Comprehensive Microscopic Analysis of Laser-Induced High Doping Regions in Silicon

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Abstract—Microscopic laser-doped regions in advanced solar cell concepts are analyzed to determine the doping density and to identify the damage caused by the laser process. For these investigations, microphotoluminescence spectroscopy and micro-Raman spectroscopy are utilized to measure doping density, internal stress, and carrier lifetime with micrometer resolution. This analysis proves the high applicability of the microspectroscopic techniques for the characterization of laser-doped regions by analyzing the profile of the advanced local doping process and the laser-induced damage particularly at the edges of the highly doped regions.

Index Terms—Laser doping, photoluminescence, Raman, solar cells.

I. INTRODUCTION

In order to further exploit the high-efficiency potential of silicon solar cells in industrial cell manufacturing, effective and industrially feasible rear side passivation and contacting schemes are needed (e.g., [1] and [2]). Recently, Suwito et al. have introduced such a scheme for n-type solar cells [3]. It is based on a passivation layer of highly doped amorphous silicon carbide on the rear side of the cell, which is locally opened by laser irradiation [4]. Simultaneously, the dopant from the passivation layer diffuses into the wafer due to laser-induced melting, and thus, diffusion in the liquid phase takes place. This highly doped region acts as a local back surface field (BSF). The highly doped layer, which serves both as a passivation layer and dopant source layer, is named PassDop layer. The process sequence is shown in Fig. 1. Using n-type base material, the PassDop concept has demonstrated to enable cell efficiencies of up to 22.4%.

For the target-oriented optimization of this and similar laser doping processes, a comprehensive and high-resolution characterization of the resulting doping distribution, carrier lifetime, and stress is desirable. A spatial resolution on the order of 1 μm is required, since the dimensions of the laser-doped structures are on this scale. In this paper, we demonstrate microphotoluminescence (μPLS) [5] and micro-Raman spectroscopy (μRS) as suitable techniques for such a characterization, since μPLS and μRS are able to measure the crucial parameter stress [6]–[8], carrier lifetime [9], [10], and doping density [11]–[13] with a resolution between 500 nm and 1 μm. Some other methods, which have been applied in the literature for the highly resolved measurement of doping densities in silicon, are scanning capacitance microscopy [14], [15], electron-beam-induced current [16], secondary ion mass spectroscopy, and spreading resistance probe (SRP). The applied microspectroscopic techniques offer the advantage over these highly resolving doping measurement techniques to provide the carrier lifetime and stress within the same measurement at comparatively low preparation effort.

II. EXPERIMENTAL

Two PassDop samples are prepared following [3] on float-zone silicon with a base resistivity of 1 Ω·cm (phosphorus or boron doped) and a thickness of 250 μm: In sample A, phosphorus is used as dopant of the PassDop layer, and in sample B, boron is used. The laser doping yields 60-μm-wide and about 2-μm-deep highly doped regions with surface doping densities on the order of several 10^{19} cm^{-3} (see [3] for a representative doping profile). In order to make the highly doped regions accessible for μRS and μPLS measurements, polished cross sections from the highly doped regions are prepared (schematic in Fig. 1).
For μRS and μPLS, we use a confocal microscope with a 532-nm excitation laser with up to 27-mW power on the sample. Details on this setup can be found in [5], [8], and [17]. μRS is commonly used to measure stress in silicon [6], [7] but is also able to measure the doping density by Fano resonance [11], [12] analysis. The Fano resonance is caused by an interaction between free carriers in their continuous states and Raman phonons in their discrete states. The resonance between these states leads to an asymmetry of the first-order Raman peak for hole densities above $5 \times 10^{17}$ cm$^{-3}$ and electron densities above $5 \times 10^{19}$ cm$^{-3}$. The peak profile $I(\Omega)$ over the wave vector $\Omega$ is described by the formula [11], [18]

$$I_{q,\Omega_{\text{peak}},\Gamma}(\Omega) = I_0 \left[ \frac{\beta + 2(\Omega - \Omega_{\text{peak}})\Gamma^{-1}}{\beta + 2(\Omega - \Omega_{\text{peak}})\Gamma^{-1}} \right]^2.$$  

From the parameters $q$ and $\Gamma$, the doping density can be calculated from μRS measurements after calibration [11], [12], [19]. $q$ is positive for high hole densities and decreases with increasing hole densities. $\Gamma$ increases with increasing hole densities [11]. Concerning the doping densities in the Pass-Dop samples, only the acceptor density can be measured with Raman measurements. For high laser powers, which generate sufficient hole densities to influence the Fano resonance, the carrier lifetime can be extracted as well [9]. Details on these techniques and the calibration for the quantitative analysis employed here can be found in [9], [13], and [20]. In this paper, for calculating the hole densities from $\Gamma$, the calibration table from [13] is used. The resolution of μRS is mainly limited by the laser wavelength and is on the order of 500 nm.

