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Comprehensive Characterization of Advanced Cell Concepts with Sub-Micron Resolution

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Abstract

We introduce a comprehensive characterization approach of microscopic technological structures in advanced silicon cell concepts. Micro-photoluminescence spectroscopy and micro-Raman spectroscopy with their submicron resolution potential are applied, which allow a direct extraction of the most important parameters. These parameters are the micron resolved carrier lifetime, the doping density and the stress induced by the process. This paper covers exemplary measurements, which demonstrate the potential of this characterization approach for process optimization, details on the measurement techniques and on the sample preparation. The structures under test are laser doped back surface fields, nickel-plated contacts, back contact structures and epitaxial layers. The presented characterization techniques are able to reveal microscopic flaws in the technological structures and thus, allow for a direct and target-oriented optimization of the investigated processes.

Photoluminescence spectroscopy; Raman spectroscopy; carrier lifetime; silicon; solar cells

1. Introduction

Until now, the electrical characterization of microscopic doping structures such as selective emitters and local back surface fields as well as of front-side contacts and epitaxial layers were mainly based on measuring their impact on global cell performance i.e. IV parameters of cells with these structures. This conventional approach only allows for indirect indications on the quality of the microstructures. As an option with high potential to fill this gap this paper introduces a comprehensive characterization concept based on micro-photoluminescence spectroscopy (μPLS) and micro-Raman spectroscopy (μRS) mapping.

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These techniques are well suited to measure the doping density [1, 2], the carrier lifetime [3, 4] and stress [5-7] with a spatial resolution of below 1 µm.

In this paper we demonstrate the potential of the microscopic spectroscopy techniques for characterization of technological structures in the photovoltaic research and industry on several different systems. These include a back contact structure, laser doped back surface fields, nickel-plated front contacts and epitaxial layers on partly opened oxide layers.

2. Measurement techniques

In this paper µRS and µPLS are utilized. The core of both techniques is a confocal setup with an excitation laser at 532 nm wavelength and an adjustable laser power between 0 mW and 26 mW on the sample focused on a spot of approximately 0.6 μm^2.

For mapping the Shockley-Read-Hall lifetime the dependence of the carrier density depth profile on the lifetime is used for the µPLS technique [4], while the µRS technique is based on the Fano resonance between holes and phonons [3].

For the doping mapping the µPLS technique makes use of the bandgap narrowing for high doping densities, which allows for the extraction of n- and p-type doping [2], and the µRS technique is based also on the Fano resonance, which limits this technique essentially to p-type doping [1, 8, 9]

From the intensity of the Raman peak the grain orientation can be extracted [5].

3. Results

The micro-spectroscopy techniques applied in this paper do not require any surface passivation but flat surfaces (variations below 0.5 µm). Thus the sample surfaces are polished for the analysis except for the back contact structure, which is already prepared on a flat floatzone silicon wafer.

3.1. Back contact structure

The back contact structure consists of a phosphor back surface field with a surface doping density of $3.8x10^{19}$ cm^{-3} and a doping depth of 0.5 µm and boron emitter with a surface doping density of $5x10^{18}$ cm^{-3} and a depth of 0.8 µm, as determined from SIMS-profiles on test samples. A schematic of the doping is depicted in Fig. 1 left. For the characterization of this contact the homogeneity of the doping and possible detrimental effects on the device performance due to the doping process are particularly important.

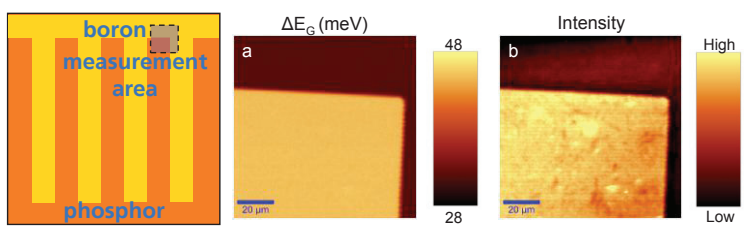

Figure 1: Left: Schematic of the doping in the back contact structure. In subsection 3.1 the marked area is characterized by means of photoluminescence. Right: a) image of the shift of the band-to-band luminescence in comparison to a lowly doped wafer and b) image of the photoluminescence intensity on the back contact structure. The bandgap shift shows a homogeneous doping within each doping area, while the photoluminescence intensity reveals significant lifetime inhomogeneities in the phosphorus doped BSF, which are most likely caused by the doping process.

