A-1-6

Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp574-575

Precise Coupling of single Germanium quantum dot to Silicon Photonic Crystal Nanocavity

Cheng Zeng,[1] Yingjie Ma,[2] Yong Zhang,[1] Zuimin Jiang,[2] Jinzhong Yu,[1] Jinsong Xia[1]

[1] Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China
[2] State Key Laboratory of Surface Physics, Fudan University, Shanghai 200433, China
Tel: +86-27-87793415 Fax: +86-27-87792225
Email: jinsongxia@gmail.com

Abstract

A silicon light emitter based on single germanium quantum dot precisely embedded in a silicon photonic crystal nanocavity is fabricated by scalable method. A sharp resonant luminescence peak is observed at 1498.8 nm, with an estimated Purcell factor of 66.

1. Introduction

Coupled single quantum dot-cavity systems have been realized in several material systems for single photon sources[1], on demand polarization–entangled photons source[2], low threshold laser oscillation[3] and strong coupling effect such as vacuum Rabi splitting[4]. However, most of these systems are based on III-V compound semiconductors, and the fabrication process is not scalable. Single quantum dot (SQD)-cavity systems on the silicon-on-insulator (SOI) platform have not, to our knowledge, been reported. SOI chip have a number of advantages, such as advanced fabrication technology for scalability, low-cost and high density integration, low transmission loss in telecom-band, and on-chip integration of electronics. The realization of QD-cavity systems on the SOI platform will pave the way to scalable quantum information applications.

In this paper, we demonstrate the feasibility of accurately embedding germanium (Ge) SQD in two -dimensional photonic crystal (PhC) L3 cavity by scalable method. Strong resonant luminescence at telecom wavelengths from Ge SQD embedded in a PhC L3 cavity is observed up to room temperature. The enhancement factor of fundamental resonant mode is ~1,300, with an estimated Purcell factor of 66. In addition, different recombination mechanisms of excited carriers through ground and excited states in Ge SQD are identified by the resonant luminescence spectra.

2. Device design and fabrication

Site-controlled self-assembled Ge SQD arrays with an ultra-low density are grown on nanohole-patterned SOI substrate via molecular beam epitaxy (MBE), as shown in Fig. 1(a). The average size of Ge QDs is about 97 nm in width and 6.7 nm in height. These QDs are buried in the center of 240 nm thick SOI lab. Nanocavities are then fabricated precisely on the QD position using electron beam lithography (EBL) and dry etching process with a mean overlay accuracy of 22 nm. A scanning electron microscope (SEM) image of the fabricated PhC L3 cavity with embedded Ge SQD is shown in Fig. 1(b). The lattice constant a is 395 nm and the radius of air holes r is $0.30a$.

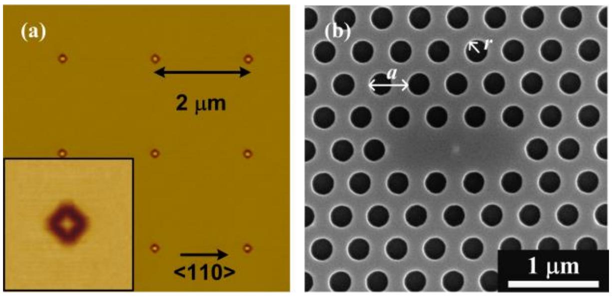

Fig. 1 PhC L3 cavity with embedded Ge SQD. (a) Atomic force microscope (AFM) micrograph of the Ge SQDs grown on the nanohole patterns with a period of 2 μm. (b) The scanning electron microscope (SEM) image of fabricated PhC L3 cavity with embedded Ge SQD.

3. Results and discussion

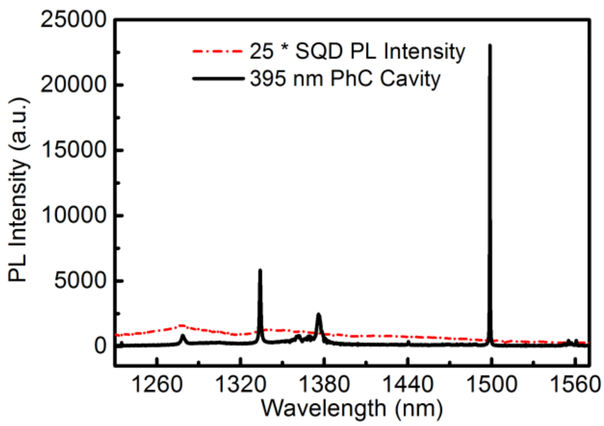

Fig. 2 PL spectra of Ge SQDs in an unprocessed membrane and a L3 nanocavity. The μ-PL spectrum are measured at T=7 K with an excitation power of 460 μW.

The micro-photoluminescence (μ-PL) results of our cavity-SQD system is shown in Fig. 2, black and red curves represent the μ-PL spectrum of in the L3 cavity and Si/Ge membrane with unprocessed Ge SQD array, respectively. Several sharp resonant peaks are observed to dominate the spectrum over an almost flat and weak background emission in the μ-PL spectrum. These resonant peaks are identified as the PhC cavity modes M0 to M3, respectively. The highest emission peak at 1,498.8 nm represents luminescence from the fundamental cavity mode (M0 mode), with an enhancement factor of ~1,318. The PL enhancement is attributed to the increased collection efficiency and the Purcell effect in the PhC cavity. The enhancement of collection efficiency for M0 mode is calculated to be ~ 20 (by 3D FDTD simulation). Then, the estimated Purcell factor for M0 mode is 1318/20 ~ 66, which is about 10 times higher than Purcell factor of the L3 caivty with Ge QDs growth by traditional self-assembled epitaxy[5]. We attribute the accurate spatial and spectral overlap between SQD and PhC cavity to be the main reason for the high Purcell enhancement.

