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Molecular beam epitaxial growth of GaSb/GaAs quantum dots on Ge substrates

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ABSTRACT

We perform structural and optical investigations of GaSb/GaAs quantum dots (QDs) grown on Ge (001) substrates by molecular beam epitaxy. Anti-phase domains (APDs) of GaAs are distributed on Ge substrate after the growth of GaAs due to the growth nature of III–V compound on group IV semiconductors having polar and non-polar behaviors. The APDs affect the QD growth as demonstrated by the growth of conventional InAs QDs on this surface. For GaSb QDs, the GaSb layer is grown on GaAs APD surface and compared with the GaSb layer on conventional (001) GaAs surface. Self-assembled QDs are formed on both surfaces but structural analysis reveals evidence of shape and size differences, which is attributed to the influence of the initial surface. Photoluminescence of GaSb/GaAs QDs grown on both Ge and GaAs substrates is studied. Emission from GaSb/GaAs QDs on Ge substrate can be detected till near room temperature (270 K).

1. Introduction

Germanium is a well-known bulk material for infrared detectors. Au-doped Ge, Cu-doped Ge and Hg-doped Ge have been used for mid- and far-infrared applications [1]. However, typical Ge detectors must be operated at low temperatures. On the other hand, GaSb/GaAs quantum dots (QDs) are type-II nanostructures having a potential for mid-infrared applications [2]. Based on quantum confinement behavior, GaSb/GaAs QD and related nanostructures could be operated at high temperatures and are stable with temperature change [3,4]. GaSb/GaAs has 7.8% lattice mismatch providing a growth condition to form self-assembled QDs in Stranski–Krastanov growth mode similar to conventional InAs/GaAs QDs. From the electronic point of view, GaSb/GaAs QD has type-II band alignment unlike the InAs/GaAs QDs. Therefore, it has interesting behaviors in many aspects [4–7]. Our ultimate aim is to utilize the advantage of GaSb/GaAs QDs and Ge substrates for opto-electronic device applications. By using a molecular beam epitaxy (MBE), one can coherently combine these different material systems into a device structure. However, growth of GaSb/GaAs QDs on Ge substrates must be well understood.

In this paper, we present structural and optical investigations of GaSb/GaAs QDs grown on (001) Ge substrate. The growth of GaAs layer on (001) Ge substrate produces characteristic anti-phase domains (APDs) on the surface. Influence of APD on the QD growth is demonstrated by the growth of conventional InAs/GaAs QDs. After that, a comparative study of the GaSb/GaAs QDs grown on APD and normal GaAs' surface is presented. Photoluminescence (PL) shows that GaSb/GaAs QDs on Ge substrate emit light in the range of 0.97–1.07 eV at low temperature (12 K) and their emission can still be detected till near room temperature (270 K).

2. Experiments

The samples were grown in a solid-source MBE system equipped with Sb valved cracker. Substrates were commercial Ge and GaAs wafers with (001) surface. After the thermal desorption of native surface oxide [8], the 0.5-μm GaAs buffer layer was grown at ~580 °C using the growth rate of 0.5 monolayer/s (ML/s). The sample was then cooled down to 350 °C for switching the atmosphere from As_4 to Sb. The GaSb QD layer was grown after the ramp-up of sample temperature to 450 °C. Nominal 3.0 ML GaSb layer was grown with V/III ratio of 2.2 (measured by a Bayard–Alpert gauge) and the growth rate of GaSb

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สำเนาถูกต้อง
Suwit Kiravittaya
สุวิทย์ กิระวิทยา

was 0.14 ML/s. The total QD growth time was 22 s. During growth, the reflection high-energy electron diffraction pattern was always monitored. Formation of GaSb QDs was indicated by the formation of spotty pattern. After the growth, the samples were either immediately cooled down for structural investigation or capped with 170-nm GaAs at 500 °C for PL study. The surface morphology is examined by atomic force microscope (AFM) (Seiko, SPA-400) in dynamic force mode in air. The PL is done using a 60-mW Ar$^+$ laser as the excitation source and a cooled InGaAs detector.

