



Room-temperature near-infrared electroluminescence from boron-diffused silicon pn-junction diodes

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Silicon pn-junction diodes with different doping concentrations were prepared by boron diffusion into Czochralski n-type silicon substrate. Their room-temperature near-infrared electroluminescence (EL) was measured. In the EL spectra of the heavily boron doped diode, a luminescence peak at $\sim 1.6 \mu\text{m}$ (0.78 eV) was observed besides the band-to-band line (~ 1.1 eV) under the condition of high current injection, while in that of the lightly boron doped diode only the band-to-band line was observed. The intensity of peak at 0.78 eV increases exponentially with current injection with no observable saturation at room temperature. Furthermore, no dislocations were found in the cross-sectional transmission electron microscopy image, and no dislocation-related luminescence was observed in the low-temperature photoluminescence spectra. We deduce that the 0.78 eV emission originates from the irradiative recombination in the strain region of diodes caused by the diffusion of large number of the boron atoms into a silicon crystal lattice.

Keywords: boron diffusion, silicon pn-junction diode, near-infrared electroluminescence

INTRODUCTION

With the development of integrated circuits (ICs), the disadvantage of traditional metal interconnection structure, such as interlayer interference, energy dissipation, and signal delay, has become a bottleneck restricting the development of ultra-large-scale integration circuits (USLIs). Optical interconnection, which uses photons to transform information, will be an ultimate solution for future progress in USLIs. Because silicon is an indirect-band-gap semiconductor and fundamentally unable to emit light efficiently, achieving efficient silicon-based light sources compatible with current IC manufacturing technology has become the key issue of silicon optoelectronics. Many routes to fabricate efficient silicon light emitters have been proposed: porous silicon (Cannah, 1990; Qin et al., 1996; Bisi et al., 2000; Zhao et al., 2005a,b), Si nanoprecipitates in SiO_2 (Pavesi et al., 2000; Wang et al., 2007), erbium-doped Si (Ennen et al., 1983; Zheng et al., 1994; Polman et al., 1995), Si/ SiO_2 superlattice structures (Lu et al., 1995), and silicon pn-junction diodes (Sveinbjörnsson, 1996; Martin et al., 2001; Ng et al., 2001; Sun et al., 2004; Lourenco et al., 2005). Among these ways, silicon pn-junction diodes have attracted much attention. The most standout advantage of this kind of light-emitter is that the fabrication process is totally compatible with USLI technology. Both ion-implantation (Sveinbjörnsson, 1996; Martin et al., 2001; Ng et al., 2001; Sun et al., 2004; Lourenco et al., 2005; Sobolev, 2010) and thermal diffusion (Kveder et al., 2004; Hoang et al., 2006, 2007) have been used to manufacture silicon pn diodes. The past few years has seen great advances in the development of silicon pn-junction diodes. Electroluminescence (EL) efficiency of 0.1–1% has been achieved (Martin et al., 2001; Ng et al., 2001). In addition to the band-to-band emission around $1.1 \mu\text{m}$, other near-infrared emissions have been found in boron-implanted and boron-diffused silicon pn diodes (Sveinbjörnsson, 1996; Sun et al., 2004). Sveinbjörnsson (1996) reported strong

$\sim 1.6 \mu\text{m}$ (0.78 eV) EL emission related to dislocation-related center D1 at room temperature from dislocation-rich silicon diodes. Sun et al. (2004) reported two luminescence bands around 1.05 and 0.95 eV related to doping spikes in boron-implanted silicon pn diodes. These emissions show great application potential in silicon optoelectronics. But the mechanism is still in dispute.

In this paper, we fabricated silicon pn-junction diodes with different boron doping concentrations. Their room-temperature EL was measured and their cross-sectional transmission electron microscopy (TEM) images were studied. The result shows that the heavily boron doped silicon pn-junction diode without dislocation loops can emit strong 0.78 eV luminescence under the condition of high current injection besides the band-to-band emission. It is considered that the 0.78 eV emission originates from the irradiative recombination in the strain regions caused by the diffusion of large number of boron atoms into silicon crystal lattice.

