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Size and Matrix-strain Effects on Ge Quantum Dots Light Emission

S. H. Chiu,[1] C. W. Tien,[1] S. D. Lin,[1] W. H. Chang,[2] H. C. Lin,[1] and Pei-Wen Li[1]

[1]Institute of Electronics Engineering, National Chiao Tung University
[2]Department of Electrophysics, National Chiao Tung University
1001 University Road, Hsinchu, Taiwan
E-mail: pwli@nctu.edu.tw

Abstract

We proposed a unique CMOS compatible, self-organized approach to grow Ge spherical quantum dots (QDs) of desired diameter at targeted spatial locations within dielectric matrix of Si_3N_4 and SiO_2. Then we advanced the investigations on the embedment matrix-induced stress and quantum-size effects on the optical properties of bandgap energy, activation energy, and exciton dynamics of Ge QDs.

1. Introduction

There emerge strong demands on the production of photonic components with mature CMOS technology in order to continue the ever increasing performance for computing and communications. However, monolithic integration of optoelectronic circuits on Si platforms has been impeded by the lack of Si-compatible light sources. Encouragingly, Ge electrically-pumping lasers have recently been reported by the conversion of Ge from the indirect bandgap to a quasi-direct one in terms of strain engineering and doping techniques. [1] However, emission efficiency form highly-tensile strained, heavily-n^+ doped Ge films is far from satisfactory due to strong free carrier absorption. Another approaches to increase emission efficiency from Ge are employing quantum confinement of Ge nanostructures and matrix strain engineering.

We are able to grow Ge spherical QDs of desired sizes at targeted spatial locations within SiO_2 and Si_3N_4 matrix in a single-step, thermal oxidation of poly-SiGe lithographically-patterned pillars over buffer layers of Si_3N_4 on Si substrates. Details of the formation mechanisms for the Ge QDs have been described elsewhere. [2, 3] In this paper, we advanced the photoluminescence (PL) measurements on Ge QDs in order to gain insights on embedment matrix-induced stress and quantum-size effects on the optical properties of Ge QDs.

2. Experimental

The fabrication of Ge QDs within SiO_2/Si_3N_4 system started with a trilayer of 25nm-thick Si_3N_4/25–70nm-thick-poly-$Si_{0.85}Ge_{0.15}$/5nm-thick SiO_2 that was sequentially deposited over Si substrates. Next, 50–180nm-wide poly-SiGe pillars were lithographically patterned and then subjected to thermal oxidation at 900°C for 20–30min in an H_2O ambient for forming Ge QDs with diameters of 20–90nm embedded within SiO_2/Si_3N_4 layers for each oxidized pillar. Then we removed buffer Si_3N_4, which is believe to impose compressive stress on Ge QDs, by rinsing samples within a H_3PO_4 bath.

3. Results and Discussion

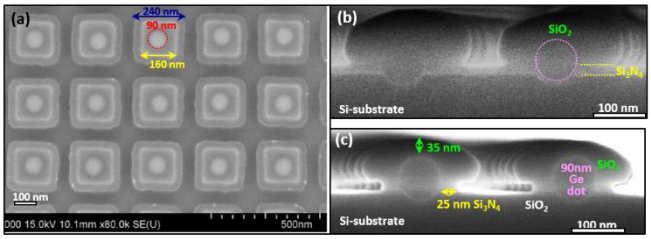

Fig. 1 Formation of Ge dots by the selective oxidation of SiGe nanopillars over buffer layer of Si_3N_4 on SOI substrate. (a) Plan-view and cross-sectional SEM micrographs of SiO_2/Ge dots/Si_3N_4 heterostructure (b) following thermal oxidation and (c) released from Si_3N_4.

Figure 1 shows SEM micrographs of arrays of Ge QDs embedded within and released from buffer layers of Si_3N_4, respectively. Considerable red and blue Raman shifts for the LO Ge-Ge phonon lines of Ge QDs embedded within Si_3N_4/SiO_2 and SiO_2 matrices, respectively, suggest that Si_3N_4 and SiO_2 impose compressive stress and tensile stress on the Ge QD (Fig. 2). The release of Si_3N_4 from the Ge QDs indeed make the QDs nearly stress-free as evidenced by an invisible shift in the LO Ge-Ge mode from the bulk one.

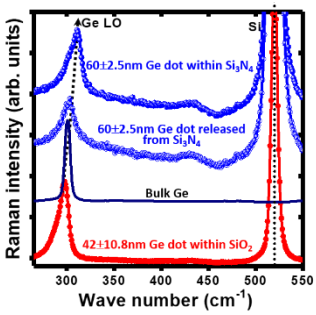

Fig. 2 Raman spectra of bulk Ge as well as Ge QDs embedded within a SiO_2, Si_3N_4/SiO_2, and released from Si_3N_4 matrix.

Effects of the compressive stressor Si_3N_4 on PL of the Ge QDs are shown in Fig. 3. There appears two minute PL peaks at 0.77eV and 0.88eV for the embedment case of Ge QDs within Si_3N_4, whereas only a distinct, strong PL peak at 0.8eV is measured on the Ge QDs released from Si_3N_4. Increasing temperature yields a successive reduction of the PL intensity for all PL peaks, and a quenching in the PL intensity is observed when $T > 150$K due to the dissociation of excitons into e-h pairs which then escape from the Ge QDs via thermionic emission into SiO_2/Si_3N_4 matrix. Activation energy for the thermionic emission process extracted from the Arrhenius plots is 9.3meV, 14.3meV, and 3.9meV for PL peaks at

0.77eV, 0.8eV, and 0.88eV, respectively. The power dependence of the PL intensity for the Ge QDs can be described by a power law of $I_{PL} \sim \eta I_0^{\alpha}$ with fitted power exponent values of 1.16, 0.94, and 0.75, respectively, for peaks at 0.77eV, 0.8eV, and 0.88eV. Both temperature- and power-dependent PL data suggest the PL peaks at 0.77eV, 0.8eV, and 0.88eV, respectively, originating from indirect bandgap, direct bandgap, and NP/TO transitions.