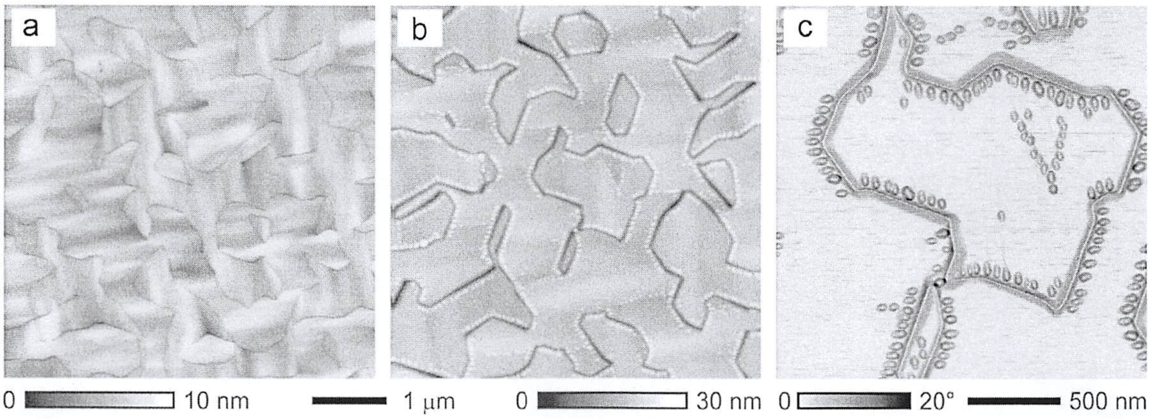

Fig. 1. (a) 5 × 5 μm^2 AFM image of 0.5-μm GaAs grown on (001) Ge (001) substrate. (b) 5 × 5 μm^2 AFM image of 1.8-ML InAs layer showing elongated self-assembled QDs located near APD boundary. QDs are mainly located on the APD boundary. (c) Magnified image (2 × 2 μm^2) of (b). The grayscale corresponds to the local surface slope.

