Growth of GaSb quantum dots on GaAs (111)A*

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(Received 2 December 2013; Accepted 17 April 2014; Published 28 June 2014)

We grew GaSb QDs on GaAs (111)A by molecular beam epitaxy (MBE). By atomic force microscopic studies, it was found that large GaSb islands with low density are formed when grown at a relatively high temperature \( T_s \sim 470^\circ C \), suggesting the large diffusion length of Ga atoms on the substrate surface. In contrast, GaSb QDs formed at a lower temperature \( T_s \sim 340^\circ C \) are much smaller (\( \sim 39 \) nm) in diameter and their density is much higher \( \sim 5.0 \times 10^{10} \) \text{cm}^{-2} \), originated from the suppression of the Ga diffusion on the substrate surface. We also grew GaSb QDs at various substrate temperatures \( T_s \) and examined how \( T_s \) affects the QD radius and height.

[DOI: 10.1380/ejssnt.2014.304]

Keywords: Gallium antimonide; Gallium arsenide; Quantum dots

I. INTRODUCTION

Thanks to the remarkable development of semiconductor technology, it has become possible to fabricate a variety of high quality quantum nanostructures. Especially, 10-nanometer-scale self-assembled quantum dots (QDs) have attracted much interest because of their importance in physics and device applications. In applying QDs to semiconductor lasers, self-assembled QDs are embedded in the active regions to realize ultralow threshold currents and temperature insensitive operation [1]. QD memories or In(Ga)As QDs on GaAs substrates has been extensively applied for single-photon emitters and entangled two photon sources for quantum cryptography [5].

In the study of self-assembled QDs, the growth of InAs or InGaAs QDs on GaAs substrates has been extensively investigated. In(Ga)As QDs with no dislocation are automatically fabricated just by depositing In(Ga)As on GaAs substrates, where the QD formation is driven by the strain due to the lattice mismatch of about 7% between InAs and GaAs. The QD formation occurs not only on (100) surfaces but also on high index substrates, such as InAs QDs on (311)A, (311)B, (411)A, and (411)B GaAs substrates [6]. In addition, In(Ga)As QDs are formed on (110) GaAs surfaces covered by an AlAs layer [7, 8] or on vicinal (111)B GaAs substrates [9, 10]. However, the deposition of InAs onto a (111)A GaAs substrate results in the layer-by-layer growth, and QDs are not formed under normal growth conditions [11].

Recently, type-II QDs have attracted strong interests, where the QDs confine only electrons or holes, keeping the others outside. This unique electronic structure leads to optical properties different from type-I QDs, such as a long radiative lifetime, a dot-shape dependent oscillator strength, and a large tunability of emitted photons. A GaSb QD buried in a GaAs matrix is one of such type-II systems, in which only holes are confined in the QD, while electrons are loosely bound by the Coulomb attractive force of the holes. GaSb/GaAs QDs are expected for the application of charge storage devices, since holes are strongly localized in the QDs, and their retention time is much longer than in In(Ga)As QDs at room temperatures [12]. Several works have been done on the formation of GaSb QDs on (100) GaAs substrates [13–22], while relatively little is known about the growth of GaSb QDs on high index substrates. In this paper, we report that the deposition of GaSb on (111)A GaAs substrates results in the formation of GaSb QDs.

II. EXPERIMENTS

For our study, GaSb QDs were grown on semi-insulating (111)A GaAs substrates by molecular beam epitaxy (RIBEER MBE2300) with a reflection high-energy electron diffraction (RHEED) system. We employed a valved cell for As, which enables us to precisely control the As flux intensity and sharply switch from the As to Sb supplies. In contrast, a conventional Knudsen cell was used for Sb. The sample surface was studied by atomic force microscope (AFM).

First, 250-nm-thick GaAs buffer layer was grown at 500°C after desorbing the surface oxide. The deposition rate of Ga was set to be about 0.16 monolayer (ML) per second. Here, the rate was determined by using the RHEED specular beam oscillations for a (100) GaAs substrate, and 1 ML of Ga indicates the amount necessary to obtain 1 ML of GaAs on the (100) surface. The beam flux of Ga and As\(_4\) were about \( 1.2 \times 10^{-7} \) and \( 5 \times 10^{-5} \) Torr, respectively. The low growth rate and the high As\(_4\) flux are necessary for fabricating a quite flat surface. After growing the GaAs buffer layer, the substrate temperature \( T_s \) was decreased from 500°C to the QD growth temperature...
(410-490°C). We then closed the As valve to deplete the As background for 200 seconds. After the pressure of the growth chamber decreased to about 5×10^{-8} Torr or less, the GaAs surface was pre-exposed to Sb4 beam flux for 50 seconds. Here, the Sb4 flux was set to be about 5×10^{-7} Torr. This procedure reduces the interface roughness and defects resulted from the uncontrollable adatom exchange effects [23]. We then deposited a nominally 3.2 ML-thick GaSb layer to form GaSb QDs. After growing the GaSb QDs, the substrate temperature $T_s$ was immediately reduced by turning off the heater current.

