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Effects of solar cell processing steps on dislocation luminescence in multicrystalline silicon

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Abstract

We examine the impacts of hydrogenation and phosphorus gettering steps on the deep-level photoluminescence spectra of dislocations and the surrounding regions in multicrystalline silicon wafers, using micro-photoluminescence spectroscopy with micron-scale spatial resolution. We found that the D1 line, originating from secondary defects around dislocation sites, was enhanced significantly after gettering but remained unchanged after hydrogenation, suggesting that the former process reduced the concentration of metal impurities around the dislocations while the latter process did not alter the relevant properties of defects and impurities. In addition, the D3 and D4 intensities were found to be unchanged after different processing steps, indicating that the intrinsic structure of the dislocations was not affected by the investigated processes. Finally, we report empirical evidence supporting the hypothesis that D3 is not the phonon replica of D4 due to their different intensity ratio at different locations in the wafers.

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Keywords: Crystalline silicon; deep level; dislocations; grain boundaries; photoluminescence (PL); photovoltaic cells

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1. Introduction

Recently, there has been an increasing interest in employing spectrally-resolved photoluminescence (PL) as an accurate and non-destructive characterization tool in silicon photovoltaics. By capturing the luminescence signal emitted from transitions of free carriers between the two band edges of crystalline silicon, fundamental properties of this material have been determined such as the band-to-band (BB) absorption coefficient [1-3], radiative recombination coefficient [2,4,5], temperature dependence of the band gap [6], and the extent of band-gap narrowing in heavily-doped silicon [7,8]. Also, BB spectral PL has been employed to extract the minority carrier diffusion length in silicon wafers [9,10] and bricks [11], to quantify light trapping in plasmonic structures [12], to investigate the effects of different surface morphologies [13,14] as well as carrier profiles [14] on the spectrum shapes, and recently to study properties of thin heavily-doped layers of cell pre-cursors [15]. On the other hand, defects and impurities occupying energy states within the forbidden gap of crystalline silicon can give rise to deep-level luminescence spectra, with the peak energies lower than that of the BB peak. These deep-level spectra contain distinct signatures for different kinds of defects and impurities such as Cr-B pairs [16], oxygen precipitates [17], Fe precipitates [18], and dislocations [19,20] in crystalline silicon.

In multicrystalline silicon (mc-Si), dislocation networks are one of the key factors limiting the final cell efficiency [21], and usually occur at small angle grain boundaries (SAGBs) and other sub-grain boundaries (sub-GBs). These dislocation sites have been reported to emit four distinct deep-level lines, known as D1, D2, D3, and D4. The doublet D1/D2 originates from secondary defects and impurities decorated around dislocations [22,23], whereas the doublet D3/D4 reflects the intrinsic properties of dislocations [22-26]. These results have been confirmed recently by Tajima *et al.* [23], in which D1 and D2 were found to occur around SAGBs, and D3 and D4 were present directly on SAGBs. Recently, utilizing the micron-scale spatial resolution of a confocal microscope PL spectroscopy system, we have shown that the D1 intensity was enhanced when the dislocations were cleaned of metal impurities after gettering, whereas the D2 intensity still remained the same, and confirmed that D1 and D2 had different origins [27]. Also, we proposed that D3 was not the phonon replica of D4 due to their different energy shifting when moving away from the sub-GBs.

Since the D lines reflect the properties of dislocations and the surrounding local conditions, they can be employed as a tool to monitor the behavior of defects and impurities around dislocations and the dislocations themselves during cell fabrication processes. Moreover, phosphorous gettering and hydrogenation are two essential steps which are naturally incorporated during the formation of diffused layers, and of antireflection coating (ARC) layers by chemical vapor deposition (CVD) and their subsequent firing. Thus, an insightful understanding of the behaviors of the D lines after these two processing steps may provide more information about the impact of gettering and hydrogenation on dislocations. Therefore, in this work, utilizing the high spatial resolution of a micro-PL (μPL) spectroscopy system, we report findings regarding the various effectiveness of the gettering process along the sub-GBs based on the D line emissions, and also investigate the behaviors of the D lines after the hydrogenation process. In addition, we also report further experimental findings to support the hypothesis that D3 is not the phonon replica of D4 [27].

2. Experimental details

The experimental setup in this study is described in detail elsewhere [27]. The μPL spectroscopy system has a spatial resolution of about 3 microns and a spectral resolution of about 0.25 nm. The sample temperature was kept constant at 79 K using a liquid-nitrogen-cooled cryostat. The samples studied here are directionally solidified, boron-doped p-type mc-Si wafers having a background doping of about 9×10^{15} cm^{-3}. Three samples were cut from three consecutive wafers in the same ingot, and chemically etched with an etchant of HF and HNO_3 to remove saw damage and to achieve optically polished surfaces. After that, the first sample was kept in the as-cut state. The second sample was passivated with a layer of SiN_x:H deposited by plasma-enhanced chemical vapor deposition (PECVD) using ammonia and silane as precursor gases. It was then annealed at 700 ^oC for 30 minutes in a N_2 gas environment in a quartz tube furnace to distribute hydrogen throughout the sample thickness. The third sample went through an extended phosphorous gettering process [28], which is described in greater details in Ref. 27. The sheet resistance of the resultant diffused layer was about 30 Ω/□. All samples were chemically etched again to remove