Formation of InSb Quantum Dots in a GaSb Matrix

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InSb nanoislands in a GaSb matrix have been fabricated and their structural and luminescence properties have been studied. The deposition of ~1.7 monolayers of InSb in a GaSb(100) matrix has been found by transmission electron microscopy to result in a 2D-3D growth mode transition and a formation of small InSb quantum dots (QDs) with lateral sizes of ~10 nm. Bright luminescence due to these QDs is observed. Stacking of the QDs results in a formation of vertical-coupled QD planes and leads to a long wavelength shift of photoluminescence line associated with the QDs. Increase in the InSb layer thickness above ~2 monolayers results in formation of 3D dislocated InSb islands with a lateral size above 60 nm and the dramatic drop of photoluminescence intensity.

Key words: InSb, nano-islands, photoluminescence, quantum dots

INTRODUCTION

Effect of spontaneous morphological transformation of a thin strained layer to array of nanoscale islands allows the *in-situ* fabrication of quantum dots (QDs).[1–5] It was shown that self-organized QDs formed by a deposition of (In,Ga)As layer on a (Al,Ga)As (100) surface are dislocation-free and exhibit high size uniformity (~10%). Using the array of QDs, it is possible to create an injection laser with ultra-high material gain and temperature stability of the threshold current.[6–8] The main driving force for the QD formation is the elastic relaxation of strain caused by lattice mismatch between the deposited material and the substrate. Spontaneous formation of QDs have been observed for different systems (Ge/Si,[9,10] InP/GaAs[11,12]), (Al,Ga)Sb/GaAs[13,14]), InSb/InP[15]).The reason to apply the QD concept to narrow gap semiconductors is to solve the problem of low gain caused by poor overlap of electron and hole states in k-space at elevated temperatures in narrow gap bulk materials and quantum wells which are caused by very small electron mass. QDs allow the lifting of the k-selection rule and result in a marked increase in material gain.

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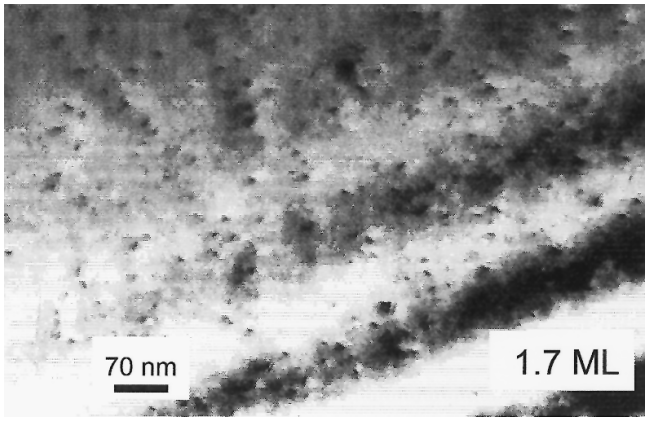
In this paper, InSb QD formation on GaSb (100) surface (lattice mismatch for this system is about 6%) has been studied.

In the work by Bertru et al.,[16] based on atomic force microscopy (AFM) studies, it was proposed that the growth of InSb on a GaSb (100) surface occurs in the Stranski-Krastanow growth mode with initial formation of an InSb wetting layer, followed by formation of 3D macroscopic islands with a lateral size of about 4000Å. In contrast, we show that it is possible to fabricate nanoscale coherent InSb islands. Furthermore, we have shown the possibility of fabricating coupled InSb-GaSb QDs and demonstrated tuning of the QD photoluminescence (PL) line position over a wide energy range.

