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Visualization of buried nanoislands in GeSi/Si and InSb/GaSb heterostructures by Cross- Sectional Atomic Force Microscopy

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Abstract. The sensitive AFM technique to study nanoislands buried in semiconductor heterostructures, e.g. GeSi/Si and InSb/GaSb systems, is presented. Due to the relaxation of elastic strains on a free surface, the usually strained nanoislands appear on the structure cleavage as subnanometer high features in relief that can be probed by atomic force microscopy. The developed technique is not time-consuming, it does not need special sample preparation and can be applied under ambient conditions.

Semiconductor heterostructures with incorporated self-organized nanoislands are important elements of modern electronic devices. Usually size and space distributions of overgrown nanoislands are analyzed by Transmission Electron Microscopy (TEM). This method requires special time-consuming procedures for preparation of several hundredth nanometer thin sample to be transparent for electrons. Excellent opportunities to study even the atomic structure of nanoislands are provided by cross-sectional Scanning Tunneling Microscopy carried out on the structure cleavages under ultra high vacuum conditions (UHV XSTM) [1-3].

Evidently, the complexities of TEM and UHV XSTM techniques limit their application for express studies of the flow of various samples generated by the semiconductor technology. Besides, in many practical cases the atomic resolution is not necessary. In this connection Cross-Sectional ambient Atomic Force Microscopy (XAFM) [4] is seemed to be a good candidate to provide 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 XAFM investigations of buried nanoislands on cleavages. The basic idea of such investigations is that the relaxation of elastic strains of nanoislands on the heterostructure cleavage may result in the appearance of subnanometer high relief features , as it has been recently found in the UHV XSTM studies for InAs quantum dots (QDs) buried in GaAs [2,3]. It was interesting to verify the effectiveness of that idea in the case of ambient XAFM studies. It was tested and proved by the results of the XAFM studies of nanoislands buried in GeSi/Si and InSb/GaSb heterostructures presented below.

We present results for two samples with GeSi self-organized nanoislands embedded in a Si matrix and one sample with InSb QDs embedded in a GaSb matrix. The first two samples contain a one layer and five layers with GeSi nanoislands. The GeSi-nanoislands were grown on the Si(001)-substrate by Molecular Beam Epitaxy (MBE) [5]. The effective thickness of deposited Ge for each layer was 7-9 monolayers (ML). In the first sample a single layer with GeSi nanoislands was capped by 700nm Si layer. In the second sample five layers of GeSi-nanoislands were separated by 60 nm Si spacers and capped by 60nm Si layer. The third sample with InSb QDs was prepared on (100) n-GaSb (Te) substrates in a solid source Varian GEN 2 MBE machine equipped with a valved As2 cracking effusion cell and a cracking antimony cell producing Sb2 molecules. In this structure 10 planes of InSb QDs separated by 30 nm were embedded in the GaSb matrix, the effective thickness of deposited InSb being 6 monolayers.

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 of single-layered GeSi/Si structure is given in Fig.1. It shows several elevations (bright spots) and depressions (dark

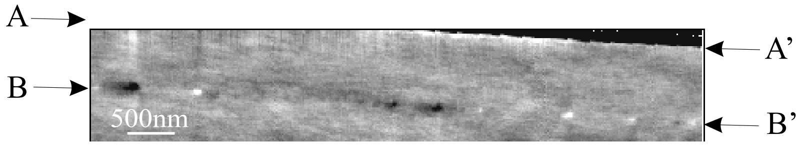

Figure 1: AFM topography image of GeSi/Si(001) structure cleavage. A-A' line corresponds to edge of the sample. B-B' corresponds to layer of GeSi nanoislands.

spots) with height of 1 nm aligned along direction B-B' spaced from the edge of the cleavage (A-A') by 700 nm 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. So, we attribute the found topographic features to the appearance of GeSi nanoislands.

Qualitative interpretation of the origin of observed elevations and depressions is the following (Fig. 2). Lattice constant of Ge is by 4.2% more than that of

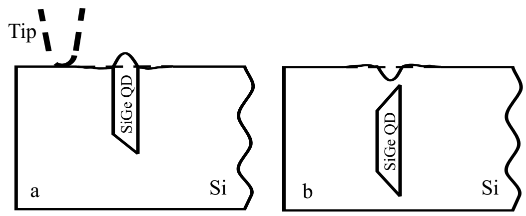

Figure 2: Illustration of elevation and depression appearance on the cleavage.

