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Studying the lateral composition in Ge quantum dots on Si(0 0 1) by conductive atomic force microscopy

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Abstract

Conductive atomic force microscopy (C-AFM) has been employed to investigate the distribution of the lateral composition in Ge quantum dots (QDs) grown by molecular beam epitaxy on p-type Si(0 0 1) substrate. Since the different conductivity of the components (Ge and Si) in the Ge QDs results in different current signals, it is then possible to obtain the information of composition distribution from the current images. We have investigated two types of samples grown at 550 °C and 640 °C, respectively, and found that the conductance distribution of these two types of QDs were significantly different. This difference can be attributed to the different degrees of Si alloying into the Ge QDs at different growth temperatures. Our results demonstrate that the dome-shaped QDs grown at the higher temperature are Si–Ge alloys with Si composition >35% at most part of the QD, while the QDs with the same shape grown at the lower temperature show high Ge distribution (>65%) in the whole dot, which are supported by the selective etching experiments.

Keywords: Conductive atomic force microscopy (C-AFM); Quantum dots (QDs); Conductance; Composition profile; Ge; Si

1. Introduction

Recently, self-assembled Ge quantum dots have attracted intense interests and been widely studied for promising applications in low-dimensional optical and electronic devices, such as single-electron transistors, far-infrared detectors and quantum dot lasers. A full understanding of the composition profile of self-assembled semiconductor QDs is of fundamental importance for applications because predictions about any optical and electronic properties in such QD-based devices are predicted reliably only if the correct material distribution is known. Several independent studies on the composition of self-assembled Ge QDs by selective etching, X-ray diffraction, X-ray photoemission spectroscopy, cross-section TEM have been reported [1–4]. However, these techniques

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either give area-averaged information containing an ensemble of dots or destroy the samples. Therefore, approaches based on scanning probe techniques are being considered.

In this work, we employed conductive atomic force microscopy (C-AFM) to study the composition distribution in Ge quantum dots fabricated on silicon substrate by analyzing their local electrical properties. C-AFM is a promising technique capable of performing local conductance measurements over a thin film surface, and it has been already used for investigating local electrical properties on semiconductors, film dislocation, carrier profiling and charge injection [5–8]. Since the conductivity of Ge is higher than that of Si, thus it is possible to employ C-AFM to image the distribution of the conductivity in a single quantum dot. Hence we can obtain the composition profile. Nominally pure Ge QDs are substantially intermixed with Si when the growth temperature is above 550 °C and the mixture degree increases with the temperature, therefore C-AFM is a powerful technique to study the Ge and Si diffusion in a single quantum dot as a function of growth temperature. In this paper, C-AFM characterizations of two kinds of samples grown at different temperatures are compared, and the results are confirmed by selective etching experiments.

2. Experimental

The self-assembled Ge QDs studied in our experiments were prepared by solid source molecular beam epitaxy (Riber Eva-32) on p-type Si(001) substrates with resistivity of 1–10 Ω cm. Before deposition, the substrates were chemically cleaned using the Shiraki method [9], and the resulting protective oxide layer was removed by heating at 1000 °C for ten minutes in the growth chamber. Then the substrate temperature was lowered to 650 °C, and 50 nm Si buffer layer was grown. Sample A was prepared by depositing 1.7 nm Ge at 550 °C, and then the sample was immediately cooled down to room temperature. For sample B, 0.85 nm Ge layer was deposited at 640 °C, and the sample was held at 640 °C for 5 min before cooling down [10,11].

Sample morphology and current images of the samples were measured by C-AFM. A commercial ambient AFM (Solver P47, NT-MDT) system was used for the AFM experiments. In the C-AFM measurements, Pt or TiN coated Si tips scanned over the sample surfaces in the contact mode (constant force) with a bias voltage. Positive bias voltages were applied to the substrate while the tip was grounded. The current between the tip and sample was measured simultaneously with the surface topography imaging, allowing direct correlation of structural features with their electrical characteristics. Before the C-AFM experiments, samples were treated at room temperature by diluted hydrofluoric acid (original 40% and dilution ratio 1:10) to remove the oxide layer. The experiments were performed in nitrogen gas to protect the samples from oxidation. For relative etching experiments, the Ge QDs were wet chemically etched in a hydrogen peroxide solution (30%), and the morphology and current images of the dots after etching were also analyzed by C-AFM for comparison.

3. Results and discussion

Fig. 1(a) and (b) shows the topographic and current images of Ge QDs (sample A, 1.7 nm Ge deposition at 550 °C) with a bias voltage of 1.0 V, respectively. The cursor profiles along the solid lines as marked in (a) and (b) are shown in Fig. 1(c). Uniform and coherent Ge QDs with two typical sizes are observed in the topographic image: the larger dots are dome shape with an average diameter of 100 nm and an average height of 12 nm, and the smaller dots are mound-shaped with an average height of 1.0 nm. To confirm the observed QDs sizes, the sample was also measured in contact mode with non-coated AFM tips, which are sharper than the coated ones, and identical results were obtained. In this paper, we mainly concern the dome-shaped QDs. Current image obtained at 1.0 V is shown in Fig. 1(b), with the cross-section profile along the solid line given in Fig. 1(c). Since Ge is readily oxidized in air, the absolute value of the measured current is weakened due to the oxidation. In our experiments, we found the distribution of the current in the