Local Control of energy structure of semiconductor quantum dots using phase change material

Motoki Takahashi, Nobuhiro Tsumori, and Toshiharu Saiki
Graduate School of Science and Technology, Keio University

Abstract

We proposed a new method to precisely control the emission energy of semiconductor quantum dot (QD) by applying a local strain due to a volume expansion of phase change GeSbTe upon amorphizatoin. We experimentally demonstrated the method through PL spectroscopy of InAs QDs on which a GeSbTe thin film is deposited. Significant red shift of PL peak energy upon amorphization and its recovery due to recrystallization by laser annealing were observed.

1. Introduction

Semiconductor quantum dots (QDs) have unique characteristics such as discrete energy levels and strong electron-hole interaction due to carrier confinement in a nanoscale volume. We can take advantage of these properties in the application of quantum communication and quantum information processing. One of the main challenges to be addressed in these applications is precise control of energy structure of electrons confined in a QD by applying a magnetic field [1], electric field [2], or mechanical strain [3]. For the energy level tuning with a magnetic field, an elaborate apparatus is needed to generate a strong field. In the case of electric field application, a strong field causes a decrease and broadening of photoluminescence (PL) emission line due to the reduction in electron-hole wavefunction overlap. Besides these drawbacks, in the current techniques, the external field cannot be applied to an individual QD.

In this study we propose a new method to locally apply mechanical strain that allows precise energy control by using a volume expansion of phase change material upon amorphization.

2. Principle

Figure 1 is a conceptual schematic of the proposed method. A crystalline GeSbTe thin film was formed on a QD sample. Nanoscale amoprhization was induced by irradiation of femtosecond or subnanosecond laser pulse, which enables nonthermal amorphization below the melting point and therefore thermal damage on the sample to be avoided. Since approximately 10% volume expansion accompanies the transformation from crystalline to amorphous phase, amorphization of the GeSbTe film, which is confined by a SiO_2 layer, can give rise to significant strain on the QD. It is expected that compressive strain leads to a blue shift of the PL peak energy of QD while tensile strain causes a

red shift. We can control the magnitude of peak shift because the amorphized volume is proportional to the number of irradiation pulse.

It should be noted that the GeSbTe film also works as an optical mask for spatially selective observation of the strain induced QD. At the wavelength of visible excitation light, since the extinction coefficient of amorphous phase is much smaller than that of crystalline phase, QDs just below the amorphized region (amorphous aperture) is selectively illuminated and photoexcited. For near-infrared PL emission, on the other hand, the GeSbTe film is almost transparent, which ensures high collection efficiency of PL signal.

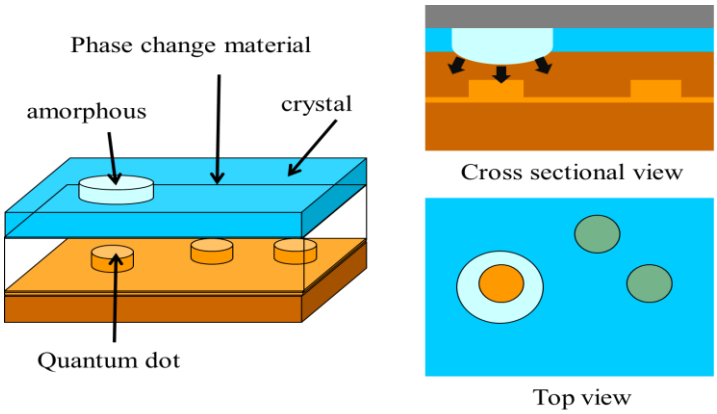

Fig. 1. Principle of local strain application to a QD using a phase change thin film deposited on a QD sample.

3. Experimental and results

To experimentally demonstrate the proposed method we performed PL spectroscopy of an InAs/InP self-assembled QD sample covered with a GeSbTe thin film (Fig. 2). InAs QDs were grown on an InP substrate by solid-source molecular beam epitaxy. After the growth of a 100-nm InP cap layer on the QDs, a 40-nm $Ge_{10}Sb_2Te_{13}$ mask layer and a 50-nm SiO_2 layer for GeSbTe confinement were deposited by sputtering.

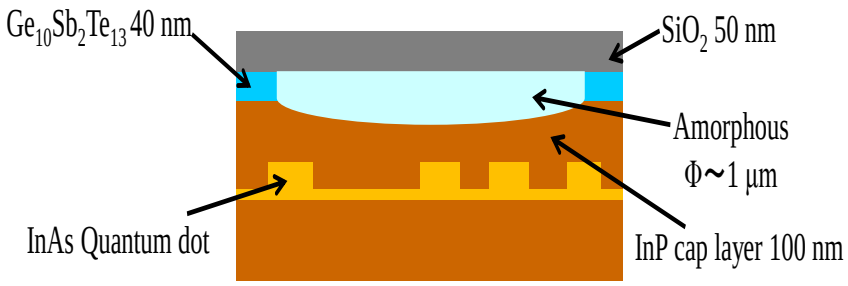

Fig. 2. Sample structure.

Local amorphization was performed by focusing femtosecond Ti: Sapphire laser pulse (□=800 nm) or Subnanosecond Q-switched solid state laser (□=532 nm) through a microscope objective. In the □PL measurement the QDs were excited by He-Ne laser light and PL signal was detected by a spectrometer and a liquid nitrogen cooled InGaAs diode array. All the measurement was performed at 7K in a cryostat.

