistance of the laser doped areas by 4PP. For n-type laser-doped samples, surface damage etched p-type substrates with the thickness of $\sim470\mu$m were used and vice versa. Phosphorus or boron spin-on-dopant (P-SOD/B-SOD) solutions, which are available commercially from Filmtronics Inc., were used as dopant sources. P-SOD or B-SOD was spun on the front surface, followed by baking in an oven at $120^\circ$C in an air ambient. Both an excimer (248 nm) laser and a Q-switched double pumped solid state (DPSS, 532 nm) laser with similar pulse duration ($\sim20$ ns) were used for dry laser processing. An LCP system (532 nm) with 50% $\text{H}_2\text{PO}_4$ solution was also used to achieve n-type doping with a liquid-jet approach. Laser doped boxes ($1.5 \times 5.0$ mm$^2$) are formed by $\sim50\%$ overlapping single laser grooves with different laser parameters. Further experiments were conducted on ion implanted samples, in which a dry laser was used to activate the implanted dopant atoms. These quarter samples were first implanted with either boron ($30 \times 15$ mm$^2$, $40$ keV, and $1 \times 10^{15}$/cm$^2$) or phosphorus ($30 \times 30$ mm$^2$, 40 keV, and $1 \times 10^{15}$/cm$^2$), and laser annealing with different laser parameters. After laser processing, all samples were subjected to an HF dip to remove the coatings and any possible passivation layers such as oxides formed during the laser processing. Then, the sheet resistance of the laser doped areas was directly measured by a four point probe measurement on the boxes. Finally, PL images of the laser doped samples were obtained with a BT Imaging LIS-R1 tool.\textsuperscript{16} An 810 nm laser, whose photons have an energy of $2.45 \times 10^{-19}$ J/photon is used to generate excess carriers and the resulting band-to-band PL radiating from the samples captured by a one megapixel silicon CCD camera. A relatively small illumination area with high intensity was used to achieve a measurable PL signal despite the relatively low lifetime of the unpassivated samples. Note that there is no rear side passivation during PL imaging.

III. RESULTS AND DISCUSSION

A. The PL intensity ($I_{PL}$) of the laser doped regions as a function of the $R_{SH}$

Figure 1 shows a PL image of a p-type silicon wafer with n-type doping boxes by different laser techniques. The incident photon flux was $8.65 \times 10^{17}$ cm$^{-2}$ s$^{-1}$ corresponding to 0.21 W/cm$^2$ illumination. The generation rate for acquiring this PL image is $\sim2.1$ Suns when considering that 1 Sun equals to 0.1 W/cm$^2$. The bottom row is DPSS laser doped from a P-SOD source with increasing laser energy (from left to right), and the middle row corresponds to the regions doped using the excimer laser from the same P-SOD with decreasing laser energy. After removing the P-SOD layer with an HF dip, the upper row is prepared by LCP with phosphorus acid solution by increasing laser energy. All the laser doped boxes in Fig. 1 show different PL intensities, and the area without laser processing shows a lower $I_{PL}$. With increasing DPSS laser energy (bottom row from the left), the $I_{PL}$ of the box increases continuously, reaches the maximum intensity at box No. 1 (as labeled in red), and then decreases. The sheet resistance ($R_{SH}$) of the DPSS laser doped boxes decreases as the laser power increases, as shown in the inset plot of Fig. 2. The lowest $R_{SH}$ is achieved at box 1, and after that the sheet resistance increases as the laser power increases. The $I_{PL}$ of the boxes as well as the $R_{SH}$ obtained by excimer laser and LCP doping.

Fig. 1. PL image of a p-type wafer with n-type doping by different laser techniques: (1) DPSS and (2) Excimer laser doping from phosphorus spin-on-dopant layer; (3) LCP with phosphorus acid solution.

Fig. 2. Normalized $I_{PL}$ of laser doped regions as a function of $R_{SH}$ for the sample in Fig. 1. The inset plot shows the $R_{SH}$ of DPSS laser doped boxes versus laser power. The blue dashed line is guide to the eye.
exhibits a similar trend to that of DPSS laser doping, reaching a maximum intensity and minimum RSH at the boxes 2 and 3, respectively. It should be pointed out that the boxes prepared with the high laser energies show low $I_{PL}$ and high RSH (e.g., boxes 4–9). Five different points are picked up at the center of each box, and an average PL intensity for each box is calculated. The PL intensity deviation of the points from the average is shown by the error bar. Fig. 2 shows the normalized inverse PL intensity ($I_{PL}^{-1}$) of the DPSS laser doped boxes as a function of RSH. The data from the excimer laser and LCP doping are also shown in Fig. 2. The $I_{PL}^{-1}$ values were normalized by the linearly extrapolated value at zero RSH. It can be seen that the RSH of the laser doped boxes increases linearly with increasing $I_{PL}^{-1}$ in the low RSH range (<200 Ω/□), which indicates that RSH of laser doped box is inversely proportional to the $I_{PL}$. For the three different laser doping techniques, the maximum PL intensities are observed at boxes 1, 2, and 3, which correspond to a minimum sheet resistance of 31, 46, and 34 Ω/□, respectively. However, the linear relationship is broken for the boxes prepared with a high laser energy (boxes 4–9), which shows high sheet resistances.

