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REVIEW ARTICLE

Ge quantum dots light-emitting devices

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Abstract Si photonics becomes one of the research focuses in the field of photonics. Si-based light-emitting devices are one of the most important devices in this field. In this paper, we review the Si-based light-emitting devices fabricated by embedding Ge self-assembled quantum dots into optical microcavities. Ge self-assembled quantum dots emit light in the telecommunication wavelength range from 1.3 to 1.6 μm, for which Si is transparent. Ge self-assembled quantum dots were grown on silicon-on-insulator (SOI) by molecular beam epitaxy (MBE) in Stranski-Krastanov (S-K) mode. Then, electron beam lithography (EBL) was used to define the pattern of optical microcavities on the wafer. Finally, the pattern was transferred onto the Si/Ge slab by inductive coupled plasma (ICP) dry etching. Room-temperature photoluminescence (PL) was used to characterize the light-emitting properties of fabricated devices. The results showed that strong resonant light emission was observed in different optical microcavities. Significant enhancement of the intensity was obtained by the optical resonance. Based on the results of PL, we designed and fabricated current-injected light-emitting devices based on Ge self-assembled quantum dots in optical microcavities. Room-temperature resonant light emission was observed from Ge dots in a 3.8 μm microdisk resonator.

Keywords Si-based light-emitting devices, Ge self-assembled quantum dots, microcavities, photonic crystal (PhC), microdisk

1 Introduction

The demand of computation power and data transmission bandwidth is becoming higher and higher due to the rapid development of the information society. The size of transistors is getting smaller and smaller, and current electronic integrated circuit on Si-platform is facing the limitation of fabrication difficulties, thermal dissipation, and bandwidth. In order to fulfill the growing demand, scientists are performing numerous efforts to develop the next-generation integrated circuit on Si platform. One of the solutions is the optoelectronic hybrid integration on Si, which has the advantages of ultra-large bandwidth and low power consumption. The extracting view is that integrating different optical components, such as Si-based light source, optical waveguide circuits, modulator, detector, and electronic integrated circuit for control on a single Si wafer. Therefore, complementary metal oxide semiconductor (CMOS) compatible Si-based light-emitting devices are inevitable for the optoelectronic integration on Si. Unfortunately, Si is an indirect bandgap material, and it is not a good light-emitting material. In order to develop Si as a light-emitting material, various proposals, such as SiGe quantum wells and dots [1–6], Si/SiGe quantum-cascade structures [7,8], Er doping [9], Si nanocrystals [10], and defects engineering [11], have been proposed for creating light-emitting centers in Si and Si-based materials. Among these methods, Si-based light-emitting devices based on Ge quantum dots have big potential since it is fully CMOS-compatible.

2 Microcavity photonic devices with Ge dots

Ge self-assembled quantum dots attract much attention due to its potential of Si-based light source. Since Ge belongs to the group IV materials and is already used in the integrated circuit industry in recent days, Ge self-assembled quantum dots-based light emitting devices are fully compatible to current CMOS technology. Ge self-assembled quantum dots can be easily grown using molecular beam epitaxy (MBE) in Stranski-Krastanov (S-K) mode. In Ge quantum dots, the radiative recombination probability is enhanced due to the space trapping of excited carriers by the type-II band structure [3–6].

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Figure 1(a) shows the atomic force microscope (AFM) image of the Ge self-assembled quantum dots. As seen in Fig. 1(a), two kinds of quantum dots, pyramids and domes, are formed during the growth. The overall dot density is around $1.6\times10^{10}/cm^2$. Figure 1(b) shows the photoluminescence (PL) spectrum of the Ge quantum dots measured at 40 K. A wide PL peak covers the wavelength range from 1.3 to 1.6 μm, for which Si is transparent. It is very important for the future integration of Si-based light source and optical waveguide circuit on a single Si chip. The big dispersion of the quantum dot size leads to the broadening of the PL spectrum. Si/Ge materials are more stable compared with porous and amorphous Si, Si nanocrystals and engineered defects in Si. Moreover, it is easy to carry out current-injection based on SiGe platform, which is important for fabricating practicable devices. However, the main drawbacks of light emission from Ge self-assembled dots are (1) lack of spectral purity; (2) lack of directionality; (3) low efficiency.

