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Demonstration of Silicon Nanocavity LED with Enhanced Luminescence

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1. Introduction

Achieving efficient light emission from silicon and related materials has received much attention as one of the future technologies of silicon photonics [1,2]. This could realize optical circuits with all silicon-based materials on complementary metal oxide semiconductor (CMOS) platforms. However, crystalline silicon has a very low emission efficiency due to the indirect electronic bandgap. Silicon nanostructures such as thin films [3-5] and quantum dots [6] have been investigated as novel silicon light emitters. Recently, as an alternative approach, photonic nanostructures such as photonic crystals (PhCs) have been utilized in order to improve the light emission properties from crystalline silicon [7-12]. Several groups have observed enhanced photoluminescence from silicon with PhC patterns [7,8] and from silicon PhC nanocavities [8-11]. The enhancement by PhC patterns is mainly attributed to the improvements of light extraction and collection efficiencies. On the other hand, in PhC nanocavities, an enhancement of emission rate due to the Purcell effect is also expected.

Light emission from silicon with photonic nanostructures has been investigated under optical excitation. For practical applications, current-injected devices need to be developed. We have already demonstrated silicon light emitting diodes (LEDs) with PhC patterns and obtained stronger electroluminescence (EL) compared with that from a silicon LED with a flat surface [12]. However, there are no reports demonstrating silicon nanocavity LEDs. PhC nanocavities are promising structures for an efficient silicon LED, owing to the aforementioned effects.

In this paper, we report the first demonstration of silicon LEDs with a PhC nanocavity. We successfully fabricated a silicon nanobeam LED with a PhC nanocavity and observed a clear peak in the EL spectrum originating from the cavity mode. The peak EL intensity from the PhC nanocavity is stronger than that of a nanobeam LED without a cavity. An enhancement ratio of up to ~14 was obtained at room temperature.

2. Sample Design and Fabrication

The device structure studied in this work is depicted as Fig. 1 (a). We fabricated silicon nanobeam waveguides on a commercially available SOI substrate. The width and thickness of the waveguide are 430 nm and 200 nm, respectively. One dimensional air hole array with a period 240 nm and radius 65 nm are introduced into the nanobeam waveguides. The cavity is formed by removing three air holes from the design, which is a typical structure as a nanocavity in two dimensional PhCs [6-9] but without shifting the air holes in this design. A three dimensional finite difference time domain (FDTD) simulation shows that this supports the fundamental mode at 1,132 nm. The spatial distribution of the main electric field component of the fundamental cavity mode is shown in Fig. 1(b). The quality factor and the mode volume for the fundamental mode are 1500 and 0.67 $(\lambda/n)^3$.

The lateral *p-i-n* diode structure is formed at the center of the nanobeam waveguide by using the area selective ion implantation as in our previous report [10]. The length of the *i*-region is designed to be around 1 μm. The *p*- an *n*-type regions connects to pads. Three nanobeams separat-

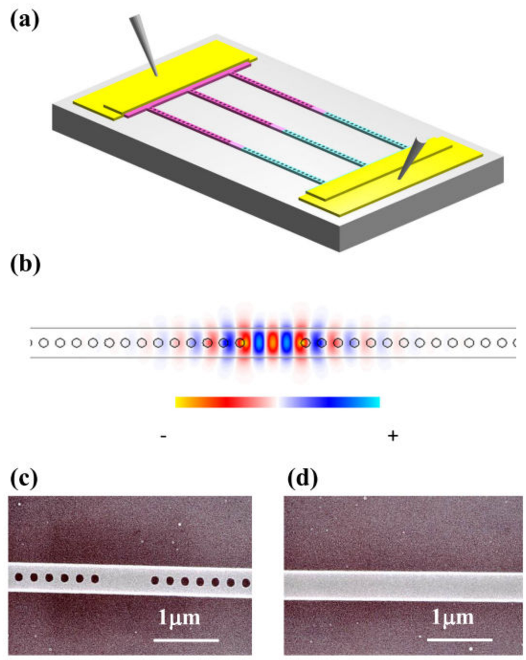

Fig. 1(a) A schematic illustration of our silicon PhC nanocavty LED. At the center of the nanobeam waveguide, a PhC nanocavity was formed. (b) A spatial distribution of the main electric field for the fundamental mode of the PhC cavity. (c,d) SEM images of fabricated nanobeam LEDs . As a reference, nanobeam LEDs without air holes are also prepared.

ed by 5 μm are included in each LED. Thus, three diodes will be operated at once. As a reference, nanobeam LEDs without periodic holes were fabricated. Scanning electron micrograph (SEM) images for both structures are shown in Fig. 1(c).