PL imaging was also applied to characterize ion-implanted, laser annealed silicon samples. Figure 3 shows the PL images of ion-implanted samples before and after laser annealing. The incident photon flux for acquiring these PL images was $1.23 \times 10^{18}$ cm$^{-2}$ s$^{-1}$, which corresponds to a generation rate of 3 Suns (0.3 W/cm$^2$). Fig. 3(a) shows a typical PL image of an ion-implanted sample before annealing, in which the implanted dopant atoms are not activated. The ion implanted area shows a slightly lower PL intensity than the un-implanted area, probably due to sub-surface damage caused by the implant process. This damage is annealed out during subsequent laser annealing. Fig. 3(b) shows the PL image of the phosphorus implanted sample after DPSS and excimer laser annealing with different laser fluences. The $I_{PL}$ of the ion implanted area increases significantly after laser annealing, due to activation of the dopant atoms, which provides a degree of field-effect surface passivation on the front surface, leading to an increase in the effective lifetime, and therefore the $I_{PL}$. With increasing laser fluence, the $I_{PL}$ of the boxes increases and reaches the maximum at boxes 1 and 2 in Fig. 3(b). The PL image of a boron implanted sample after excimer laser annealing also shows a similar $I_{PL}$ change, as shown in Fig. 3(c). The normalized $I_{PL}^{-1}$ of the laser annealed boxes as a function of RSH in Figs. 3(b) and 3(c) are shown in Fig. 4, and the inset plot shows the RSH of the excimer laser annealed boxes versus laser fluences. The $I_{PL}^{-1}$ values were normalized in the same way. Again we note that the RSH of the laser annealed boxes increases linearly with increasing $I_{PL}^{-1}$, which is similar to that of the laser doping results presented above. A non-linear deviation is again observed for the boxes with high RSH (boxes 3 and 4 in Figs. 3(b) and 3(c)).

Laser doping or annealing generally involves shallow melting of the silicon surface by laser radiation, dopant diffusion into the melt, and subsequent liquid phase epitaxial recrystallization from the underlying silicon. As the diffusion coefficient for dopants in the liquid phase is much higher than in the solid state diffusion, junctions up to several microns of depth can be formed in a short period of time. With a laser energy that is lower than the ablation threshold, a defect-free epitaxial layer will grow from the melt without impact on the
effective lifetime after the laser processing.\textsuperscript{26,27} As the laser fluence increases, the melt lifetime and depth increase, which leads to a lower \( R_{\text{SH}} \). However, when the laser fluence exceeds the ablation threshold, the \( R_{\text{SH}} \) of the laser processed region increases because of silicon evaporation as well dopant evaporation.\textsuperscript{28} Moreover, a high laser power may cause severe ablation of silicon, which could lead to a radically different doping profile, and also increased surface roughness, which may affect the PL emission. This may explain the deviation for the boxes with high \( R_{\text{SH}} \) prepared by high laser energy.

**B. Theoretical derivation of the relationship between \( I_{\text{PL}}^{-1} \) and \( R_{\text{SH}} \)**

In the PL imaging technique, the measured \( I_{\text{PL}} \) is proportional to the product of the total electron and hole concentrations giving\textsuperscript{29}

\[
I_{\text{PL}} \propto \Delta n(\Delta n + N_A) \text{ for any injection level,} \tag{1}
\]

where \( \Delta n \) is the excess carrier density and \( N_A \) is the doping concentration for a p-type sample. For a sample in which recombination is dominated by heavily-doped regions at the surface, the effective lifetime (\( \tau_{\text{eff}} \)) is inversely proportional to the emitter saturation current density (\( J_{\text{oe}} \))\textsuperscript{30}

\[
\tau_{\text{eff}}^{-1} \propto J_{\text{oe}}(\Delta n + N_A) \text{ for any injection level.} \tag{2}
\]

Under steady-state conditions, which occur during PL imaging, the \( \tau_{\text{eff}} \) is also given by,\textsuperscript{17}

\[
\tau_{\text{eff}} = \frac{G}{\Delta n}, \tag{3}
\]

where \( G \) is the generation rate. Eq. (3) yields \( \tau_{\text{eff}}^{-1} \propto G/\Delta n \), which combined with Eq. (2) gives

\[
G/J_{\text{oe}} \propto \Delta n(\Delta n + N_A). \tag{4}
\]

