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Defect diagnostics in multicrystalline silicon using scanning techniques

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Abstract

During crystal growing, many dislocations are created in the multicrystalline silicon (mc-Si) material. Presence of these dislocations significantly changes the electrical properties of mc-Si wafer. We report here on photoluminescence (PL) and electron beam induced current (EBIC) mapping of recombination centers in low recombination regions limiting a performance of the mc-Si solar cells. By comparing PL mapping with the distribution of dislocations, we present experimental evidence that the 0.8 eV band corresponds to electrically active dislocation networks. At low temperature, a characteristic quartet of the dislocation D-lines was observed. One of these dislocation lines (D1) can be tracked as temperature increased and linked to the "defect" band. We also found using temperature dependent EBIC correlated with PL mapping that intense defect band luminescence originates from dislocation with low level of impurity contamination. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Silicon; Dislocations; Photoluminescence; Lifetime; EBIC

1. Introduction

Vigorous growth in the photovoltaic market over the past decade has been predominantly driven by advances in crystalline silicon technology. Multicrystalline silicon (mc-Si), which can be produced by ribbon or block-casting techniques, can meet both a low-cost production and a high efficiency requirement for solar cells. Since mc-Si wafers are inhomogeneous, this motivated development of mapping techniques to track recombination activity of defects across entire wafer and solar cell. We report here on photoluminescence (PL) and electron beam induced current (EBIC) mapping of recombination centers in high recombination regions of mc-Si wafers. These regions limit solar cell performance, and their monitoring, characterization, and reduction is a primary goal in the search for approaches to achieve high cell conversion efficiencies. We present experimental evidence that high recombination regions are characterized by an intense "defect" PL band, associated with contaminated dislocations, which are electrically active at room temperature.

2. Samples and methods

Materials used in this study were boron doped mc-Si wafers grown by Edge-defined Film-fed Growth (EFG) technique. The photoluminescence mapping and PL spectra were analyzed using SPEX-500 M grating spectrometer coupled to a liquid nitrogen cooled Ge detector. The PL signal was processed using a conventional lock-in technique. The PL spectra were corrected to the spectral response of the optical setup. A 800 nm AlGaAs laser diode operating in a pulse mode with a peak power up to 140 mW was used. Photoluminescence mapping at room temperature was performed by placing a mc-Si wafer on a computer controlled $X-Z$ moving stage. Spatial resolution in PL maps was limited by the diameter of the laser spot, which was approximately

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0.5 mm. Temperature study was carried out between 4.2 and 300 K in the variable temperature liquid helium cryostat.

3. Experimental results

Inhomogeneity in electronic properties of mc-Si wafers gives rise to distinct high and low lifetime regions. In the regions with low recombination activity and high value of the lifetime, the PL spectrum at room temperature consists of the band-to-band line with maximum at 1.09 eV. This line is caused by the phonon-assisted recombination of bound and non-bound free electrons and free holes [1]. On the contrary, regions with enhanced recombination activity and reduced minority carrier lifetime exhibit also an intensive "defect" PL band with the maximum at about 0.8 eV (Fig. 1, spectrum 1). The defect band maximum varies between 0.76 and 0.8 eV from point to point on the same wafer. Recombination properties of the 0.8 eV band were described previously [2].

The intensity of the defect band is highly inhomogeneous across the wafer. In Fig. 2, we present room temperature PL maps of band-to-band intensity (a) and defect band intensity (b). The dark areas on PL maps correspond to the low PL intensity while the light areas represent the high PL intensity. We observe a distinctive reverse correlation of two maps, i.e. regions with high band-to-band PL show negligible defect luminescence, and opposite, strong defect band is observed in regions with reduced band-to-band peak.

