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# Evaluating depth distributions of dislocations in silicon wafers using micro-photoluminescence excitation spectroscopy

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**Abstract**

Combining micro-photoluminescence spectroscopy and photoluminescence excitation spectroscopy, we are able to observe the evolution of the luminescence spectra from crystalline silicon wafers under various excitation wavelengths. By interpreting the relative change of the luminescence spectra, we can detect and examine the distributions of the dislocations, as well as of the defects and impurities trapped around them, segregated at different depths below the wafer surface. We show that in multicrystalline silicon wafers, the dislocations and the trapped defects and impurities, formed during the ingot growth and cooling, are distributed throughout the wafer thickness, whereas those generated in monocrystalline wafers by a post-diffusion thermal treatment are located near the wafer surface.

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## 1. Introduction

Photoluminescence spectroscopy (PLS) and photoluminescence imaging (PLI) have been demonstrated to be powerful characterization tools in silicon photovoltaics. Utilizing the advantages of these two techniques, the so-called hyperspectral PL imaging technique, which combines both PLS and PLI, has been employed to capture macroscopic PL images from multicrystalline silicon (mc-Si) wafers in both spatial and spectral dimensions [1,2].

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Therefore, macroscopic properties of different radiative recombination centers at various locations in mc-Si wafers can be investigated separately. However, due to the limited number of pixels from the camera employed to detect a large area on the wafers, the spatial resolution of this hyperspectral PL-based method is on the order of several hundred micrometers [1-2]. As a result, microscopic properties of submicron features in crystalline silicon (c-Si) wafers and solar cells have not been accessible via this technique.

Recently, courtesy of the high spatial resolution from confocal optics, micro-PLS (μPLS) has been utilized to investigate electronic and optical properties of many submicron features in c-Si wafers and solar cells, such as dislocations [3-6], metal precipitates [7], or damage induced by laser-doped processes [8-10]. In addition, photoluminescence excitation (PLE) spectroscopy, in which the relative PL intensity at a certain wavelength is monitored when the excitation energy is varied, is a powerful technique to study fundamental properties of silicon and defects, such as the optical band gap in degenerate silicon [11,12] or oxygen-related deep defects in irradiated silicon [13]. Recently, we have applied a technique combining μPLS and PLE to evaluate spatial distributions of structures and defects separated at different depths inside silicon wafers [14].

Dislocation sites are an important lifetime killer in silicon solar cells [15]. The dislocations themselves are not only an effective recombination channel for free carriers, but also act as trapping sites for other defects and impurities due to the local stress and strain around them. These trapped defects and impurities, in turn, reduce the free carrier concentrations even further. The dislocations and the trapped defects and impurities can be generated either during the crystal growth of an ingot, or in subsequent solar cell fabrication steps. Due to the different natures of these two processes, the spatial distributions of the dislocations and the trapped defects and impurities are expected to be different. Therefore, in this work, we apply our recently-developed μPLS-PLE technique [14] to study the distributions of dislocations and other defects generated during these two processes. Defects formed during mc-Si ingot growth are shown to be distributed uniformly depth-wise in the silicon wafers, whereas the process-induced defects are found to reside near the wafer surfaces.

## 2. Experimental details

The sample investigated in Section 3 is a <100>-oriented float-zone boron-doped c-Si wafer. It was first chemically etched in an HF/$HNO_3$ solution to remove saw damage. It went through a thermal diffusion process in a $BBr_3$ gas source at 1050 $^{o}$C for 1 hour, and was then annealed in pure nitrogen gas at 1090 $^{o}$C for 5 hours while the borosilicate glass (BSG) and boron-rich layer (BRL) were both still present on the wafer surfaces. These process steps are aimed to generate dislocations, along with other defects and impurities, located below the wafer surfaces. After that, any residual BSG and BRL layers were finally removed prior to performing the PL measurements.

The sample investigated in Section 4 is a directionally solidified, boron-doped p-type mc-Si wafer with a background doping of about $9\times10^{15}$ cm$^{-3}$. This wafer was also first chemically etched in an HF/$HNO_3$ solution to remove saw damage. After that, it was immersed in a defect etchant consisting of acetic/$HNO_3$/HF acids for 16 hours. The purpose of this second etching step is to delineate sub-grain boundaries (sub-GBs), which are otherwise not observable under a confocal microscope. These sub-GBs are known to have a high density of defects and impurities forming during the ingot growth and cooling process [5].

The setup of our μPLS system is described elsewhere [5,14]. The excitation light source is a supercontinuum laser (NKT SuperK Extreme EXR-20) with a tunable wavelength range from 490 nm to 2 μm. In this work, excitation wavelengths between 510 nm and 810 nm with a bandwidth of 10 nm were employed. The on-sample power was kept constant at 6 mW for all excitation wavelengths. The diameter of the illuminated spot on the samples varied between ~1 μm (for 510-nm excitation wavelength) and ~2 μm (for 810-nm excitation wavelength). The spectral response of the entire system was determined with a calibrated halogen-tungsten light source.

## 3. Dislocations and impurities distributed near the wafer surface

In this section, we apply the combined PLS-PLE technique to detect dislocations, as well as other defects and impurities, distributed near the wafer surface. Figure 1a shows the normalized PL spectra from the boron-diffused and annealed c-Si wafer, excited with different wavelengths at 79 K. There are 3 distinct components in the spectra. The first component is the Band-to-Band (BB) peak at ~1130 nm emitted from the underlying c-Si substrate. The

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