Comparing the injection dependence in Eq. (1) and (4) shows that

\[
I_{\text{PL}}^{-1} \propto J_{\text{oe}}/G \text{ for any injection level.} \tag{5}
\]

Eq. (5) demonstrates that \( I_{\text{PL}}^{-1} \) is proportional to \( J_{\text{oe}} \) at any injection level. Furthermore, Alamo and Swanson reported that the saturation current density of heavily doped silicon by diffusion can be described as\textsuperscript{31}

\[
J_{\text{oe}} = \frac{q n_i^2}{\int_0^x \frac{N_{D_{\text{eff}}}}{D_p} \, dx + \frac{N_{D}(W)}{S}}, \tag{6}
\]

where \( q \) is the elementary charge, \( n_i \) is the intrinsic carrier density, \( W \) is the emitter thickness, \( N_{D_{\text{eff}}} \) is the effective doping profile in the emitter, \( D_p \) is the diffusion constant of minority carriers, and \( S \) is the surface recombination velocity. For the unpassivated emitter, \( S \) is very large; \( J_{\text{oe}} \) becomes

\[
J_{\text{oe}} = \frac{q n_i^2}{G_{\text{eff}}(W)}. \tag{7}
\]

where \( G_{\text{eff}}(x) = \int_0^x \frac{N_{D_{\text{eff}}}}{D_p} \, dx \), and \( G_{\text{eff}}(W) \) is called the effective Gummel number of the emitter.\textsuperscript{30} For a heavily doped emitter with a typical surface concentration between \( 10^{18} \) and \( 10^{20} \) cm\(^{-2}\), the minority carrier mobility almost remains constant according to Klakken’s model.\textsuperscript{32} Therefore, we could approximately consider that

\[
\int_0^x \frac{N_{D_{\text{eff}}}}{D_p} \, dx \propto R_{\text{SH}}^{-1}. \tag{8}
\]

Combining (7) with (8), we get

\[
J_{\text{oe}} \propto R_{\text{SH}} \text{ for unpassivated emitters.} \tag{9}
\]

Cuevas et al. have demonstrated experimentally that in practice, the \( J_{\text{oe}} \) of a silicon wafer with thermally diffused heavily doped and unpassivated surfaces is proportional to the emitter \( R_{\text{SH}} \).\textsuperscript{25,33} which is the opposite behaviour to that of passivated emitters. The increase in \( J_{\text{oe}} \) with \( R_{\text{SH}} \) for un-passivated samples results from the fact that only the field-effect passivation of the dopant profile is present, and so a more heavily doped surface provides a greater degree of passivation, and therefore a lower \( J_{\text{oe}} \).\textsuperscript{33} Note that in general, it is possible to achieve doped surfaces with similar sheet resistances, but with very different \( J_{\text{oe}} \) values, by altering the dopant profile. Therefore, Eq. (9) is not universally valid for unpassivated samples. To check if the relationship described in Eq. (9) can be applied to the laser doped regions in this work, an experiment was designed and carried out on a p-type quarter substrate with high resistivity (>100 \( \Omega \cdot \text{cm} \)). A 30 \( \times \) 30 mm\(^2\) n-type LCP doped region was achieved at the front side, and the \( R_{\text{SH}} \) of the LCP doped region measured by the 4PP was \( \sim 80 \Omega/\square \). After RCA cleaning, the rear side of the sample was passivated by SiNx, and the front side was left unpassivated. Then, the \( J_{\text{oe}} \) of the LCP doped region was determined by the QSSPC technique with the sample in high injection. The obtained \( J_{\text{oe}} \) was \( \sim 960 \) fA/cm\(^2\), which is consistent with the published result for an unpassivated diffused phosphorus emitter with the same \( R_{\text{SH}} \) (\( \sim 920 \) fA/cm\(^2\)).\textsuperscript{33}

We can therefore conclude that the laser doped regions have almost the same quality as thermal diffusions with the same \( R_{\text{SH}} \) for un-passivated, or contacted surfaces. Therefore, Eq. (9) is applicable to the laser doped regions in the absence of passivation, which is the relevant case for the laser doped regions under metal contacts of solar cells. Combining Eqs. (5) and (9) then gives the result which we observe experimentally

\[
I_{\text{PL}}^{-1} \propto R_{\text{SH}}. \tag{10}
\]

Eq. (10) indicates that \( I_{\text{PL}}^{-1} \) of the laser heavily doped regions without passivation is proportional to the \( R_{\text{SH}} \), which is consistent with the experimental results, as shown in Figs. 2 and 4.

