Formation of InAs Quantum Dots on GaAs(100) by Chemical Beam Epitaxy

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We report the formation by chemical beam epitaxy (CBE) of InAs dots on GaAs(100) tilted 2° off toward the nearest (110). Atomic force microscope images and transmission electron microscope (TEM) photographs showed that highly uniform dots were grown in the Stranski-Krastanow growth mode. An average dot density of ∼10^{10} cm^{−2} was obtained by changing the deposition thickness. The shape of the quantum dots was initially round and then became elongated along the [0 11] direction due to the preferential growth of InAs with increasing deposition thickness. TEM and transmission electron diffraction images also showed that 90% of the strains in the InAs islands grown at a 2 ML of InAs deposition were relieved by the formation of 90° misfit dislocations in the (111) plane, whereas the strains were not relaxed in coherently grown islands with a 1 ML of InAs deposition. CBE growth of InAs is found to produce self-assembled InAs dots or wires with quantum sizes on highly lattice-mismatched GaAs(100) substrates.

I. INTRODUCTION

The formation of quantum dots is very important for optoelectronic applications as well as for nanometer-scale science [1]. For this reason, various formation methods have been investigated. The most favored process involves the etching of quantum wells by nanolithography [2–4]. This process, however, suffers from some drawbacks, such as the limited resolution of lithography and the defects created by etching. It has been shown that the growth of a highly lattice-mismatched semiconductor layer on a substrate can lead to the spontaneous formation of semiconductor clusters with sizes in the quantum range.

A promising method for clean and defect-free formation of dot structures directly on epilayer surface is the Stranski-Krastanow (S-K) growth method. This growth mode begins with an initial two-dimensional (2D) layer deposition on the substrate. After a critical layer deposition thickness is achieved, the surface transformation into three-dimensional (3D) highly strained dots occurs coherently on the heterostructure interface. The advantages of this dot fabrication technique are that nano-lithography and etching or implantation-induced process are not necessary. InAs which has a 7% lattice mismatch with GaAs is known to grow on GaAs initially as a strained 2D layer, and then as gradually relaxed 3D dots [5]. Such growth has been observed in InAs/GaAs [5–9] and InGaAs/GaAs systems [10,11] formed by metalorganic chemical vapor deposition (MOCVD) or by molecular beam epitaxy (MBE).

In this study, we have further investigated the growth mechanism and structural defects in the self-organized InAs dots grown by chemical beam epitaxy (CBE) on a GaAs(100) substrate tilted by 2° toward (110). We found that there were no misfit dislocations in the InAs islands at 1 monolayer (ML). These InAs islands formed at a 1-ML coverage can be utilized as quantum dots.

II. EXPERIMENTAL

Growth of InAs was achieved in a CBE system which consisted of an ultrahigh vacuum growth chamber and a source gas control system. Group V and III source gases were introduced by automatic absolute pressure-controlled leak valves without a carrier gas. The detailed configuration of the system used in this work has been de-
Fig. 1. AFM image of an InAs layer grown with a 0.5 ML of InAs. Monolayer steps are observed on the InAs surface grown on GaAs(100) tilted 2° off toward (110).

scribed in previous studies [12]. The growth of InAs was

performed on Cr-doped GaAs(100) tilted 2° off toward (110). Prior to the growth, the substrate was heated at 150°C to remove moisture and subsequently annealed at 600°C for 15 min under an arsenic pressure of $5 \times 10^{-4}$ Torr to remove the surface oxide layer from the GaAs substrate. Triethylgallium (TEG), trimethylindium (TMI), and cracked arsine were used as source gases for the GaAs buffer layer and the InAs quantum dots. The V/III ra-

Fig. 2. AFM images of InAs 3D islands grown at different coverages of InAs deposition: (a) 1 ML, (b) 2 ML and (c) 5 ML.

Fig. 3. Plan-view g(220) bright-field TEM image of InAs 3D islands grown at (a) a 1-ML of InAs and (b) 2 ML of InAs. Fringes in the island image of (b) are considered to be patterns caused by 90° misfit dislocations.

Fig. 4. [011] cross-section TED pattern of InAs 3D islands grown at 5 ML of InAs deposition. The diffraction spots are split in two due to the difference in the lattice constants for InAs and GaAs.
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III. RESULTS AND DISCUSSION

AFM was employed to measure the size and the shape of the InAs islands for different thicknesses of InAs deposition. Figure 1 shows the surface morphology of a sample with a 0.5 ML of InAs deposition. The AFM image shows monatomic steps which originate from the miscut of the GaAs(100) substrate. No indication of InAs island formation is observed in the AFM image, suggesting that the InAs epilayer is uniformly deposited on the GaAs surface on an atomic scale without the formation of InAs islands. However, many InAs islands formed on the sample with a 1-ML coverage of InAs deposition, as shown in Fig. 2(a). This figure shows round-shaped InAs dots with a 400-Å diameter and a 50-Å height. The dot density was 2.5 × 10^10 cm^-2. These results suggest that 3D islands grow between 0.5 and 1 ML of InAs deposition.