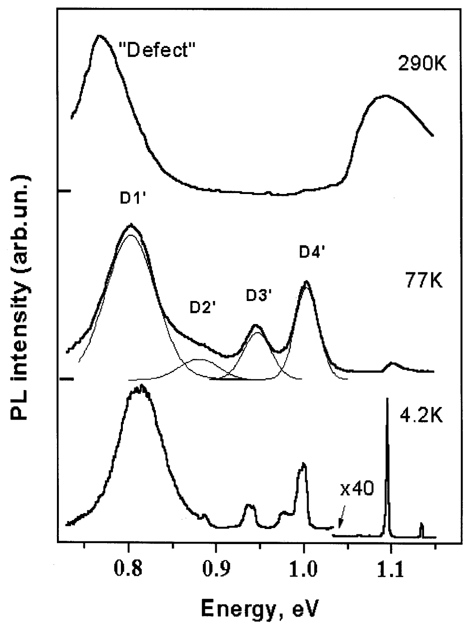

Fig. 1. PL spectra of an EFG wafer at different temperatures. The spectrum at 77 K is deconvoluted numerically to resolve four individual D_1'–D_4' Gaussian peaks.

We reported previously [2,3] that the topography of band-to-band PL distribution correlates with distribution of minority carrier lifetime across the wafer. Fig. 3(b) shows both band-to-band PL and diffusion length line scans. We statistically proved using mapping technique that the band-to-band PL positively correlates with minority carrier lifetime.

To assess a possible origin of the defect band luminescence, we performed measurements of PL spectra at low temperature. Three PL spectra at different temperatures measured at the same spot on an EFG wafer are compared in Fig. 1. At room temperature, the defect band is centered at 0.77 eV. As temperature is lowered, the defect peak shifts to higher energy corresponding to the temperature dependence of Si band gap. At 77 K, rich spectral features are now observed at energies below 1.05 eV. Two bands appear at 0.95 and 1.00 eV. At lower energies, the PL spectrum shows the defect maximum at 0.80 eV with a barely resolved additional band as a shoulder. This band was identified with defect maximum at room temperature. At 4.2 K (Fig. 1, spectrum 3), the band-to-band emission is replaced with exciton lines dominated by the TO-phonon replica of the boron bound exciton at 1.093 eV. Along with the increasing intensity between 77 and 4.2 K, the PL bands below 1.05 eV are now much narrower ($\sim$10 meV) and exhibit additional sub-bands. The only exception is the 0.8 eV band, which retains a large half-width of $\sim$60 meV down to 4.2 K.

We performed a numerical deconvolution of the 77 K PL spectrum in the range of 0.72–1.05 eV, and found that the entire spectrum can be satisfactory fit by four Gaussian peaks, D1′–D4′ [2]. A set of four similar PL lines, known as D1–D4, with very close energies to those seen here, was previously observed and studied in detail in plastically deformed Cz and float-zone Si single crystals [4]. These bands are attributed to dislocations. The range of dislocation density, measured in low lifetime regions of our mc-Si wafers, (1–$8 \times 10^6\,cm^{-2}$) is in the lower end of the range of dislocation densities reported for the plastically deformed Si exhibiting the dislocation D-lines.

To check further an assumption on dislocation origin of the defect band, we compared the band-to-band and defect band PL distributions in EFG wafer with recombination activity distribution measured on the same wafer by EBIC (Fig. 2). It should be pointed that PL mapping and EBIC mapping have different spatial resolutions. The black areas on EBIC maps are related to the region with high recombination activity of dislocations. In this correlation EBIC/PL study, it became clear that the regions of low band-to-band and high defect PL are caused by dislocations.

