Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 608-609

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# Control of GaSb/GaAs Quantum Nanostructures by Molecular Beam Epitaxy

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## 1. Introduction

The GaSb/GaAs quantum nanostructures, especially quantum dots (QDs), are of great interest for infrared optoelectronic devices, memory applications and spin controlled devices. The self-assembled GaSb/GaAs QDs based on the Stranski-Krastanov (SK) mechanism have been studied recently [1,2]. In case of the GaSb/GaAs hetero-epitaxial growth, it is difficult to control the heterointerface because of two different group Ⅴ elements. In addition, size fluctuation of the self-assembled GaSb/GaAs QDs was large so far: photoluminescence (PL) linewidth of about 100 meV. Recently, we have demonstrated uniform self-assembled InAs/GaAs QDs by molecular beam epitaxy (MBE) using the SK mode [3,4]. It was attributed to self size-limiting effect and enhancement of the surface migration of the growth species by control of the growth conditions.

In this article, we present control of GaSb/GaAs(001) quantum nanostructures (quantum wells (QWs) and QDs) in MBE growth. Real-time control of the growth process using reflection high-energy electron-beam diffraction (RHEED) yielded the well-controlled GaSb/GaAs QWs with one monolayer (ML) in thickness. The 1-ML-thick GaSb layer was used as a template for the SK growth of the GaSb/GaAs QDs. Additionally, by adjusting the growth conditions, size fluctuation of the GaSb QDs was effectively suppressed: narrow PL linewidth of 67 meV was obtained.

## 2. Control of 1-ML GaSb QWs

The exchange of the GaAs surface for the GaSb one can be accomplished by switching $As_4$ irradiation to $Sb_4$ one during the growth interruption. Figure 1 shows RHEED intensity of a specular beam as a function of the irradiation time of $Sb_4$ flux ($5\times10^{-8}$ Torr). Prior to the $Sb_4$ irradiation, the GaAs buffer layer was grown at 590 ℃ on the GaAs(001) substrate. The substrate temperature was cooled down to 470℃, and then the Sb shutter was opened after a stop of the $As_4$ irradiation. By the $Sb_4$ irradiation, the GaAs-c(4×4) surface quickly changes into the (1×3) surface, which reveals the formation of the GaSb surface. Here, we observed one-cycle oscillation of the specular beam intensity, as shown in Fig.1. The exchange reaction between arsenic and antimony atoms induces the surface strain due to lattice mismatch between the GaAs and the GaSb. Therefore, it is considered that the intensity oscillation of the specular beam represents the rough-and-flat transition of the strained GaAs-GaSb surface: the one-cycle oscillation corresponds to the formation of 1-ML-thick GaSb layer. Following the first oscillation, the specular beam intensity saturated and then gradually decreased. It suggests that the activation energy of the exchange reaction between group Ⅴ elements much increases for more than 2 ML in thickness. By the real-time monitor of the specular beam intensity and control of the $Sb_4$ irradiation, we can obtain 1-ML-thick GaSb layer on the GaAs.

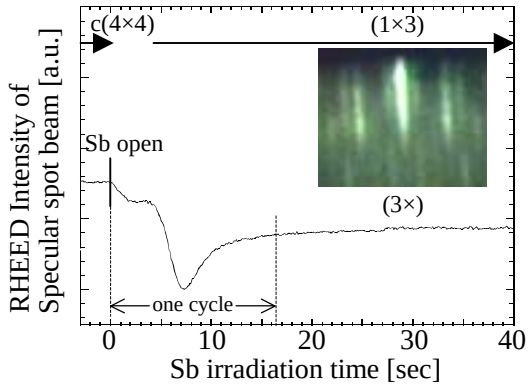


Fig.1. RHEED intensity of a specular beam as a function of the irradiation time of $Sb_4$ flux.

Figure 2 shows (110) cross-sectional scanning transmission electron microscopy (STEM) image of the 1-ML-thick GaSb QW formed by above real-time control technique. One can see the flat and abrupt heterointerface of the GaSb/GaAs. The observed thickness of the GaSb QW corresponds to less than 2～3 ML, including the step structures. Figure 3 shows low temperature (12 K) PL spectrum of the 1-ML GaSb QWs. The strong and sharp PL with a linewidth of 11 meV was obtained. It reveals high crystal quality and uniform thickness of the GaSb QWs.

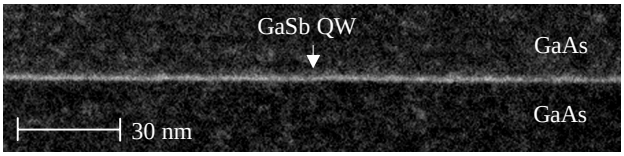


Fig.2. (110) cross-sectional STEM image of the GaSb QW.

