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Determination of the outward relaxation of cleaved strained InAs structures by scanning tunneling microscopy

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Abstract

When a semi-conductor structure containing strained layers such as quantum wells (QWs) or quantum dot layers is cleaved, the surface will relax outward in order to release built-in strain. This outward relaxation is directly linked to the composition of the strained layers, and can thus provide accurate information about the local composition of these layers. By using cross-sectional scanning tunneling microscopy (X-STM) it is possible to measure this outward relaxation. The measured height profiles, however, are also dependent on the chemical composition of the measured surface, resulting in an extra height contrast in the images. In order to analyze only the outward relaxation, it is necessary to suppress this latter chemical component in the STM measurements. This can be achieved by choosing the proper tunnel conditions.

Keywords: STM; Electronic contrast; Quantum dot; Quantum well; Relaxation; Strain

1. Introduction

The tip height in scanning tunneling microscopy (STM) measurements in the constant current mode is directly linked to the local density of states (DOS) of a (semi-) conducting surface. The contour followed by the tip, while scanning the surface is both dependent on the topography and chemical composition of the surface. The effects, which occur during STM measurements due to this fact, have not been investigated extensively yet [1]. If a sample, containing strained layers such as a strained quantum well, is cleaved, the surface will relax outward in order to release strain [2]. This outward relaxation can be linked to the local composition of such strained layers. In order to be able to determine this local composition, the ‘‘real’’ topography has to be separated from the topography originating from differences in the DOS, due to chemical differences between the materials of the strained layers and the surrounding matrix [2–4]. We investigated strained structures consisting of InGaAs within a GaAs matrix. These structures were cleaved and the outward relaxation upon cleavage of these strained layers was investigated by cross-sectional scanning tunneling microscopy (X-STM).

2. Theory

The height of the relaxation profiles of the cleaved strained structures measured with X-STM shows a dependency upon the tunnel voltage at which the

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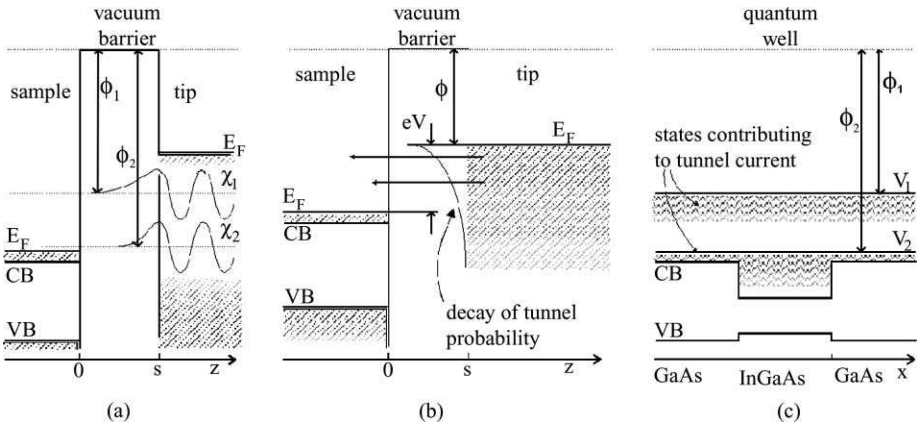

Fig. 1. (a) Electron states wave functions at a different energy show a different penetration behavior in the vacuum barrier. (b) The tunnel current is dominated by contributions from electron states having the lowest barrier height. This is due to the decay of the tunnel probability as function of vacuum barrier height. (c) Tunneling at different tip voltages above different materials results in different relative contributions of the electronic states involved in the tunneling process.

profiles were taken. This voltage dependent behavior of the apparent measured height in STM measurements can be explained by examining the tunnel process in more detail [2,5,6]. The relevant electron states involved in the tunnel process lie within the energy window between sample and tip Fermi energy states and do not equally contribute to the tunnel current [7]. The decay length of these wave functions depends on the height of the vacuum barrier for the specific state under consideration. The higher the vacuum barrier, the shorter the penetration depth of the wave function in the vacuum barrier is, see Fig. 1a. This results in a decrease of the tunnel probability, as the overlap between the tip and the sample decreases.