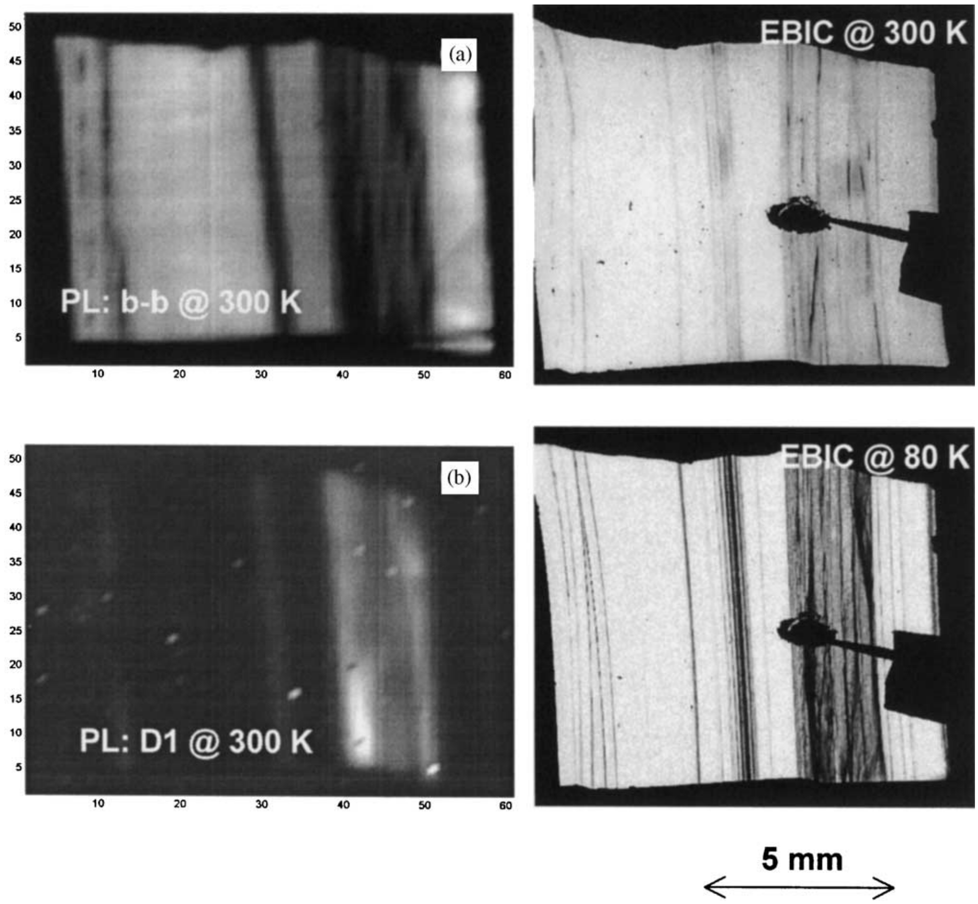

Fig. 2. Room temperature band-to-band (a), defect band (b) PL maps (on the left) and high resolution EBIC maps at room temperature and 80 K (on the right) in EFG wafer.

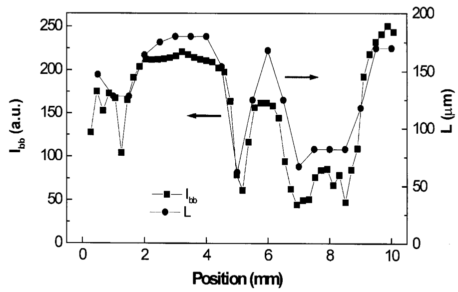

Fig. 3. Line scans of the defect concentration [1] expressed as the ratio of defect PL to band-to-band PL (1) and dislocation density (2) in an as-grown EFG wafer. A vertical arrow indicates the region with a high dislocation density and low defect concentration.

We conclude that the defect PL is associated with dislocations with moderate degree of impurity contamination. In fact, recombination activity of dislocations strongly depends on both the metal impurity contamination and temperature. According to the model proposed in Ref. [5], a moderate contamination level is exhibited as reduction of EBIC contrast at high temperature compared to 77 K EBIC contrast. This is exactly a case of 0.8 eV PL band defects, as illustrated in Fig. 2. If the contamination level is too low ("clear" dislocation) or too high (dislocation decorated by metal silicate precipitates) the defect PL band luminescence is vanished. However, a relatively low contamination level of dislocations, in the order of 10 impurity atoms per micron of the dislocation length produces distinguishable defect band luminescence.

This study demonstrates a utility of the spectroscopic PL mapping to monitor electrically active dislocations at various contamination levels of precipitated defects.

Acknowledgements

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