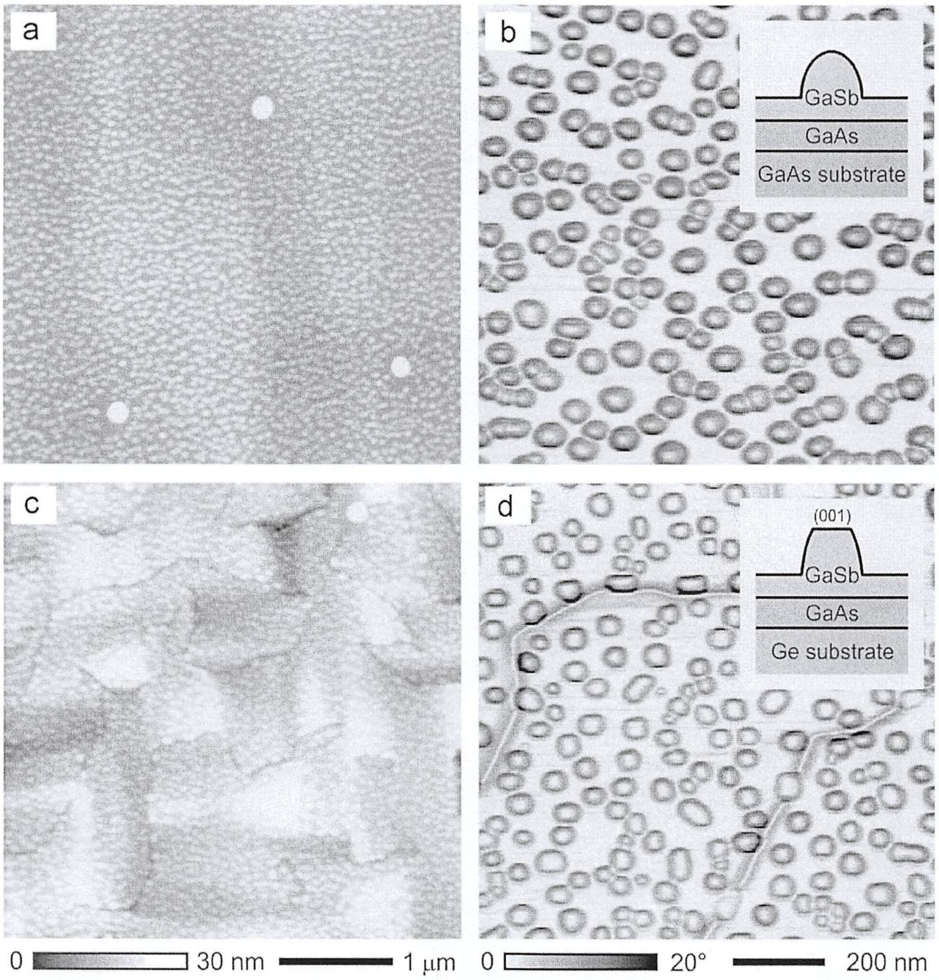

Fig. 2. (a) 4 × 4 μm^2 AFM image of 3.0-ML GaSb QD layer on GaAs (001) substrate. (b) Magnified image of (a) (1 × 1 μm^2) with the surface slope scale. QDs are dome-shaped with rather irregular base. (c) 4 × 4 μm^2 AFM image of 3.0-ML GaSb QD layer on Ge (001) substrate. (d) Magnified image of (c) (1 × 1 μm^2) with the surface slope scale. QDs have a plateau on top. Insets of (b) and (d) show the schematic of the grown structure and the obtained QD shape.

สำเนาถูกต้อง

Suwit Kiravittaya

สุวิทย์ กิระวิทยา

3. Results and discussion

Epitaxial layer of GaAs could be grown on Ge substrates since Ge and GaAs are mostly lattice-matched [9,10]. However, when a polar epitaxial layer of GaAs is grown on non-polar Ge substrates, APDs are typically formed. Fig. 1(a) shows a surface of 0.5-μm-thick GaAs grown on (001) Ge substrate. The surface is decorated with large APDs (in micron scale). Domain boundary is a kind of defect, which might affect the optical and electrical properties of the nanostructure grown on top. However, when the GaAs' APD size is large compared to the size of QDs, the unique QD properties should remain and be useful for device applications.

To demonstrate the influence of APD on QD growth, we grew conventional InAs QDs on the GaAs surface decorated with APDs [11]. Fig. 1(b) shows an AFM image of the InAs QDs on the surface. We found that InAs QDs are intensively located at the APD boundary. In addition, the QDs have an elongated shape with their elongation being aligned with the grain boundary (Fig. 1(c)). According to the study of In(Ga)As QD shape on normal surface [12,13], the elongation of InAs QD shape is expected to be along $[1\bar{1}0]$ crystallographic direction. When the dot formation is observed on one side of a particular domain wall, there will be no dots on the other side of the same domain wall. This indication confirms that the crystal orientation of each APD is perpendicular to that of its neighbor.

For a direct comparison, the GaSb QD growth on both (001) Ge and (001) GaAs substrates was done at the same MBE growth run. Fig. 2 shows the AFM images of 3.0 ML GaSb/GaAs QDs on GaAs substrate (Fig. 2(a) and (b)) and on Ge substrate (Fig. 2(c) and (d)). On the GaAs substrate, high density ($\sim 1.7 \times 10^{10}$ cm^{-2}) of GaSb QDs is observed on flat surface. Few large GaSb clusters, which may have originated from the Ostward ripening, are also seen. Magnified AFM image (Fig. 2(b) shows that the GaSb QDs are dome-shaped with rather irregular bases. Inset of Fig. 2(b) shows a schematic of the sample and QD structure.