This back contact structure is characterized here by means of µPLS. The homogeneity of the doping within the differently doped regions is extracted from the band-to-band peak shift (Fig. 1 a), while the homogeneity of the carrier lifetime within both regions is extracted from the peak intensity (Fig. 1 b).

3.2. Laser doped back surface field

The here analyzed samples feature laser induced phosphor and boron back surface fields. The doping is in-diffused from a highly doped silicon carbide layer (*PassDop* layer) by local laser heating of the sample [10, 11]. More details on this advanced high efficiency process can be found in Ref. [10].

Since the laser process can induce stress and damage in the surrounding silicon, these parameters and the homogeneity of the doping density are analyzed for the laser doped back surface fields. For this investigation cross sections are polished after the laser doping.

3.2.1. Doping density measurement

The Fano analysis detects doping densities within the back surface field (BSF) of up to $6x10^{19}$ cm^{-3} (Fig. 2 left side). The width of the BSF is about 2 µm, which is in agreement with SRP measurements in ref. [10]. 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 very inhomogeneous and hook-shaped. This is confirmed by the µPLS measurement (Fig 2 left side), which underestimates the doping density due to its lower spatial resolution.

For the doping measurement of the phosphorus doped BSF the µPLS doping mapping is applied. The doping density measurement shows a more homogeneous BSF with doping levels of up to $2x10^{18}$ cm^{-3}. Since in this sample the depth of the BSF is in the order of the spatial resolution, the doping level is underestimated.

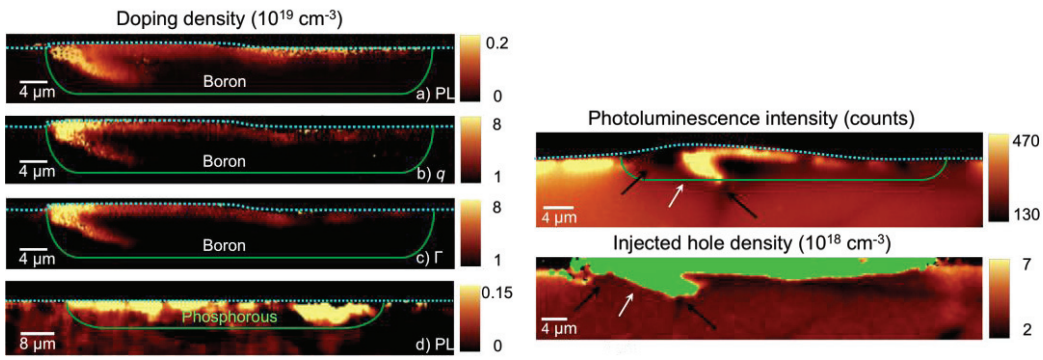

Figure 2: Left: Doping density measured by µPLS a) for the boron doped BSF and d) for the phosphorus doped BSF. The Fano analysis provides a higher spatial resolution for the boron doped BSF. The doping density can be calculated from b) the asymmetry parameter *q* and from c) the peak width Γ. The approximate regions of the BSFs are marked with solid green lines, the sample surfaces with dotted blue lines. Right: a) Intensity of the PL peak measured with µPLS around the boron doped BSF. Outside of the highly doped region (bright) the decreased photoluminescence density shows an increased recombination activity in an area of approximately 5 µm width. The solid green line marks the region of the BSF, the dotted blue line marks the sample surface. This result is confirmed by the Fano analysis b).

3.2.2. Carrier lifetime measurement

The effect of the laser process on the carrier lifetime is less intense 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 photoluminescence intensity measured by micro-photoluminescence spectroscopy shows a 4 µm wide region with reduced carrier lifetime (Fig. 2 right side a). This result is confirmed by the Fano analysis of the µRS measurement (Fig 2 right side b).