The vacuum barrier between the tip and the sample is classically a forbidden region for the electrons. In this region, the wave function can be expressed as

$$\psi(z) = \psi(0)\,e^{-\kappa z} = \psi(0)\exp\left(\frac{-\sqrt{2m\varphi}}{\hbar}z\right) \quad (1)$$

where φ is the vacuum barrier height, z the tip-sample distance and m the electron effective mass. The tunnel probability w of this state is

$$w \propto |\psi(0)|^2 \exp\left(\frac{-2\sqrt{2m}}{\hbar}z\sqrt{\varphi}\right) \quad (2)$$

The tunnel probability shows an exponential behavior on the vacuum barrier height, which is different for different states that contribute in the electron tunnel process. Electron states observing the lowest vacuum barrier will thus dominate the tunnel process, see Fig. 1b.

For tip Fermi energies aligned with the GaAs or InGaAs conduction band minimum (CBM), the increase in current can be huge when moving from the GaAs to the InGaAs, see Fig. 1c. Due to this increase in current, the feedback system of the STM will retract the tip, in order to maintain a constant current. This results in a lager value of the measured "apparent" outward relaxation profile of the investigated structure, as the electronic contrast is very high here. However, at energies high above the CBM, the electronic contrast is much lower as the tunnel current is dominated by electron states high above the conduction band, see Fig. 1c. Putting a positive voltage on the sample with respect to the tip, which is grounded, addresses these tunnel states. This is called empty-states imaging.

For tip electronic states near the valence band maximum (VBM) of the semi-conductor surface, a similar effect occurs. However, the vacuum barrier heights are in this case much higher, so the relative differences in barrier height above the GaAs and InGaAs are much smaller, resulting in a much smaller voltage dependency. By putting a negative voltage on the sample, these states can contribute in the tunnel process. This is called filled-states imaging.

In order to obtain STM images that only show the "real" topography, the measurements should be performed at high (preferable negative) voltages.

3. Experimental

The X-STM measurements were performed under UHV ($p < 4 \times 10^{-11}$ Torr) conditions, using an Omicron STM1, TS-2 scanner. The preparation of the tips was as described in [8]. The measurements were performed on in situ cleaved (1 1 0) GaAs surfaces, in the constant current mode. Both the negative and positive sample voltages were used. By imaging at positive voltages (empty states) the group III elements (gallium and indium) are imaged and at negative voltages the group V element (arsenic) is imaged [9].

All structures were grown by molecular beam epitaxy (MBE). The first structure contained two $In_xGa_{1-x}As$ quantum wells (QWs), which had a different indium content (about 5 and 14%), see Fig. 2.

The second sample contained five layers of low growth rate (0.01 ML/s) Stranski–Krastanov grown InAs quantum dots within a GaAs matrix. The X-STM measurements show that the dot layers are un-coupled, see Fig. 3. which is to be expected, as the spacing between the quantum dot layers was 50 nm.