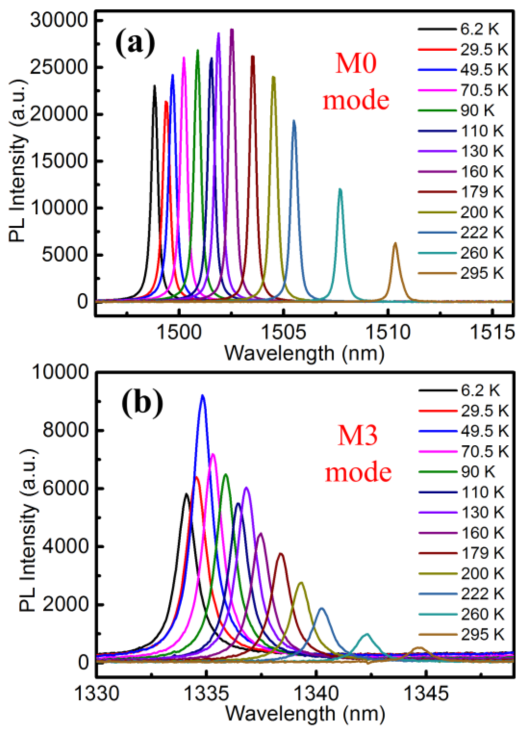

Fig. 3 The temperature dependence of μ-PL spectra. (a) and (b) show measured PL peaks of M0 and M3 modes at different temperatures. Strong resonant luminescence peaks are observed up to room temperature.

Fig. 3 (a) and (b) show the temperature dependence for the M0 and M3 modes of L3 cavity. Strong resonant luminescence peaks are observed up to room temperature. The peak intensity of M0 mode increases as the T_{PL} increases and reaches to a maximum when T_{PL}=160 K. Similar trend is also applied for M3 mode, but the peak intensity of M3 mode reaches to a maximum at a lower temperature (T_{PL} =49.5 K). Strong intensity roll off is observed for T_{PL} >160 K (M0 mode) and T_{PL} >49.5 K (M3 mode), which can be fitted by an activation energy, E_a, characterizing the barrier against thermalization of excitons from QD structure into the outer wetting layer or Si matrix. The activation energy of M0 and M3 modes are fitted to be 151 and 83 meV, respectively. The PL peak of M0 mode and M3 mode are assigned to be light emission from QD ground state and excited state recombination, respectively. The difference of activation energy and photon energy between M0 and M3 mode (68 meV) are close to the energy difference between ground state and excited state (82 meV)[6]. The Si/Ge QD system has a type-II energy band alignment along the growth direction. Interband optical transitions are classifed as four kinds of recombination processes: spatially indirect across the Si/Ge interface, spatially direct transitions inside the Ge QD through both the ground state and the exited state of confined holes. When the temperature increases, holes and electrons which are previously trapped in the wetting layer at low temperature could be thermally activated to move to the QD, resulting in an increase of PL intensity. On the other hand, a redistribution of the emission from the spatially indirect band to the spatially direct band will happen due to the increase of the temperature, resulting in higher oscillator strength and higher PL intensity[7]. When the temperature goes even higher (>160K for M0 mode, >50K for M3 mode), the thermalization of excitons causes less holes participating the QD interband optical transition leading to the significant dropping of PL intensity.

4. Conclusion

In summary, we demonstrate the feasibility of controllable coupling of a Ge SQD with a PhC nanocavity on SOI substrate. Strong resonant luminescence from Ge SQD embedded in PhC L3 cavity is observed up to room temperature. The PL spectra of Ge SQD with cavity enhancement help us to get further understanding of optical properties of type II band alignment in Ge QDs. The dot ordering and alignment approach provides a scalable, low cost and CMOS compatible way to fabricate Si-based SQD-cavity systems, showing a promising candidate for Si-based non-classical devices.

References

[1] A. J. Shields, "Semiconductor quantum light sources," *Nature Photonics*, vol. 1, pp. 215-223, Apr 2007.

[2] A. Mohan, M. Felici, P. Gallo, B. Dwir, A. Rudra, J. Faist, *et al.*, "Polarization-entangled photons produced with high-symmetry site-controlled quantum dots," *Nature Photonics*, vol. 4, pp. 302-306, 2010.

[3] M. Nomura, N. Kumagai, S. Iwamoto, Y. Ota, and Y. Arakawa, "Laser oscillation in a strongly coupled single-quantum-dot–nanocavity system," *Nature Physics*, vol. 6, pp. 279-283, 2010.

[4] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatüre, S. Gulde, *et al.*, "Quantum nature of a strongly coupled single quantum dot–cavity system," *Nature*, vol. 445, pp. 896-899, 2007.

[5] Y. Zhang, C. Zeng, D. Li, Z. Huang, K. Li, J. Yu, *et al.*, "Enhanced 1524-nm Emission From Ge Quantum Dots in a Modified Photonic Crystal L3 Cavity," *Photonics Journal, IEEE*, vol. 5, pp. 4500607-4500607, 2013.

[6] P. Boucaud, S. Sauvage, M. Elkurdi, E. Mercier, T. Brunhes, V. Le Thanh, *et al.*, "Optical recombination from excited states in Ge/Si self-assembled quantum dots," *Physical Review B*, vol. 64, p. 155310, 2001.

[7] M. Larsson, A. Elfving, W.-X. Ni, G. V. Hansson, and P.-O. Holtz, "Growth-temperature-dependent band alignment in Si/Ge quantum dots from photoluminescence spectroscopy," *Physical Review B*, vol. 73, p. 195319, 2006.