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Demonstration of a Silicon Photonic Crystal Slab LED with Efficient Electroluminescence

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1. Introduction

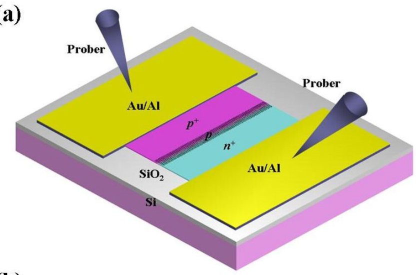
Silicon photonics has been receiving much attention as a key technology for implementing optical interconnections in large scale integration (LSI) circuits [1]. Among the optical components required for the implementation, efficient light source is a missing fundamental device in silicon photonics. A number of researches aiming for realizing silicon-compatible efficient light sources have been conducted by utilizing silicon-related materials, such as porous silicon, silicon nanocrystals, silicon germanium superlattices, germanium quantum dots, and erbium ions doped in silicon [1]. Even after the demonstration of silicon light emitting diode (LED) with a relatively high efficiency as an indirect material [2,3], silicon did not attract researches so much because of its indirect nature of the electronic bandgap. Recently, enhanced photoluminescence from crystalline silicon has been demonstrated by utilizing photonic nanostructures such as photonic crystal (PhC) [4] and PhC nanocavities [5-7]. In these structures, the extraction efficiency of emitted photons and the emission efficiency inside the material can be enhanced due to the light diffraction effect and the Purcell effect. Towards practical applications, however, current-injected devices with enhanced luminescence are to be developed. A limited number of reports on the electroluminescence (EL) from crystalline silicon have been published. Surface-textured structures [3] and use of distributed Bragg reflectors [8] have resulted in enhancement of EL intensity from silicon. By utilizing PhC structures, more efficient silicon LEDs are expected to be realized due to the aforementioned effects.

In this paper, we report on the first demonstration of a silicon LED with a PhC structure. A lateral *p-i-n* LED with PhC slab consisting of crystalline silicon shows a 13-fold enhancement of EL integrated intensity compared to that from a LED without PhC structure.

2. Sample Fabrication

Fig.1 (a) shows a schematic image of our lateral *p-i-n* silicon LED with a PhC slab structure. The devices were fabricated on a silicon-on-insulator (SOI) wafer, which consists of a 200-nm-thick top Si layer (*p* type and resistivity 9-18 Ωcm) on a 1000-nm-thick buried SiO_2 layer. The p^+ type area and n^+ type regions were fabricated by implanting boron and phosphorous ions at a dose of 4 x 10^{15}/cm^2 and 3 x 10^{15}/cm^2 respectively. The wafer was then annealed for 30 min at a temperature of 1000℃ in a nitrogen atmosphere to activate the ions. Then, the PhC structures were fabricated by electron beam lithography and *p-i-n* islands were isolated by photo-lithography. Finally, aluminum contact pads covered with gold were formed by metal evaporation and lift-off techniques. A SEM image of the central part of a device is shown in Fig. 1 (b). We also fabricated SOI LEDs without PhC patters in parallel. The active area between the n^+ and p^+ regions is 250 μm in width and 5 μm in length parallel to the current flow.

(a)



(b)

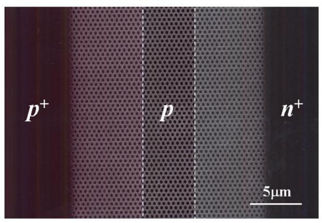


Fig. 1: (a) Schematic image of silicon PhC LED, (b) SEM image of PhC region at the center of the device

3. Experimental Results and Discussions

The devices were characterized at room temperature. Each LED was driven with probes independently. Fig. 2(a) shows *I-V* characteristics of a Si PhC LED and a SOI LED. The lattice constant *a* and radius of air holes *r* of the PhC pattern are 750 nm and 0.32*a*, respectively. The series resistance of the SOI LED is 28kΩ, which agrees well with a resistance of the active region between the n^+ and p^+ regions calculated from the resistivity of the 200-nm-thick top Si layer. The PhC LED has the almost same electric characteristics as to the SOI LED. This confirms that the

