Research Article
Structural and Luminescence Properties of SiGe Nanostructures with Ge Quantum Dots

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Abstract: A study of technological parameters of growing of SiGe like number of Ge nano layers, layers thickness and temperature of substrate are reported. These parameters play an important role in the optical properties of SiGe nanostructures with Ge quantum dots. A long lifetime of radiative recombination for band-to-band transition is attributed to indirect band in Si. As a consequence, the dominant recombination at deep level defects is non-radiative. In order to enhance the intensity of luminescence band at 0.8 eV that related to radiative recombination of Ge quantum dots, the hydrogen plasma ion treatment of SiGe nanostructure were utilized. Improving of the luminescence intensity is an important parameter to increase the quantum efficiency of optoelectronic devices based on the Si nano layer with Ge quantum dots.

Keywords: Ge quantum dots (QD), internal strain, photoluminescence, SiGe nanostructure

INTRODUCTION

Since silicon has an indirect band gap the radiative recombination life time is very long. The main objective in the Si-based semiconductor optoelectronics is to improve luminescence efficiency (Paul, 2004). One of the promising methods is considered the creation of SiGe nanostructures with Quantum Dots (QD) Ge, which has the high luminescence efficiency at room tempera-ture (Pchelyakov *et al*., 2000). In the past decade significant attention is paid to create heterostructures SiGe with the possibility of controlling optical properties (Larsson *et al*., 2003) due to changes in sizes (below 10 nm) achieved the highest possible density QD arrays Ge ($\geq 10^{12}$ cm^{-2}) (Shklyaev and Ichikawa, 2001). Recently a method for controlling nucleation (Ray *et al*., 2011) and uniformity of growth in three dime-nsional islands Ge, based on pulsed irradiation by low-energy ions Ge own (≤ 100 eV), during heteroepitaxy nanostructures SiGe of molecular beam (Dvurechenskii *et al*., 2005). In this study, the improvement on structural and luminescence properties of SiGe nano-structures with QD Ge, grown under different conditions is presented.

METHODS OF EXPERIMENT

The investigated structures were grown by Molecular Beam Epitaxy (MBE) from solid sources on Si substrates with (001) orientation at the Institute of Physics Semiconductor RAS (Pchelyakov *et al*., 2000). The full chemical processing was conducted on Si wafers to remove Si oxide plants at T≈720°C, before the creation of layers by MBE. After removing of SiO$_2$ from Si substrate, buffer layer of silicon was grown at T≈750°C with a thickness of ~50 nm (Sample R15). The QD Ge layer with a thickness of 0.848 nm was grown at 300°C in sample R16. In the sample R14, thickness increase to ~10 nm. For sample R18, 6 layers of Ge were grown at 300°C with the thickness of 0.848 nm separating by five Si layers with a thickness of ~5 nm with gradual increasing in temperature from 300 to 500°C. More data about the layers are presented in the Table 1.

The photoluminescence (PL) spectra of samples immersed directly in the liquid helium were measured. The non-equilibrium charge carriers in nanostructures SiGe was generated by using a YAG: Nd laser with a diode-pumped, operating at a wavelength of 532 nm (second harmonic) with a capacity of 200 mW and the diameter the light beam to 1 mm^2. The exposed light from samples continue to the lens focused onto the spherical mirror with a focal length of the f~15 cm. Spectral composition of the radiated light from samples was analyzed by diffraction monochromator MDR-23 with a focal length of the mirror lens f~60 cm, equipped with a 600 groove/mm grating blazed (dispersion 26 A/mm). The outgoing light from monochromator detected by InGaAs p-i-n photodiode (Hamamatsu, Japan).