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 image of the cleavage surface of the structure with five layers of GeSi/Si nanoisland is shown in Fig. 3. There are seen five lines of surface undu-

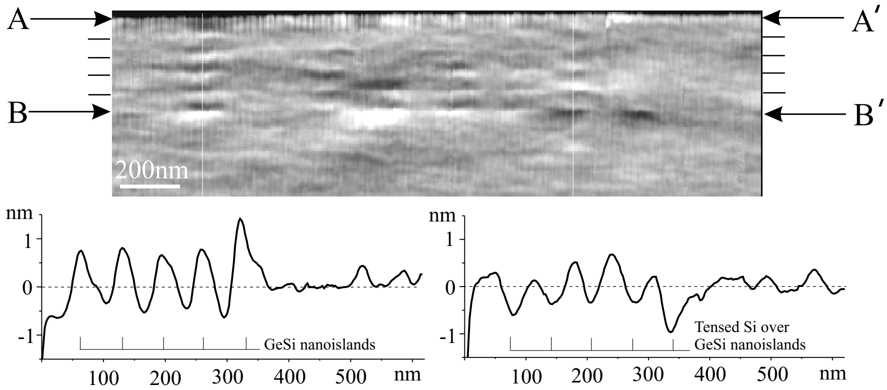

Figure 3: AFM topography image of the cleavage of 5-layered GeSi/Si heterostructure. A-A' line corresponds to edge of the sample. B-B' line corresponds to the first GeSi layer. Profiles demonstrate the details of a vertical alignment of 5 elevations (left) and 5 depressions (right). It is also seen an obvious up and down lifting of the Si matrix surface in between GeSi nanoislands.

lations going in parallel with the structure surface and spaced by 60 nm. Some undulations demonstrate vertical alignment in all five layers. 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. 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 vertical alignment of nanoislands. This phenomenon is well known and described by the strain driven mechanism of growth [6].

In Fig.4 AFM data on the cleavage of InSb/GaSb heterostructure are presented. The quantum dot layers can be revealed already on the topography image in Fig.4a. However, the presence of the cleavage steps complicates identification of a low, less then 2 angstrom high, features. Better conditions for quantum dots observation were found by application of method of nanostiffness measurements [7]. This AFM mode was specially designed to distinguish different materials on the surface on the base of difference in their mechanical properties. In the middle part of Fig. 4b all ten periods of InSb QDs layers are clearly seen. The nanostiffness relief along each QD layer is discontinuous, and features like dark dashes can be observed. The features have lateral sizes of 30-50 nm, which is typical for InSb quantum dots [8,9], besides some of them are vertically stacked. Thus the XAFM technique allows to study also InSb QDs which are much smaller then GeSi nanoislands.

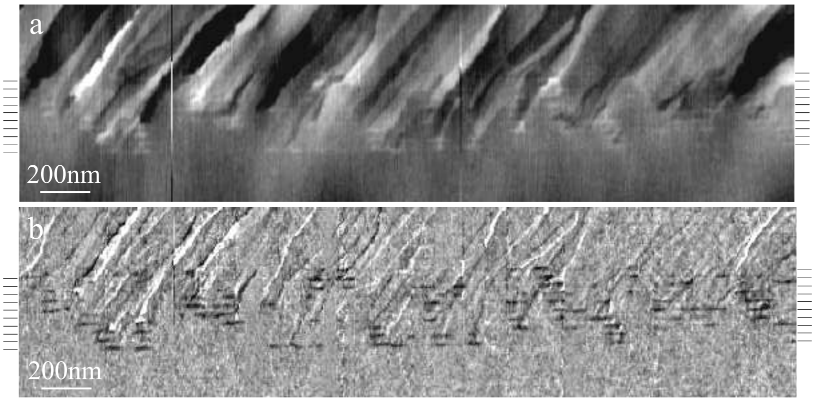

Figure 4: Topography image (a) and nanostiffness map (b) of GaSb layer with 10 layers of InSb quantum dots.

In conclusion, we have demonstrated the efficiency of ambient X-AFM methods to reveal buried nanoislands in semiconductor structures via studying topography and mechanical properties of the structure 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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