Ambient AFM observation of strained SiGe nanoislands embedded in Ge/Si structures on the structure cross-sections

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Abstract. An efficiency of the Cross-Sectional Atomic Force Microscopy (X-AFM) in observation and studies of buried semiconductor nanoislands has been demonstrated. For the GeSi nanoislands burried in Si matrix it was shown that GeSi nanoislands can be revealed on the structure cleavages as nanometer high features in surface relief. The mechanism of nanoislands manifestation is the relaxation of elastic strains accumulated in nanoislands and surrounding area of Si matrix on a free cleavage plane.

In modern physics of semiconductor devices the great interest is addressed to heterostructures with embedded nanoislands. Direct observation of buried nanoislands is one of the main chalenges in studying such nanoheterostructures. Usually, visualisation of overgrown nanoislands is made by Transmittion Electron Microscopy (TEM). However, this method requires a complicated time-consuming procedures for preparation of several hundredth nanometer thin sample to be transparent for electrons. Also, visualisation of overgrown nanoislands can be done by Scanning Tunneling Microscopy carried out on the structure cleavages (XSTM) [1-3]. Nevertheless, this method requires ultra high vacuum conditions to avoid surface oxidation. Evidently, the complexities of TEM and UHV X-STM techniques limit their application for express studies of various samples produced by the semiconductor technology. Besides, in many practical cases the atomic resolution is not necessary. In this connection, ambient Cross-Sectional Atomic Force Microscopy (X-AFM) [4] is seemed to be a simple, operative and effective method of investigation of buried nanoislands with a nanometer resolution. However, until now, as far as we know, there were no X-AFM investigations of buried nanoislands on cleavages. So, this work was focused on discovering the possibilities of X-AFM method for studying of overgrown nanoislands at cleavages.

We present the results of X-AFM studies for the samples with GeSi self-organized nanoislands embedded in a Si matrix. The samples contained one or five layers of the GeSi nanoislands. The GeSi-nanoislands were grown on the Si(001) substrate by Molecular Beam Epitaxy method (MBE) [5]. The effective thickness of deposited Ge for each layer was 7-9 monolayers (ML). The sample with one layer of GeSi nanoislands was capped with 700 nm thick Si cover. In the sample with five layers of GeSi-nanoislands these layers were separated by 60 nm Si spacers and capped with 60 nm thick Si cover. For a comparative study it was also grown a structure consisting of 5 periods of $Ge_{0.3}Si_{0.7}$ quantum wells with thickness of 9 nm, separated by Si layers with thickness of 30 nm and capped with 30 nm Si layer.

AFM measurements have been carried out with the P-47 SEMI (NT-MDT) device working in contact and resonant (tapping) modes. Silicon cantilevers with tip curvature of 15-20nm (SCNC12, NT-MDT) were used.

The AFM topography image of the cleavage surface Ge/Si structure with one layer of GeSi nanoislands is presented in Fig.1. It shows several elevations (bright spots) and depressions (dark spots) with height of 1 nm aligned along direction B-B' spaced from the edge of the cleavage (A-A') by 700 nm

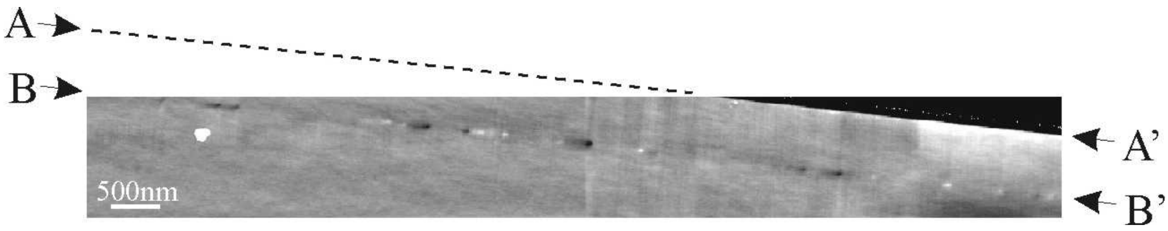

Fig1. AFM topography image of GeSi/Si(001) structure cleavage. A-A' line corresponds to edge of the sample. B-B' corresponds to layer of GeSi nanoislands.

which corresponds to the thickness of the capping layer in that sample. The width of these features in growth plane (~100 nm) correlates with the average lateral diameter of uncapped GeSi nanoislands on the growth surface measured on the reference sample (Fig. 2). So, we attribute the found topographic features to the appearance of GeSi nanoislands.

