A micro-photoluminescence-based technique is presented, to quantify and map sheet resistances of boron-diffused layers in silicon solar cell precursors with micron-scale spatial resolution at room temperature. The technique utilizes bandgap narrowing effects in the heavily-doped layers, yielding a broader photoluminescence spectrum at the long-wavelength side compared to the spectrum emitted from lightly doped silicon. By choosing an appropriate spectral range as a metric to assess the doping density, the impacts of photon reabsorption on the analysis can be avoided; thus, an accurate characterization of the sheet resistance can be made. This metric is demonstrated to be better representative of the sheet resistance than the surface doping density or the total dopant concentration of the diffused layer. The technique is applied to quantify sheet resistances of 12-μm-wide diffused fingers in interdigitated back-contact solar cell precursors and large diffused areas. The results are confirmed by both 4-point probe and time-of-flight secondary-ion mass spectrometry measurements. Finally, the practical limitations associated with extending the proposed technique into an imaging mode are presented and explained.

1. Introduction

Heavily-doped regions are critical components of crystalline silicon (c-Si) solar cells. They form the required p-n junctions allowing separation of free electrons and holes. A useful parameter to characterize the heavily-doped layers is their sheet resistance. However, due to their high doping concentrations and direct contacts with metal, the heavily-doped layers are often very recombination active, and hence, they can significantly reduce the cell performance. Hence, there is often a requirement to minimize the surface area of the heavily-doped layers to achieve high-efficiency solar cells. Therefore, it is challenging to quantify the sheet resistance of these heavily-doped regions in a contactless and non-destructive manner once their feature sizes approach micrometer scales. Current techniques to characterize the sheet resistance — such as electrochemical capacitance voltage (ECV), 4-point probe, and secondary-ion mass spectrometry (SIMS) — all have limitations due to either their spatial resolutions or their destructive natures. Isenberg et al. used free-carrier absorption of photons having wavelengths between 3 and 5 μm, emitted from a hot plate placed at the back surface of the investigated wafers, to determine their sheet resistances. This method yielded a spatial resolution of 50 μm. However, it requires a calibration wafer with the same background doping, thickness, and surface optics. Juhl et al. and Zhu et al. calculated sheet resistances from lateral voltage drops between light-excited regions and dark regions. The inhomogeneous illumination patterns were achieved by using either an optical filter or a digital micromirror device (DMD). However, it remains difficult to access micron-scale structures in solar cells due to limits in feature sizes of the patterns.

In recent years, with the advent of micro-photoluminescence spectroscopy (μ-PLS) tools, equipped with confocal optics, microstructures in Si wafers and solar cells can be investigated with very high spatial resolution, enabling the study of dislocation clusters, grain boundaries, metal and oxide precipitates, and locally laser-doped regions. Woehl et al. and Gundel et al. applied μ-PLS measurements at room temperature on carefully...
cross-sectioned and polished solar cell precursors to reveal the depth profile of heavily-doped regions, based on the shift of the photoluminescence (PL) peak caused by bandgap narrowing. This method is both restricted to relatively thick doped layers (tens of microns) such as aluminum-alloyed regions and it is destructive. Heinz et al.\cite{14} used integrated PL intensities whereas Roig et al.\cite{15} used an intensity-weighted spectral position of the entire PL spectrum emitted from the heavily-doped layers to determine their doping densities. These authors performed μ-PLS measurements from above the sample surface at room temperature and use calibration curves from uniformly heavily-doped wafers to extract the doping densities of the heavily-doped layers. This approach is restricted to heavily-doped layers whose doping profiles are uniform depth-wise. Also, in principle, it can be affected by photon reabsorption due to the use of the entire spectrum as the measurement parameter. Nguyen et al.\cite{17} proposed to assess doping densities of thin heavily-doped regions (typically used in solar cell applications) by performing μ-PLS measurements at low temperatures utilizing the distinct PL peak emitted from the heavily-doped layer itself. The position, intensity, and shape of this peak are strongly dependent on the doping profile of the heavily-doped layer, allowing high-resolution mapping of the doping profiles of the heavily-doped layers (Han et al.\cite{18}). However, a disadvantage of this technique is the requirement to use low temperatures (~80 K).