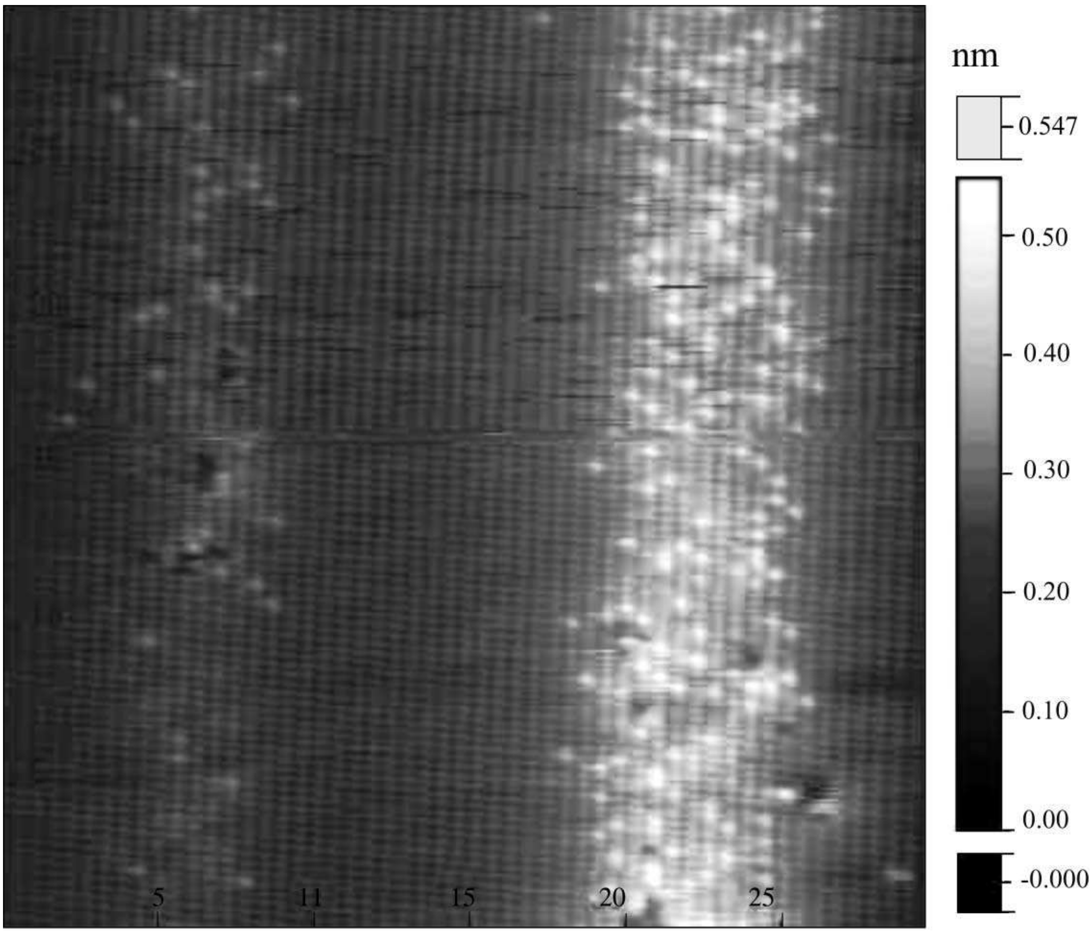

Fig. 2. Atomic resolution X-STM image (30 nm × 30 nm) of the double InAs quantum well structure. Tunnel voltage: $V = +2.5$ V; tunnel current: $I = 198$ pA.

