Room-temperature electroluminescence from dislocations in silicon

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Abstract

We report on electroluminescence at room temperature from n^+–p silicon diodes containing high densities (10^8–10^9 cm^{-2}) of dislocations at the junction interface. In addition to the electroluminescence (EL) from band-to-band transitions we observe a signal with a comparable intensity peaked at ~1.6 μm (0.78 eV). From studies of the luminescence below room temperature, we deduce that the 1.6 μm emission originates from the well known dislocation-related center D1. The D1 electroluminescence intensity at 300 K increases linearly with current density with no observable saturation. The external quantum efficiency of the D1 electroluminescence at room temperature was estimated to be of the order of 10^{-7}.

Keywords: Electroluminescence; Dislocations

1. Introduction

Light emission from silicon has recently received considerable attention. The main focus has been on the visible photoluminescence (PL) of porous silicon [1], but considerable effort has also been put into investigations of infrared light emission from erbium-doped silicon [2,3]. Although electroluminescence (EL) at room temperature has been reported from such erbium-doped devices, the light intensity is still insufficient for practical use. More recently, Kveder et al. [4] reported faint electroluminescence from plastically deformed silicon at room temperature. They attributed the light emission to the well known dislocation-related center D1, which luminescence had previously been reported to vanish at temperatures above 200 K [5].

2. Experimental details

The starting material in our study was high purity float-zone boron doped silicon wafers with resistivity of 20 Ω cm. The dislocations were generated after the sample surface had been melted using a high-power (20 W) focused Ar$^+$ laser beam. The substrate was kept at room temperature while the beam was scanned over the wafer surface with a scanning speed of 10 cm s^{-1}. The separation between the parallel stripes made by the laser beam was approximately 40 μm. After the recrystallization such a material has typically dis-

location densities at the surface of approximately 2×10^9 cm^{-2}. This surface region extends to depths of 1–2 μm. Below the surface layer the dislocation densities are of the order of 10^8 cm^{-2} down to depths of 5–10 μm [6].

After recrystallization, the samples used for the EL studies were pre-deposited with phosphorus on the dislocated side using solid diffusion sources. The pre-deposition temperatures were between 800 and 900 °C with duration of 30 min. Prior to phosphorus diffusion the wafers were RCA cleaned to avoid metal surface contamination. Mesa structures were then fabricated by wet chemical etching. For ohmic contacts aluminum was evaporated onto the highly phosphorus-doped side, while gold was evaporated onto the p-type substrate. Different sample geometries were investigated but the EL data presented here were collected from an n^+–p diode with an area of 0.0375 cm^2.

The PL and EL studies were carried out in a cryostat cooled with liquid nitrogen or helium. The PL excitation was the Ar 514.5 nm laser line and the luminescence data were collected using a monochromator (SPEX 1 m focal length) and a nitrogen-cooled germanium detector. The luminescence spectra are not corrected for the overall spectral response of the experimental setup.

3. Results and discussion

Fig. 1(a, dotted curve) shows the photoluminescence spectrum at 4.2 K of a laser-melted sample. Apart from the bound exciton TO emission (BE$_{TO}$) the strongest features
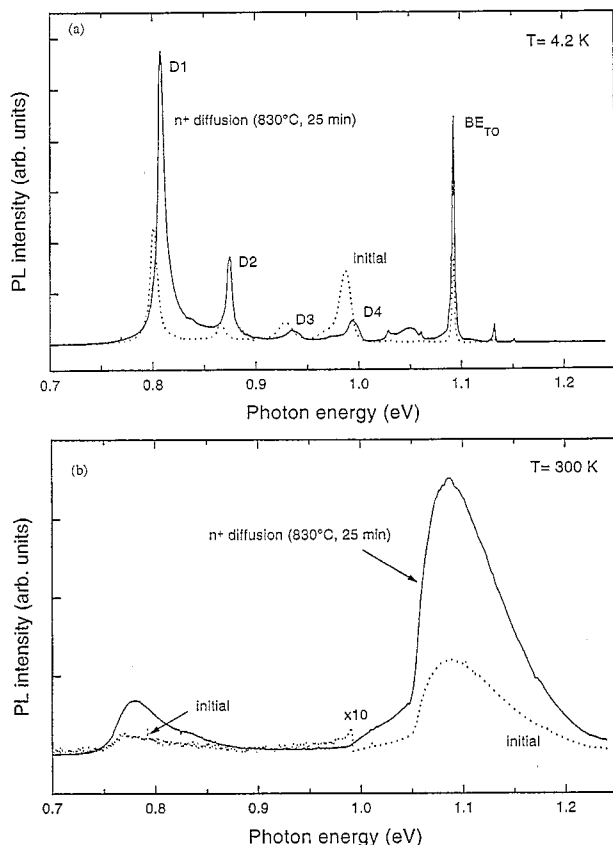
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Fig. 1. (a) Dotted curve: PL spectrum of a laser melted p-type silicon, solid curve: after phosphorus diffusion at 830 °C for 25 min. T = 4.2 K. (b) Same as in (a) except at room temperature. Argon ion laser excitation ~ 150 mW mm^{-2}.