SAMPLE GROWTH

The samples investigated were grown on the GaSb (100) substrate by conventional solid source molecular beam epitaxy (MBE) using a Riber-32P (MBE) machine. InSb layers with different average thickness were inserted in central part of a GaSb layer and confined at both sides by five-period 20Å AlSb-20Å GaSb superlattices. The dots were covered by GaSb immediately after formation. The initial substrate temperature was 500°C. It was lowered to 420°C prior



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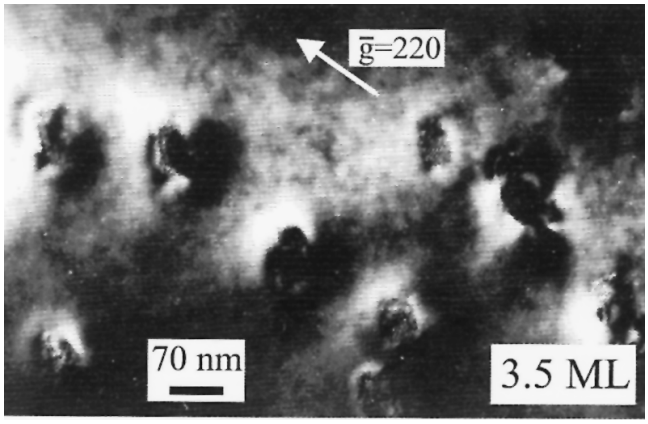

b

Fig. 1. Plan view TEM micrograph of structure with 1.7 ML (a) and with 3.5 ML, and (b) InSb layers in a GaSb matrix.

to deposition of the InSb layer and was kept at this temperature during the deposition of the rest of the structure. Transmission electron microscopy (TEM) studies were carried out using a Philips EM420 microscope operated at an electron accelerating voltage of 100 kV. TEM specimens were thinned to electron transparency in plan-view configuration using a sequential mechanical dimpling, polishing, and chemical etching. For AFM imaging, the reference samples without the GaSb/AlSb cover were used. Photoluminescence was excited with a semiconductor laser with a photon energy 1.52 eV and an output power of 300 W/cm^2. PL was detected by a cooled InSb photodiode.

RESULTS

The transformation of InSb layer with the QD formation takes place at the deposition of InSb layer with effective thickness above ~1.7 monolayer (ML).[16] Formation of very large and, indeed, dislocated clusters have been observed. In our case, samples overgrown with GaSb has been studied by TEM and a completely different picture was observed. Figure 1a shows a TEM image of a sample with 1.7 ML thick InSb layer. No mesoscopic QDs are observed. At the same time, a lot of small InSb islands are found. The islands have exhibit a dash-like contrast and are aligned mostly along two in-plane directions. The

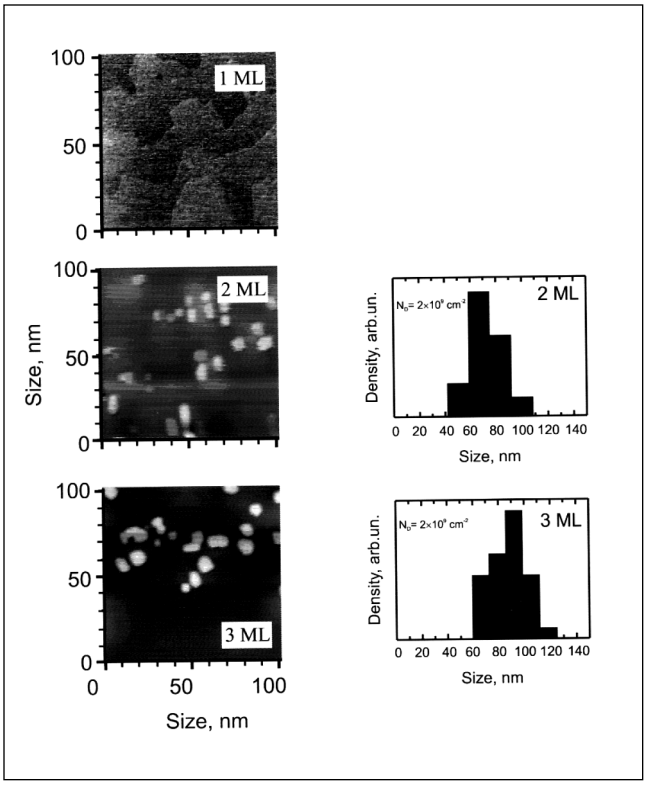

Fig. 2. AFM images of the QDs for structure with different thickness of InSb layer in GaSb matrix.

length of the islands is estimated to be around 10 nm and their density is about ~6×10^{10} cm^{-2}. Large islands elongated along the [3, $\bar{1}$,0] direction were observed by TEM in a sample with 3.5 ML thick InSb layer (Fig. 1b). These islands are too large to form coherent insertions and are dislocated. The islands have sizes within the range of 60–100 nm and their composition was estimated to be close to pure InSb according to the measured Moiré fringe spacing.

