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Effect of thin intermediate-layer of InAs quantum dots on the physical properties of InSb films grown on (001) GaAs

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ABSTRACT

In this study the formation of a semiconducting InSb layer, preceded by the growth of an intermediate layer of InAs quantum dots, is attempted on (001) GaAs substrate. From the analysis of atomic-force-microscopy and transmission-electron-microscopy images together with Raman spectra of the InSb films, it is found that there exists a particular layer-thickness of ~0.5 μm above which the structural and transport qualities of the film are considerably enhanced. The resultant 2.60-μm-thick InSb layer, grown at the substrate temperature of 400 °C and under the Sb flux of 1.5×10^{-6} Torr, shows the electron mobility as high as 67,890 cm^2/Vs.

1. Introduction

Recently, indium antimonide has received a great deal of attention because of its ultra-high electron mobility of ~78,000 cm^2/Vs and narrow band-gap of 0.17 eV. These characteristics make InSb a unique III–V compound-semiconductor suitable for applications to high-performance micro-Hall sensor [1], high-speed magnetic sensor [2,3], and long-wavelength photodetectors [4–6]. However, since for practical applications InSb must be deposited on a semi-insulating substrate, attempts have been made to grow InSb films on readily-available substrates such as Si or GaAs. The major difficulty in the growth of InSb on either substrate, however, is that the lattice constant of InSb is considerably larger than that of Si or of GaAs resulting in respective lattice mismatch of ~19% or of ~14.5%.

The choice of GaAs as a substrate for the growth of InSb has been relatively more common including the use of compliant universal substrate [7], step-grade buffer consisting of AlSb and InAsSb [8], and low temperature–high temperature (LT–HT) method [9–11]. However, as briefly outlined above, competitive growth of InSb on GaAs inevitably requires a rather-thick buffer layer or a specific procedure in order to overcome the strain difference between them. In the case of the LT–HT method, as well as the inconvenient change in growth temperature for the sequential growths of LT- and HT-layers of InSb, relatively-longer process time for the initial growth of considerably thick LT-layer was also necessary. For example, to achieve the value of electron mobility over 50,000 cm^2/Vs by LT–HT method, growth of total InSb layer with a thickness greater than 2 μm was required [12].

On the other hand, since InAs is a material whose lattice parameter is located midway between those of GaAs and InSb, use of InAs as an intermediate layer will be the most suitable choice for the growth of InSb on GaAs. Furthermore, it is of particular interest that appropriate quantum dots (QDs) have been utilized as a defect-reduction layer (DRL), including the use of GaN–QD-buffer for the growth of GaN on sapphire [13] and that of InAs QDs for the fabrication of a 1.5 μm-laser device on GaAs [14] or for the growth of InSb on Si [15]. Hence, for the present case of InSb growth on GaAs substrate, similar application of InAs QDs as a DRL seems to be a viable alternative to the use of thick buffer layer or complicated growth-processes.

We have, therefore, attempted the insertion of an intermediate layer of InAs QDs between the GaAs substrate and the InSb layer with the goal

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toward the growth of relatively-defect-free, high-quality layers of InSb. In particular, the layer-thickness dependence of morphological, structural and transport properties of the InSb film is investigated to elucidate the role of intermediate, InAs-QD layer as a defect-reducer.

2. Experiments

In this study, InSb layer was grown on a semi-insulating, (001) GaAs wafer using the solid-source, molecular-beam-epitaxy system (Riber compact 21-E model). Fig. 1(a) shows the schematic diagram of the growth-structure used in this study. The oxide layer on the surface of GaAs was first removed by heating the substrate at temperature exceeding 600 °C under As_2 atmosphere. Then, upon changing the substrate temperature down to 580 °C, a buffer layer of GaAs was deposited to a thickness of ~100 nm. The temperature of the substrate was subsequently lowered to 480 °C for the growth of InAs QDs with a thickness corresponding to about 3 mono-layers using the Stranski–Krastanow mode, followed by an annealing for 1 min. The successive formations of GaAs buffer and InAs QDs were monitored by the change of reflection-high-energy-electron-diffraction (RHEED) pattern from (2×4) to spots due to QDs upon switching the injection source from Ga to In.

As a final step, the substrate was cooled down to 400 °C and the growth of InSb layer was carried out. During the growth of InSb layer under Sb_2 ambient, RHEED pattern was seen to change from the initial dotted (blurry)-pattern to a streaky one at ~1 min and, finally, into (1×3) upon eventual growth of InSb films with thicknesses in the range of 0.16–2.60 μm.

In the growth process, standard Knudsen cells were used for In and Ga sources while valved-crackers of Riber and Veeco being used for As and Sb sources, respectively. Both tips of the crackers were heated at 900 °C to provide As_2- and Sb_2-mode fluxes. The growth rates of GaAs buffer, InAs QDs, and InSb layer were 0.14 nm/s, 0.14 nm/s, and 0.48 nm/s, respectively. The respective beam-equivalent-pressures (BEPs) for As_2 and Sb_2 fluxes were 1.2×10^{-6} Torr and 1.5×10^{-6} Torr.

