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Long-wavelength infrared photoluminescence from InGaSb/InAs quantum dots

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ABSTRACT

We study the growth of self-assembled InGaSb/InAs quantum dots (QDs) and investigate how gallium can be used to reduce the optical transition energy in the InSb QD system. InGaSb QDs were grown on InAs (001) substrates by metal-organic vapor-phase epitaxy (MOVPE) and the material was characterized by photoluminescence (PL) measurements. A PL peak wavelength is demonstrated beyond 8 μm at 77 K, which is significantly longer than what has been reported for InSb QDs. The results suggest that InGaSb QDs can be grown at a larger size than InSb QDs leading to reduced confinement in the QDs.

1. Introduction

Self-assembled InSb quantum dots (QDs) have recently attracted interest for use as the active material in light-emitting diodes (LEDs), lasers and photodetectors in the 3–5 μm mid-wavelength infrared (MWIR) band [1–5]. With their type-III band alignment to the InAs single crystal they provide a rather unique platform that can allow for low-energy optical transitions in the III/V material system [6]. As discussed by Yeap et al. small QDs with strong confinement effects are observed in the material resulting in bound hole states in a type-II configuration with transition energies in the MWIR band [7]. We recently proposed and investigated a method to increase the dot size and consequently extend the wavelength by adding gallium to the QDs [8]. In this paper, we extend this investigation and report on the growth and optical properties of InGaSb QDs grown on InAs (001) substrates by metal-organic vapor-phase epitaxy (MOVPE) under various conditions. Photoluminescence (PL) is demonstrated in a series of single-QD-layer test structures with peak wavelengths in the interval 4.5–8.5 μm and emission which extends up to 12 μm at 77 K. This is significantly longer than what has been reported for InSb QDs and the result is interpreted as an effect of reduced confinement in the InGaSb QDs.

2. Theory

The InSb/InAs and GaSb/InAs heterojunctions both have a type-III broken gap band alignment and are suitable for generating low-energy optical transitions in the III–V material system [6]. The ternary alloy InGaSb is exceptional in the sense that the compressive strain can be varied between 7% and 0.6% while still retaining the type-III band alignment to InAs. This property can be a useful tool for tuning the growth of QDs with respect to size since the strain is an important parameter for the QD growth mechanism and can act to limit the growth of QDs [9]. We here estimate the composition-dependent band alignment in the InGaSb/InAs system by calculations based on the formalism of deformation potential theory for the case of biaxially strained bulk material grown on a (001) crystal plane as described by Gustafsson et al. [10]. The calculation is done using tabulated parameters from Ref. [11] and a linear interpolation of the ternary material valence band offsets and is presented in Fig. 1.

3. Experimental details

Single QD-layer samples for PL measurements were grown on undoped (001) InAs substrates ($1–3 \times 10^{16}$ cm^{-3} *n*-type carrier concentration) in the temperature range 470–530 °C using an Aixtron 200/4 horizontal MOVPE reactor system with hydrogen as carrier gas. The total reactor pressure and gas flow was 100 mbar and 15 standard liters per minute respectively. Trimethylindium (TMIn), triethylgallium (TEGa), trimethylstibine (TMSb) and arsine (AsH_3) were used as precursors.

The samples consist of the following epitaxial layers: a 200 nm InAs buffer, an InGaSb QD layer with a nominal thin film thickness of 8–16 ML and finally a 50 nm InAs capping layer, grown with the V/III ratios 150, 0.6–1.6, and 75 respectively. The InAs buffer layer growth rate was calibrated to 0.37 nm/s and 0.39 nm/s for the growth temperatures 490 °C and 530 °C respectively, using X-ray

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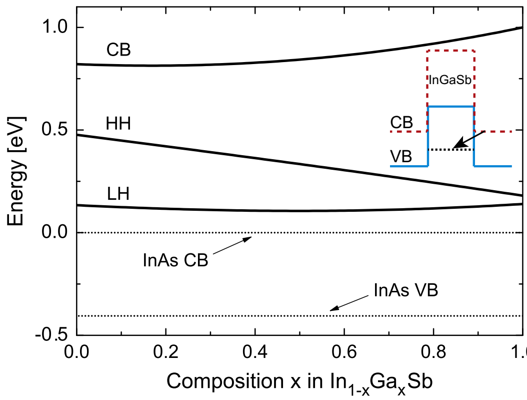

Fig. 1. Calculated band energies of InGaSb biaxially strained to InAs (001) at 77 K. The inset schematically indicates the expected type-II recombination path for a InGaSb/InAs quantum structure with a bound state in the valence band.

diffractrometry (XRD). Similarly, the growth rate for the capping layer was measured to 0.20 nm/s. In addition, growth of relaxed bulk InSb material at 490 °C was used to estimate the growth rate of the InGaSb QD layers to 0.06 nm/s. Notably, the referred InGaSb compositions are based on the nominal molar input flow ratios of the constituent group III atoms to the reactor chamber. Here, XRD analysis was done on lowly strained InGaSb quantum well (QW) material with indications that the gallium incorporation is slightly lower than reflected by the nominal molar input flow ratio.

The PL measurements were done on samples cooled to 77 K using a Cobolt Samba diode-pumped solid-state laser emitting at 532 nm as excitation source. A Bruker V70 Fourier transform infrared (FTIR) spectrometer, with an installed 16 μm cut-off wavelength HgCdTe detector and step-scan functionality, was used to measure the spectral emission.

