391. THE INFLUENCE OF VIBROACOUSTICS ON SELF-ORGANIZING OF SIGE NANOSTRUCTURES ONTO SILICON SUBSTRATE

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Abstract. Microprocessor electronics is based on silicon technology. The growth of microprocessor circuit’s speed, the increase of elements integration, the development of Si light-emitting semiconductor devices demands the introduction of new functional principles and technologies in silicon electronics. Recently optical lithography cannot provide the necessary level of miniaturization. Electron-beam and scanning lithography are also unproductive. The object of researches was Ge/Si (001) heterosystems with nanoislands obtained using different technological conditions. In Ge/Si heterosystems the kinetics of formation of nanoislands is still not completely clear, beginning from the definition of critical thickness of nanolayer, vibroacustics, temperatures. Raman spectroscopy (RS), high resolution X-ray diffractometry and scanning atomic force microscopy (AFM) for research of physical mechanisms of nanoislands formation, character of deformation fields and processes of diffusion of silicon from substrate in wetting layer and nanoislands were applied. Such combination of analysis methods has allowed to obtain structure’s parameters as elastic deformations, structure, density of nanoislands, their sizes and form variation generated at different physical conditions (temperature, acoustic vibration). The photon (optical and acoustic) spectrums of self-organized nanostructures, generated during molecular-beam epitaxy (MBE) growth of Ge on Si substrate have been investigated using method of RS. The componental structure and values of elastic deformations in nanoislands obtained by the variation of epitaxial temperature at identical thickness of deposited Ge layer and by variation of Ge layer thickness at identical temperature has been estimated by atomic force microscopy method.

Keywords: vibroacoustics, self-organized nanostructures, Ge/Si heterosystems with nanoislands

Introduction

The interest to nanomaterials with particles sizes less than 100 nm is growing for the improvement of quality, reliability and durability of technical systems. This means the overcoming a fundamental physical barrier, where the quantum dimensional effects are actual and all properties of a solid body drastically change. Therefore nanostructures have the important advantage comparing with microstructures due to the fact that changing the geometrical sizes and a configuration of nanoobjects the properties of nanomaterials can be managed. There is an opportunity to obtain important parameters of structure and first of all - energy spectrum of charge carriers and photons. One of perspective directions in silicon electronics is the application of self-induced growth of Ge nanoislands onto Si substrate. The physical essence of the method is the reduction of elastic energy of system during a transition from two-dimensional epitaxial to diffusional three-dimensional growth with distribution of

Ge islands on a surface of the sample. Thus nanoislans can get two different forms: pyramid and dome. Lateral sides of pyramids are planes (105), while for domes – (113) and (102). Two models can explain the existence of two different forms of nanoislands. The first one supposes that each separate form of strained islands has an adequate minimum of specific energy and activated transition can be between these potential walls divided by a barrier [1]. The idea of the second model consists of the change of chemical potential of nanoislands takes place during transition of the equilibrium state from pyramid to dome [2]. This occurs at the certain critical volume of nanoisland when dome energy becomes less pyramid energy of the same volume. The object of our researches was Ge/Si (001) heterosystems with nanoislands obtained using different technological conditions. In Ge/Si heterosystems the kinetics of formation of nanoislands is still not completely clear beginning from the definition of critical thickness of nanolayer, vibroacustics, temperatures, etc.

The problem statement

The purpose of researches is the clarification of external factors influenced on synthesis of self-organized nanostructures onto silicon substrate. The investigation of dimensional effects in superthin semi-conductor heterostructures has promoted the occurrence of new devices as resonant tunnel diodes and transistors, quantum well lasers, etc. [3]. The majority of these structures have been realized on the basis of A^3B^5 semiconductors with well-known zone structure and defined effective masses of charge carriers. Such materials represent the first type of heterostructures and have direct optical transitions. However microprocessor electronics is based on silicon technology. The growth of microprocessor speed, the increase of elements integration, the development of Si light-emitting semiconductor devices demands the introduction of new functional principles and technologies in silicon electronics. Recently optical lithography cannot provide the necessary level of miniaturization. Electron-beam and scanning lithography are also unproductive.

