Nanohills in SiGe/Si Structure Formed by Laser Radiation

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Abstract:

Formation of self-assembling nanohills induced by irradiation of nanosecond Nd:YAG laser pulses on the $Si_{0.7}Ge_{0.3}$/Si hetero-epitaxial structures is reported. The atomic force microscope study of the irradiated surface morphology has shown a start of nanohills formation after laser irradiation of the intensity I=7.0 MW/cm^2. The giant "blue shift" of photoluminescence spectra with maximum intensity in region of 700-800 nm (1.76 - 1.54 eV) is explained by the Quantum confinement effect in the nanohills. The maximum of this photoluminescence band slightly shifts to shorter wavelengths with the increase of the intensity of laser pulses used for sample treatment. Appearance of the 300 cm^{-1} Ge-Ge vibration band in Raman scattering spectra for sample irradiated with I=20.0MW/cm^2 is explained by Ge phase formation. Formation of the Ge-rich phase is explained by localization of Ge atoms drifting toward the irradiated surface under the thermal gradient due to strong absorption of laser radiation.

Keywords: *nanohills, SiGe, laser, hetero-epitaxial structure.*

1. Introduction

Nowadays, nanostructures are the most investigated object in solid-state physics, especially concerning the quantum confinement effect (QCE) in quantum dots (QD) [1], quantum wires [2] and quantum wells [3]. In the case of nanosize structures the energy band diagram of a semiconductor is strongly changed leading to crucial change of properties such as electrical, optical, mechanical and thermal.

It is known that in indirected band-gap semiconductors such as Si and Ge radiative electronhole recombination efficiency strongly enhances in nanostructures due to QCE [4]. Moreover, shift of photoluminescence (PL) spectrum toward high energy of spectrum, so called "blue shift", has been predicted [4] and observed in Ge [5] and Si [6] single crystals. A new flexible possibility is predicted to change the semiconductor basics parameters into QDs of $Si_{1-x}Ge_x$ solid solution both by change of x and QDs diameter. Increase both content of Ge atoms - x, and diameter of QDs leads to the same effective shift of PL spectrum toward low energy of spectrum, so called "red shift". It has been shown that increase of x from 0.096 to 0.52 leads to shift of maximum position in IR part of PL spectrum toward low energy (0.3 eV) [7]. The same, "red shift" of PL spectrum on 0.7 eV has been observed for nanoparticles with diameter 5-50 nm and x = 0.237 - 0.75 in visible part of spectrum [8]. Authors explain this result by the incorporation of the Ge atoms into Si nanoparticles and associated surface state. Another effect has been observed in [5], for pure Ge crystal decrease of QDs diameter till 4 nm leads to "blue shift" of PL spectrum maximum position up to 1.1 eV [5] in comparison with PL spectrum of bulk crystal. Therefore in this paper we will show that the main role in control of PL spectrum and its intensity is QCE with small influence of Ge content.

From application point of view in optoelectronics, the investigation of light-emitting diodes based on $Si_{1-x}Ge_x$ structure has been of much interest due to the possibility to change the radiation wavelength in near infrared region of spectrum (~1.5 µm) by varying the concentration of solid solution components [4]. This structure is in good compatibility with Si technology.

Therefore this study is focused on formation of optical properties of nanostructures induced by laser radiation on the surface of $Si_{1-x}Ge_x$/Si hetero-structures.

2. Experiment

Crystal $Si_{1-x}Ge_x$ alloys were grown on Si(100) wafers by Molecular Beam Epitaxy (MBE). $Si_{1-x}Ge_x$ films were grown by MBE on top of a 150 nm thick Si buffer layer on Si. Alloys containing 30% Ge were used in the experiments. The surface of a $Si_{1-x}Ge_x$/Si structure was irradiated by 15 ns pulses of a Nd:YAG laser (wavelength 1064 nm, power 1MW). The spot of laser beam of 3 mm diameter was moved by 20 µm steps over the sample surface. The experiments were performed in ambient atmosphere at pressure 1atm, at room temperature (T=20 °C) and 80% humidity. The structural and optical characteristics of Ge nanostructures were studied by atomic force microscope (AFM), photoluminescence, excited by 488 nm radiation of Ar ion laser and Raman scattering (RS), excited by 514.5 nm radiation of an Ar ion laser.