For the GaSb QDs grown on GaAs APD on Ge substrate, the QDs are distributed on the entire surface of GaAs APDs even at the domain boundary (Fig. 2(c)). The dots have large non-uniformity and they have no elongated shape as observed in the case of InAs QDs (Fig. 1(c)). From this result, we believe that the formation/relaxation mechanism of GaSb QDs on the APD surface is quite different from that of InAs. In the case of GaSb, the APDs do not affect the QD position, i.e., the QDs are densely formed everywhere on the surface. This effect can be due to the higher sticking coefficient (and lower diffusibility) of Sb atoms [14,15]. The GaSb QDs might easily form on the surfaces due to the short diffusion length of Ga and Sb atoms/molecules unlike InAs grown at the chosen rate and temperature [13]. This results in dense GaSb QD array formed without having the influence of APDs on the QD position.

On closely observing the shapes of GaSb QDs on GaAs' APD surface, we found that mostQDs have (001) plateau on top while their base is rather non-uniform (Fig. 2(d) and its inset). Comparing with the dome-shaped GaSb QDs on GaAs substrate, we propose that the different QD shape is due to the difference in strain state. Presence of APD boundary in the initial surface reduces the strain for GaSb material during the QD formation. Therefore, GaSb experiences lower mismatch and forms into a different QD shape. Shape-dependence on mismatch strain has been observed in other materials [12,16].

Fig. 3 shows an analysis of AFM image shown in Fig. 2. The histogram of QD height and diameter of GaSb QDs on GaAs and Ge substrates are shown in Fig. 3(a) and (b), respectively. Note that the QD diameter is obtained from the base area of QDs with circular QD-base approximation. The distributions of QD height and diameter are well characterized by normal (Gaussian) distributions. Comparing the obtained values, we found that the average QD height shows a marked difference. The origin of this observation is due to the difference in QD shape. As mentioned above, the GaSb QDs on Ge substrate have plateau on top. Therefore, the QD height must be lower for approximately the same QD volume in both arrays.

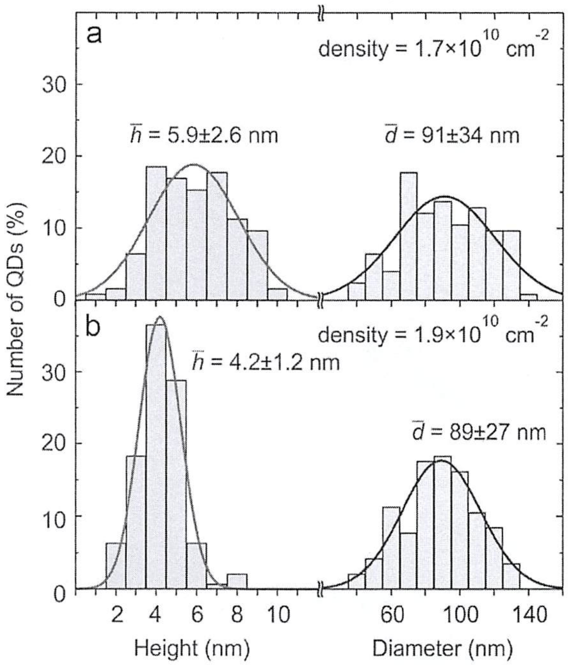

Fig. 3. Histograms of height and diameter distributions of GaSb/GaAs QDs on (a) GaAs and (b) Ge substrates. The solid lines are Gaussian fits. Average height and diameter are indicated in the figures.