are the dislocation-related signals D1–D4 [5]. The solid curve shows the corresponding spectrum of the dislocated sample surface after phosphorus diffusion at 830 °C for 25 min. The D1 and D2 emission is enhanced, while the D3 and D4 emission is significantly reduced. The shift of the D1–D4 lines towards higher energies is due to strain release of the dislocated surface upon annealing [7].

Fig. 1(b) shows the corresponding PL spectra at room temperature. After the laser treatment (dotted curve) the spectrum shows a broad peak at 1.1 eV due to phonon assisted band-to-band transitions and a weak signal at ~ 0.78 eV (1.6 μm). After phosphorus diffusion at 830 °C for 25 min (solid curve), there is an increase in the band-to-band emission but, more important, the 0.78 eV signal is enhanced by two orders of magnitudes.

We found that the enhancement of the 0.78 eV emission was due to the heat treatment, since reference samples annealed at 830 °C but without phosphorus diffusion showed similar luminescence enhancement. However, the samples had to be RCA cleaned prior to the annealing to avoid metal contamination. Otherwise, we find that the room-temperature luminescence is greatly reduced. The reason for this behavior is not understood, but the PL spectra taken at 4.2 K of samples without RCA cleaning show Cu contamination in the form

of Cu pair luminescence [8]. This suggests that non-radiative recombination centers introduced by the in-diffusion of impurities (Cu or other metals) from the sample surface are responsible for the lack of luminescence at room temperature.

The room-temperature emission at 0.78 eV vanished if 14 μm were etched off the sample surface, the D1 intensity at 4.2 K decreased at the same time by a factor of about 20. This indicates that D1 is the origin of the 0.78 eV emission at room temperature. This is also supported by the data in Fig. 2.

Fig. 2 shows the PL spectra of a phosphorus diffused sample (830 °C) taken at three different temperatures. At 77 K the dominant PL feature coincides in energy with the D1 line at 4.2 K and the shoulder at ~ 0.88 eV is presumably the D2 line. However, at room temperature the signal has decreased significantly and is shifted towards lower energies. The energy shift from 4.2 K to room temperature is ~ 30 meV, compared with the decrease of ~ 45 meV of the silicon bandgap. Based on these data, we tentatively assign the 0.78 eV signal at room temperature to the D1 center.

Fig. 3 shows EL spectra of a n$^+$–p junction diode at room temperature. The inset gives a schematic of the sample structure. The maximum EL intensity was obtained when the emis-
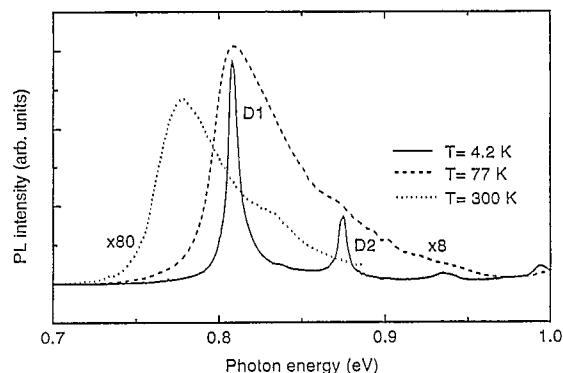