AFM images of the investigated sample with InSb coverages cooled immediately after deposition of the QD sheet are shown in Fig. 2. As can be seen from the image, deposition of ~1 ML InSb results in formation of flat interface. Increase in the InSb layer thickness up to ~2 ML results in formation of 3D islands having lateral sizes of about ~80 nm and height less than ~12 nm and are characterized by a relatively large size dispersion. The density of the islands is about 2×10^9 cm^{-2}. Future increase in the InSb layer thickness to 3 ML leads to increase in sizes of the QDs keeping constant the QD density. For deposition thickness above 1.7–2 ML InSb, there is a sharp transition to formation of large dislocated islands.

A PL spectrum at 77K of the sample where no InSb insertion was introduced contains only one line associated with exciton recombination in the bulk-like GaSb epilayer, as is seen in Fig. 3. The insertion of an InSb layer with an effective thickness of 0.5 ML results in an appearance of a new line (I) with maximum at ~0.79 eV and width of ~8 meV. An increase in the thickness of InSb deposition layer to 1 ML leads to long wavelength shift of PL line maximum. This shift

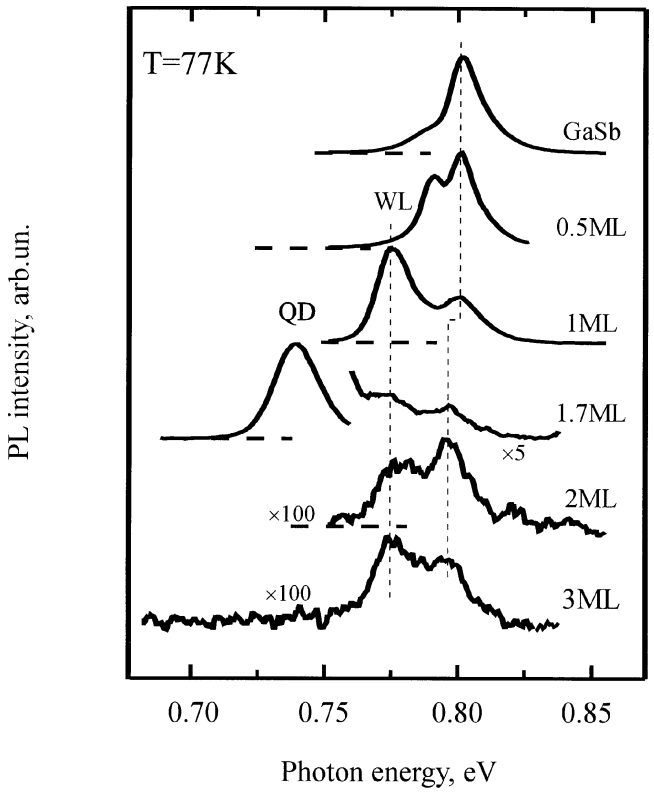

Fig. 3. PL spectra of the structures with InSb layer of different thickness at temperature of 77K.

indicates that the deposition of InSb layer with effective thickness below 1 ML results in, indeed, formation of nanoscale 2 D InSb islands rather then mesoscopic clusters. Lateral confinement of carriers localized in the islands induces a decrease in localization energy and shifts the optical transition energy with respect to one for 1 ML InSb insertion. Similar formation of elongated 1 ML-height nanoscale islands by submonolayer deposition was observed for InAs layer on GaAs (100) surface.[17]