In this work, we present a method to characterize and map sheet resistances of heavily boron-doped layers, prepared by thermal diffusion processes, with micron-scale spatial resolution using a μ-PLS system at room temperature. The proposed technique is demonstrated to overcome the limitations mentioned above. First, we explain the underlying mechanism of the proposed μ-PLS-based technique. After that, we separate the impact of optical and electronic properties of the wafers on the PL spectra, and determine appropriate ranges of the spectra to yield a parameter that accurately reflects the sheet resistances. We then verify that this parameter is most representative of the sheet resistances, rather than the surface dopant densities or total dopant concentrations of the diffused layers. Based on numerous diffused Si samples whose doping profiles are known, we establish calibration curves for quantifying sheet resistances of various diffused regions, and we demonstrate micron-scale mapping of the sheet resistance on 12-micron-wide boron-diffused fingers. The results are confirmed by 4-point probe

**Figure 1.** Comparison of PL spectra emitted between diffused and non-diffused Si wafers at (a) 80 K and (b) 300 K, excited with the 532-nm laser. The spectra were normalized to the Si BB peak.

**Figure 2.** (a) Absorption depths of photons in c-Si at 80 and 300 K, calculated from Ref.\cite{26} (b) Impact of photon reabsorption on PL spectra at 300 K. Compared to the 200-μm-thick sample (200-μm curve), both the surface reflectivity (200-μm, rear reflector curve) and the wafer thickness (400-μm curve) affect the short-wavelength side of the normalized spectra, but do not change the long-wavelength side. Therefore, the observed change in the long-wavelength side is due to the diffused layer (400-μm, 160-ohm sq cm curve). (c) PL spectra of diffused wafers with different sheet resistances at 300 K. The two broken vertical lines indicate the spectral range unaffected by the optics and the diffused layers.
and time-of-flight (TOF) SIMS measurements. Finally, we present and explain practical limitations associated with extending the method into an imaging mode.

2. Experimental Details

The first sample set consists of thirty boron-diffused samples fabricated from float-zone (FZ) 100-Ω·cm n-type Si wafers. They had various diffusion profiles and were used to establish calibration curves for sheet resistances. Their sheet resistances ranged from 20 to 200 Ω·sq−1, covering a practical range for photovoltaic applications. The second sample set consists of three interdigitated back-contact (IBC) solar cell precursors fabricated from FZ 5-Ω·cm n-type Si wafers, whose finger width is ~12 μm. The third sample set is a nonuniform boron-diffused wafer. It was placed close to dummy wafers inside the diffusion quartz tube so that the gas flow could not reach the wafer center, creating a very nonuniform diffusion across the wafer surface. The doping profiles were measured using an ECV profiler, and the sheet resistances were measured using a 4-point probe apparatus.

