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Room temperature 1.55 µm electroluminescence from Ge quantum dots embedded in H1-type photonic crystal nanocavities using lateral current injection

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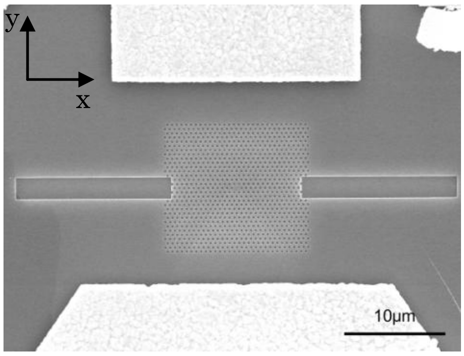
1. Introduction

Light emitting devices with full complementary metal oxide semiconductor (CMOS) process compatibility have been strongly desired for silicon photonics. Since Si itself has low light emission efficiency, light sources have been proposed by utilizing rare earth doping, nanocrystals, Si/SiO_2 superlattices, Si/Ge nanostructures and tensile strained Ge. Among these solutions, Ge quantum dots have band gap corresponding to the wavelength in the telecommunication band and are fully CMOS compatible. We have shown the efficiency of light emission can be significantly enhanced by combining Ge quantum dots (QDs) and photonic crystal cavities. However, most of these devices are based on impractical optical pumping and it's important to fabricate current injected light emitting diodes for optoelectronic integration. Recently we have reported room temperature electroluminescence (EL) from microdisk [1]. However, the emission wavelength was around 1.2-1.3 µm and the efficiency is still needed to be improved. In this work, we report room temperature EL from Ge QDs embedded photonic crystal (PhC) nanocavity with H1-type defect injected by using a lateral PIN diode.

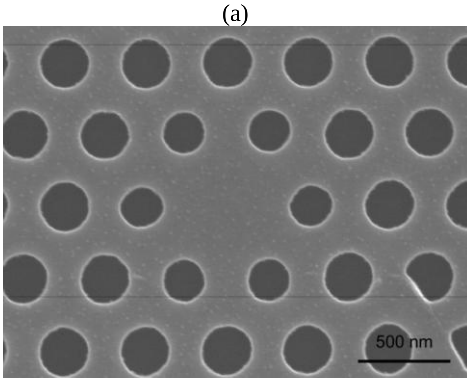
2. Methods

The Ge quantum dots were firstly grown by solid source molecular beam epitaxy (SSMBE) on silicon-on-insulator (SOI) substrate with 60 nm-thick Si and 2 µm-thick buried oxide (BOX). Ion implantations of As with multiple energies of 25 keV, 50 keV, 100 keV and doses of 2×10^{14} cm^{-2}, 5×10^{14} cm^{-2}, 5×10^{14} cm^{-2}, and BF_2 with multiple energies of 25 keV, 50 keV, 75 keV and doses of 2×10^{14} cm^{-2}, 5×10^{14} cm^{-2}, 3×10^{14} cm^{-2}, were performed for uniform ion distribution along with depth direction. A 10 seconds rapid thermal annealing was then carried out at 1000 ºC in the Ar atmosphere. The PhC nanocavities were defined by electron beam lithography (EBL) and reactive ion etching (RIE). At last, metal electrodes were evaporated and defined by lift-off.

Figure 1 shows the scanning electron microscope (SEM) images of a fabricated device. The lateral PIN structure was formed across the cavity along y axis to inject the carriers into the cavity. The cavity is formed by removing one hole from a hexagonal PhC lattice with designed lattice constant of a = 440 nm and hole radius of 0.26a, that is, so-called H1 cavity. The six nearest-adjacent holes surrounding the defect was pushed away from the cavity center after reducing their radii by 0.04a in order to obtain higher Q-factor [2].



(a)

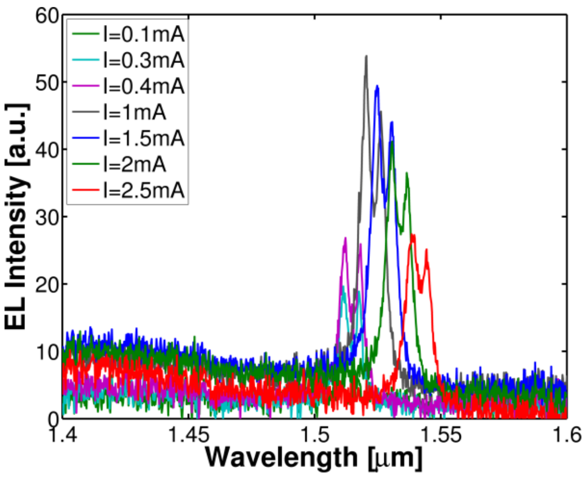


(b)