μPLS can measure the carrier lifetime and the doping density quantitatively by evaluating the depth profile of the generated carriers [10]. The PL intensity can be used as qualitative measure for the carrier lifetime in the case of homogeneous doping densities and vice versa. Since the bandgap energy narrows at high doping densities, the PL spectrum is shifted to longer wavelengths at high doping densities. The shift of the band-to-band peak is extracted from a fit of the spectrum at each measurement point with an empirical function as described in [8]. From this shift, the doping density can be calculated. In order to calculate the doping density from the PL peak shift, we use the data in [21]. The resolution of μPLS is limited by the diffusion of the free carriers. Since the injection densities are on the order of $5 \times 10^{18}$ cm$^{-3}$, Auger recombination limits the diffusion length to about 1 μm, which consequently defines the spatial resolution.

III. RESULTS

A. Doping Density Measurement

The polished cross sections of the highly doped regions are investigated by μPLS and μRS. For μPLS, the laser power is 26 mW on the sample, and for μRS, the laser power is 26 mW for the carrier lifetime and stress analysis and 0.7 mW for the doping density measurement.

The doping density in the boron-doped BSF is measured with μPLS and μRS. The Fano analysis detects doping densities within the BSF of up to $6 \times 10^{19}$ cm$^{-3}$ (Fig. 2). The width of the BSF is about 2 μm, which is in agreement with SRP measurements in [3]. The measured doping levels are partly higher than the levels measured by SRP, which can be ascribed to the inhomogeneity of the BSF and the considerably lower lateral resolution of SRP which leads to an averaging over lower and higher doped areas. At the left side, the doping is found to be very inhomogeneous and hook shaped. This is confirmed by the μPLS measurement (Fig. 2), which underestimates the absolute value of the doping density due to its lower spatial resolution.

For the doping measurement of the phosphorus BSF only, μPLS can be applied, since the Fano resonance occurs for $n^+$ only at electron densities above $5 \times 10^{19}$ cm$^{-3}$. The doping density measurement shows a more homogeneous BSF with doping levels of up to $2 \times 10^{18}$ cm$^{-3}$. Since, in this sample, the depth of the BSF is on the order of the spatial resolution, the doping level is underestimated compared to the SRP measurements in [3], which show a maximum doping density of $2 \times 10^{19}$ cm$^{-3}$.

B. Carrier Lifetime Measurement

The effect of the laser process on the carrier lifetime is less pronounced for the phosphorous than for the boron laser-doped region. Since the doping can be measured more reliably for the boron-doped BSF, the results are discussed further for the p-type sample. Outside of the laser-doped region, the PL intensity measured by μPL shows a 4-μm-wide region with reduced carrier lifetime (Fig. 3(a)). This laser-induced lifetime decrease is particularly high at the edges of the BSF and varies strongly around the BSF. At the areas, which are marked by black arrows, the damage is particularly strong, whereas at the white arrow, only a slight decrease in PL intensity is observed. This result is confirmed by the Fano analysis of the μRS measurement (Fig. 3(b)). The injected hole density and thus the carrier lifetime show the same behavior as the PL intensity.
C. Stress Measurement

The $\mu$RS measurement also detects some laser-induced mechanical stress on the crystal. Since within the BSF the position of the Raman peak is dominated by the shift due to the high doping densities, only the measurement signal outside the BSF is analyzed (Fig. 4). In the vicinity of the BSF, the stress is significantly increased. At the position with less effect on the effective carrier lifetime (white arrow), the compressive (negative) stress is high. At the black arrows, tensile stress is predominantly measured.

IV. DISCUSSION AND CONCLUSION

The microspectroscopic analysis of the laser-doped BSFs has been able to measure the doping density within the BSFs with a high spatial resolution on the order of 1 $\mu$m and hence enables 2-D mapping the doping profile induced by the PassDop concept [3].

Furthermore, $\mu$PLS and $\mu$RS give valuable information for future optimization of the process parameters by detecting inhomogeneities in the doping density and the impact of the laser process on the carrier lifetime near the BSFs. The injection conditions of the $\mu$PLS and $\mu$RS measurements, which are far higher than under typical solar cell operation, were shown to be well transferable to low injection conditions in [10], since the Shockley–Read–Hall lifetime is proportional to the inverse defect density for both low injection and high injection.

The Raman stress analysis gives first indications for the reason of a reduced carrier lifetime. Around the presently processed highly doped regions, the stress is significantly increased. Tensile and compressive stresses are present at different positions. These stresses might develop due to the thermal strain during the fast heating by the laser and the subsequent cool down. Stress can be partly relieved by the formation of dislocations [7], which, in turn, can act as recombination centers and limit the carrier lifetime. The fact that the compressive stress is particularly high at the white arrow, where only a faint carrier lifetime decrease is observed, might be due to the piezoresistance of silicon [22], which leads to a weaker recombination flux and hence a lower recombination activity of defects at compressive stress [23], [24]. However, also stress-induced dislocation formation might be responsible for the high recombination activity in some areas.

In conclusion, $\mu$PLS and $\mu$RS allow for a comprehensive characterization of laser-doped microscopic structures by measuring doping density, recombination activity, and stress. In the measured samples, the effect on the carrier lifetime was more intense for the boron doping than for the phosphorous doping. This is in good agreement with $V_{oc}$ measurements on these cells, which show systematically higher $V_{oc}$’s for the phosphorus BSFs than for the boron BSFs. This information output makes these techniques highly suitable for the optimization of new device concepts, e.g., solar cells with laser-doped structures.

ACKNOWLEDGMENT

The authors would like to thank M. Winterhalder and G. Räuber for the sample preparation.

REFERENCES


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