Further increase in the average InSb thickness from 1 to 1.7 ML leads to a long wavelength shift of PL and to an increase in the PL line width. Taking into account the TEM data obtained for the 1.7 ML InSb sample, one may conclude that this PL behavior is associated with the radiative recombination of excitons via the locally formed InSb QDs. QD size and shape dispersion results in the increase of PL line width. Besides the QD line, the PL spectrum contains a short wavelength line (WL). The position of the WL line is practically coincident with the PL line in the spectrum of the sample with 1 ML InSb layer. Therefore, this line is likely associated with a recombination processes via the regions with two-dimensional 1 ML thickness InSb coverage. From this observation, one can estimate the effective thickness of the wetting layer as being about 1 ML. We believe that stacking of the small QDs is very promising for creation of a QD superlattice. A PL spectrum of the structure with three sheets of vertically coupled InSb QDs separated by 5 ML GaSb spacers is shown in Fig. 4. It is clearly seen that the stacking of QDs leads to significant long

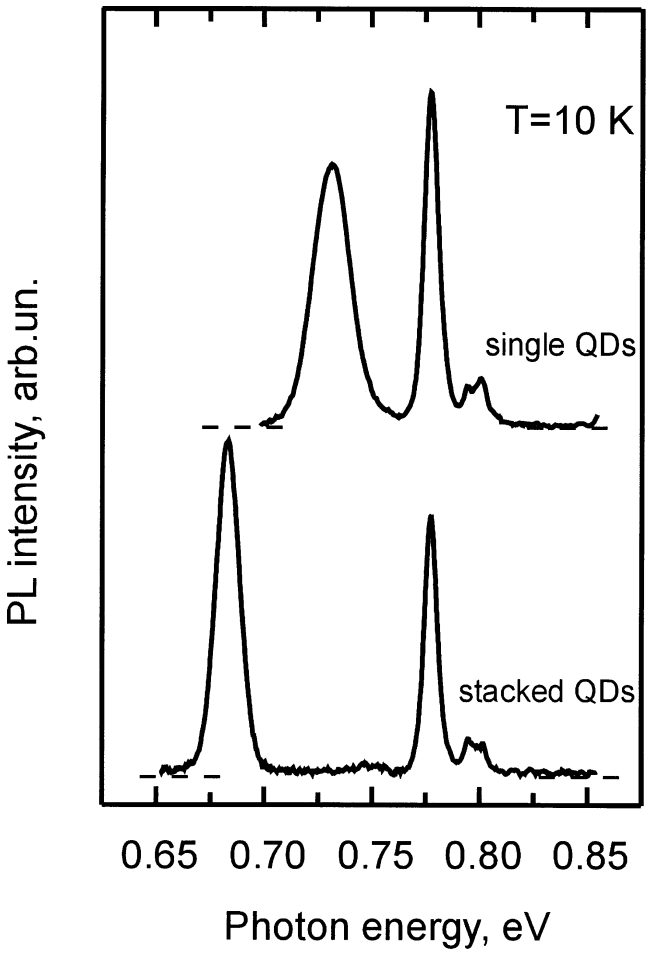

Fig. 4. PL spectra of the samples with one QD plane and three QD planes separated by 5 ML GaSb barriers.

wavelength shift of the PL line associated with the recombination via QD states.

Increase in the InSb layer thickness above 2 ML causes a dramatic decrease in PL intensity (Fig. 3). Moreover, the QD line disappears from the PL spectra and only high energy lines remain. This PL behavior is in agreement with the TEM data (Fig. 1b) which show formation of dislocated islands for corresponding average deposited thickness.

CONCLUSIONS

To conclude, we have shown that uniform and coherent InSb islands can be formed in a GaSb matrix for below 2 ML InSb deposition. These islands with a dash-like shape and a length of 10 nm exhibit bright luminescence. By vertically correlated growth of the several sheets of QDs separated by 5 ML thick GaSb layers, we fabricated vertically coupled InSb QDs and shift the PL wavelength further to the infrared spectral range. According to our preliminary results, vertically coupled InSb-GaSb QDs can be very advantageous for light emitting devices operating in the 2–4 μm range.

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