Excitation and pressure effects on photoluminescence from silicon-based light emitting diode material

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The influence of excitation wavelength and pressure on the photoluminescence (PL) of silicon light-emitting diode material prepared by boron implantation is reported. The PL spectra show an anomalous increase in total intensity with increasing temperature, and this luminescence is found to be strongest with increasing laser penetration depth away from the sample surface. The PL peak shifts towards lower energy at a rate of –14 meV/GPa with increasing pressure. This agrees with earlier optical absorption measurements on the indirect band-gap of silicon, confirming that this emission is closely related to this transition.

1. Introduction

Because of the indirect nature of its fundamental band gap, silicon is a poor light-emitting material. However, its extensive applications in microelectronics make fully integrated silicon-based optoelectronics one of the major and necessary technological challenges to science. Thus, various ways have been attempted to produce a Si-based light emitter, such as quantum confined systems, defects, impurities or heterostructures (see Light Emission in Silicon: From Physics to Devices, 1997 for references). The diode material measured here is produced by implanting boron ion into an n-type substrate to form p-n junction. Implantation damage is reduced by subsequent annealing. This method has been shown to produce efficient devices compatible with standard ultra large scale integration (ULSI) processing technology (Dekorsy et al. 2004, p.471, Emel’yanov et al. 2004, p.40, Ng et al. 2001, p.192) with increased electroluminescence (EL) efficiency at room temperature. The proposed model for the increased EL efficiency of this material at room temperature is the introduction of dislocation loops which improves carrier confinement (Lourenco et al. 2004, p.239, Ng et al. 2001, p.192), although excitonic traps which store and supply electron-hole pairs at elevated temperatures (Sun et al. 2003, p.3885) and also high bulk Shockley-Read-Hall lifetimes (Kittler et al. 2005, p.967) have also been suggested.

In this paper we investigate the luminescence at various temperatures and pressures in an attempt to understand its nature and origin. We report the results of a photoluminescence (PL) study of this material in the temperature range between 11 K and 300 K at atmospheric pressure, with the intention of observing any distinct effects of laser excitation photon energy. We also report the pressure dependence of PL at room temperature and discuss in connection with the earlier high-pressure optical absorption measurements on the indirect band gap of silicon by Welber et al. (1975, p.1021).

2. Experiments

The device material studied here was made by boron implantation at a dose of $1 \times 10^{15}$ cm$^{-2}$ at an energy of 30 keV into a device grade CZ (Czochralski) n-type silicon substrate of
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resistivity $2-4 \ \Omega \ \text{cm}$. The sample was subsequently annealed in a nitrogen atmosphere for 20 minutes at 950°C activating the boron dopants and forming a p-n junction. The array of dislocation loops formed has been observed using cross sectional transmission electron microscopy (Ng et al. 2001, p.192). These are typically about 80-100 nm in diameter and are spaced around 20 nm apart, in a planar region parallel to the p-n junction. The dislocations are centred around 150 nm from the surface and the depletion region edge on the upper p-side is at around 200 nm. These devices have an ultimate quantum efficiency of about 0.1% without optimization. Details of fully processed and working light-emitting diodes made from this material can be found in (Ng et al. 2001, p.192).

Luminescence at atmospheric pressure was excited using the 488 nm, 532 nm, 682 nm, and 783 nm lines of lasers, to examine the effects of excitation wavelength at several temperatures between 11 K and 300K. The emitted spectra from the front surface of the material were dispersed through a single grating monochromator, and detected with a cooled photomultiplier and a conventional photon-counting system. PL measurements at room temperature as a function of pressure up to about 3 GPa were made with a diamond anvil cell. The sample was thinned down to 50 $\mu$m and loaded into a hole of metal gasket together with a small chip of ruby for pressure calibration. The pressure transmitting media was a methanol ethanol 4:1 mixture. Excitation is at 514 nm.

3. Results and Discussions

No appreciable PL was seen from the silicon material before boron implantation. Figure 1 shows the PL spectra of boron-implanted silicon for several temperatures between 80 K and 300 K. Excitation is at 2.54 eV (488 nm). With increasing temperature from 80 K to 300 K, the photon energy of PL peak shifts from 1.098 eV to 1.088 eV, following the decrease in the silicon indirect band gap with temperature when corrected for the transverse optical (TO) phonon energy. This sample clearly shows intense PL spectra at higher temperatures. The integrated PL intensity is plotted in Fig. 2. These temperature results agree well with previously reported electroluminescence (EL) and PL (Ng et al. 2001, p.192) and other authors EL (Dekorsy et al. 2004, p.471, Emel’yanov et al. 2004, p.40) measurements on similar material. However, such results are anomalous and in contrast to the PL results for normal silicon substrates or other III-V materials.