Figure 3 demonstrates the optical mask effect of the GeSbTe film. Compared to a non-masked region (blue), the number of QDs observed through the amorphous aperture (red) is significantly reduced. Figure 4 shows PL peak shifts accompanying amorphization and successive recrystallization of the GeSbTe film. Upon amorphization the PL peak exhibited a red shift and it recovered to original peak position when the amorphized region is recrystallized by laser annealing. In Fig. 5, the maximum red shift as large as 1.2 meV was obtained.

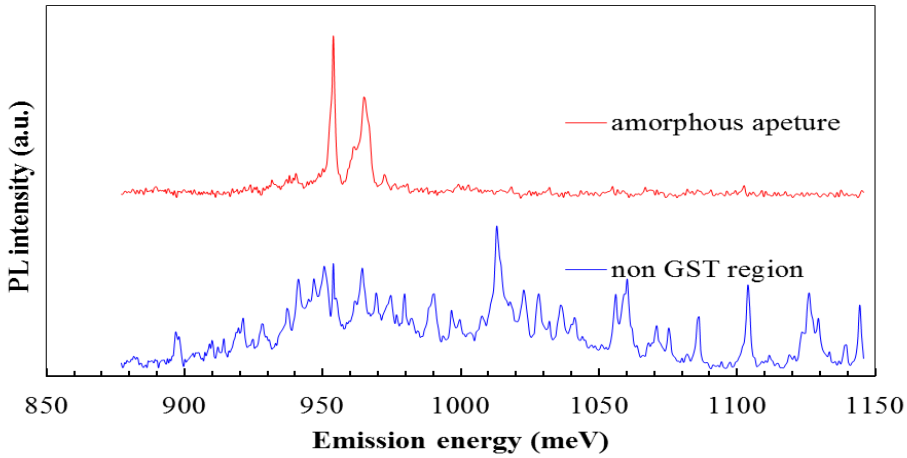

Fig. 3. PL spectra of InAs QDs obtained at non-masked region (blue) and through the amorphous aperture(red).

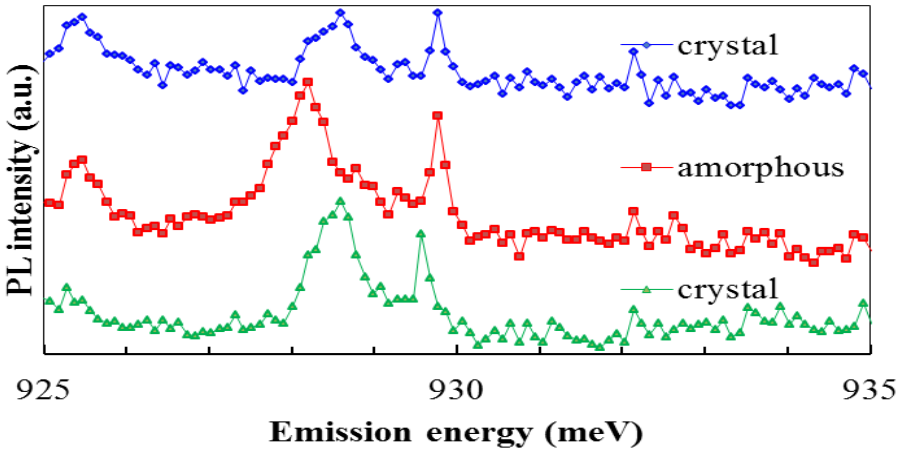

Fig. 4. PL spectra of InAs QDs measured before (green) and after (red) amorphization. The PL peak energy recovered to the original position after recrystallization by laser annealing (blue).

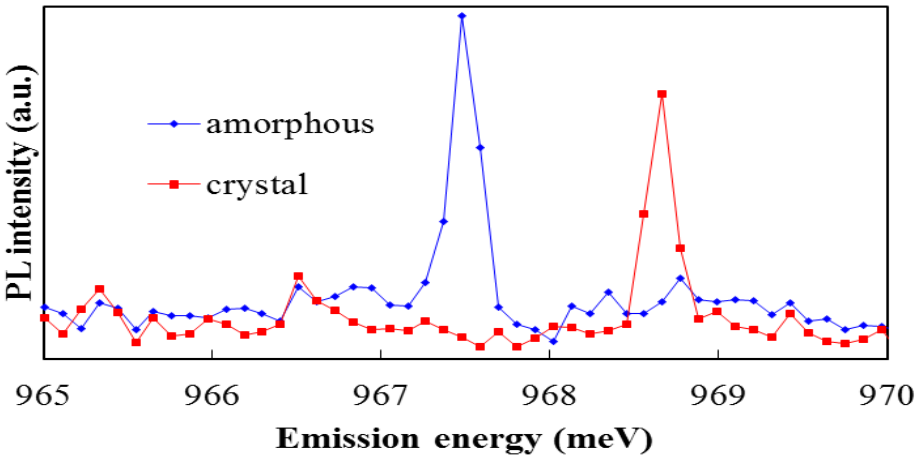

Fig. 5. The maximum PL peak shift we obtained upon amorphization.

4. Acknowledgement

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5. References

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