3. Results and Discussion

The three-dimensional surface morphology of $Si_{0.7}Ge_{0.3}$/Si hetero-epitaxial structure recorded by AFM measurements after irradiation by the Nd:YAG laser at intensities of 7.0 MW/cm^2 (a) and 20.0 MW/cm^2 (b) is shown in Fig. 1. In Fig. 1(a) are seen the nanohills of the average height of 11 nm formed by laser radiation at the intensity of 7.0 MW/cm^2. Similar nanohills of the average height of 27 nm seen in Fig. 1(b) have been obtained by irradiation intensity of 20 MW/cm^2. Due to higher irradiation intensity they are more compact in diameter and higher.

The three-dimensional surfaces morphology of the same spots as in Fig.1 a) and b) are shown in Fig.1 c) and d).

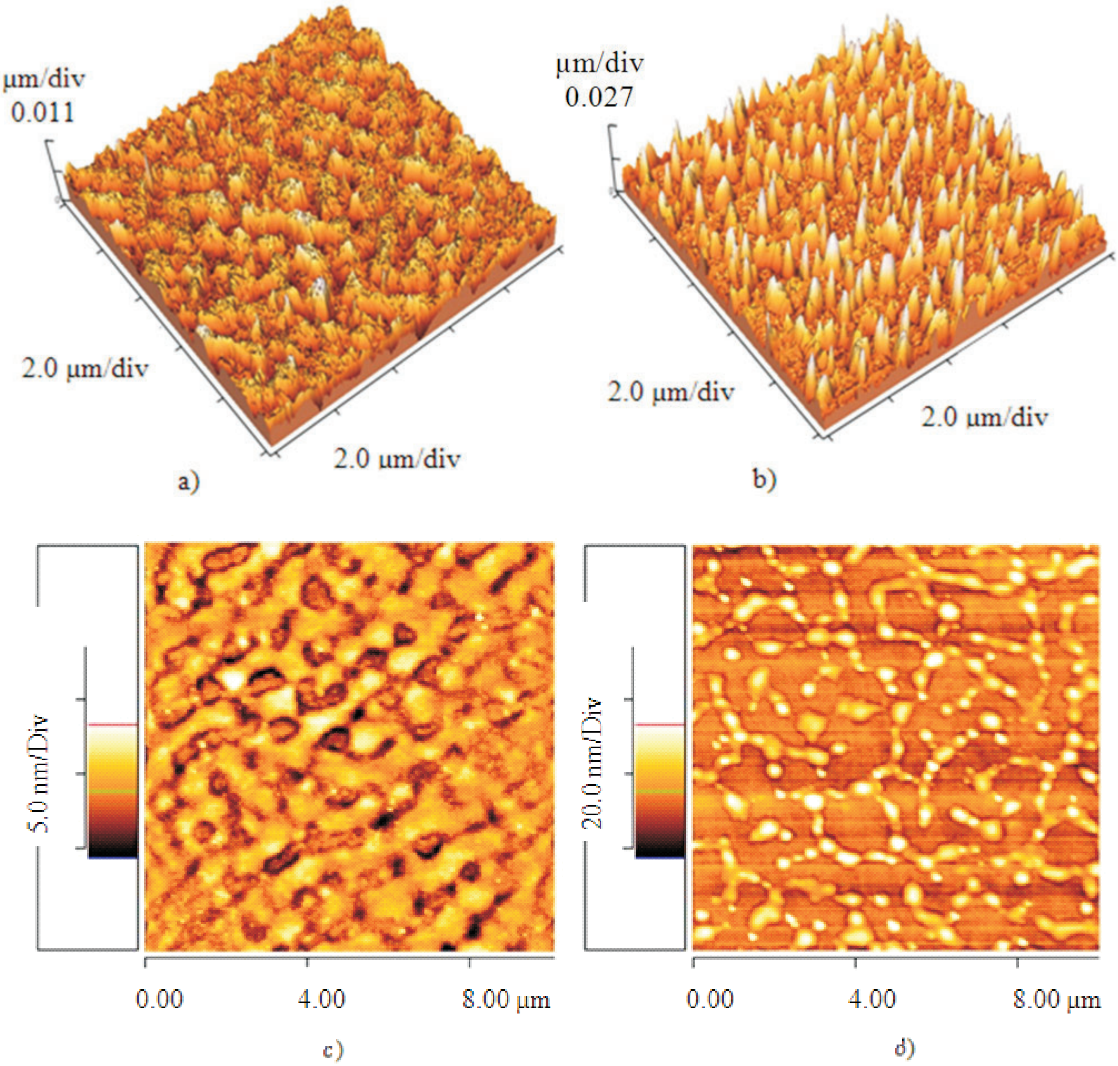

Fig. 1. Three-dimensional AFM images of $Si_{0.7}Ge_{0.3}$/Si sur-faces irradiated by the Nd:YAG laser at intensity a)7 MW/ cm² and b) 20 MW/cm² and two-dimensional surface mor-phology of the same spots of structure at intensities: (c) 7.0 MW/cm² and (d) 20.0 MW/cm².

