Ge/Si nanostructures with quantum dots grown by ion-beam assisted heteroepitaxy

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Abstract. Effect of low-energy ion-beam irradiation during Ge on Si(100) growth on characteristics of Ge nanoislands array is studied. It is shown by STM that pulsed ion-beam action leads to an increase in Ge nanoislands density. The dependence of Ge nanoislands density upon ion energy is non-monotonous with maximum at 150 eV. RBS data indicate a perfect crystal structure of Ge nanoislands. By Raman spectroscopy the Ge content in SiGe quantum dots is estimated to be higher than 75%.

1. Introduction
Self-assembled Ge quantum dots (QD) on Si(100) have been intensively investigated as the basis of novel electronic and optical devices. The well-defined sizes with little dispersion and high density of QD are generally required for any practical applications [1, 2]. It is a challenge to meet all these requirements simultaneously. A promising way to achieve the homogeneous size distribution and high density of QD is using pulsed irradiation by low-energy (~100 eV) Ge$^+$ ions during the heteroepitaxy. We have found that the pulse low-energy ion irradiation during Ge/Si heteroepitaxy stimulates nucleation and growth of three-dimensional Ge islands characterized by high density of islands and small average size and low size dispersion [3]. The observed phenomena were studied by molecular dynamics (MD) and Monte-Carlo (MC) simulation. It was shown that about 5 interstitials are produced in Si bulk by an ion impact [4]. Areas of local tensile strain above the interstitial atoms are responsible for the change in the binding energy of the Ge adatoms. MC modeling has shown that the places where the ions impact the surface become the centers of preferential nucleation of three-dimensional islands. The results of the MC simulations have demonstrated a good agreement with the experimental data [5].

In the present work we study the low-energy ion-beam-assisted growth of three-dimensional Ge nanoislands on the Si(100) as dependent on the growth temperature, energy of ions and degree of ionization of molecular beam. The effect of ion irradiation on the defect generation and the composition of Ge/Si(100) nanostructures were studied by the Raman spectroscopy, Rutherford backscattering and transmission electron microscope techniques.

2. Experimental
The samples were grown by molecular-beam epitaxy (MBE) on p-Si(100) wafers. Two growth modes were implemented: 1) conventional MBE of Ge on Si (sample M); 2) MBE with pulsed
irradiation by a beam of low-energy Ge$^+$ ions (MI). The ion energy could be controllably varied from 50 to 250 eV. A system of ionization and acceleration of Ge$^+$ ions provided the degree of ionization of Ge molecular beam from 0.02% to 0.5%. The pulsed irradiation (with the pulse duration $\tau$~0.5 s) was applied after each completed germanium monolayer (ML) was deposited. The incident angle of the molecular and ion beams was 54º. The deposition rate was approximately 0.1 ML/s and the substrate temperature was varied within interval from 250 ºC to 450 ºC. In all experiments the total amount of Ge deposited was 5 ML. In addition, multilayer Si/Ge structures were grown. 15-nm-thick Si spacer layers and a 50-nm-thick cap Si layer were deposited at 500ºC by the conventional MBE (with no irradiation).

The morphology of the surface was in situ examined by scanning tunneling microscopy (STM). Crystal perfection of Ge/Si structures were analyzed by RBS and TEM. The elemental composition of the multilayer structures was studied by Raman spectroscopy. The spectra were recorded at room temperature using an automated setup based on a DFS-52 spectrometer. An Ar$^+$ laser ($\lambda$=514/5 nm) was used as the source of excitation.

3. Experimental results

Figure 1 presents STM images of surface with three-dimensional (3D) islands formed after the deposition of 5 Ge ML. In the M type sample (Figure 1, a) the density of 3D islands is $2.1\times10^{11}$ cm$^{-2}$ with the mean size of the islands 22 nm and the size dispersion 3 nm. In the MI-type sample (Figure 1, b) the density of Ge islands is $9\times10^{11}$ cm$^{-2}$, the mean size of the islands is 6.5±0.7 nm.

![Figure 1. STM images (200 × 200 nm) of surface with 3D islands: (a) conventional MBE and (b) MBE with pulsed irradiation by Ge$^+$ ions. Conditions: the molecular Ge flux density is $7\times10^{13}$ cm$^{-2}$s$^{-1}$, the temperatures of substrate is 350ºC, the ion beam energy is 140 eV, the pulse duration is 0.5 s, and ion flux density is $3.1\times10^{11}$ cm$^{-2}$s$^{-1}$.](image)

Using STM data the temperature dependences of Ge islands density were obtained. In the M-type experiment (Figure 2, curve 1) the density goes down at temperature varying from 250 ºC to 350 ºC, whereas at the further increase of temperature (from 350 ºC to 450 ºC) no significant change in the density is observed. The temperature dependence of Ge islands density for MI-type samples (Figure 2, curve 2) exhibits a similar behavior. However, the density of Ge islands observed in MI-type samples was higher as compared with that in M-type ones.

The effect of ion energy and integrated flux of Ge ions on the density of 3D islands is presented in Figure 3 and Figure 4, respectively. The density of islands increases as the ion energy is varying from 50 eV to 150 eV. At higher energies the density goes down. The dependence of islands density on the integrated flux of Ge ions also has a maximum at the flux value of $10^{12}$ cm$^{-2}$. 
RBS spectra from SiGe nanostructures are shown in Figure 5. The backscattering yield from Ge layers turns out to be sensitive to the growth conditions [3]. Raman spectra of multilayer samples M and MI with Ge$_x$Si$_{1-x}$QD are presented in fig.5. Raman peaks at 307-315 cm$^{-1}$ and 370-430 cm$^{-1}$ correspond to Ge-Ge and Ge-Si optical phonons, respectively. Using the standard analysis procedure [6, 7, 8] we estimated that the Ge content $x$ in Ge$_x$Si$_{1-x}$QDs is higher than 0.75.

**4. Conclusions**

It was demonstrated that, at specific values of the integrated ion flux (less than $10^{12}$ cm$^{-2}$) and ion energy (100-140 eV), the mean size of 3D Ge islands decreases, their density increases, and the island size dispersion is reduced as compared to those observed for the conventional MBE. The
experimentally revealed size ordering of islands is associated with the synchronization of island nucleation under pulsed ion irradiation. Our experimental results demonstrated that Ge/Si(100) heteroepitaxy with pulsed low-energy ion beam action enables creation of defect-free 3D Ge islands. The pulsed ion irradiation during the growth of Ge/Si structures does not lead to significant mixing of the Ge and Si layers.

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