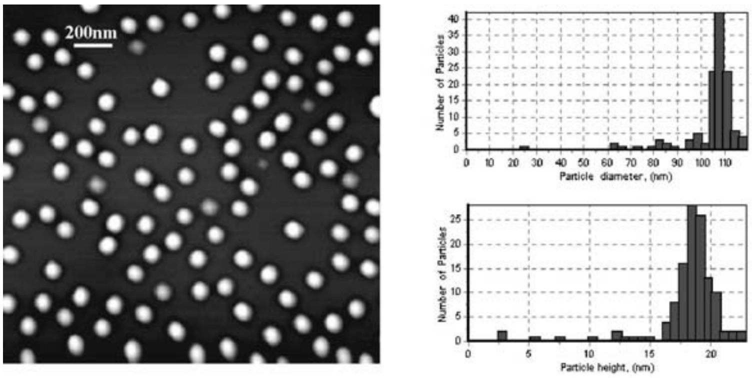

Fig.2 AFM topography of uncapped GeSi nanoislands on the growth surface (left) and GeSi nanoislands distributions by height and diameter (right).

Qualitative interpretation of the origin of observed elevations and depressions is the following. Lattice constant of Ge exceeds by 4.2% that of Si. So, GeSi nanoisland should be compressed inside a Si matrix, at the same time Si matrix surrounding the nanoisland should be tensed. When the cleavage plane crosses a GeSi nanoisland, the local compressive elastic strains in the GeSi nanoisland relax on the surface by the formation of small elevation. When the cleavage plane goes in the vicinity of GeSi nanoisland (at the distance of order of nanoisland diameter), tensile elastic strains in Si matrix near the nanoisland relax on the surface creating local depressions.

The AFM topography image of the cleavage surface of the structure with five layers of GeSi nanoisland is shown in Fig. 3. There are seen five lines of surface undulations going in parallel with the structure surface and spaced by 60 nm. Some undulations demonstrate vertical alignment in all five layers. Profiles in Fig. 3 demonstrate the details of a vertical alignment of elevations (left) and depressions (right). It is also seen an obvious up and down lifting of the Si matrix surface in between GeSi nanoislands what reveals strains in Si matrix and determine their character. Unlike this situation, in the reference structure with five GeSi quantum wells without GeSi nanoislands, we have found undulations that were continuous along the interfaces and several times smaller by height (Fig.4).

So, the features observed in structure with five-layers of nanoisland can be interpreted as manifestation of GeSi nanoislands in different layers. It is worth to note the observed partial

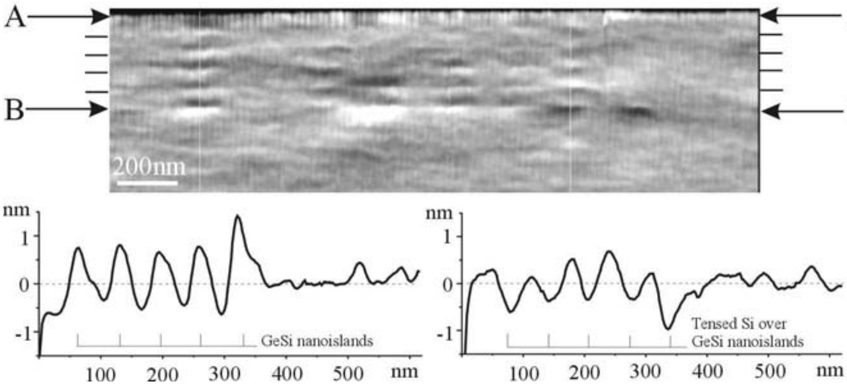

Fig.3 AFM topography image of the cleavage of 5-layered GeSi/Si heterostructure. A-A' line corresponds to edge of the sample. B-B' line corresponds to the first GeSi layer.

vertical alignment of nanoislands. This phenomenon is well known and described by the strain driven mechanism of growth [6].

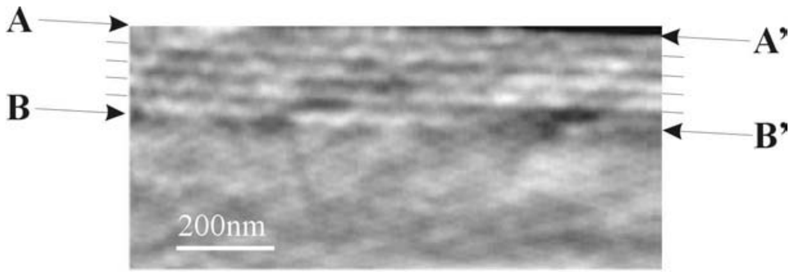

Fig.4. AFM topography image of the cleavage of structure with 5 layers of $Ge_{0.3}Si_{0.7}$ quantum wells. A-A' line corresponds to edge of the sample. B-B' line corresponds to the first GeSi quantum well.

In conclusion, we have demonstrated the efficiency of ambient X-AFM method to reveal buried nanoislands in semiconductor structures via studying topography of cleavage surfaces. It was found that there are two types of nanoislands manifestation on the cleavage surface: 1) as local elevations when cleavage plane crosses the nanoislands and 2) as local depressions when cleavage plane propagates in a matrix in the close vicinity above the nanoislands. X-AFM observations permit to analyze nanoislands sizes, distributions, effects of vertical alignment in multilayer structures and nanoisland elastic interaction in the same layer. As well, X-AFM observations open a direct access to the study of strain accumulation and relaxation in layered structures with arrays of nanoislands.

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