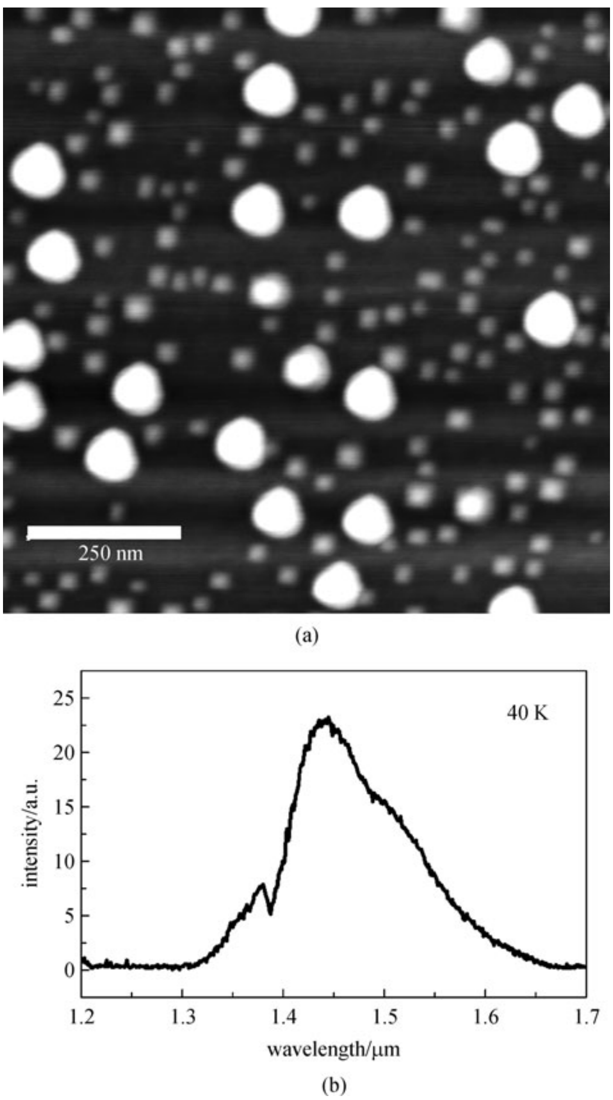

Fig. 1 (a) AFM image of the Ge self-assembled quantum dots grown at 600°C by gas-source MBE; (b) PL spectrum of Ge self-assembled quantum dots at 40 K

Optical microcavity, which is one of the current hottest research focuses, can solve these problems in principle [12,13]. Optical microcavities will modify the light emission from Ge dots embedded inside due to the optical resonance. The spontaneous emission rates of Ge dots will be modified by the electromagnetic field with the cavity. Only the emission at discrete wavelengths, corresponding to the cavity modes, will be selected and enhanced, and the other emission will be suppressed due to the Purcell effect [12]. The enhancement is proportional to the quality factor over the mode volume of the cavity modes. Different microcavities have been used to modulate, enhance, and control the light emission from Ge self-assembled quantum dots.

Kawaguchi and his colleagues embedded Ge self-assembled quantum dots into planar microcavities formed by SiGe/Si distributed Bragg reflectors (DBRs) [14–17]. The DBRs were formed by growing strain-balanced $Si_{0.73}Ge_{0.27}$/Si pairs on a relaxed $Si_{0.89}Si_{0.11}$ buffer layer on graded buffer on Si substrate using gas-source molecular beam epitaxy (GS-MBE). A one-wavelength-thick $Si_{0.89}Si_{0.11}$ with Ge dots was embedded into two DBRs. Figure 2(a) shows the reflectivity of the cavity structure at room temperature and Fig. 2(b) shows the PL spectrum of the cavity sample together with the PL spectrum of a reference sample without cavity at 10 K. The dip in the reflectivity spectrum indicates the resonant wavelength of the cavity. The shape of the PL spectrum of the cavity sample is completely different to the spectrum from reference sample showing the function of the cavity. The highest peak is assumed to be the resonant peak of the cavity. Angular dependence of PL intensity was also observed giving another evidence of the optical resonance induced by the cavity structure.

Compared with vertical cavities formed by SiGe/Si DBRs, microdisk and microring [18] resonators are simple and easy to fabricate. Strong and sharp resonant PL has been observed from Ge self-assembled quantum dots in both microdisk and microring resonators [19,20].