For InAs on GaAs, the 2D layer region is approximately 1-2 ML thick [13], although its complete absence has been reported [14]. At a film thickness of 2 ML, the shapes of quantum dots became elongated compared to the round shapes of the initial ones, as shown in Fig. 2(b). Island elongation is in the [011] direction which is perpendicular to the arsenic dimmer raw on the InAs surface. Such growth of InAs islands in the fast growth [011] direction continued at the higher coverage of 5 ML, as shown in Fig. 2(c). The diameters of the round islands and the widths of the elongated ones were not significantly different, but the heights increased slightly as the InAs film thickness increased from 2 to 5 ML. Figure 2(c) shows that the dot densities decrease with increasing InAs thickness due to the growth in the preferential direction [011], resulting in the coalescence of several small quantum dots.

A TEM image using the (220) reflection, which is sensitive to strain, was used to investigate the misfit dislocation formation due to the 7% lattice mismatch in the InAs islands at the initial stage of growth. Figures 3(a) and 3(b) are plan-view g(220) bright field TEM images of quantum dots formed at 1 and 2 ML of InAs film thickness, respectively. The plan-view TEM observations show almost the same results for the island shape as those from the AFM. In Fig. 3(a), there are many dotted images which indicate that InAs islands have formed. We do not observe any indication of misfit dislocations in the dotted image, suggesting that the strains caused by the lattice-mismatch between the coherently grown InAs and the GaAs substrate are not relaxed at all. On the other hand, when 2-ML-thick InAs is grown, many fringes are seen in the InAs island image, as shown in Fig. 3(b). Because the critical thickness of InAs grown on GaAs is widely known to be a few ML’s of InAs, these fringes are considered to be patterns caused by the misfit dislocations. The TEM image in Fig. 3(b) suggests that strains accumulated in the InAs islands grown at 2 ML of InAs deposition are relieved by the formation of 90° dislocations [15] in the (111) plane, as shown in Fig. 3(b).

Furthermore, the degree of strain relaxation in the InAs islands was measured by a [011] cross-section TED pattern taken from the thin-foil specimen which included a 5-ML coverge of InAs and the GaAs substrate, as shown in Fig. 4. This figure shows that each diffracted spot from the sample is split into two spots in both the [100] and the [011] directions due to the different lattice constants of InAs and GaAs. The lattice parameter of InAs was calculated from the distances between the spots for both the (400) and the (022) spots, assuming that the GaAs substrate was an undistorted material with a bulk lattice parameter of 5.65 Å. The results show that InAs has a lattice parameter of 6.04 Å perpendicular to the surface and 6.00 Å parallel to the surface. The average value of the InAs lattice constant was estimated to be 6.02 Å. The average InAs lattice constant obtained from the relaxed samples suggests that 90% of the strain is relaxed by the formation of 90° misfit dislocations in the strained InAs islands.

The growth mechanism of InAs on GaAs(100) is considered to work as follows: At the very beginning of InAs growth on GaAs, the surface energy is reduced by the covering of the GaAs surface with InAs, as shown in Fig. 1, because the surface energy of InAs is less than that of GaAs. Once the surface is covered by InAs, the strain energy increases with increasing InAs thickness. When the strain becomes dominant, InAs starts to grow in a 3D growth mode to reduce the total energy by forming strained InAs islands.

Moreover, the degree of strain relaxation in the InAs islands was measured by a [011] cross-section TED pattern taken from the thin-foil specimen which included a 5-ML coverge of InAs and the GaAs substrate, as shown in Fig. 4. This figure shows that each diffracted spot from the sample is split into two spots in both the [100] and the [011] directions due to the different lattice constants of InAs and GaAs. The lattice parameter of InAs was calculated from the distances between the spots for both the (400) and the (022) spots, assuming that the GaAs substrate was an undistorted material with a bulk lattice parameter of 5.65 Å. The results show that InAs has a lattice parameter of 6.04 Å perpendicular to the surface and 6.00 Å parallel to the surface. The average value of the InAs lattice constant was estimated to be 6.02 Å. The average InAs lattice constant obtained from the relaxed samples suggests that 90% of the strain is relaxed by the formation of 90° misfit dislocations in the strained InAs islands.

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IV. CONCLUSIONS
The initial stage of InAs growth by CBE on GaAs(100) tilted 2° off toward nearest (110) has been studied by AFM and TEM. The AFM and TEM images showed highly uniform dots formed by the S-K growth mode. An average areal dot density of $\sim 10^{10}$ cm$^{-2}$ was obtained by changing the deposition thickness. The shape of the quantum dots was initially round, but became elongated along the direction of [011] due to the preferential growth process with increasing deposition thickness. Two plan-view TEM images at 1 and 2 ML of InAs and a TED at 5 ML of InAs suggested that small islands grew coherently, while the misfit dislocations were generated in the large islands to release the 90% strain. The change of growth mode at different InAs coverages was made understandable through considerations of the surface energy and the strain energy.

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