RESULTS AND DISCUSSION

Figure 1 shows X-ray diffraction of SiGe structure alternating nanolayers of Si and Ge. X-ray diffraction analysis of SiGe nanostructures carried out on a

Table 1: Parameters of the silicon substrate and GeSi nanostructures layers with different amounts of quantum dots Ge

Samples	Name of layers	The number of layers	The thickness of layers,nm	Temperature of growth,° C
Si substrate-single crystal, R1	-	-	300	-
Nanostructure Si substrate/Si epitaxial layer, R15	Si buffer	1	50	750
Nanostructure Ge/Si, R16	Si buffer	1	50	750
	Ge quantum dots	1	0.848	300
	Si closing	1	50	300-500
Nanostructure Ge/Si, R14	Si buffer	1	50	750
	Gequantum dots	1	10	300
	Si closing	1	50	300-500
Nanostructure Ge/Si, R17	Si buffer	1	50	750
	Ge quantum dots	12	0.848	300
	Si separating	11	5	300-500
	Si closing	1	50	500
Nanostructure Ge/Si, R18	Si buffer	1	50	750
	Ge quantum dots	6	0.848	300
	Si separating	5	5	300-500
	Si closing	1	50	500

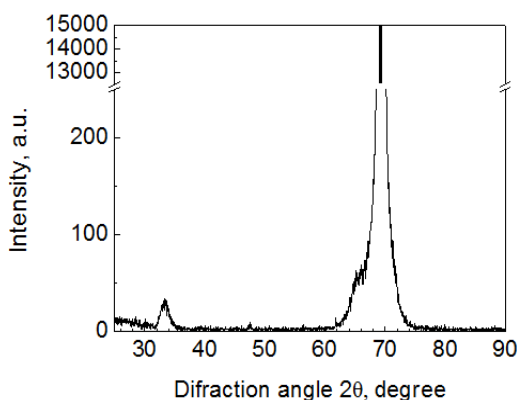

Fig. 1: X-ray diffraction pattern of GeSi nano-structures with 12 layers of Ge quantum dots

DRON-3 using a monochromator on carbon CuKα radiation. According to X-ray diffraction, the most intense reflex is (400) in the diffraction angle $2\Theta{\sim}69.158°$ from the Si substrate with the preferential orientation from plane (100). In the range of angles $2\Theta{\sim}66.00°$ on the contour the main reflection (400) Si exhibits a superposition of weak intensity reflection, relating to the layers with quantum dots Ge. The ratio of intensities of the reflections Si(400)Ge (400) was ~230. Our experiments show the possibility of controlling the content of Ge in nanostructures SiGe in Ge quantum dots formed layers, which is important parameter in the quality of generated heterostructure. Based on the experimental values of the diffraction angles of reflection (400) for Si and Ge, corresponding values lattice constants were calculated and consist of: a = 5.428 Å for Si and a = 5.655 Å for Ge. Some deviation of these values from known lattice constants Si and Ge in database JCPDS-ICDP, PDF-2, 2002 (a = 5.430 Å for Si and a = 5.657 Å for Ge) may be attributed to the tension on interfaces nanolayers SiGe. It can be assigned the defussion of silicon and germanium to form interface heterolayers solid solutions of SiGe at epitaxial growth Ge nanoclusters on nanolayers silicon.