It is well-known that microdisk resonators support whispering-gallery modes (WGMs), which are confined closed to the edge [18]. Figure 3 shows the scanning electron microscope (SEM) image of a fabricated microdisk [19]. In the disk, three Ge dots layers are embedded inside. Figure 4 shows the measured room-temperature μ-PL spectrum of a microdisk with a 4 μm diameter when the pumping laser spot is located at different locations of the disk. To activate the WGMs, the pumping laser spot is located close to the edge of the disk for Fig. 4(a). Strong PL signal is observed in the range from 1.1 to 1.6 μm. For comparison, the bottom reference PL spectrum is recorded in the unprocessed region on the chip under the same condition. It is a typical room-temperature PL spectrum for Si and there is no obvious signal in the emission range of

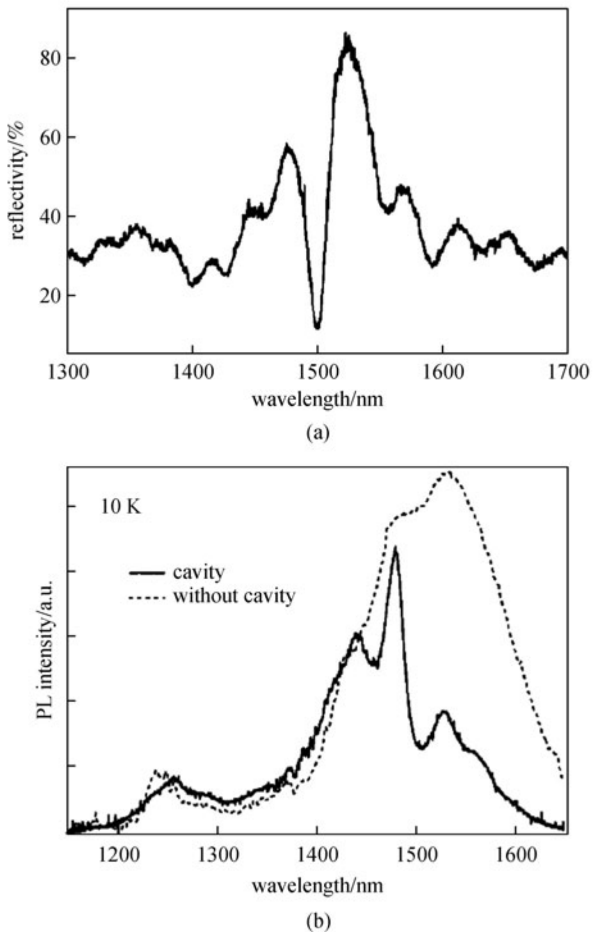

Fig. 2 (a) Reflectivity spectrum of planar cavity with Ge dots formed by SiGe/Si DBRs; (b) PL spectrum at 10 K from Ge quantum dots in cavity formed by SiGe/Si DBRs (The dashed line shows PL spectrum of reference sample without cavity. This figure is adopted from Ref. (15))