Research methodology

Raman spectroscopy (RS) and the scanning atomic force microscopy (AFM) allow to study the mechanism of self-organizing of GeSi nanoislands growth on a silicon substrate, to define their componental structure, values of mechanical stresses depending on external physical influences and quantities of Ge epitaxial layers. RS, high-resolution X-ray diffractometry and AFM were applied for research of physical mechanisms of nanoislands formation, character of deformation fields and processes of diffusion of silicon from substrate in wetting layer and nanoislands. Such combination of analysis methods has allowed to obtain structure's parameters as elastic deformations, structure, density of nanoislands, their sizes and form variation generated at different physical conditions as temperature, acoustic vibration.

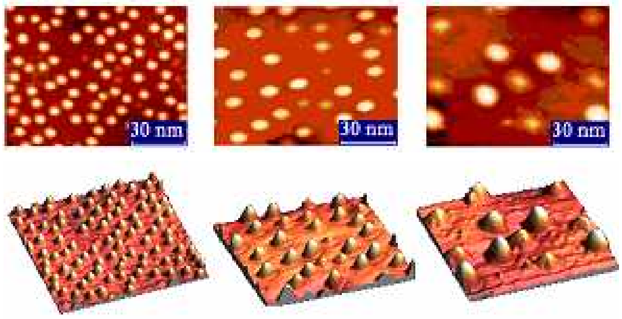
Research results and discussion

In this work the photon (optical and acoustic) spectra of self-organized nanostuctures generated during MBE growth of Ge onto Si substrate have been investigated by method of Raman spectroscopy. The componental structure and sizes of elastic deformations in nanoislands were estimated by the variation of epitaxial temperature at identical thickness of Ge layer and by the variation of Ge layer thickness at identical temperature. The external diffusion caused by stress fields at nanoisland's bases has been increased with growth of temperature. This phenomenon has led to the formation of SiGe nanoislands with significant Si part (60 % at 750 ^{o}C in nanoislands with pyramid form). Such composition causes nanoisland's stability at greater sizes without transformation in dome-shaped islands. Experiments have shown, that the sizes and islands distribution on a substrate surface have a statistical origin and significant dispersion. One of ways to improve the uniformity of the nanoislands sizes and their distribution is the growing of same form nanoislands by the variation MBE parameters as temperature, nominal thickness of epitaxial layer and deposition speed of atoms. Another way of the improvement of islands sizes uniformity is the application of silicon substrate with a certain deviation angle from (100) or the application of synchronous growth of islands [4], which it is possible to reach using the acoustic vibration and pulse ultrasound. Investigated structures were obtained by MBE method on Si (001) substrate with buffer silicon layer of 200 nm thickness. Some samples were prepared for such experiments. In samples of the first series the Ge layer thickness were varied from 3 up to 12 monolayers, the growth temperature was a constant (750 ^{o}C) for all samples. In the second series of samples all Ge layers have one thickness (8 monolayers), epitaxy was realized at different temperatures (600, 700, 750 ^{o}C). For the analysis of experimental data used a technique allowing to find average values of parameters and their errors [5]. The surface morphology of structures with nanoislands was investigated on AFM NanoScope IIIa (Digital Instruments) using a Tapping mode. Measurements were carried out by probes with high degree of symmetry and section radius 4 nm at 10 nm distance from an edge. It allowed to neglect the tip effect during the analysis of the nanoislands form and volumes. AFM images of SiGe nanoislands with equal Ge layer thickness (8 monolayers) and different vibration modes are showed in Fig. 1.

Analysis of AFM images has shown, that the greatest density ($1{,}2\cdot10^{10}$ sm^{-2}) of nanoislands was observed at temperature 660 ^{o}C and acoustic vibration 22,4 kHz, 18,6 kW/m^2. Thus only about 11 % of islands had the pyramid form. At growth temperature of 705 ^{o}C the density of islands decreases up to $2{,}6\cdot10^{9}$ sm^{-2} and the relative quantity of pyramids increased up to 39 %. At growth temperature of 750 ^{o}C the density of islands decreased up to $8{,}4\cdot10^{8}sm^{-2}$ and the quantity of pyramids increased up to 58%. Except acoustic vibration and temperatures variation the synthesis of self-organized SiGe nanostructures onto silicon substate can be managed changing the thickness of Ge monolayers. AFM images of islands received at three different nominal thickness of Ge layer (6, 8 and 12 monolayers) and identical 705^{o} C growth temperature, presented in Fig. 2.