![Fig. 1 Typical PL spectra of boron-implanted silicon for several temperatures between 80 K and 300 K. Excitation is at 488 nm (2.54 eV).](image)
To see how these PL features are related to the presence of dislocation loops in the boron-implanted silicon, different excitation photon energies, 2.33 eV (532 nm) and 1.82 eV (682 nm) are used. Figure 3 shows the comparison of typical PL spectra of boron-implanted silicon for two different temperatures, 11 K and 300 K. When excited at 2.33 eV, as shown in Fig. 3(a), the PL spectrum at 300 K is brighter than that at 11 K. At 1.82 eV in Fig. 3(b), however, it is clearly shown that the PL peak intensity at 11 K becomes larger than that at 300 K.

The dislocation loops are centered around 150 nm beneath the surface, and optically generated carriers at the surface should be separated from those deeper down in the sample by the dislocation barrier. This strongly affects the PL spectra excited at different wavelength (i.e., different penetration depth). When sample is excited at a longer photon wavelength, the PL signal from the shallow region and, thus, the effects of dislocation loops are hindered or modified by emissions from the deeper region of the bulk silicon substrate.

Fig. 3  Comparison of PL spectra of boron-implanted silicon measured at 300 K and 11 K. Excitations are at (a) 532 nm (2.33 eV) and (b) 682 nm (1.82 eV).
Fig. 4 Comparison of PL spectra of ordinary silicon substrate measured at 300 K and 11 K. Excitations are at (a) 532 nm (2.33 eV) and (b) 682 nm (1.82 eV).

These tendencies are also examined by similar measurements on ordinary silicon substrate with no boron implantation. Figure 4 shows the comparison of typical PL spectra from silicon substrate with resistivity of 4-6 Ω-cm at 11 K and 300 K. The PL features obtained are rather similar to those shown in Fig. 3(b) and there is no essential difference between the PL results for two different excitation photon energies as shown in Figs. 4(a) and 4(b).

Fig. 5 Typical PL spectra of boron-implanted silicon at 300 K, under different pressures up to about 3 GPa.

Figure 5 shows typical PL spectra for the sample under pressure at 295 K. Results are consistent with EL from these devices. No such measurements has been reported in the literature since the PL has been too weak to measure without the detection system using a photomultiplier tube with low noise and high sensitivity extended from visible to near-infrared region up to 1400 nm.
Figure 6 show how the peak moves to lower energy with increasing pressure. No evidence of quenching was seen in the sample PL up to about 3 GPa, and the current study was limited only by the pressure range available for this particular DAC. A linear dependence of $-14\pm1$ meV/GPa is obtained. The value of this shift agrees with the earlier optical absorption measurements (Welber et al. 1975, p.1021, Paul and Warschauer 1958, p.102) on the indirect band-gap of silicon which gave $-14.1\pm0.6$ meV/GPa over a range of 0 to 10.6 GPa and $-15$ meV/GPa over 0 to 0.8 GPa, respectively. This also agrees with the value $-14$ meV/GPa obtained from recent EL measurements at 110 K up to 1 GPa by A.D. Prins (personal communication, May 20, 2005). These confirm that the emission is closely related to the indirect band-gap of silicon.

4. Conclusions

We have observed the effects of excitation energy and pressure on PL from light emitting diode material produced by boron implantation and annealing. The integrated PL intensity increases with temperature which is anomalous when compared to most systems. The temperature dependence of the silicon introduced dislocation loops are studied at various excitation wavelengths, changing the penetration depth. The PL intensity increases at shorter excitation wavelength. This tendency is emphasized at shorter wavelength excitation. It is considered that difference of temperature dependence reflects the effect of penetration depth. The influence of pressure up to around 3 GPa on the PL spectra of the material is also reported. The observed PL peak position shifts to lower energy at a rate of $-14$ meV/GPa in agreement with earlier absorption studies and thus shows the mechanism to be closely related to the silicon indirect band edge.

References