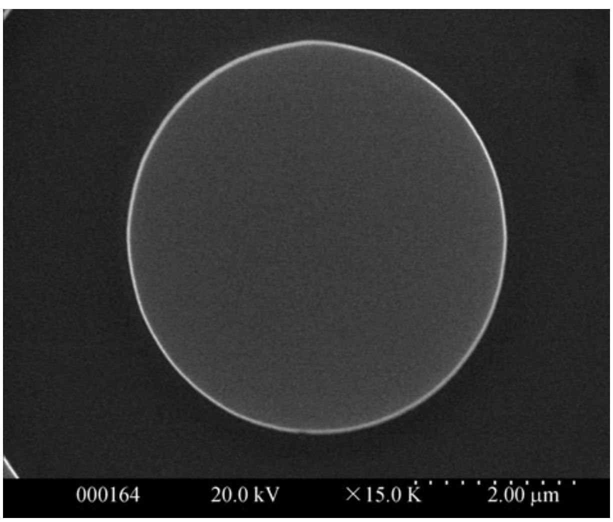

Fig. 3 SEM image of fabricated microdisk resonator with Ge quantum dots

Ge dots. Compared with the reference, the PL intensity from Ge quantum dots is significant enhanced in the microdisk resonator. This enhancement may be attributed to two factors, the Purcell effect [12] and enhancement of extraction efficiency due to the light scattering at the disk edge. Two kinds of resonant peaks, the sharp peaks and the broad peaks, exist in the spectrum shown in Fig. 4 (a). The sharp resonant peaks are superimposing with the lower broad peaks. The quality factors of the sharp peaks are in the range from 600 to 800, and the quality factors of the broad peaks are much lower. It is proved that the sharp resonant peaks correspond to the WGMs supported by the disk because they can be activated only when the pumping spot is located at the edge of disk. When the laser spot is located at the disk center, the recorded μ-PL spectrum is shown in Fig. 4(b). As it can be seen in the figure, the sharp resonant peaks disappear, and only the broad resonant peaks remain. It is reasonable since the pumping at the center of disk cannot activate the WGMs, because they are confined to the edge of the disk. All the sharp resonant peaks in the range from 1.2 to 1.6 μm are identified by calculations [10,18] and listed in Fig. 4(a). As shown in Fig. 4, the broad peaks can be activated at both the edge and the center of the disk. We attribute these broad peaks to Fabry-Pérot (F-P) like modes, which are different from WGM and can be activated at everywhere inside the disk. The F-P like modes correspond to another way of resonance: light propagates along the axis of the disk and is reflected by the opposite edges of the disk. The resonant wavelength for TE-polarized F-P modes is computed and shown by the short vertical lines in Fig. 4(b). The numbers below the short lines are the order of the corresponding F-P modes. Because large amount of optical power escapes from the cavity when light is reflected by the edges of the disk, the quality factors of F-P modes are much smaller than that of WGMs as shown in Fig. 4(b).

F-P modes in microdisk are not useful due to its low quality factors. These modes consume part of excited carriers, which leads to a decreasing of the intensity of wanted WGMs. The structure of microring is similar to that of microdisk, but the central area is etched to form a ring-shaped waveguide. Since the light propagation along the axis of the disk is terminated by the central air hole, F-P modes are not supported by microrings. The light can only propagate along the ring waveguide, which leads to the WGMs. Figure 5 shows the SEM image of a 3 μm microring resonator with Ge dots [20]. The width of the waveguide is 0.7 μm. Ten layers of Ge self-assembled quantum dots were grown on SOI wafer with a 2 μm buried dioxide (BOX). Figure 6 shows the room-temperature μ-PL spectrum of the 3 μm microring resonator. The upper back line represents the μ-PL of the microring, while the lower grey line represents the μ-PL spectrum in unpatterned region on the same sample under same configuration. Multiple sharp resonant peaks, corresponding to the WGMs, are observed at room

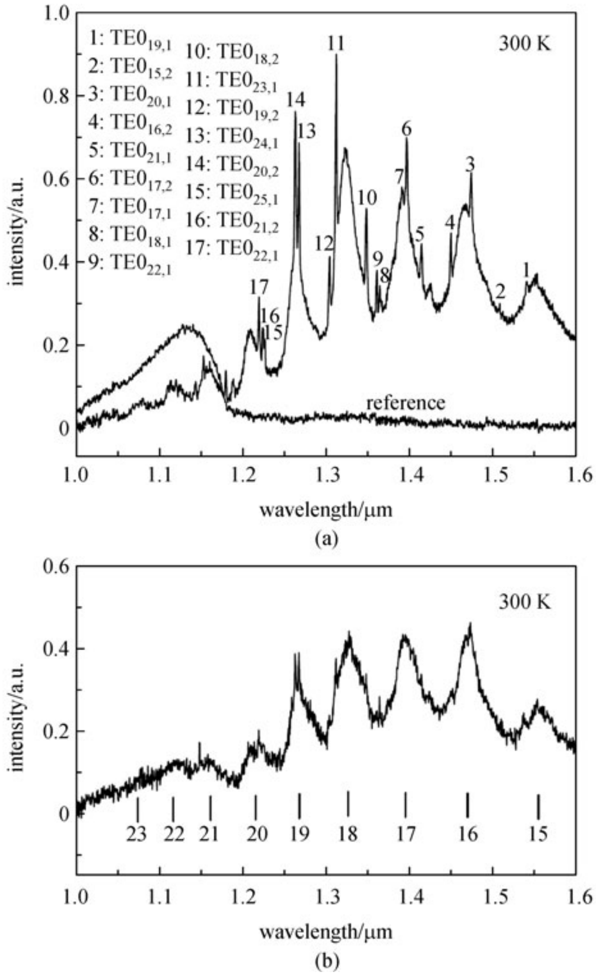

Fig. 4 Room-temperature μ-PL spectra of a 4 μm micro disk with Ge dots. (a) Pumping laser spot is located at the disk edge. The reference spectrum at the bottom is recorded in PhC pattern-free region; (b) pumping laser spot is located at the disk center