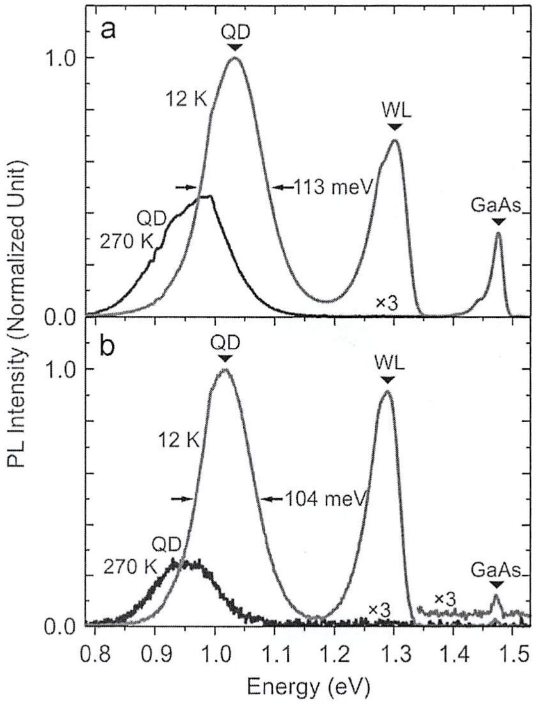

Fig. 4. PL spectra obtained from GaSb QDs on (a) GaAs substrate and (b) Ge substrate. The measurement temperatures are 12 K and 270 K. Intensities of the spectra at 270 K are related to the normalized spectra at 12 K. Three main peaks are attributed to GaSb QD, GaSb WL, and GaAs.

สำเนาถูกต้อง
Suwit Kiravittaya
สุวิทย์ กิระวิทยา

Normalized PL spectra obtained from GaSb/GaAs QDs on GaAs and Ge substrates are shown in Fig. 4. For the low-temperature (12 K) spectra, three distinct peaks are observed at 1.00–1.05 eV, 1.27–1.30 eV and 1.46–1.48 eV. They correspond to the emission from GaSb QDs, GaSb quantum well (or wetting layer (WL)) and GaAs, respectively [4,5]. Comparison of peak positions reveals a slight redshift of QD emission from sample with Ge substrate as compared to the QD emission from GaAs substrate. This redshift might be explained by lowering the strain accumulated in GaSb QDs on Ge. Since the mismatch strain between the GaSb and GaAs is large (7.8%), the variation of bandgap can strongly be affected by the strain. Slightly relaxation of strain in GaSb is due to the presence of APD redshifts in the QDs emission. Apart from the main QD peak, emissions from GaSb quantum well, which is the WL, are also well observed at low temperature. This indicates a good one-dimensional confinement on both samples. While two main peaks have quite similar features, the GaAs peak from the sample with Ge substrate shows much lower intensity. This is due to the fact that the GaAs in the sample contains many defects. Without normalization, the emissions from GaSb QDs and WL on Ge substrate are about one order of magnitude lower than those on GaAs substrate for the whole measurement temperature range (12–300 K).

The PL emission from GaSb QDs can be detected at elevated temperatures. The QD emission redshift to 0.9–1.0 eV at high temperature is mainly due to the shrinkage of the bandgap. The highest temperature for detecting PL signal from QD on Ge substrate is at 270 K while the emission from QD on GaAs can still be observed at room temperature (not shown). This result implies that the non-radiative recombination at the APD boundary is dominant at high temperatures. Since at an elevated temperature the carriers can thermally activate and diffuse at longer distance, the influence of nearby defects around QDs becomes noticeable.

4. Conclusions

We have presented a study on the self-assembled GaSb/GaAs QDs growth on the GaAs surface with and without APDs. The GaAs APDs are formed by the growth on non-polar Ge substrate. These APDs clearly influence the QD growth in the case of InAs QDs. Elongation and local alignment of InAs QDs are clearly observed on APD surface. For GaSb QDs, the growth of GaSb shows that self-assembled QDs can similarly form on both surfaces without and with APDs. Detailed structural comparison reveals that the GaSb QDs on APD surface have plateau on top. We attribute this observation to the influence/difference of the strain state of initial surface. Finally we compared the PL of GaSb/GaAs QDs grown on Ge and GaAs substrates. Rather similar emission at low temperature is observed while the emission from GaSb/GaAs QDs on Ge substrate can be detected up to near room temperature (270 K). The latter is due to the presence of APD boundary near the emitter. This work is an essential step towards the development of Sb-based opto-electronic devices on Ge substrate.

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สำเนาถูกต้อง

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สุวิทย์ กิระวิทยา