4. Results and discussion

Fig. 2 shows the measured PL from a series of InGaSb QD samples grown at 470 °C with different QD-layer gallium content in Fig. 2a and different QD-layer thickness in Fig. 2b. In these samples the peak at 3 μm can be assigned to PL from recombination over the InAs bandgap whereas the shoulder towards longer wavelength can be related to shallow levels in the InAs bandgap as discussed by Fisher and Krier [12]. The peaks observed at longer wavelengths are attributed to QD type-II transitions. We observe shorter emission wavelengths for samples with higher gallium contents which indicates the effect of a larger bandgap and/or smaller dot sizes where an increase in the type-II transition energy is expected. We furthermore observe that the peak PL wavelength increases when the QD layer thickness is increased from 8 to 12 ML. However, when the QD layer thickness is further increased, there is no significant shift in the PL peak wavelength but the linewidth increases, suggesting that an unevenly distributed QD growth occurs which might indicate the initial onset of non-elastic strain relaxation effects in the QD layers.

The PL measured from a series of InGaSb QD samples grown at 510 °C with different QD-layer gallium content and different QD-layer thickness is presented in Fig. 3a and b, respectively. As in the previous case, the peaks at 3 μm are attributed to InAs while the peaks at longer wavelengths are associated with QD type-II transitions. In Fig. 3a we observe that the peak emission wavelength increases when the gallium content is increased from 20% to 40%. This indicates an increase of the QD sizes due to the reduced strain and/or altered growth conditions due to the addition of gallium in the QD layer. Moreover, we see in Fig. 3b that the peak wavelength can be extended by increasing the QD layer thickness from 8 ML to 14 ML after which no further shift is observed. The emission intensity decreases drastically in the sample with 16 ML QD layer thickness, presumably due to plastic relaxation and defect-mediated non-radiative recombination.

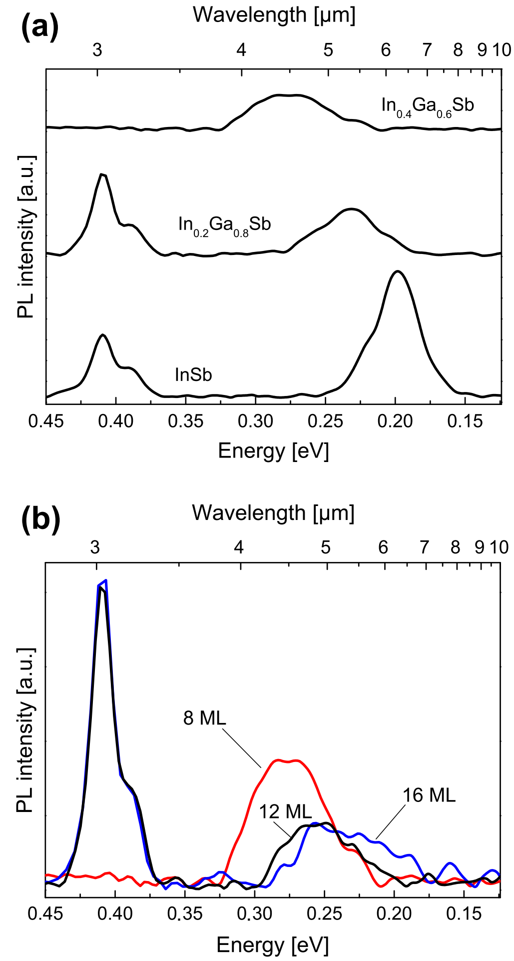

Fig. 2. PL measured at 77 K in samples grown at 470 °C with a V/III ratio of 0.8 containing (a) In(Ga)Sb QD layers with varied composition and a thickness of 8 ML and (b) a $In_{0.6}Ga_{0.4}Sb$ QD layers with varied thickness. For unknown reasons a very weak signal from the InAs bandgap was measured in the 8 ML In0.6Ga0.4Sb QD sample. The laser pumping power was 36 mW except in the case for the 8 ML $In_{0.4}Ga_{0.6}Sb$ QD layer sample in which it was 67 mW.

Fig. 4 shows the measured PL from two samples with different gallium content grown at 530 °C. Here we observe QD-related PL peaks at 5.1 and 7.4 μm for the sample with 20% and 40% gallium, respectively. Notably, the PL peak of the 40% Ga QD-layer sample has a significant redshift as compared to the corresponding samples grown at 470 °C and 510 °C (Figs. 2b and 3a). This suggests that the growth temperature has an important influence on the growth mechanism of the InGaSb QDs and considering the expected bandgap increase with increased gallium concentration it is interpreted that gallium can promote the growth of larger QDs.

The PL from $In_{0.6}Ga_{0.4}Sb$ QD layer samples grown at different V/III ratios at 530 °C is presented in Fig. 5. As in the previous figures, PL peaks corresponding to the InAs bandgap are observed at 3 μm whereas the peaks in the range 6–8.1 μm are attributed to QD-layer PL of type-II character. In Fig. 5 it is furthermore observed that the QD PL peak wavelength and intensity varies as a function of V/III ratio, with a PL peak wavelength maximum of 8.1 μm for a V/III ratio of 1.2.

In Fig. 6 the PL from InGaSb single QD layer samples with varied thickness and composition grown at a V/III ratio of 1.2 is shown.