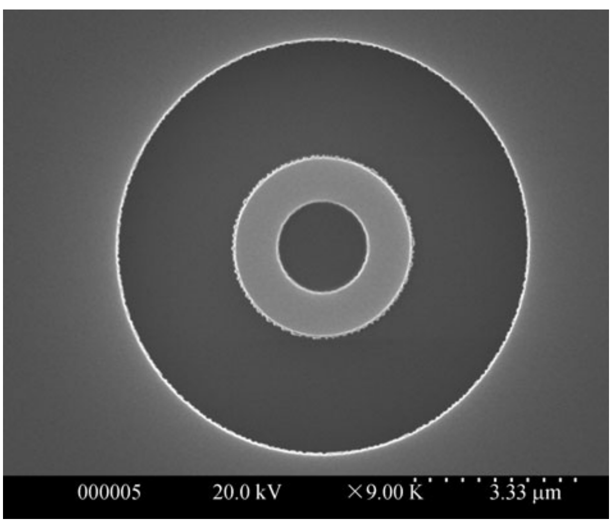

Fig. 5 SEM image of a fabricated microring resonator with Ge dots

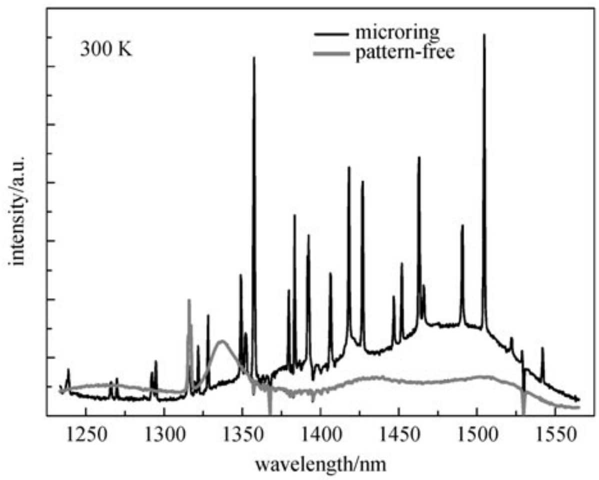

Fig. 6 Room-temperature μ-PL spectra of a 3 μm microring resonator with Ge quantum dots (The top black line is recorded in the microring. The bottom grey line is recorded in the pattern-free region under same condition)

temperature. The quality factors of these resonant peaks are in the range of 1800–2200, which are much higher than the value of the photonic crystal (PhC) and microdisk resonators fabricated on SOI wafers with a 400 nm BOX. A highest quality factor around 3000, corresponding to a 0.5 nm line width, has been achieved for a 4 μm microring resonator with a 1 μm waveguide width. The increase of the quality factor is mainly attributed to the increase of the BOX thickness of the SOI wafer used in the microring fabrication, which leads to the dramatically decrease of coupling loss to the Si substrate. Compared with the unpatterned region, the PL intensity is significantly enhanced.

PhC microcavities provide more flexibility in the design of small microcavities with higher performances. For example, the wavelength of resonant peaks can be controlled by tuning the lattice constant of the PhC structure. Combination of Ge self-assembled quantum dots with PhC cavities was proven to be a possible direction for Si-based light source [20–26]. Figure 7(a) shows the schematic structure of the PhC microcavities reported in Refs. [21,22]. Three layers of Ge self-assembled quantum dots are grown on an SOI wafer with a 400 nm BOX as internal light emitters. The microcavity is formed by introducing defects into two-dimensional PhC lattice. The PhC lattice is designed to have an optical bandgap covering the emission range of Ge dots from 1.3 to 1.6 μm. Due to the optical bandgap, the surrounding PhC structure provides the in-plane optical confinement. And the optical confinement in the normal direction is provided by total internal reflection (TIR) at the interface between silicon and air. Therefore, three-dimensional optical confinement is achieved by this structure. Figure 7(b) shows an SEM image of a fabricated T6 cavity. The