MATERIALS AND METHODS

Two kinds of boron diffusion sources were prepared by dissolving B_2O_3 into SiO_2 latex with B^{3+} concentration of 0.203 mol/L (marked as A) and 0.569 mol/L (marked as B), respectively. Boron sources were spin onto the surface of (100) oriented n-type Czochralski-grown Si substrates ($2 \sim 10 \Omega \text{ cm}$, $500 \mu\text{m}$ in thickness) after the substrate wafer was cut into $15 \text{ mm} \times 15 \text{ mm}$ slices and carefully cleaned by standard RCA process. Rapid thermal treating method was used to form shallow pn junction by boron diffusion at 1100°C for 5 min in the flowing high-purity N_2 atmosphere. After a pn junction was formed, an indium tin oxide (ITO) electrode with a thickness of 100 nm was deposited on the p-layer side by magnetron sputtering, and an Al electrode with a thickness of 100 nm was evaporated on the n-layer side. Thus, a pn-junction diode was prepared.

The carrier concentration and the depth of pn junctions were studied by an SSM350 instrument of spreading resistance profile (SRP). The microstructure of pn junctions was measured by a transmission electron microscope (TEM, JEOL 2010). Photoluminescence (PL) and EL signals were recorded using an Edinburgh FLS920P Spectrometer with a nitrogen-cooled near-infrared photomultiplier tube. The low-temperature PL measurements were performed over the range of 20~300 K by using a helium flow cryostat.

RESULTS AND DISCUSSION

Figure 1 is the SRP results of pn junctions made from the two boron sources (A and B). It is clear from the figure that shallow pn junctions were formed. It can be seen that Sample B made from the B boron source has the higher carrier concentration than Sample A made from the A boron source. The surface carrier concentration of Sample B reaches $4.6 \times 10^{17} \text{ cm}^{-3}$, while that of Sample A is $5 \times 10^{16} \text{ cm}^{-3}$. It is necessary to notify that the SRP measures the activated dopant density only, which does not take into account the possible dopant clustering at the surface, so there can be a large amount of boron doping, which is inactive. The depth of Sample B pn junction is about 250 nm, a little deeper than that of Sample A, which is about 200 nm.

Figure 2 shows the I - V curves of the two pn diodes. As shown in the figure, both the pn diodes perform good rectifying properties. The forward current increases quickly with the voltage while the reverse current stays low. Under the same forward bias, the current of Sample B is greater than that of Sample A. This is because Sample B has the higher carrier concentration and less resistance. In addition, the turn-on voltage of Sample B is about 0.7 V, bigger than that of Sample A, which is about 0.6 V. The reason is that the pn-junction barrier of Sample B with higher doping concentration is larger, so that the forward voltage needed to overcome the barrier is larger.

The room-temperature EL spectra of Sample B and Sample A are different, as shown in **Figure 3**. In the room-temperature

EL spectra of Sample A, only band-to-band emission is observed as the current increases. In contrast, Sample B emits 0.78 eV EL besides the band-to-band emission under the condition of high current injection ($>705 \text{ mA}$) and its intensity increases greatly with the current. The band-to-band emission of both pn diodes demonstrates a small red shift with the increasing current; this is related to the device heating in response to the current injection.

Sveinbjörnsson (1996) and Xiang et al. (2012a,b) have reported strong emission of 0.78 eV EL at room temperature from silicon pn diodes containing dislocations. They have also found

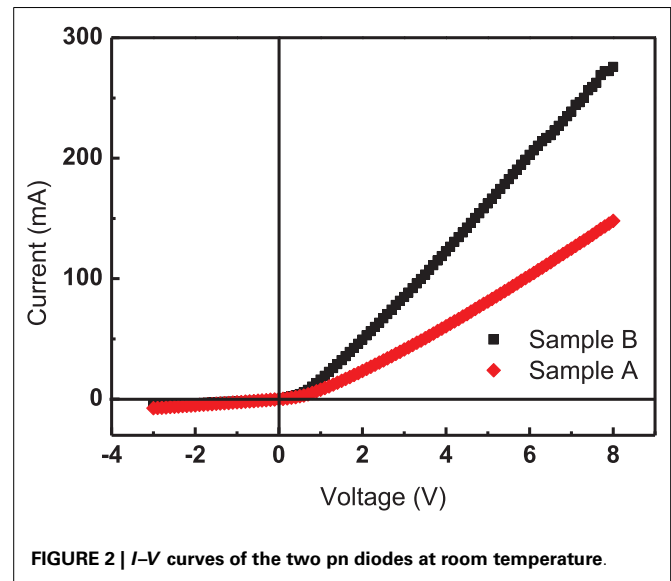


FIGURE 2 | I - V curves of the two pn diodes at room temperature.