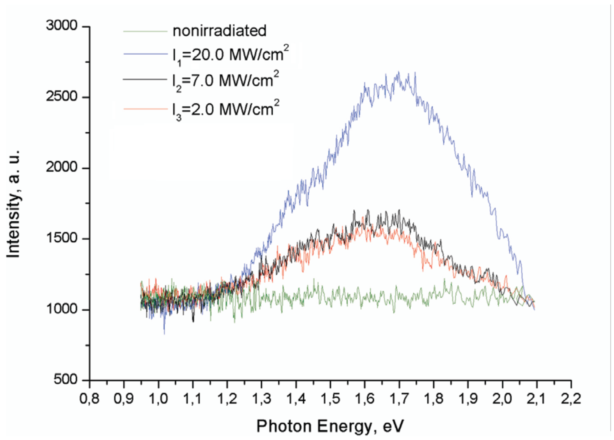

Fig. 2. PL spectra of $Si_{0.7}Ge_{0.3}$/Si hetero-epitaxial structures before and after irradiation by Nd:YAG laser radiation at intensities 2.0 MW/cm², 7.0 MW/cm², and 20.0 MW/cm².

PL spectra of the $Si_{1-x}Ge_x$/Si hetero-epitaxial structures with the maxima at 1.60 -1.72 eV obtained after laser irradiation at intensities of 2.0 MW/cm², 7.0 MW/cm² and 20.0 MW/cm² are shown in Fig. 2. The spectra are unique and unusual for the material, because, depending on Ge concentration, the band gap of SiGe is between 0.67 eV and 1.12 eV [7]. As seen from Fig. 2, the $Si_{1-x}Ge_x$ structure emits light in the visible range of spectrum and the intensity of PL increases with the intensity of irradiation.

After irradiation of the $Si_{1-x}Ge_x$/Si hetero-epitaxial structure by the laser at intensity of 7.0 MW/cm² the surface structure begins to look as spots on unwetting material, for example, it looks like water spots on a glass, Fig. 1(c). It means that laser radiation induces segregation of Ge phases at the irradiated surface of the material. This conclusion is in agreement with data from paper [11] where it was shown that Ge phase starts formation at 50% concentration of Ge atoms in SiGe solid solution. According to the Thermogradient effect [9], it is supposed that laser radiation initiates the drift of Ge atoms toward the irradiated surface of the hetero-epitaxial structure. The maximum of the PL band at 1.70 eV is explained by the QCE [10]. Position of the observed PL peak compared with the bulk material shows a significant "blue shift". The maxima of PL spectra of the $Si_{1-x}Ge_x$/Si hetero-epitaxial structure slightly shift to higher energy when the laser intensity increases from 2.0 MW/cm² to 20.0 MW/cm², which is consistent with the QCE too. Our suggestions, concerning to Ge phase formation, are supported by the Raman spectra. After laser irradiation at the intensity of 20.0 MW/cm^2 a Raman band at 300 cm^{-1} appears in the spectrum. This band is attributed to the Ge-Ge vibration and is explained by formation of a new Ge phase [11] in the $Si_{1-x}Ge_x$/Si hetero-epitaxial structure.

The following model is proposed for explanation of dynamics of nanostructures formation.

4. Model

After irradiation of a $Si_{1-x}Ge_x$/Si hetero-epitaxial structure by strongly absorbed laser radiation the large gradient of temperature occurs (108 K/m) [9]. It causes the Ge atom drift towards the irradiated surface of the semiconductor. The creation of Ge phase leads to the formation of Ge/Si heterostructure. As a result of difference in Ge and Si lattice constant the mechanically stressed Ge layer occurs on the irradiated surface. The plastic deformation of mechanical stresses in Ge layer takes place with a growth of cone-like nanostructures according to modified Stransky-Krastanov's method.

5. Conclusion

1. Formation of nanohills by laser irradiation of the $Si_{0.7}Ge_{0.3}$/Si hetero-epitaxial structure is shown to be possible.
2. Photoluminescence spectra of the $Si_{1-x}Ge_x$/Si hetero-epitaxial structure with nanohills are explained by the Quantum Confinement effect.
3. Formation of a new phase of crystalline Ge nanohills is found on the surface of $Si_{0.7}Ge_{0.3}$/Si hetero-epitaxial structures after laser irradiation at intensities exceeding I=2.0 MW/ cm^2.

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