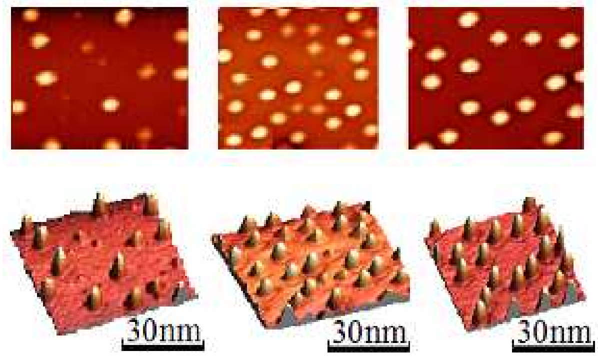
In all cases the formation of nanoislands began at nominal thickness Ge layer did not exceed 3 monolayers. First only islands of pyramidal form were appeared. At nominal thickness of Ge layer (6 monolayers) the quantity of domes prevailed. The density of nanoislands increased, when thickness of Ge layer grew from 6 up to 8 monolayers, but the volume of pyramids and domes in this case essentially did not change. For the samples obtained at thickness of epitaxial Ge layer of 12 monolayres the density of islands grew a little, however their average volume noticeably increased due to the complete disappearance of pyramidal islands. This phenomenon also was confirmed by other author's works [3]. Controlled synthesis of nanoislnads at one nominal thickness and rising temperature from 660 up to 750^{o} C, or at constant temperature (705^{o} C) but increasing the nominal thickness of epitaxial Ge layer from 6 up to 12 monolayers, can be intensified by acoustic vibration during MBE. One series of samples consisted of islands covered Si monolayers, other series of samples contained nanoislands synthesized at the same modes, but not covered by Si. Parameters of MBE were identical to all samples: temperature of deposition was 660 ^{o}C, nominal layer thickness - 8 monolayers, speed of deposition nearby 0,12 A/sec.

It was found that additional nanoislands appeared after an additional vibroacoustic action (Fig. 3). The same equipment as in work [6] was used for this experiments. The excitation of RS spectra was carried out by Ar+ laser with 488 nm wavelength radiation. The signal was registered by the cooled photoelectronic multiplier using photons counting mode. For more exact definition of RS band known values of Ar+ laser plasma lines were used. The surface morphology of structures with nanoislands was investigated by AFM. It is known [7-9], that islands having the form of pyramids or domes are formed at epitaxial temperature 600 ^{o}C and depositing the 9 Ge monolayers on a silicon substrate. The parity of domes and pyramids under such MBE conditions makes d/p=89/11. It is known as bigger the attitude of islands height to lateral sizes, as significant relaxation occurs in them. Raman spectrum intensity of nanoislands in arbitrary units (I) are shown in Fig. 4. The second order acoustic vibration of silicon substrate and integumentary layer takes place in the area of Ge-Ge, Si-Ge and Si-Si of Raman spectrum.



a) b) c)

Fig. 1. AFM image (the top view and axonometric projection) of self-organized nanoislands (dGe=8 monolayers) grown at 750^{o} C and: a) 880 kHz, 18,6 kW/m^2; b) 880 kHz, 200 kW/m^2; c) 22,4 kHz, 18,6 kW/m^2



a) b) c)

Fig. 2. AFM image (the top view and axonometric projection) of self-organized nanoislands grown at temperature 750^{o} C, 22,4 kHz, 18,6 kW/m^2. Nominal thickness of epitaxial Ge layer: a) 6 monolayers; b) 8 monolayers; c) 12 monolayers

Fig. 3. AFM image (axonometric projection) of self-organized SiGe nanoislands, including new nanoislands after vibroacoustic action. There intensity 18,6 kW/m^2 (islands 1, 3), 200 kW/m^2 (islands 2, 4) and frequency 880 kHz (islands 1,2) and 22,4 kHz (islands 3,4)