![FIG. 1: AFM images (1×1 μm²) of GaSb islands on GaAs (111)A substrate grown at 470°C.](image)

![FIG. 2: AFM images (1×1 μm²) of GaSb QDs on GaAs (111)A substrate grown at 430°C.](image)

**III. RESULTS AND DISCUSSION**

To evaluate the QD size and density, we carried out AFM measurements in a non-contact mode. Figure 1 shows an AFM image of the sample surface, where a nominally 3.2 ML-thick GaSb layer is deposited on GaAs (111)A at $T_s = 470$°C. Large GaSb islands with low density are formed, suggesting the large diffusion length of Ga atoms on the substrate surface. On average, the lateral size and height of the GaSb islands are about 73 nm and 2.5 nm, respectively. Their density $N_{QD}$ is about 7.5×10^{9} cm^{-2}. The GaSb islands are formed in flattened polygonal shape where the internal angles are multiples of 60 degrees, reflecting the atomic geometry on the (111) surface.

Figure 2 shows an AFM image of the sample surface on which GaSb is deposited at $T_s = 430$°C. Note that small GaSb QDs are successfully formed in high density, where the QD diameter and the density are about 39 nm and 5.0×10^{10} cm^{-2} on average. At this low temperature ($T_s \sim 430$°C), the Ga diffusion on the substrate surface is suppressed, leading to the formation of denser and smaller QDs.

To investigate the effect of the substrate temperature $T_s$, we grew GaSb QDs (or islands) on GaAs (111)A surfaces at $T_s = 410-490$°C. Figure 3 shows the temperature $T_s$ dependence of the average radius $\langle r \rangle$ of GaSb QDs. As the temperature $T_s$ increases from 410 to 490°C, the average radius $\langle r \rangle$ increases by about three times, resulting from the larger diffusion length of Ga atoms on the substrate surface at higher temperatures. This tendency is similar to that for other QD systems such as In(Ga)As and InP QDs [24–26]. Note that the radius $\langle r \rangle$ is almost constant below $T_s = 450$°C and drastically increases at $T_s > 470$°C. This suggests that the Ga atom diffusion is significantly pronounced above 470°C.

Figure 4 shows the average height $\langle h \rangle$ of GaSb QDs as a function of the growth temperature $T_s$. Note that the height $\langle h \rangle$ is less affected by the growth temperature and almost constant with $T_s$. This is not the case for Stranski-Krastanov (SK) growth of GaSb QDs on GaAs (100) and (311)A surfaces, where the height $\langle h \rangle$ increases as
the layer exceeds a critical thickness, a 10-nanometer-scale layer fashion, which results in a thin wetting layer. After the growth of GaSb QDs initially proceeds in a layer-by-layer fashion, which may be caused by their growth modes. In the SK mode, such as the interfacial misfit (IMF) mode or the Volmer-Weber (VW) mode. This issue will be left as a subject of future experimental and theoretical studies.

In summary, the growth of GaSb quantum dots (QDs) on GaAs (111)A substrates were studied. By molecular beam epitaxy (MBE), GaSb QDs were grown on GaAs (111)A substrates. Atomic force microscopic studies (AFM) showed that large GaSb islands with low density are formed at a relatively high temperature ($T_s \sim 470\degree C$). In contrast, smaller GaSb QDs are formed in high density at a lower temperature ($T_s \sim 430\degree C$). By growing GaSb QDs at various temperatures $T_s$, we also examined how $T_s$ affects the QD shape.

IV. CONCLUSIONS

In summary, the growth of GaSb quantum dots (QDs) on GaAs (111)A substrates were studied. By molecular beam epitaxy (MBE), GaSb QDs were grown on GaAs (111)A substrates. Atomic force microscopic studies (AFM) showed that large GaSb islands with low density are formed at a relatively high temperature ($T_s \sim 470\degree C$). In contrast, smaller GaSb QDs are formed in high density at a lower temperature ($T_s \sim 430\degree C$). By growing GaSb QDs at various temperatures $T_s$, we also examined how $T_s$ affects the QD shape.

FIG. 4: Average height $\langle h \rangle$ plotted as a function of the QD growth temperature $T_s$. In the case of the hetero growth on GaAs (111)A, however, misfit dislocations are often caused, resulting in the strain relaxation. H. Yamaguchi et al. showed that the strain is largely relaxed because of dislocations and the layer-by-layer growth occurs, when InAs is deposited on GaAs (111)A substrates [11]. A Babkevich et al. showed that the deposition of about 7-nm-thick GaSb on GaAs (111)A results in the strain relaxation of more than 95% [28]. It is likely that such misfit dislocations occur and the strain is relaxed in our experiment. We therefore speculate that our GaSb QDs are formed in a growth mode other than the SK mode, such as the interfacial misfit (IMF) mode or the Volmer-Weber (VW) mode. This issue will be left as a subject of future experimental and theoretical studies.

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