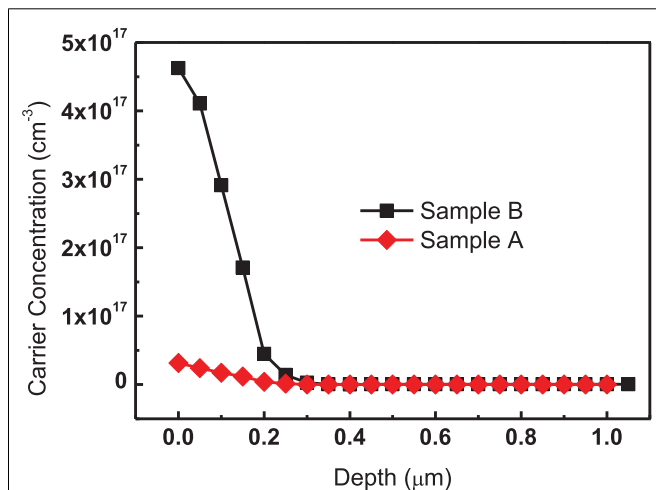


FIGURE 1 | Spreading resistance profile spectra of pn junctions made from Sample A and Sample B fabricated with two boron sources.

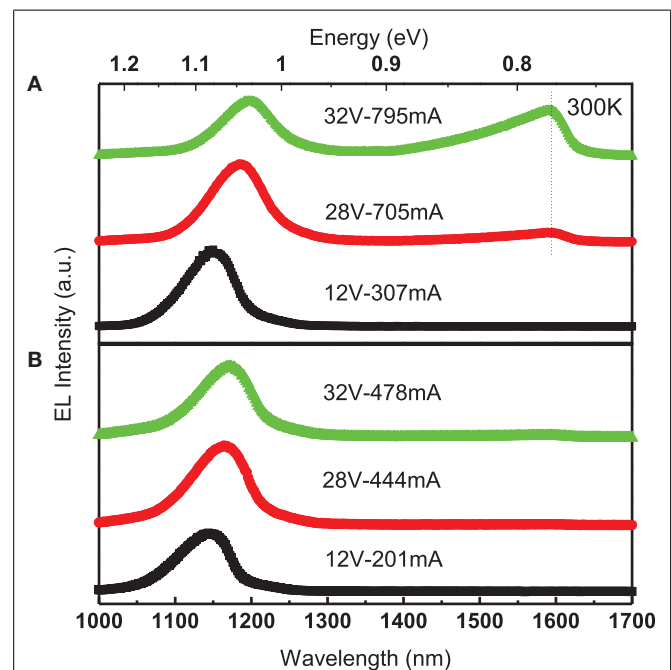
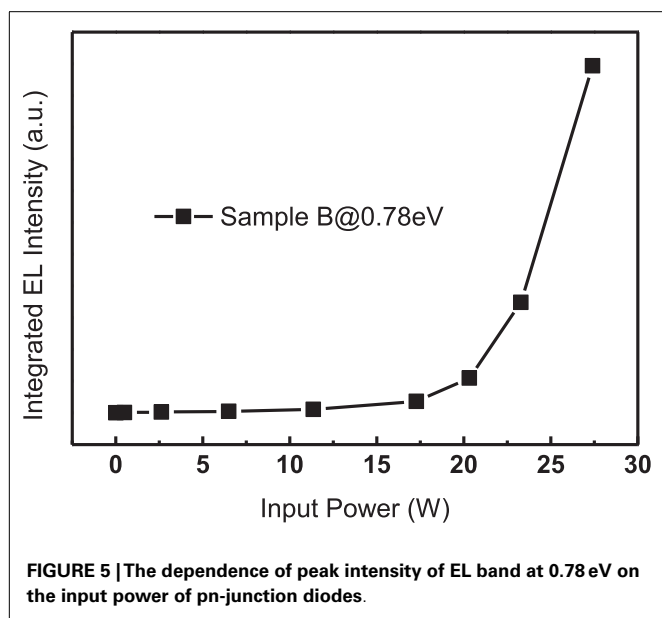
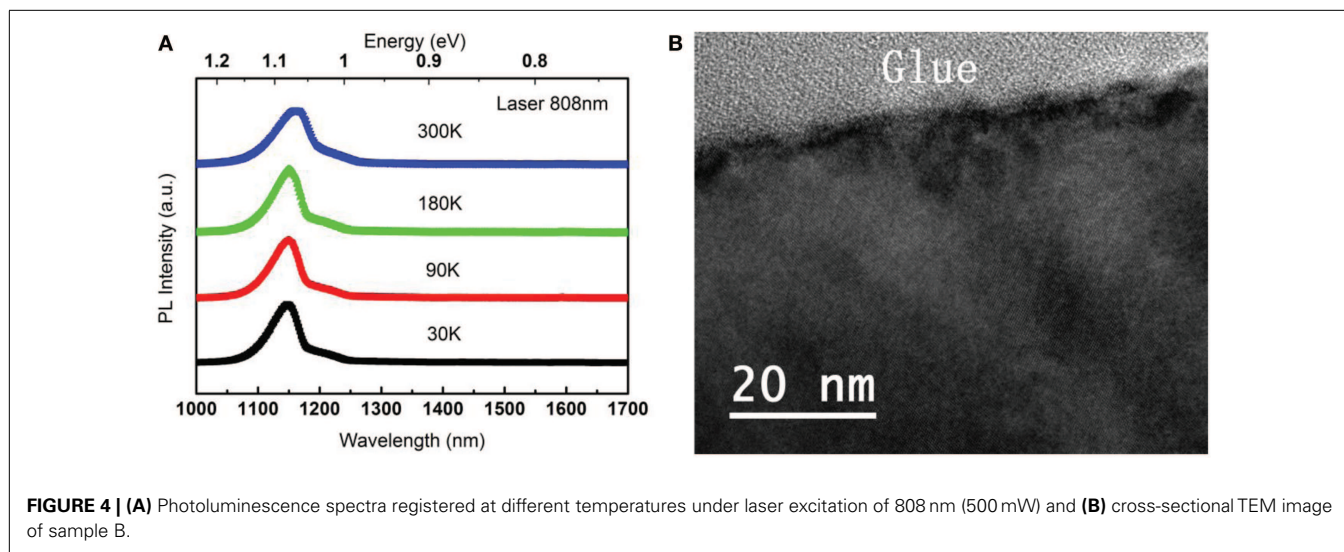