The μ-PLS system employed in this study was a Horiba LabRAM system at the Australian National University (ANU), equipped with confocal optics and a liquid-nitrogen-cooled InGaAs array detector. The excitation source was a diode-pumped solid-state (DPSS) 532-nm laser. The laser light was focused into the sample surface via two objective lenses—a 50× lens whose numerical aperture is 0.55 and a 10× lens whose numerical aperture is 0.25. The on-sample illumination spot size was ~1 and ~2.5 μm for the 50× and 10× lenses, respectively. The on-sample power was kept constant at ~20 and ~40 mW, yielding power densities of 25 kW·mm−2 (25 × 10⁶ suns) and 8 kW·mm−2 (8 × 10⁶ suns), for all spectral PL measurements with 50× and 10× lenses, respectively. The spectral response of the entire system was determined with a calibrated halogen-tungsten light source. The sample temperature was controlled using a liquid-nitrogen-cooled Linkam stage.
The two PL imaging systems employed were custom-built systems. The first imaging system, at the National Renewable Energy Laboratory (NREL), was operated at both 80 K and room temperature, and was equipped with an InGaAs array camera, a DPSS 532-nm laser, and an objective lens with a field of view of ~800 μm in diameter. The laser light was passed through a beam cluster (100-ns pulse width, 0.1-pA pulsed beam current). The second imaging system, at the University of New South Wales (UNSW), was operated at room temperature and was equipped with an InGaAs array camera and various light-emitting diodes (LEDs) whose wavelengths ranged from ultraviolet to near-infrared, with intensities from 0.05–0.1 mW mm⁻² (0.05–0.1 sun). Due to their micron-scale image resolution, we refer to these techniques as “μ-PL imaging.”

An ION-TOF TOF-SIMS V time-of-flight SIMS (TOF-SIMS) spectrometer was utilized for imaging and depth profiling of boron in this study. Analysis was completed utilizing a 3-lens 30kV BiMn primary ion gun. A Bi⁺ primary-ion beam was used for depth profiles (operated in bunched mode, 10-ns pulse width, and 1-pA analysis current), and imaging was completed with 100-nm lateral resolution using a Bi₃⁺ primary ion-beam cluster (100-ns pulse width, 0.1-pA pulsed beam current). Sputtering during depth profiling was accomplished with a 3-kV oxygen ion sputter beam (20-nA sputter current). All spectra during profiling were collected at or below a primary ion dose density of 1 x 10¹² ions cm⁻² to remain at the static-SIMS limit.

3. Background and Method Description

In this section, we explain the underlying mechanism of the technique. **Figure 1a** compares normalized PL spectra emitted from Si wafers with and without boron-diffused layers, excited with the 532-nm laser at 80 K. The Si substrate emits a sharp peak at ~1130 nm and a small shoulder at ~1200 nm. The former is the main band-to-band (BB) emission assisted by a transverse-optical phonon, denoted as “Si BB.” The latter is a zone-center optical phonon replica (PR) of the main BB peak.[20] denoted as “PR of Si BB.” In the case of the diffused wafer, the diffused layer itself also emits a distinct PL peak at ~1160 nm and a small shoulder ~1230 nm. The 1160-nm peak and the 1230-mm shoulder are also a band-to-band emission and its phonon replica, respectively. They are shifted to longer wavelengths compared to those of the Si substrate due to band-gap narrowing effects in the heavily-doped Si layer.[21–23] Therefore, we denoted them as “HDBB” (Heavily-doped Band-to-Band) and “PR of HDBB.”

At room temperature, due to thermal broadening effects, the PL peaks emitted from both the diffused layer and the underlying substrate merge and form a very broad peak, as shown in **Figure 1b**. However, the long-wavelength side of the spectrum emitted from the diffused wafer is still significantly different from that emitted from the non-diffused wafer due to the HDBB peak. Therefore, in principle, one can use this spectral property to assess doping densities of diffused layers even at room temperature.

At low temperatures, there is no photon reabsorption due to the very small values of the absorption coefficient in the wavelength range of interest.[24–27] Thus, any change in the relative spectral shape reflects changes in electronic structures inside Si wafers. In contrast, at room temperature, due to photon reabsorption, wafer optics (thickness and surface reflectivity) can significantly affect the relative spectral shape. Therefore, we need to separate the effects of the optics and the diffused layers on the normalized spectra at room temperature.