**C. Numerical simulations**

To check the validity of the conclusion that \( I_{\text{PL}}^{-1} \) is proportional to \( J_{\text{oe}} \) under the experimental conditions we have used, a range of measurement conditions have been simulated...
using Quokka, which is a freely available and fast 2D/3D solar cell simulation tool. Quokka solves the semiconductor equations in the bulk of a unit cell, utilizing quasi-neutrality and conductive boundary approximations. The one dimension version of Quokka, which is done by setting open circuit as the terminal condition and defining virtual contacts in such a way so as to not significantly influence the simulation results, is used to fit the \( J_{oe} \) of laser doped regions to the PL intensity. The mean PL signal is implemented as described in Ref. 24, and the \( I_{PL}/C_0 \) values were normalized by the linearly extrapolated value at zero \( J_{oe} \). The rear side is assumed to be essentially unpassivated, with a surface recombination velocity of \( 10^5 \) cm/s. Figure 5 shows the 1D Quokka simulation results under different generation rates (0.3, 1, 2, 3, and 5 Suns), substrate thicknesses (200, 470, 1000 \( \mu \)m), bulk resistivity (0.1, 1, 10, 100 \( \Omega \)-cm), and substrate types (p- and n-type). One simulation process can be finished within 1 min. In most cases, we do indeed find that \( J_{oe} \) increases linearly with increasing \( I_{PL} \), although in some cases a non-linear deviation can be observed in the higher \( J_{oe} \), for example, for the low resistivity wafers (0.1 \( \Omega \)-cm), as shown in Fig. 5(c). However, even in this case, the relationship is still quite linear for the \( J_{oe} \) values lower than \( \sim 500 \) fA/cm\(^2\). The simulations confirm that \( I_{PL}^{-1} \) is proportional to \( J_{oe} \) for the experimental conditions used in this work.

For unpassivated surfaces, the laser doped regions studied here show a similar \( J_{oe} \) to that of diffused regions with the same \( R_{SH} \), which was shown in Sec. III A. Therefore, the \( J_{oe} \) values of the laser doped boxes with different \( R_{SH} \) in Figs. 2 and 4 can, in principle, be extracted from the empirical result of Kerr’s work. Fig. 6 shows the normalized \( I_{PL}^{-1} \) as a function of extracted \( J_{oe} \) for n-type laser doped regions on p-type substrate, as shown in Figs. 1 and 3(b). The Quokka simulations at the generation rates of 2.1 and 3.0 Suns are shown together, as shown by the dashed lines. A p-type substrate with 470 \( \mu \)m thickness and 100 \( \Omega \)-cm resistivity is used in the simulation. For both 2.1 and 3.0 Suns, the normalized \( I_{PL}^{-1} \) values show good agreement with the Quokka simulation results, which indicates that the modeling assumptions are valid. Moreover, this eventually proves that the relationship between \( R_{SH} \) and \( J_{oe} \) for the thermal diffused, unpassivated surfaces applies also to those laser doped regions.

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**FIG. 5.** Quokka simulations of \( I_{PL}^{-1} \) versus \( J_{oe} \) under different conditions: (a) generation rate; (b) substrate thickness; (c) bulk resistivity; and (d) substrate type. Apart from the variables, the parameters are set as 2 Suns generation rate, 470 \( \mu \)m thickness, 100 \( \Omega \)-cm bulk resistivity, and p-type substrate.
FIG. 6. Normalized $I_{PL}^{-1}$ as a function of extracted $J_{oe}$ for n-type laser doped regions in Figs.1 and 3(b). Quokka simulations of the normalized $I_{PL}^{-1}$ as a function of extracted $J_{oe}$ for n-type laser doped regions in Figs.1 and 3(b). Quokka simulations under the generation rate of 2.1 and 3.0 Suns are shown by the dashed lines together.

IV. CONCLUSIONS

In summary, we have investigated the $I_{PL}$ of laser doped regions as a function of $R_{SH}$ by PL imaging. We show that, in general, the $I_{PL}^{-1}$ of a sample in which recombination is dominated by a heavily surface-doped surface is proportional to $J_{oe}$ at any injection level. Since the $J_{oe}$ is also proportional to the $R_{SH}$ for passivated and unpassivated surfaces, we demonstrate that with increasing $I_{PL}$, the $R_{SH}$ of the laser doped regions decreases linearly. This provides the basis for a simple method to determine the optimized laser doping parameters to achieve a relative low $J_{oe}$ and $R_{SH}$. The application of this method to obtain the $J_{oe}$ and $R_{SH}$ values of laser doped regions could be achieved by a larger laser doped control region on which the $J_{oe}$ and $R_{SH}$ can be measured directly with other methods, and this then allows the proportionality constant to be determined for the other laser processed areas on the same or similar wafer. The work also proved that laser processed regions have a similar quality as thermal diffusions with the same $R_{SH}$ for passivated or metal contacted surfaces. However, it should be note that a significantly lower quality of the laser processed regions may be observed if passivated.

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