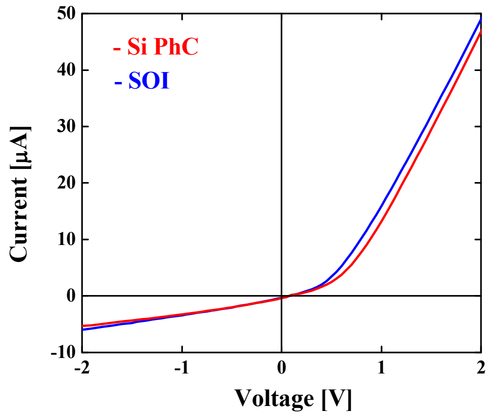


Fig. 2: *I-V* characteristics for Si PhC LED (red curve) and for SOI LED (blue curve).

fabrication processes for PhC structures on lateral *p-i-n* diodes does not heavily degraded their electrical performances.

We have successfully observed EL form the samples under the forward biased conditions. EL signals were collected by using an objective lens with a magnification of x20 and a numerical aperture of NA=0.4 and detected by a liquid-nitrogen-cooled InGaAs photodiode array through a single grating monochromater. Fig.3 shows the EL spectra of the Si PhC LED and the SOI LED at the same injected current of 2 mA. Clearly, the EL intensity from the PhC LED is largly enhanced compared to that from the SOI LED. The enhancement ratio of the peak EL intensitiy is approximately 15 at the injected current of 2 mA. The PhC pattern in this device contains no cavity structure and the spectral region of silicon light emission owing to its interband transision around the electronic bandgapis located above the light line. Therefore, large Purcell enhancement or photonic bandgap effects does not contribute to the enhancement. However, high density of lealy modes in the silicon emission region enhances the extraction efficeincy. The spectral shape of the specrum from the device with PhC structure reflects the distribution of these leaky modes. We confrimed the change of the spectrum depending on the structure (not shown).

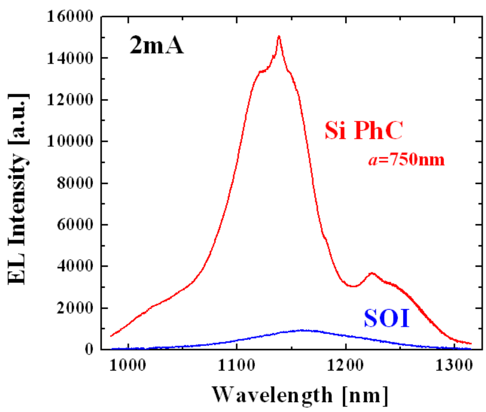


Fig. 3: EL spectra from PhC LED (red curve) and SOI LED (blue curve) measured at 2 mA.

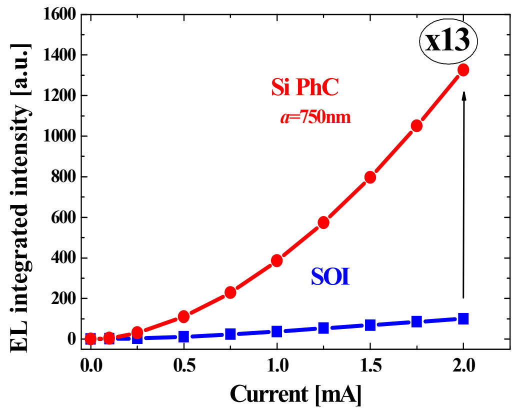


Fig. 4: *I-L* characteristics of Si PhC LED (red) and SOI LED (blue).

The PhC structre also improves the efficeincy, which is defined by the ratio of detected integrated intensity to the injected current. Fig. 4 shows the current v.s. light output (*I-L*) characteristics for the Si PhC LED and the SOI LED. For all injected currents, the PhC LED shows a lagerer integrated EL intensity than that from the SOI LED. At a current of 2 mA, integrated intensitiy from PhC LED is approximately 13-times stronger than that from SOI LED.

4. Conclusions

We fabricated a Si LED with PhC structure and observed a stronger EL compared to that from a SOI LED. The enhancement ratios of peak and integrated EL intensities approach up to 15 and 13, respectively. This is the first demonstration of Si PhC LED. Further improvement of device performance can be expected by introducing PhC nanocavities. Our result shows a potential advantage of photonic nanostructures for realizing highly efficient Si light emitting devices.

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