Therefore the spectrum of Si layer was subtracted from each of experimental spectra for the correct interpretation of them. In Raman spectra of $Si_{1-x}Ge_x$ solid solution (islands generated at temperature 600 ^oC) three basic bands corresponded to Ge-Ge, Si-Ge and Si-Si vibrations were highlighted. The thin moistening layer (3-4 monolayers, 1 monolayer equal 1,4 Å) did not influenced the Raman spectrum due to sampling rules [10]. Apparently from experimental Raman spectra, despite the presence of two different forms islands, only one band of vibrations for each type of (Ge-Ge, Si-Ge, Si-Si) takes place. It can be resulted because of the volume of dome-shaped islands is more than one order exceed volume of pyramidal islands and domes give the basic influence to the spectrum. From Fig.4 (curve 1) it is visible, that after growing of Si islands the bands frequency changes. Using AFM it is very important to have qualitative probes and strictly to carry out the maintenance instruction of devices. Images of the test lattices obtained by different probes are presented in Fig. 5

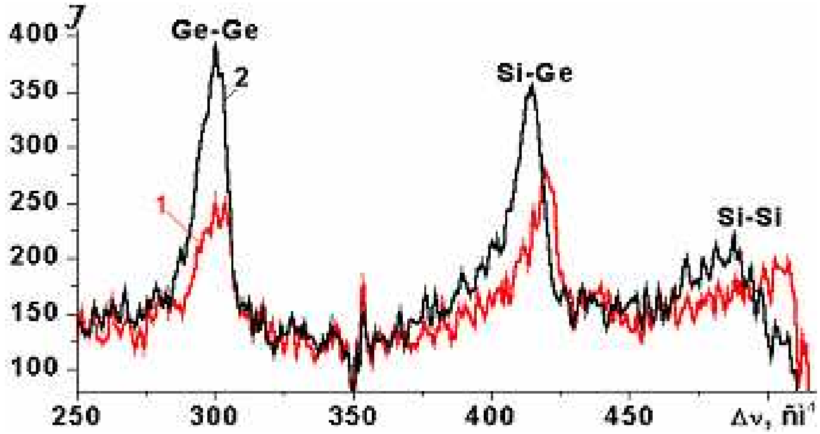
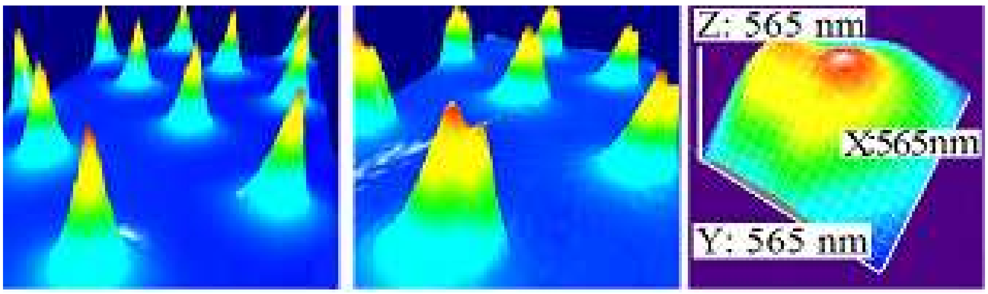


Fig. 4. RS spectrum of SIGe nanonislands: 1) under action of acoustic vibration: 2) generated at temperature 660 ^oC during deposition of 8 Ge monolayers. The spectrum of a Si substrate is not presented



a) b) c)

Fig. 5. AFM images of test lattices TGT (NT-MDT, Russia) received by: a) high quality probe of series NSG-11; b) chopped edge of probe due acoustic vibration; c) reconstructed edge of probe (length of XYZ axes identical). Distance between nanoislands is about 3 micrometers, height - 0,7 micrometers

Conclusions

During experimentation the influence of temperature and vibroacoustics on acceleration of self-organizing SiGe and Ge nanoislands generated in conditions of operated synthesis was shown. The application Si for growth of nanoislands leads to greater Si concentration in nanoislands and increase of mechanical strains in them. It should be taken into consideration during development of opto- and nanoelectronic devices. It was cleared that the variation of Ge atoms deposition speed in range from 0,12 A/sec up to 0,39 A/sec and identical other parameters (temperature, vibration, pulse ultrasound, change of monolayer thickness) leads to change of islands density and their sizes without changes of structure and value of their elastic deformations. Nanoislands generated at 480…660^o C has a form as clusters (domes and pyramids with height up to 20 nm) with density from $1{,}2\cdot10^{10}$ up to $8{,}4\cdot10^{8}$ sm^{-2}. The dome-shaped islands easier relaxed due to the greater quantity of Si.

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