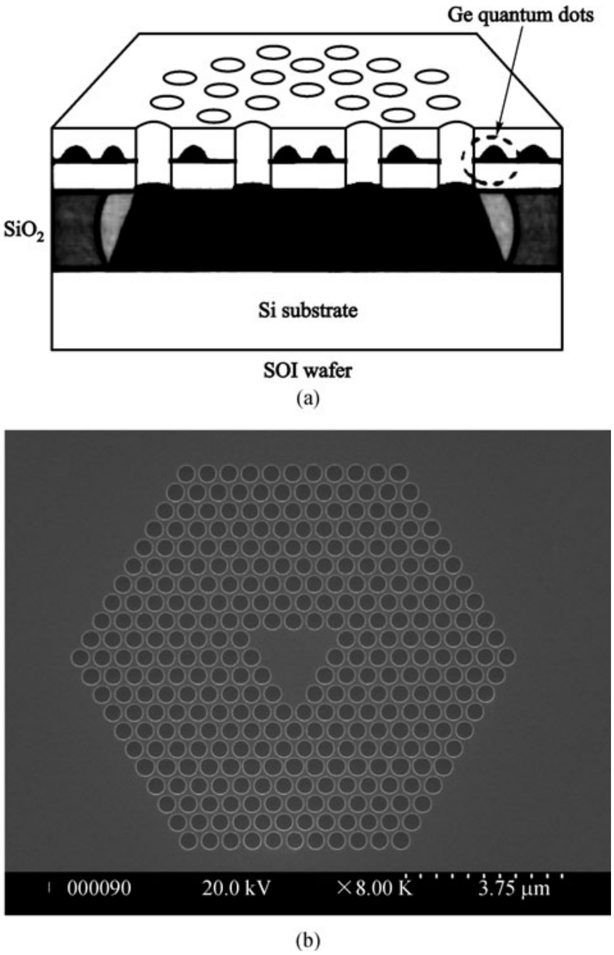

Fig. 7 (a) Schematic structure of PhC microcavity with Ge self-assembled quantum dots; (b) SEM image of fabricated T6 cavity

triangular-shaped cavity is formed by removing the central 10 air holes. Since the length of the cavity edge is 6 periods, we denote it as T6.

Figure 8 shows the room-temperature μ-PL spectrum and reference spectrum from T6 cavity. The PhC lattice constant and the diameter of the air holes are 460 and 322 nm, respectively. Strong resonant room-temperature light-emission is observed. Multiple resonant luminescent peaks in the range from 1.3 to 1.6 µm dominate the spectrum and each peak represents one cavity mode supported by the PhC microcavity. The reference spectrum at the bottom of Fig. 8 is recorded in the PhC pattern-free region of the same sample under the same condition. Significant enhancement is achieved due to the optical resonance in the cavity. Purcell effect may enhance the on-resonance luminescence greatly and suppress the spontaneous emission rate at the other wavelengths as shown in Fig. 8. The full-width-half-maximum (FWHM) of the strongest peak located at 1.39 µm is 3.15 nm, which corresponds to a quality factor around 440 and the largest quality factor of 600 is observed for the peak located at 1.5 µm.

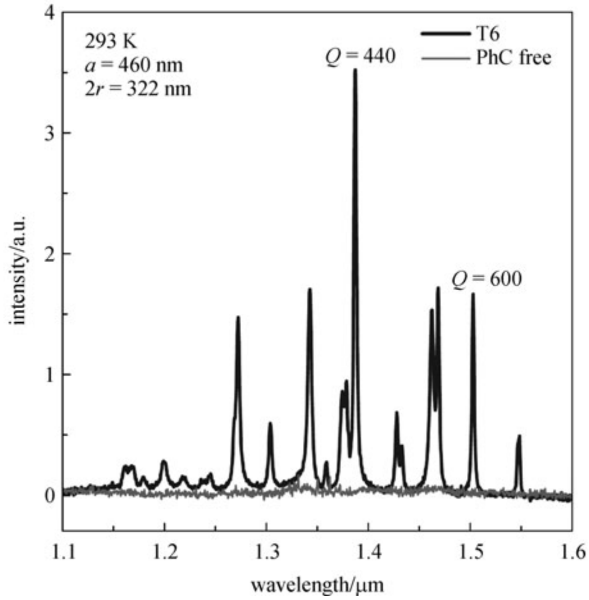

Fig. 8 Room-temperature μ-PL spectrum from T6 microcavity. Pumping power is 0.2 mW at 514.5 nm. The reference spectrum at the bottom is recorded in PhC pattern-free region