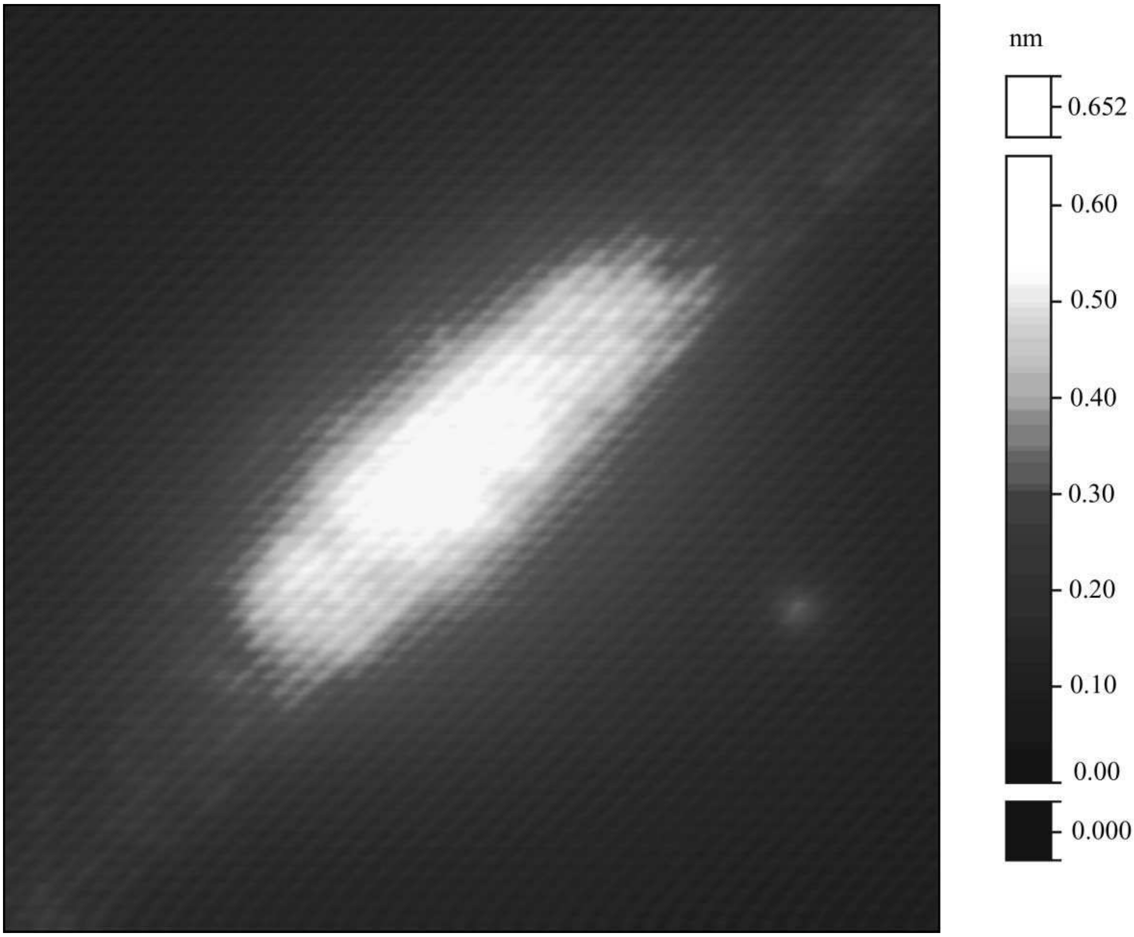

Fig. 3. X-STM topography image (35 nm × 35 nm) of a self-assembled InAs quantum dot in a GaAs matrix.

The amount of InAs deposited during formation of each dot layer was 2.4 ML.

4. Results

Fig. 4 shows the profiles of the QW structure for different image voltages in empty states. At low voltages the chemical contrast can be as high as the topography contrast. From these profiles, and other profiles measured in the filled states mode, the apparent height of the QW II is determined at different tunnel voltages, see Fig. 5. They are measured at the center of the well with respect to the surrounding GaAs, far away from the wells.

The apparent relaxation profiles obtained from the filled state images are, as expected, more or less independent of the applied tunnel voltage. In empty states, there is a strong chemical contrast at low tunnel voltages. The voltage dependent X-STM measurements of the height profiles show that filled states images or high voltage empty states images are best suitable for obtaining real topographic information, as suggested by the theory.

Fig. 6 shows the apparent height of the quantum dots as function of the image voltage, analogous to the QW measurements. The apparent height of the surface relaxation shows similar dependence as for the QW. In contrast to the QW data, the empty state height contrast approaches a constant value, above

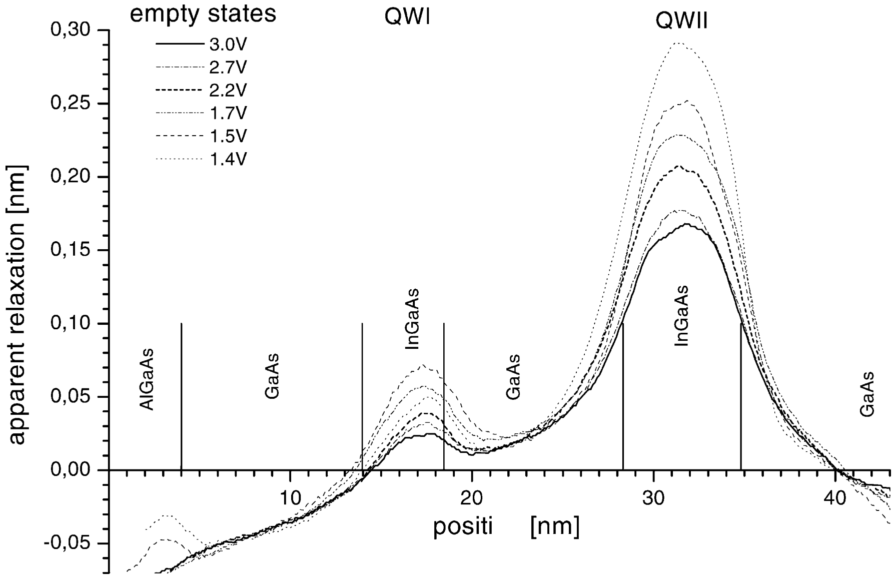

Fig. 4. Apparent outward relaxation profiles for QW I and II at different positive tunnel voltages.

approximately 2.4 V. The empty states values do not approach the filled states values at higher voltages. This could be caused by the presence of a high indium concentration in the cleaved dot surface. As indium atoms are much bigger than gallium atoms, they can give rise to the imaged topography. The height difference due to a single indium atom in an empty states image is about 50 pm. This can explain the difference in