3.3. Nickel-plated front-side contacts

Nickel-plated contacts offer the advantages of high aspect ratios, low series resistances and comparatively low costs [12]. However, the nickel plating process must be well controlled to avoid the in-diffusion of nickel into the space charge region and the consequent partial shunting of the solar cell [13]. The effect of this nickel in-diffusion is here analyzed by measuring the high recombination activity of the nickel. In order to demonstrate the potential of our measurement technique during technological developments, we investigate a sample, that was tempered at 500 °C for 10 minutes, representing a non-ideal tempering process with a too high temperature for the chosen emitter depth. In order to measure the carrier lifetime below the contacts polished cross sections are prepared.

The in-diffused nickel below the contact after this non-optimized process is clearly visible by means of the strongly reduced Shockley-Read-Hall lifetime in this region (Fig. 3), which was measured by µPLS. Below the valleys of the random surface pyramids the lifetime is particularly reduced, which could be confirmed by µRS measurements with an even higher spatial resolution. In contrast, on a sample processed within the correct temperature window, the damage-free preparation of Ni-plated contacts was demonstrated.

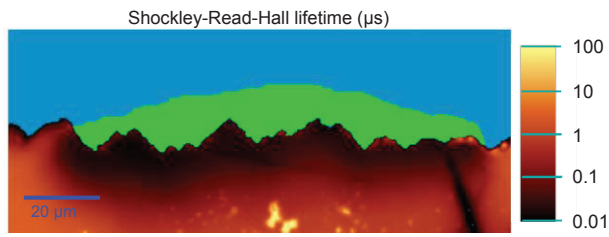

Figure 3: Shockley-Read-Hall lifetime below a nickel-plated contact, which was tempered at 500 °C for 10 min.

3.4. Epitaxial layer

The here analyzed concept for thin film crystalline silicon cells was recently introduced by Drießen et al. in Ref. [14], where details on this concept can be found. The concept is based on an epitaxial layer as solar cell base, which is grown on a silicon substrate. The silicon substrate is covered by an oxide layer for light trapping purposes, which is opened along seed lines in order to allow for an epitaxial growth (see Fig. 4).

To allow for a time resolved ex-situ measurement of the epitaxial layer growth the epitaxial layer is alternating boron doped with a density of either 5×10^{16} cm^{-3} or 2×10^{18} cm^{-3}.

In this paper we comprehensively analyze the quality of the epitaxial layer for two samples on polished cross sections after a non-optimized epitaxial growth process. In sample A the seed lines are parallel to the [100] direction of the monocrystalline substrate wafer, in sample B parallel to the [110] direction. The substrate wafer surface is (100) oriented.

The results of the two samples with different orientations show strikingly different results (Fig. 4): For sample A the epitaxial layer is monocrystalline, the stress is limited to the region around point B and the

lifetime is not reduced compared to the substrate wafer. In contrast the epitaxial layer in sample B is multicrystalline, strong stress extends over the entire layer and the carrier lifetime is strongly reduced.