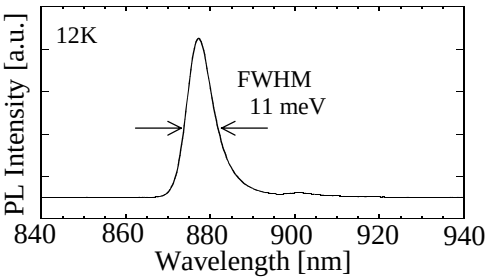


Fig.3. PL spectrum (12 K) of 1-ML GaSb QW. The excitation power density of $Ar^+$ laser was 3.2 W/cm$^2$.

### 3. Suppression of size fluctuation of GaSb QDs

The GaSb QDs were self-formed on the 1-ML-thick GaSb/GaAs layer by simultaneous supply of Ga and $Sb_4$ flux at 470℃. At the initial growth, the two-dimensional (2D) growth of the GaSb occurs, and then the 2D growth rapidly transits to the 3D growth at about 2.5 ML in coverage. In order to enhance the surface migration of the growth species, we attempted the growth of the GaSb QDs under low growth rate (0.04 ML/s) and low $Sb_4$ pressure ($5\times10^{-8}$ Torr) conditions (condition L). The GaSb coverage was 3.5～4.0 ML.

Figure 4 shows two atomic force microscopy (AFM) images of the GaSb dots grown respectively under condition L (a) and condition H (high growth rate (0.18 ML/s) and high $Sb_4$ pressure ($3\times10^{-7}$ Torr) (b). Large size fluctuation of the GaSb dots having an anisotropic shape was observed for condition H. On the contrary, the growth at condition L improved uniformity in the dot size, as we expected. Additionally, the dot shape changed into an isotropic cap. The dot density was $1\times10^{10}$ cm$^{-2}$ for condition L. Although the facet formation was not clearly observed during the growth of the GaSb dots, the lateral size tended to saturate for more than about 3 ML in coverage. This size-limiting phenomenon is very important for getting the uniform QDs [4]. After the SK growth of the GaSb dots at condition L, the GaAs capping layer was grown at 450℃. Figure 5 shows (110) cross-sectional STEM image of the embedded GaSb QDs. The GaSb QDs having a dome-like shape are formed on the wetting layer. The lateral size of the QDs is 20～30 nm, and the height is about 12 nm. The aspect ratio of the GaSb QDs is higher than that of the conventional InAs ones.

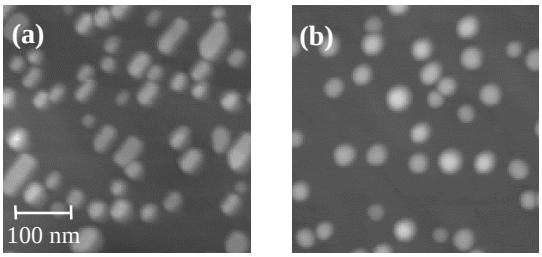


Fig.4. AFM images of GaSb dots grown respectively at condition H ((a): growth rate of 0.18 ML/s, $Sb_4$ pressure of $3\times10^{-7}$ Torr) and condition L ((b): 0.04 ML/s, $5\times10^{-8}$ Torr).

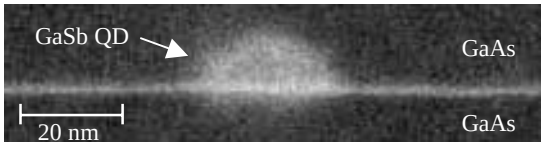


Fig.5. (110) cross-sectional STEM image of GaSb QDs grown at condition L.

The high aspect ratio also suppresses the size fluctuation. Figure 6 shows PL spectrum (12 K) of the GaSb QDs grown at condition L. The PL peak wavelength appears at about 1140 nm. The observed optical emission from the type Ⅱ-GaSb/GaAs QDs is due to the transition between electrons in the GaAs conduction band and holes confined in the GaSb QDs, closing with heterointerface. Therefore, the PL linewidth includes not only inhomogeneous broadening in the dot size but also energy distribution of electrons in the GaAs conduction band. As shown in Fig.6, we could obtain the narrowest PL linewidth of 67 meV, which reveals suppression of the size fluctuation of the GaSb QDs. It is mainly attributed to the migration enhancement effect, caused by low growth rate and low $Sb_4$ pressure conditions.

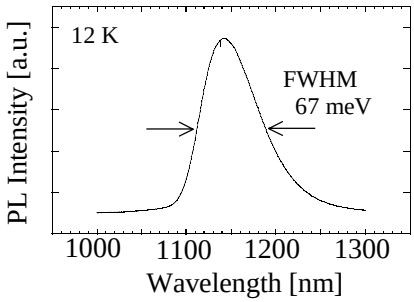


Fig.6. PL spectrum (12 K) of GaSb QDs. The excitation power density of $Ar^+$ laser was 3.2 W/cm$^2$.

### 4. Conclusions

We presented control of the GaSb/GaAs(001) QWs and QDs in the MBE growth. By using a RHEED real-time monitor, 1-ML-thick GaSb layer was formed precisely. Low growth rate and low $Sb_4$ pressure were effective conditions to reduce size fluctuation of the GaSb QDs, and, as a result, narrow PL linewidth of 67 meV was successfully obtained.

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