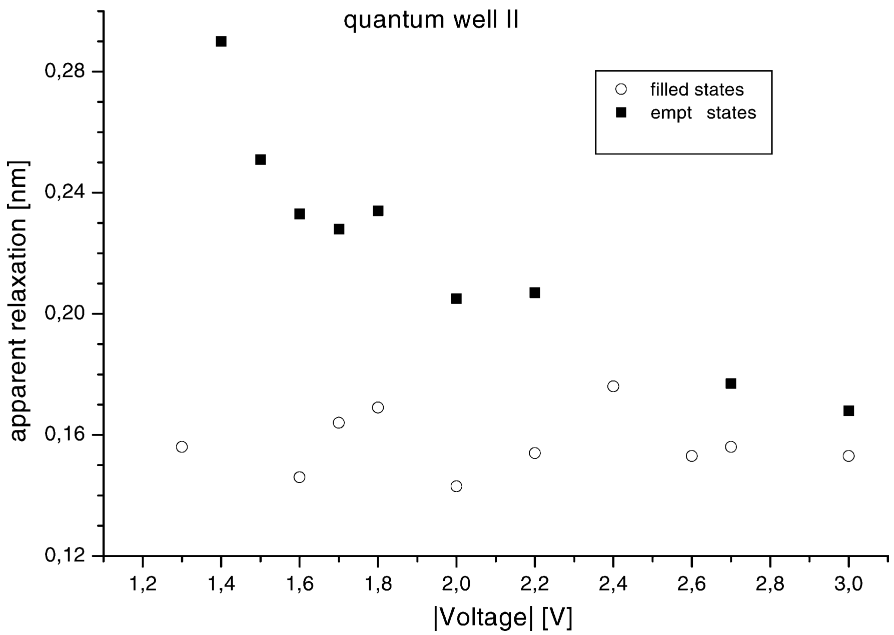

Fig. 5. Apparent outward relaxation height at the center of QW II as a function of applied tunnel voltage.

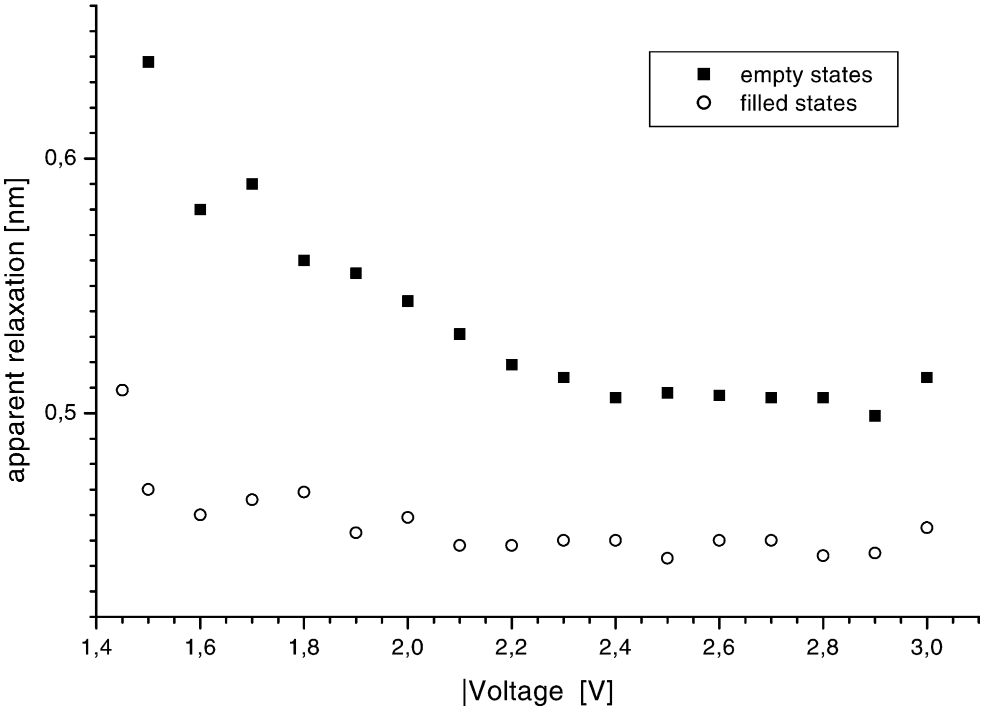

Fig. 6. Apparent outward relaxation height at the center of the quantum dot as function of applied tunnel voltage.

the saturation value of the apparent relaxation profiles between the empty- and filled-states imaging modes.

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