Figure 2 shows the PL spectra of SiGe heterostructures with different amounts of QD layers Ge. As can be seen, the PL spectra of the sample silicon KDB-50 with a buffer layer of Si (sample R15) contain the typical PL line related to the intrinsic luminescence of Si and recombination of excitons bound, which related to boron atoms. It should be noted that the line free and bound excitons are not resolved in our experimental conditions. The most high-energy line $FE^{NP}{\sim}1.151$ eV is due to the zero-phonon recombination (NP) of free excitons (FE). Next in the PL spectra follow low-energy lines due to the recombination of free excitons with participation of acoustic and (or) optical phonons: $FE^{TA}{\sim}1.132$ eV (with transverse acoustic phonons with energy TA~18.3 meV), $FE^{TO}{\sim}1.090$ eV (with transverse optical phonons with energy TO~58 meV) line $FE^{TO+IV^a}{\sim}1.060$ eV (with participation of the phonons and phonon IV^a with energy~23 meV, corresponding to intervalley electron scattering), $FE^{TO+O^\Gamma}{\sim}1.031$ eV (with the participation of the phonons and phonon $O^\Gamma{\sim}64.5$ meV in the center of the zone with zero wave vector). Experiments have shown (Fig. 2) growing a buffer layer on a Si (Sample R15) does not change the general type and intensity intrinsic luminescence of Si. For a sample R16 with thin layer Ge, line 1.122 eV were detected, which may be attributed to the zero-phonon recombination of excitons at Ge atoms in the surface layers of Si. In the case of a thick layer of Ge (sample R14), PL spectra exhibits two broad PL band of 0.77 eV and 0.82 eV, which is usually attributed to quantum points Ge (Larsson *et al*., 2003). More clearly of these two bands can be seen in the case of the formation of 6 layers of QD Ge (sample R18). The intensity of the luminescence increases considerably and there is low-
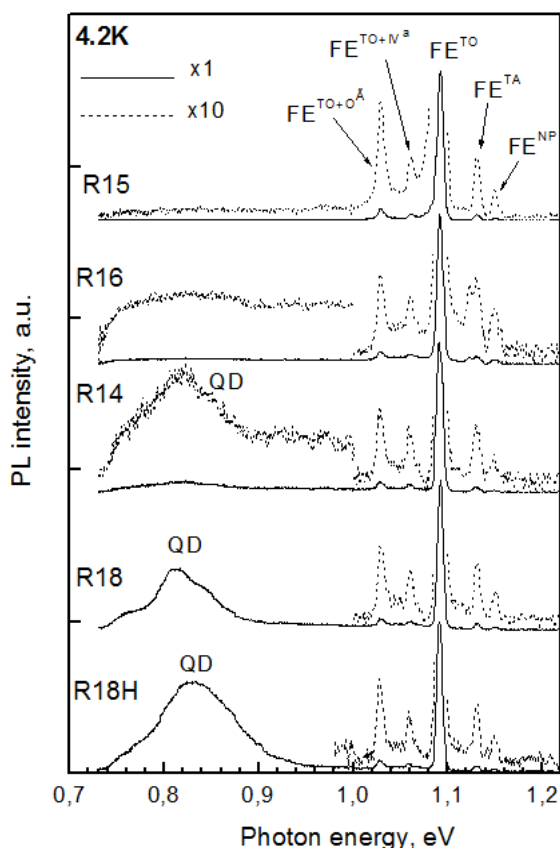
Fig. 2: Photoluminescence spectra of the structure substrate Si/epitaxial layer of Si (R15) and nanostructures GeSi layers with different amounts of quantum dots Ge (R16, R14, R18)

energy shift of the maximum Ge QDs band from 0.82 eV (sample R14) to 0.81 eV (sample R18), that can be associated with existence of stronger internal stresses in the structure of six alternating layers of Si and QD Ge. Figure 2 shows that treatment of the sample R18 to hydrogen plasma at a pressure of 4 Torr ion energy of ~10-20 eV at 200°C in time 45 min (sample R18H) leads to change in the spectral shape of the broad PL band and the shift of the maximum from 0.81 eV to 0.83 eV, which is related to passivation energy states of Ge quantum dots by hydrogen and (or) the interface SiGe nanostructures. The PL band of samples R18 and R18H were investigated versus excitation power levels in the range of 0.05 to 3.5 w·cm^{-2}. The results have revealed increasing of band intensity without changing their shape and spectral position with increasing of excitation power levels. These experimental data can be explained by increasing of the stability of the energy levels in the band gap QD Ge, through the radiative recombination. process these radiative recombination can be linked with holes localized at the quantum dot

Ge and electrons Si-matrix localized at the interface SiGe.

CONCLUSION

The large increase (3-10 times) in the intensity of the luminescence in the near infrared spectral region 0.7-0.9 eV (band 0.81 eV), is due to direct radiative recombination of electrons and holes in the quantum dots Ge, with increasing number of deposited layers of Ge and increasing the size of Ge quantum dots in nanostructures SiGe. This effect is important for the development of light emitting instrument nanostructures SiGe, with high quantum yield of luminescence in the infrared region of the spectrum, as a new class of semiconductor devices. It was established that the thermal annealing nanostructures SiGe with Ge quantum dots in a hydrogen plasma at 200°C leads to a significant increase (~5 times) of the intensity of the luminescence band with a maximum 0.83 eV, due to radiative recombination of charge carriers in the quantum dots Ge. This effect is related to the passivation energy states of Ge quantum dots by hydrogen and (or) the interface SiGe nanostructures. Effect of increase in luminescence intensity with passivation by hydrogen can be used to increase the efficiency of light-emitting p-n structures formed based nanostructures SiGe.

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