To study the dependence of the resonant peak wavelengths on the PhC lattice constant, T6 microcavities with different lattice constants were fabricated and tested by room-temperature PL measurements [22]. Figure 9

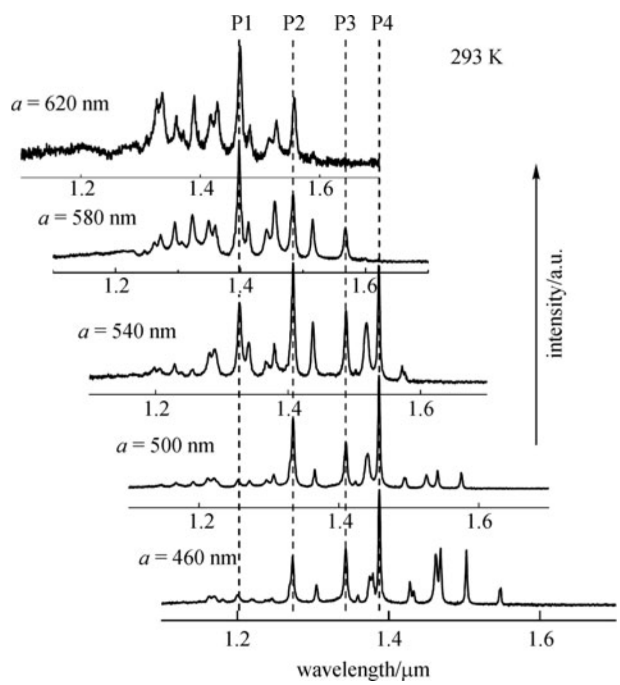

Fig. 9 Room-temperature μ-PL spectra from T6 microcavities with different lattice constants. The scale of wavelength axis decreased and moved to clearly show the relationship between the spectra. The vertical dashed lines show the alignment of four selected resonant peaks

shows the room-temperature μ-PL spectra from the T6 microcavities with different PhC lattice constants. To clearly show the relationship between the luminescent peaks for different cavities, the scale of the wavelength axis of the spectra is decreased by the reciprocal ratio of the lattice constant, and the axis is shifted to match the peak positions. Comparing the five spectra, it is obvious that the resonant peaks move to the longer wavelength side when the lattice constant is increased. It is reasonable considered that the photonic bandgap of the PhC structure is proportional to the lattice constant of the PhC lattice. The vertical dashed lines indicate the peak positions of four selected peaks, and the peak positions coincide well among different cavities. This agreement comes from the scaling law of PhC structure. Recently, a quality factor as high as 20000 has been already achieved for the resonant light emission from Ge dots in PhC line defect cavities [27].

For practical devices, current-injection is necessary in Ge dots-based light-emitting devices (LED). Electroluminescence (EL) from SiGe heterostructures has been reported by several research groups [28,29]. Room-temperature resonant EL from Si microdisks with Ge dots was report recently [30]. Figures 10(a) and 10(b) show the schematic structure and SEM image of the fabricated device, respectively. Figure 10(c) shows the EL spectrum recorded at room-temperature under an injected current of 0.1 mA. Clear EL is observed in the wavelength range from 1 to 1.4 µm. Several peaks are seen in the spectrum, and they may be assigned to the optical resonance in the microdisk. There are three major peaks locating at 1.185, 1.238, and 1.295 µm, respectively. Three dimensional finite-difference-time-domain (FDTD) simulations identify these peaks. Figure 10(d) shows the calculated TM-polarized-like resonant peaks of the device. Three peaks locating at 1.191, 1.241 and 1.296 µm are well corresponded to the three major peaks in the EL spectrum. The mode profiles of these peaks are shown by the insets in Fig. 10(d). They are WGMs with the order of $TM0_{2,27}$, $TM0_{3,12}$, and $TM0_{3,12}$. The demonstration of current-injected Si-based light emitting devices based on Ge dots in optical microcavities shows a possible direction for the ultimate Si light source for the hybrid integration on Si.