FIGURE 3 | Room-temperature EL spectra at different electrical currents of two pn diodes: (A) for sample B and (B) for sample A.



dislocation-related bands in the low-temperature PL spectra. They tended to regard the peak at 0.78 eV in PL spectrum at room temperature as a red-shifted luminescence band D1. However, for Sample B, no other luminescence band is found in the low-temperature PL spectrum (the pump power intensity is 0.22 W/cm^2) except the band-to-band emission and no dislocations are observed in the cross-sectional TEM image as shown in **Figure 4**. It can be seen from **Figure 4B** that Sample B is free from dislocations. Our work suggests that the 0.78 eV EL at room temperature has no direct connection with dislocations or dislocation-related luminescence bands. In fact, lots of lattice damage regions can be seen near the surface of Sample B in the TEM image. As mentioned before, although the measured dopant concentration by SPR is relatively low, a significant amount of inactive boron doping may exist, so we think that the observed

lattice distortion is caused by large number of boron atoms diffusing into silicon lattice. Under the condition of high current injection, these regions can trap carriers and form effective irradiative recombination centers, which are related to the 0.78 eV luminescence.

Figure 5 shows the dependence of peak intensity of 0.78 eV on the input power. When the input power is low, there is no 0.78 eV EL emission. When the input power reaches $\sim 15 \text{ W}$, Sample B starts to emit 0.78 eV luminescence and its intensity increases almost exponentially with the input power with no observable saturation. This means that if the turn-on power of the 0.78 eV emission could be sufficiently decreased, a highly efficient light source would be achieved.

CONCLUSION

In this paper, two silicon pn diodes with different boron doping concentrations were fabricated by boron diffusion. We studied their room-temperature near-infrared EL. The results show that in the EL spectra of the heavily boron doped diode, a luminescence peak at $\sim 1.6 \mu\text{m}$ (0.78 eV) was observed besides the band-to-band line ($\sim 1.1 \text{ eV}$) under the condition of high current injection, while in that of the lightly boron doped diode, only the band-to-band line was observed. In addition, no dislocations were found in the cross-sectional TEM image and no dislocation-related luminescence was observed in the low-temperature PL spectra. The 0.78 eV emission is proved to have no direct connection with dislocations or dislocation-related luminescence bands. In fact, lots of lattice damage regions can be seen near the surface of the highly doped diode in the TEM image. We deduce that the 0.78 eV emission may originate from the irradiative recombination in these regions. What is more, the intensity of 0.78 eV emission increases exponentially with the input power without observable saturation, which may be used as an efficient light source in future.

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