3. Experimental Results and Discussions

The devices were characterized at room temperature. Fig. 2 shows current-voltage characteristics of silicon nanobeam LEDs with PhC nanocavity and without PhC patterns. In spite of remarkable leakage currents under reversed-bias conditions, turn-on behavior is observed for both diode structures. Series resistances for both structures are 1.60 kΩ and 1.36 kΩ, respectively. Air holes reduce the cross section for the current flow. This results in a higher resistance for the nanobeam LED with the PhC nanocavity.

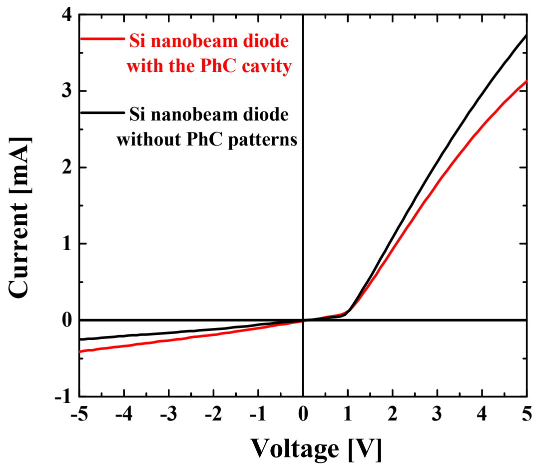

Fig. 2: Current-voltage characteristics of the fabricated nanobeam silicon LED with PhC cavity (red line) and without PhC patterns (black line)

EL spectra were measured by using a conventional μ-PL setup. EL signals form the diodes under forward bias were collected using an objective lens with a magnification of x50 and a numerical aperture of NA=0.42, and detected by a liquid-nitrogen-cooled InGaAs photodiode array through a single grating monochromator. Figure 3 shows the EL spectra from a single nanobeam out of three nanobeams with PhC cavity and without PhC patterns at the same injected current of 1 mA. A clear peak with a quality factor of approximately 317 was observed at around 1115 nm and assigned as the resonant cavity mode calculated by the FDTD. The EL signals from the LED with the PhC cavity is much larger than that from the LED without PhC patterns over the whole range of the emission wavelengths. This enhancement of background emission is mainly due to the redirection of emitted photon by air holes. The cavity mode EL intensity is estimated after substracting the background emission, and it is approximately 14 times larger than EL intensitisy from the nanobeam LED without air holes at the same wavelength.

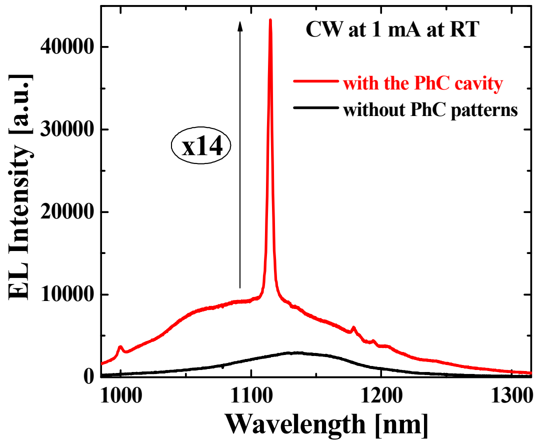

Fig. 3: μ-EL spectra from the silicon nanobeam LED with the PhC cavity (red line) and without PhC patterns (black line) measured at 1 mA.

4. Conclusions

We fabricated a silicon LED with a PhC nanocavity and observed a clear peak in the EL spectum, originating from the fundamental cavity mode. The peak EL intensity from PhC nanocavity is stronger than that of a nanobeam LED without cavity. An enhancement ratio of up to ~14 was obtained at room temperature. This is not only the first demonstration of silicon nanocavity LED but also the first current-injected devices with a nanobeam structure. Our result shows a potential advantage of photonic nanocavities for realizing highly efficient Si light emitting devices.

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