**Figure 2a** shows the absorption depth of photons in c-Si at both 80 and 300 K, calculated from Ref.[26] **Figure 2b** compares normalized PL spectra of samples with different surface reflectance and thicknesses. Compared to the 200-μm-thick sample (200-μm curve), both the surface reflectance (200-μm, rear reflector curve) and the wafer thickness (400-μm curve) affect the short-wavelength side of the normalized spectra, but do not alter the long-wavelength side due to the very large absorption depth on this side. Hence, the observed change on the long-wavelength side is due only to the diffused layer...
(400-μm, 160-ohm sq−1 curve). Figure 2c shows the evolution of the long-wavelength side versus doping densities, characterized by the sheet resistances, of diffused layers. The results show that by choosing an appropriate spectral range, we can assess the doping densities of the diffused layers without interference from the wafer optics. Moreover, in Figure 2b and c, the spectral range between 1120 and 1140 nm, indicated by the two broken vertical lines, is relatively consistent across all samples, regardless of the optics and the diffused layers. Therefore, we take the ratio of the integrated intensities between 1140–1250 nm and 1120–1140 nm as a metric for assessing the diffused layers.

The sensitivity for the HDBB peak depends strongly on the experimental setup, as recently reported by Roig and co-workers [15] at room temperature. The sensitivity is improved when detecting near surface regions, which is done using short excitation wavelengths, high injection levels (Auger-limited diffusion lengths), a high numerical aperture objective lens, and a small confocal pinhole. Therefore, one would observe various degrees of impacts of diffused layers on PL spectra with different experimental setups (see Figure S1 in Supporting Information).

In the following sections, we will establish calibration curves for the specific experimental configurations used in this work.

4. Quantification of Sheet Resistance Using μ-PLS

In this section, we first examine correlations between the PL intensity ratio defined above, and the surface doping density, the total dopant concentration, and the sheet resistance of diffused layers. Figure 3a–c plot the PL ratios versus these parameters for the 532-nm laser, 20-mW power, 50× objective, and at 300 K. Figure 3d displays the doping profiles from ECV for a selection of diffused samples used in this work. In Figure 3a, the data are very scattered, showing no correlation between the PL ratio and the surface doping density. Meanwhile, the trend versus sheet resistance (Figure 3c) is much more evident than the trend versus total dopant concentration (Figure 3b). The stronger correlation with the sheet resistance than with the total dopant concentration stems from the fact that sheet resistance is a depth-wise integration of the product of the doping density \( N_A \) and the majority carrier mobility \( \mu \), \[ \rho_s = \int \frac{N_A \mu}{1 + \frac{N_A}{N_E}} \mathrm{d}z \] Meanwhile, PL intensity is a depth-wise integration of \( D_n \) (\( D_n + N_A \)), \[ I = \int D_n \mathrm{d}z \] in which the excess carrier density \( \Delta n \) is also related to the mobilities of both majority and minority carriers. Therefore, among the three parameters (surface doping density, total dopant concentration, and sheet resistance), the intensity ratio between 1140–1250 nm and
1120–1140 nm reflects most clearly the sheet resistance of the diffused layers. From thirty different diffused samples whose sheet resistance ranges from 20–200 ohm sq⁻¹, we can establish a calibration curve to interpolate any sheet resistance within this range for different boron-diffused regions, as depicted in Figure 3c. Note that this parameterization curve is only an arbitrary choice.

Now, we apply the technique on fingers in IBC solar cell precursors. Different diffusion processes were performed to create different diffusion profiles. Sheet resistance maps of three fingers in the three samples, determined from the calibration curve in Figure 3c, are displayed in Figure 4a–c. Their sheet resistances determined by 4-point-probe measurements and TOF SIMS profiles are also included for comparison. The 4-point-probe sheet resistances were measured on controlled wafers going through the same diffusion conditions as the three IBC cell precursors. The TOF SIMS profiles were measured in the middle of the three fingers and then converted into sheet resistances. The results from the three methods agree with each other, demonstrating that the technique can be employed to quickly determine sheet resistances of locally heavily-doped regions.