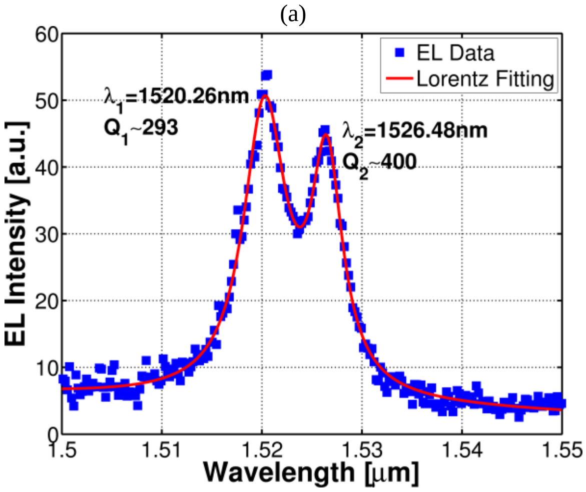
Fig. 1 SEM images of a fabricated light emitting diode. (a) Top view of the fabricated device with electrodes. The lateral PIN diode is formed across the cavity along y axis. (b) Zoomed view of the modified H1-type PhC nanocavity.

3. Results and Discussion

The light emitting diode was characterized by micro-photoluminescence system under DC current source. Figure 2 (a) shows the EL spectra with different injected currents at room temperature. Clear resonant peaks associated with PhC cavity modes and Ge QDs can be seen in the spectra. The peak wavelengths are around 1.55 µm thanks to the proper design of the cavity geometry parameters. One may observed a wavelength splitting between the two resonant peaks, which is typical in an H1-type cavity. H1 cavity usually has a twofold degenerated fundamental mode with orthogonal polarizations due to the geometry symmetry. However, due to the fabrication imperfectness, the symmetry is broken and the degenerated mode is split into two separated modes [3]. According to Lorentz fitting shown in Fig. 2 (b), the two peaks in the EL spectrum under 1 mA current have a wavelength spacing of about 6 nm and Q-factors of 293 and 400, respectively. The Q-factors decrease as the injected current increases, which is mainly attributed to the increased free-carrier absorption. This absorption loss also leads to a light emission intensity reduction at high injected current. The peak wavelengths show a red-shift against the current due to the increase of the refractive index caused by joule heating.



(a)



(b)

Fig. 2 Room temperature EL spectra of the fabricated H1-type PhC nanocaivty light emitting diode. (a) EL spectra with different injected currents. (b) Lorenz fitting of the resonant peaks with the injected current of 1.0 mA.

Compared with the PL results of a reference free-standing H1 cavity without electrical structures, as shown in Fig. 3, both the Q-factor and luminescence intensity of the EL peaks are rather low. This might be related to the vertical asymmetry of our cavity structure due to the existence of the BOX layer. First, the vertical asymmetry will lead to in-plane TE-TM coupling loss to the cavity mode, thus decreases the Q-factor [4]. Second, the optical confinement of SiO_2-cladding side is weaker than that of air-cladding side, and the upward radiation from the cavity becomes weaker than the downward radiation. So only a very small portion of the light emission is collected by the optics on top. We thus believe that the optical performances of the cavity can be improved further by using a free-standing structure.

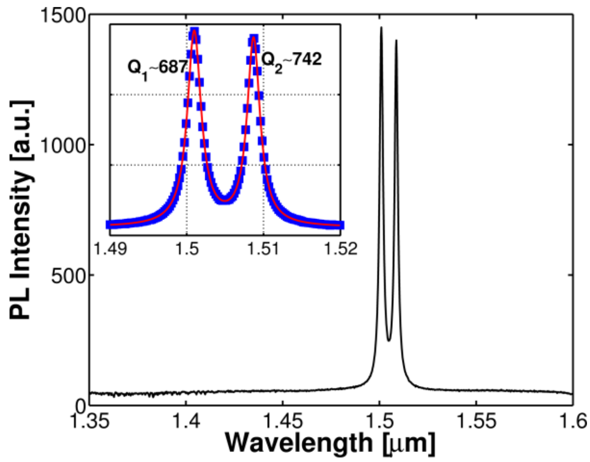


Fig. 3 Room-temperature PL spectrum of a reference free-standing H1 cavity without electrical structures. The inset shows the Lorentz fitting of the resonant peaks and their Q-factors.

4. Conclusions

Ge QDs embedded photonic crystal nanocavity light emitting diodes were successfully demonstrated by using lateral PIN diode structure. Under DC current injection, clear resonant peaks around 1.55 μm wavelength associated with the PhC cavity modes and Ge QDs was observed. The result shows large potential for applying Ge QDs to silicon photonics as the light emitting devices.

Acknowledgements

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