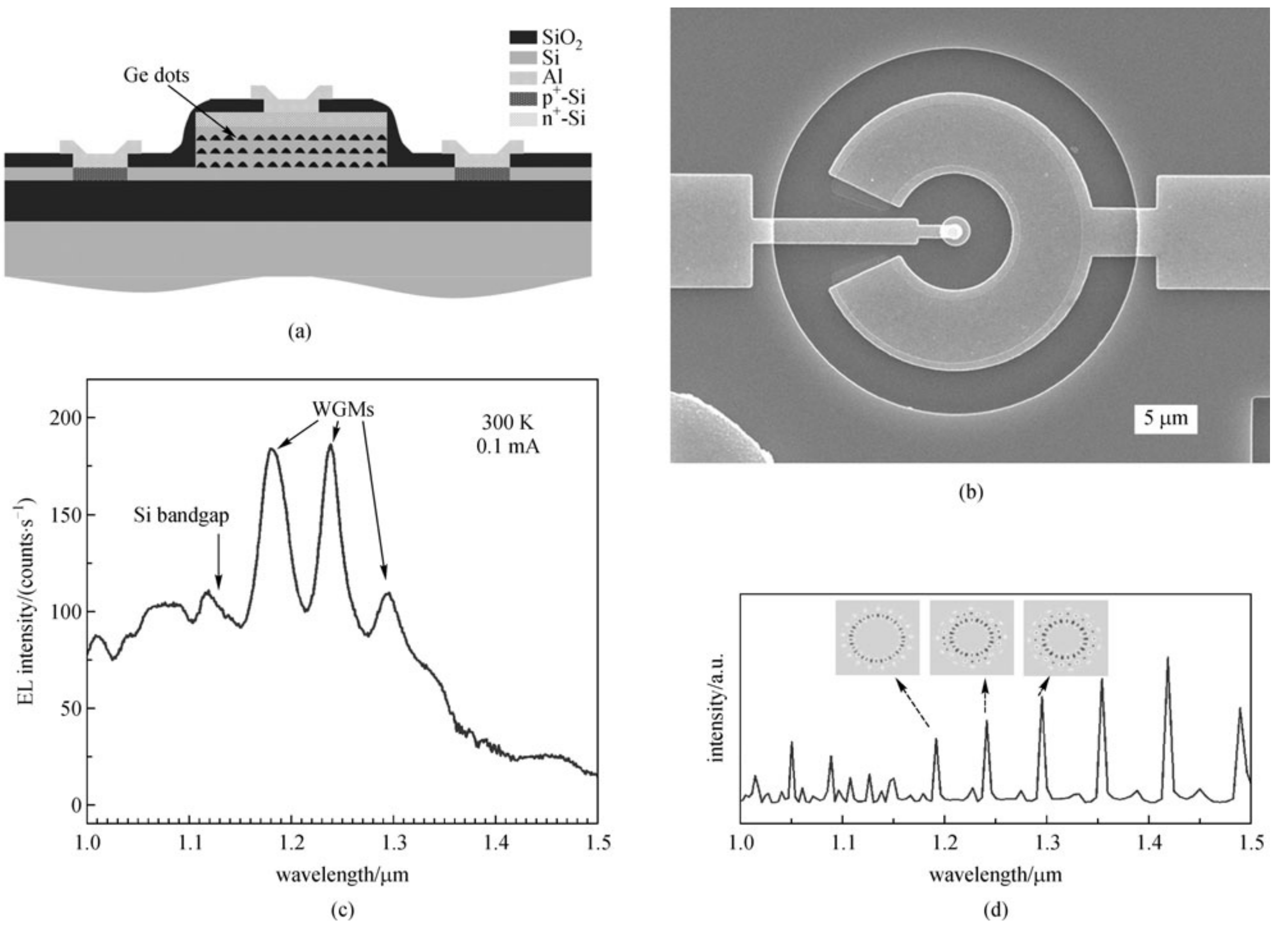

Fig. 10 (a) Schematic structure of Ge dots microdisk EL device; (b) SEM image of a 2.8 µm microdisk EL device; (c) EL spectrum of the device undercurrent of 0.1 mA recorded at room-temperature; (d) calculated resonant wavelengths of TM-polarized-like WGMs supported by microdisk. Insets show the mode profiles of WGMs

3 Conclusions

Si-based light source in the telecommunication wavelengths is one of the most important components for future optoelectronic hybrid integration on Si, which is a possible answer to keep the Moore's law going in the next tens of years. Strong room-temperature resonant light emission from Ge self-assembled quantum dots in optical microcavities shows a promising way to fabricate fully CMOS-compatible Si-based light emitting devices. It is highly attractive to the wide applied physics community, photonics community, and also the IC industry. It will contribute to the ultimate Si-based light source, optical interconnections inside Si chips, and accelerating the emerging of the "optical age of silicon".

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