On the other hand, the proper formation of InAs QDs was also confirmed by atomic-force-microscopy (AFM) image shown in Fig. 1(b). The AFM measurements using XE-100 model of PSIA were carried out in the contact-mode with CSC12 cantilever. The analysis of AFM image shows that the density of QDs is around 6.0×10^{10}/cm^2 with the average height and width of 4.9 ± 1.5 nm and 37.9 ± 6.4 nm, respectively.

It should be noted that in the present study we have used the optimized conditions for successive growths of InAs QDs and InSb film. The results of the parametrical study on the effect of variations in the growth conditions such as the size, density and formation scheme of InAs QDs as well as the changes in conditions for InSb-deposition upon the properties of InSb films will appear in our next paper.

The room-temperature electron mobilities of InSb films grown in this study were measured using 6-contacts, 64 μm × 80 μm Hall-pattern with physical property measurement system. The difference between the measured values for the Hall bars oriented along [110] and [1–10] directions was found to be negligible.

Raman scattering measurements were performed using the 514.5-nm excitation wavelength of Ar-ion laser at room temperature in a backscattering geometry along the growth direction of the samples. Scattered light from the sample was dispersed through a spectrometer equipped with a 2400 grooves/mm grating, and recorded using a liquid-nitrogen cooled charge-coupled device detector. The spectrometer was calibrated using the known peak values of a mercury light source.

The cross-sectional structure and morphology of the samples, prepared by ion-milling process, were analyzed by using transmis sion-electron-microscopy (TEM) and high-resolution-scanning TEM (HR-STEM) of Titan 80-300 model (with monochromatic and Cs-corrected probe) operating at 300 keV.

3. Results and discussion

In Fig. 2(a), 10 μm × 10 μm AFM images are shown for InSb films grown at T_g of 400 °C and under BEP of 1.5×10^{-6} Torr with layer

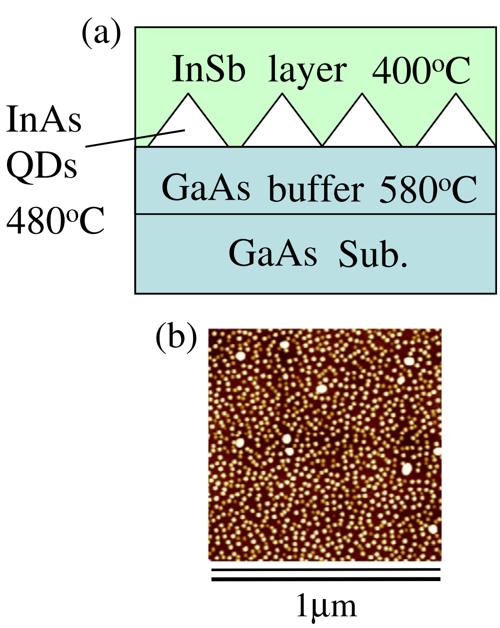

Fig. 1. (a) Schematic diagram of the growth structure, (b) 1 μm × 1 μm AFM image of InAs QDs on GaAs.

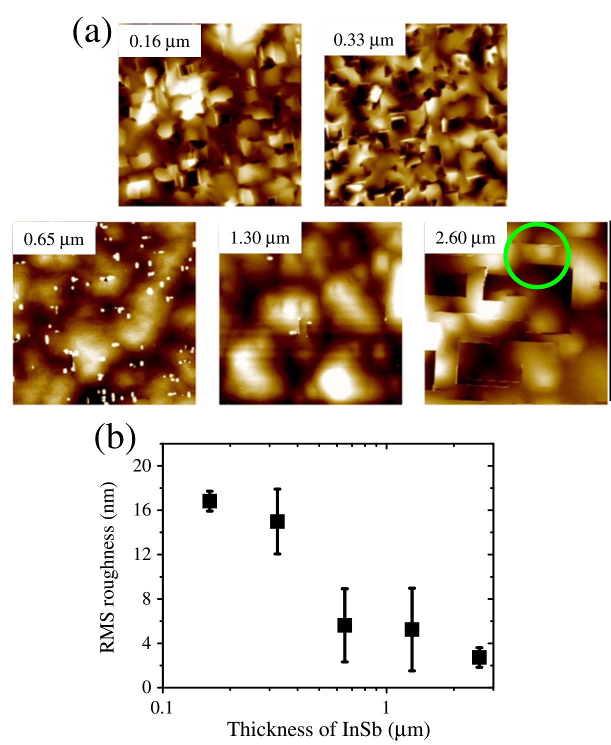

Fig. 2. (a) 10 μm × 10 μm AFM images of InSb layers with thicknesses in the range of 0.16–2.60 μm. (b) Plot of RMS roughness deduced from AFM images in (a) as a function of InSb-layer thickness. All InSb films are grown at T_g of 400 °C and under BEP of 1.5×10^{-6} Torr.