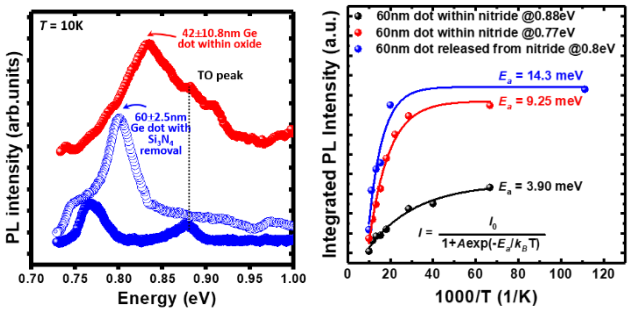

Fig. 3 (a) PL spectra measured at T = 10K on 60nm Ge QDs embedded within SiO_2, with Si_3N_4 in close proximity and with Si_3N_4 removal. (b) the Arrhenius plot of the integrated PL intensity at peak energy of 0.77eV and 0.8eV, respectively, for Ge nanodots embedded within Si_3N_4 or not, respectively.

Further support for our inference is the measured PL decay time extracted from temperature-dependent PL temporal behaviors as shown in Fig. 4. At T < 40K, the carrier lifetime for the indirect bandgap PL peak at 0.77eV is 22ns, which is a factor of 20X enhancement for the direct bandgap PL peak at 0.8eV with decay time of 1.1ns. At higher temperatures, the reduction of carrier lifetime is attributable to the nonradiative, thermal activation of carriers out of the Ge QDs into the SiO_2/Si_3N_4 systems.

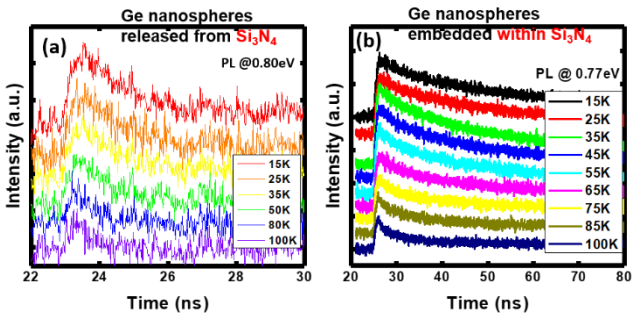

Fig. 4 Time-resolved PL decays for PL peaks at (a) 0.8eV and (b), 0.77eV measured from 60nm Ge dots embedded within Si_3N_4 or not over temperatures ranging from 15–100K.

In line with our previous results, we quantitatively assess the optical properties of 7–90nm Ge QDs being subjected to compressive or tensile stress, depending on the embedment matrix of Si_3N_4 or SiO_2. Important experimental support for matrix strain effect on the electronic structures of Ge QDs is shown in Fig. 5(a), in which at given QD sizes an enhancement in the bandgap energy is measured on the compressively-strained Ge QD embedded within Si_3N_4 than the tensile-strained Ge QDs within SiO_2. Another experimental quantitative evidences for the quantum-size effect on Ge QDs are that optical bandgap energy and excitons lifetime are highly dependent on the QD diameter. Both optical parameters are inversely proportional to the QD diameter and appear to have a drastic increase when the QD size is less than 20nm, very close to the Bohr radius (24.9nm) for bulk Ge. Larger values of the exciton lifetime for smaller Ge QDs demonstrates the applicability of our Ge QDs/SiO_2/Si_3N_4 heterostructures for the development of low-threshold semiconductor lasers.

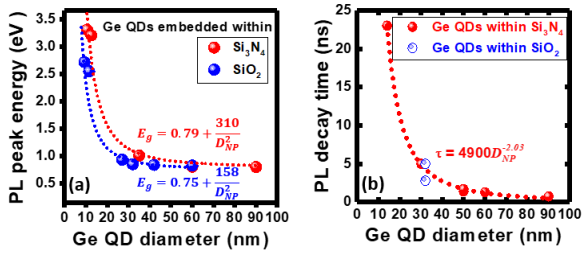

Fig. 5 Size-dependent (a) PL peak energy and (b) PL decay time of Ge QDs embedded within SiO_2 and Si_3N_4.

3. Conclusions

We proposed a unique, CMOS-compatible process approach for the formation of Ge spherical QDs within SiO_2 and Si_3N_4 matrix within a single oxidation step. The process-controlled capability to produce highly-compressive and tensile strained Ge QDs allows us quantitatively assessed the optical bandgap energy and exciton dynamics of the Ge QDs. Armed with the matrix strain and quantum-size engineering, size-tunable direct bandgap transitions and large values of exciton lifetime are achievable from our Ge QDs, enabling the applicability of our Ge QDs/SiO_2/Si_3N_4 heterostructures for the development of low-threshold semiconductor lasers.

Acknowledgements

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References

[1] R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, and J. Michel, Optics Express, **20** (2012) 11316.

[2] K. H. Chen, C. C. Wang, Tom George and P. W. Li, *Appl. Phys. Lett.* **105** (2014) 122102.

[3] T. George, P. W. Li, K. H. Chen, K. P. Peng and W. T. Lai, *J. Physics D: Appl. Phys.*, **50** (2017) 105101.