Fig. 2. Photoluminescence spectra showing the evolution of the dislocation-related lines D1 and D2 with temperature. Argon ion laser excitation ~ 150 mW mm^{-2}.
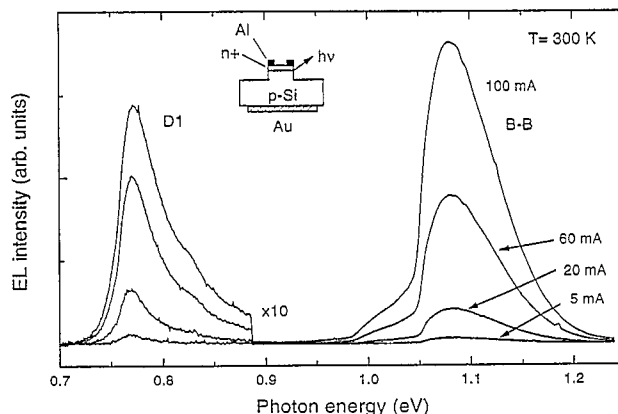

Fig. 3. Electroluminescence spectra at 300 K from a n$^+$–p diode for different forward bias currents. The signal at ~ 1.1 eV is due to phonon assisted band-to-band transitions (B–B), while the peak at ~ 0.78 eV is assigned to the D1 dislocation center. These data were collected from the n$^+$–p junction on the side of the structure (see inset).
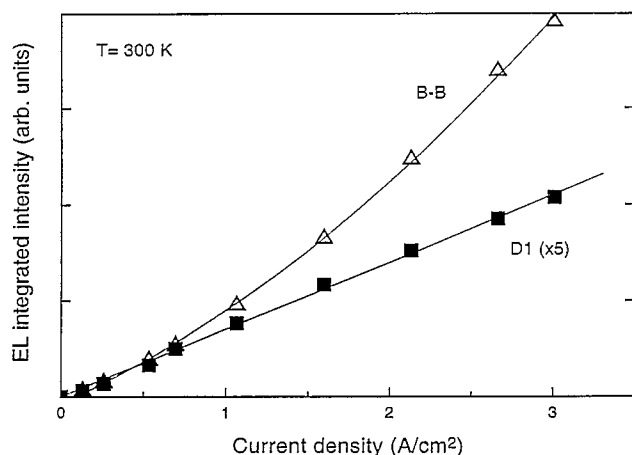
Fig. 4. Integrated EL intensity of the band-to-band luminescence (B–B) and the D1 signal as a function of current density.

sion was collected from the sample edge at the n^+–p junction. The n^+–p junction is located at a depth of approximately 0.4 μm and the phosphorus density at the surface is 1×10^{20} cm^{-3}. The diode was excited by a current source at a frequency of 67 Hz.

Fig. 4 shows the EL intensity as a function of the current density for both the D1 emission and the band-to-band signal. The D1 emission increases linearly with current density and no saturation is observed, while the band-band emission shows a nonlinear behavior. However, the band-to-band emission shifts towards lower energies for currents above ~ 80 mA, suggesting that the sample temperature is above room temperature. We found that the intensity ratio between the band-to-band emission and D1 is very sensitive to temperature. Heating the sample above room temperature results in saturation of the D1 intensity, while cooling slightly below room temperature results in a significant increase in the D1 signal at the same time as the band-to-band emission decreases.

The light intensities from these devices are similar when using optical or electrical excitation of 150 mW. We therefore estimate the ratio of the quantum efficiencies of EL and PL to be close to unity. The D1 light output power was estimated to be roughly 0.025 μW when exciting with electrical power of 150 mW. This estimate was made by comparison with a Nd:YAG 1.064 μm laser line of known power. This gives an external quantum efficiency of the order of 10^{-7} for the D1 emission, which is comparable to the values reported in literature for the band-to-band emission [9].

4. Conclusions

We have observed room-temperature dislocation-related light emission from n^+–p silicon diodes peaked at a wavelength of 1.6 μm. The external quantum efficiency of this emission is estimated to be of the order of 10^{-7}. Further improvements in the device structure are expected to increase this efficiency. This includes low-temperature oxidation of the sample surface to passivate etch-induced surface damage.

Acknowledgements

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