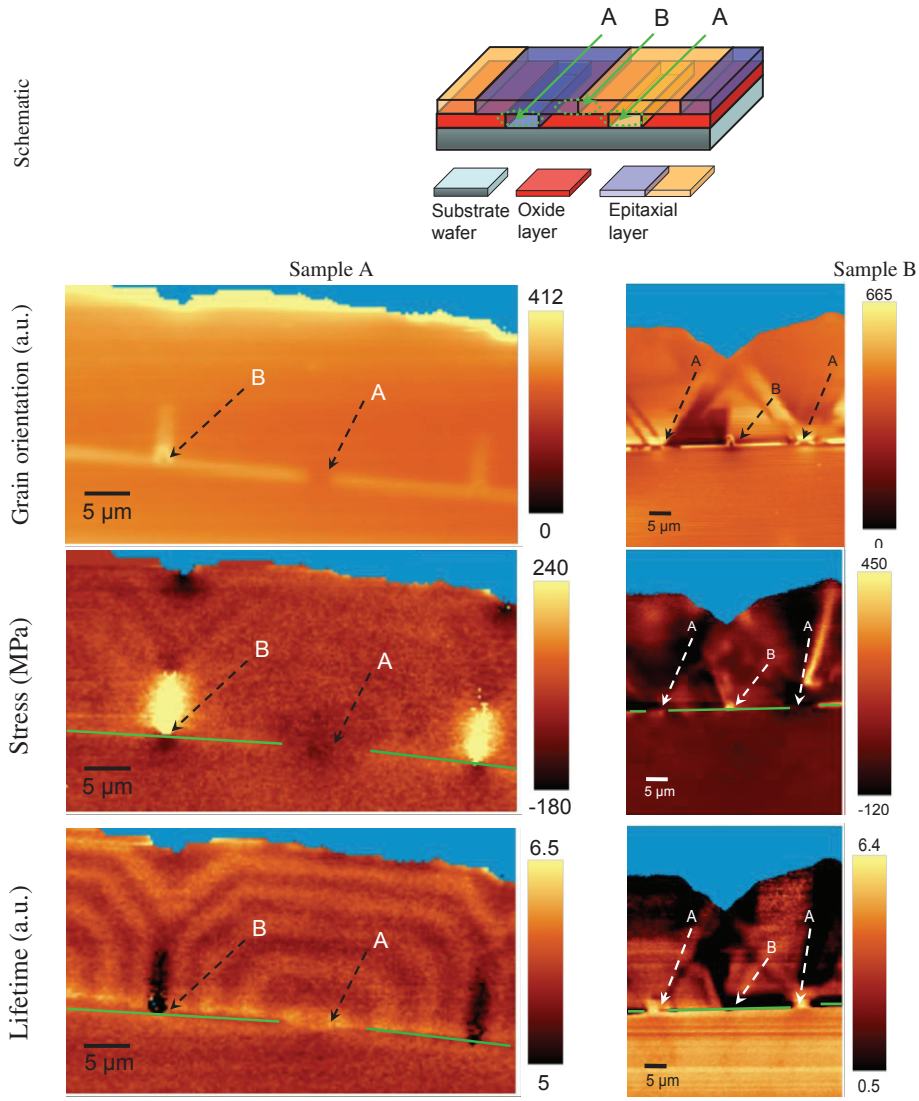

Figure 4: On top: Schematic of the epitaxial layer concept. The lines, where the oxide layer is opened, are labeled as “A” and the lines, where the epitaxial layers grown out of two adjacent lines merge, are labeled as “B”. Comparison of the grain orientations, the stress and the carrier lifetime in the epitaxial layers with differently oriented oxide opening lines.

4. Conclusion and discussion

So far it was hardly possible to directly investigate the electrical properties such as carrier lifetime and doping density in micro-structures. In this paper we proved the applicability and usefulness of a new characterization approach comprising micro-photoluminescence spectroscopy and micro-Raman

spectroscopy for the characterization of technological structures. These techniques provide the most relevant parameters carrier lifetime, doping density, grain orientation and stress with a submicron resolution. This is demonstrated on a back contact structure, laser doped back surface fields, nickel-plated front contacts and epitaxial layers on partly opened oxide layers.

On the back contact structure we proved the applicability for the measurement of doping and carrier lifetime homogeneities, which might be affected by doping processes.

The analysis of the laser doped BSFs showed, that the success of laser doping processes can be evaluated by means of the proposed characterization approach. Furthermore laser induced material damage was detected with high spatial resolution, which is crucial for an efficient process optimization.

The high applicability of the microscopic characterization techniques for the process optimization of front-side contacts was demonstrated on a nickel-plated contact, where the nickel in-diffusion could be directly measured for a non-optimized plating process with a too high temperature of 500 °C.

The new characterization approach was also proven to be suited for the analysis of silicon thin film concepts by measuring carrier lifetime, stress and grain orientation in an epitaxial layer.

In conclusion the proposed characterization approach based on micro-photoluminescence and micro-Raman spectroscopy is well suited for the efficient process optimization of microscopic solar cell structures including contacts, doping structures and thin film concepts.

Acknowledgements

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