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Formation of InAs quantum dots and wetting layers in GaAs and AlAs analyzed by cross-sectional scanning tunneling microscopy

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Abstract

We have used cross-sectional scanning-tunneling microscopy (X-STM) to compare the formation of self-assembled InAs quantum dots (QDs) and wetting layers on AlAs (1 0 0) and GaAs (1 0 0) surfaces. On AlAs we find a larger QD density and smaller QD size than for QDs grown on GaAs under the same growth conditions (500 °C substrate temperature and 1.9 ML indium deposition). The QDs grown on GaAs show both a normal and a lateral gradient in the indium distribution whereas the QDs grown on AlAs show only a normal gradient. The wetting layers on GaAs and AlAs do not show significant differences in their composition profiles. We suggest that the segregation of the wetting layer is mainly strain-driven, whereas the formation of the QDs is also determined by growth kinetics. We have determined the indium composition of the QDs by fitting it to the measured outward relaxation and lattice constant profile of the cleaved surface using a three-dimensional finite element calculation based on elasticity theory.

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1. Introduction

Self-assembled InAs quantum dots (QDs) embedded in an AlAs matrix have been of recent interest because of their larger confinement potential compared to InAs QDs in a GaAs matrix and their use in resonant tunneling devices [1]. In order to understand the formation and the electronic properties of InAs QDs in AlAs, detailed information about the composition of the QDs is needed. Several studies have been reported on the effect of

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indium supply and growth temperature on the structural and optical properties of InAs QDs grown on AlAs [2,3]. It has been shown that InAs QDs grown on AlAs exhibit smaller sizes and larger densities compared to InAs QDs that were grown on GaAs under similar growth conditions. This has been attributed to a reduced diffusion of In adatoms on the AlAs surface due to a higher surface roughness and the larger Al-bond strength [2].

We have used cross-sectional scanning-tunneling microscopy (X-STM) measurements to determine the composition of InAs QDs and wetting layers grown on AlAs, and compare this to InAs QDs which were grown on GaAs under identical growth conditions.

2. Experiment

The QDs were grown by molecular beam epitaxy on doped GaAs (1 0 0) wafers. During growth of the QDs the substrate temperature was maintained at 500 °C. A 1.9 ± 0.1 monolayer (ML) of InAs was grown in a cycled way, i.e. with a 3 s pause after each deposition of 0.25 ML, at a slow growth rate of 0.043 ML/s. After a 500 nm doped ($1 \times 10^{18}\,\mathrm{cm}^{-2}$) GaAs buffer layer the following sequence was grown: 20 nm GaAs/1.9 ML InAs/40 nm GaAs/1.9 ML InAs/40 nm GaAs/50 nm GaAs (doped $1 \times 10^{18}\,\mathrm{cm}^{-2}$)/20 nm GaAs/4×(20 nm AlAs/1.9 ML InAs/20 nm AlAs/40 nm GaAs). To reduce interface roughness, the bottom AlAs barriers were grown at 600 °C followed by a growth interruption prior to InAs deposition.

The X-STM measurements have been performed in an ultra-high-vacuum (UHV) chamber with base pressure $< 2 \times 10^{-11}$ Torr on the UHV-cleaved (1 1 0) cross-sectional surface. Tips were prepared by electro-chemical etching of polycrystalline tungsten wires and treated in the vacuum with a self-sputtering technique [4].

3. Results and discussion

In Fig. 1(a) we show a large-scale filled-states topography X-STM image of the structure. Three layers of QDs grown on AlAs and two layers of QDs grown on GaAs are visible in the image. Compared to GaAs, the QDs grown on AlAs show a smaller size and have a significantly larger density of about $3 \times 10^{11}\,\mathrm{cm}^{-2}$. By imaging at a high voltage ($V_{\mathrm{sample}} = -3\,\mathrm{V}$), electronic contributions to the contrast in the image are minimized and only the true outward surface relaxation due to the lattice mismatch (7%) between the InAs and surrounding GaAs or AlAs matrix is imaged [5]. Because in X-STM one does not know the exact position of the cleavage with respect to the centre of the QD, many QDs were imaged and the largest

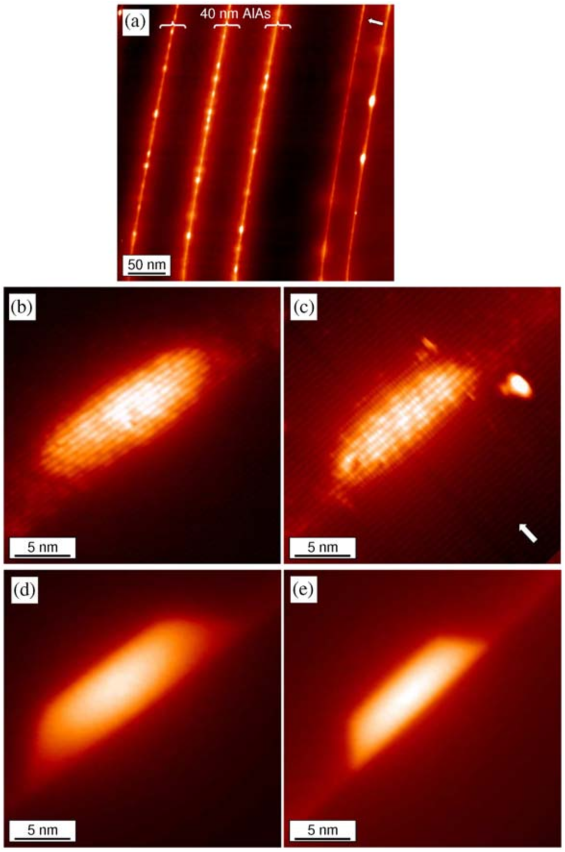

Fig. 1. Filled-states topography X-STM image of (a) three QD layers embedded in 40 nm thick AlAs barriers and two QD layers grown in GaAs, (b) InAs/GaAs QD, (c) InAs/AlAs QD. (d) and (e) show the calculated outward relaxation corresponding to (b) and (c). The colour scale for (b) and (d) is 0 (dark) to 600 pm (bright). The colour scale for (c) and (e) is 0 (dark) to 450 pm (bright). $V_{\mathrm{sample}} = -3\,\mathrm{V}$.