However, around the finger edges in Figure 4, we can observe nonuniformities of sheet resistances. Hence, we continue performing TOF SIMS scans across these fingers to verify whether these nonuniformities are due to variations in doping profiles or due to carrier smearing occurring during the µ-PLS measurements. Figure 5 compares the scanning profiles across the finger in 4a between the µ-PLS and TOF SIMS measurements. The SIMS profiles have sharper edges, whereas the µ-PLS profiles show broader edges. The arrows in Figure 5 indicate locations between which the difference occurs. The results demonstrate that the spatial resolution of the µ-PLS setup presented here is limited to ~3 μm around the edges of the locally heavily-doped regions.

Next, we continue applying the method on large-area samples. To scan a large area, we employed the 10× objective lens. Using the same procedure, we established a calibration curve for the 10× lens and displayed the results in Figure 6a. The 10× data are more scattered than the 50× data due to the weaker impacts of the diffused layers on the PL spectra captured with the 10× lens. Figure 6b and c show sheet resistances established by the µ-PLS method and the 4-point probe measurement. The two results are matched very well, demonstrating the applicability of the technique on large-area samples. Note that the diffusion in Figure 6b is not a typical diffusion process in our standard solar cell fabrication. This sample was placed very close to dummy wafers in the diffusion quartz tube so that the gas flow could not reach the wafer center, thus creating a very nonuniform diffusion across the surface to best demonstrate the feasibility of our technique on large areas.

5. Practical Limitations of Extending to Imaging Mode

In this final section, we discuss practical limitations preventing us from extending the µ-PLS mapping method described above into imaging modes. In principle, one could image the entire sample using a standard PL imaging tool and appropriate long-pass and short-pass filters. For example, we could use an 1140-nm long-pass filter to capture the PL image of the longer-wavelength side (affected by diffused layers), and an 1140-nm short-pass filter to capture the image of the shorter-wavelength side (not affected by diffused layers). If the optics and thickness are uniform across the sample, the intensity ratio between the long-pass and short-pass images could qualitatively reflect the sheet resistances of the diffused layers. However, the problem arising in the imaging mode is that the injection level is much lower than that in the µ-PLS measurements due to the spatial spreading of the excitation source. Under such reduced injection conditions, even though the laser light is absorbed near the surface, the generated excess carriers redistribute across the whole wafer thickness and laterally underneath the diffused layer. Furthermore, the lower depth of focus makes PL imaging less sensitive to the surface region. Therefore, the collected PL signal can be totally dominated by the underlying substrate.

To demonstrate these limitations, we capture PL intensity ratios from the IBC cell precursor using both µ-PLS mapping and µ-PL imaging techniques and display the results in Figure 7. The feature in this figure is a net of fingers forming the bus bar. The sheet resistance of the diffused region is 80 ohm sq⁻¹. The thin lines at the edge of the fingers in Figure 7b and c are artifacts due to different surface reflectances. In Figure 7a, the diffused fingers clearly show an enhanced PL ratio even at room temperature. In Figure 7b and c, due to low injection levels and the low depth of focus, these features are not observed. A sequence of similar images taken with ultraviolet (365 nm) to visible (505 nm) excitation light neither shows diffused patterns (Figure S3), although the absorption depth of the 365-nm light is only 10 nm, i.e., the excess carriers must be generated almost entirely in the diffused layer.

6. Summary

We have presented a technique for determining sheet resistances of boron-diffused layers in silicon wafers using micro-photoluminescence spectroscopy mapping at room temperature. By using the long-wavelength side of the PL spectrum, we can avoid the impacts of photon reabsorption on our analysis. We have demonstrated that the integrated intensity of the long-wavelength side of the normalized photoluminescence spectra has a strong correlation with the sheet resistance, rather than the surface doping density, of the diffused layers. We have then established calibration curves to quantify the sheet resistance of both locally diffused regions and large diffused areas. Finally, we have demonstrated that extending the method into an imaging mode has practical limitations due to the relatively low injection level in the imaging systems used here.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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