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GaAs in GaSb: a new type of heterostructure emitting at 2 μm wavelength

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We report growth as well as optical and structural studies of a new type of a GaAs/GaSb heterostructure, with 1–3 monolayer thick GaAs layers embedded within unstrained GaSb. In such structures the GaAs layer is under tensile stress, in contrast to the situation in which self-organized growth of quantum dots is commonly observed. The structure emits light in the 2 μm wavelength range. The emission characteristics are explained by a combination of quantum confinement effects and localization on nanoscale potential fluctuations.

Lattice mismatched semiconductor systems such as InAs/GaAs, (Ga,In,Al)Sb/GaAs, InAs/InP and InP/InGaP under appropriate conditions can form self-organized quantum dots (QDs).[1–5] QDs have recently attracted considerable interest due to their rich physics and optoelectronic applications, especially in prospective laser sources.[6] Most of the published works concern the situation when a thin strained layer is inserted in a matrix of an unstrained wider band-gap semiconductor with a smaller lattice constant. Quantum well (QW) and QD structures with different types of band offsets have been studied, including both type I[1,4,5] and type II[2,3]) band line-ups. The common feature of all these heterostructures is that the narrow band-gap material is under compressive strain. Furthermore, the surrounding matrix material is usually a relatively wide band-gap compound such as GaAs or InP. As a result, the possible operating wavelength of such QD lasers is shorter than 1.55 μm. The potential advantage of type II QDs for the suppression of the Auger recombination channels make them particularly promising for light emission in the near- and mid-IR region, particularly above 2 μm, where conventional types of semiconductor lasers meet severe problems due to Auger processes.[7] It is thus important to be able to extend the emission wavelength range of type II QD heterostructures to cover the region above 2 μm.

In this paper we demonstrate a new type of a lattice-mismatched heterostructure characterized by intense photoluminescence (PL) in the spectral range of 1.7–2.3 μm at low temperatures. The samples contain ultrathin GaAs layers grown pseudomorphically in a GaSb matrix. The GaAs thickness was varied between 1 and 3 monolayers (MLs), within a typical range for the formation of self-organized QDs driven by the 7% lattice mismatch between GaAs and GaSb.[2] In contrast to the systems studied previously, the GaAs layer inserted into GaSb is under tensile stress and it can serve as a model for experimental studies of such systems, particularly that in the reversed structures (GaSb in GaAs) the self-organized QD formation is reasonably well documented.[2,3] To the best of our knowledge, the only work concerned with the emission properties of comparable structures was reported recently by Glaser *et al.*,[8] who observed a strong emission from AlAs monolayers in AlSb.

Both single GaAs/GaSb structures and a superlattice (SL) were grown by molecular beam epitaxy (MBE) on GaSb(001) substrates at a constant temperature of 520 °C. Conventional solid source effusion cells were used to produce Ga, Al and As_4 fluxes, whereas an Sb_2 flux was supplied from a RB-075-Sb cracking cell. The single structures contain a 0.5 μm thick GaSb buffer layer followed by a 0.3 μm GaSb layer with an ultrafine GaAs layer of varying thickness inserted in the centre and confined by 30 nm $Al_{0.5}Ga_{0.5}Sb$ barriers on both sides. The GaAs layer is grown under (2 × 4)As-stabilized conditions with a 10 s growth interruption before and after to avoid As and Sb flux intermixing. The growth time of GaAs was varied between 2 and 5 s in different samples, which corresponds to the intended GaAs thickness of between 1.2 and 3 MLs, respectively. Several samples were grown without substrate rotation to ensure a uniform variation of the GaAs thickness along the substrate surface. As a result, the available GaAs thicknesses range from 0.8 to 3.5 ML. A ten-period 1.2 ML-GaAs/4 nm-GaSb SL sample was grown under the same conditions. The PL experiments were performed in a closed-cycle He cryostat or a liquid nitrogen cryostat, in the temperature range from 8 to 300 K. CW laser diodes emitting either at 0.8 or at 1.3 μm were used for the PL excitation.

The SL structure was characterized by X-ray diffraction (XRD). Fig. 1 shows a (004) θ–2θ XRD rocking curve measured in the SL sample. Both a zero-order SL reflection and higher-order satellites are prominent, providing an estimate of the SL period of 4.3 nm and nominal thickness of GaAs layers within the SL of 1.2 ML, in good agreement with design specifications. The simulation of the rocking curve was performed according to semi-kinematical approximation in which a scattering kinematical amplitude from the layers is added to the dynamical diffraction from a substrate. The model used is described in detail elsewhere.[9] In particular, the simulation of the SL XRD rocking curve in Fig. 1 yields an estimate of the average broadening of the layers along the growth direction, resulting *e.g.* from the effects of inter-diffusion and segregation during MBE growth.[10] This effect is observed through a fast decrease of the relative intensities of the SL satellites with the satellite order. The obtained broadening of the GaAs layers in our sample is 4–5 ML. In such case the formation of ideal abrupt GaAs QWs can be ruled out, as well as the formation of a dense array of thick 3-dimensional (3D) QDs. Rather, the XRD data describe a SL built from GaAsSb layers, with spatial non-uniformities due to the nanoscale alloy composition or thickness fluctuations.

A set of the samples was studied by transmission electron

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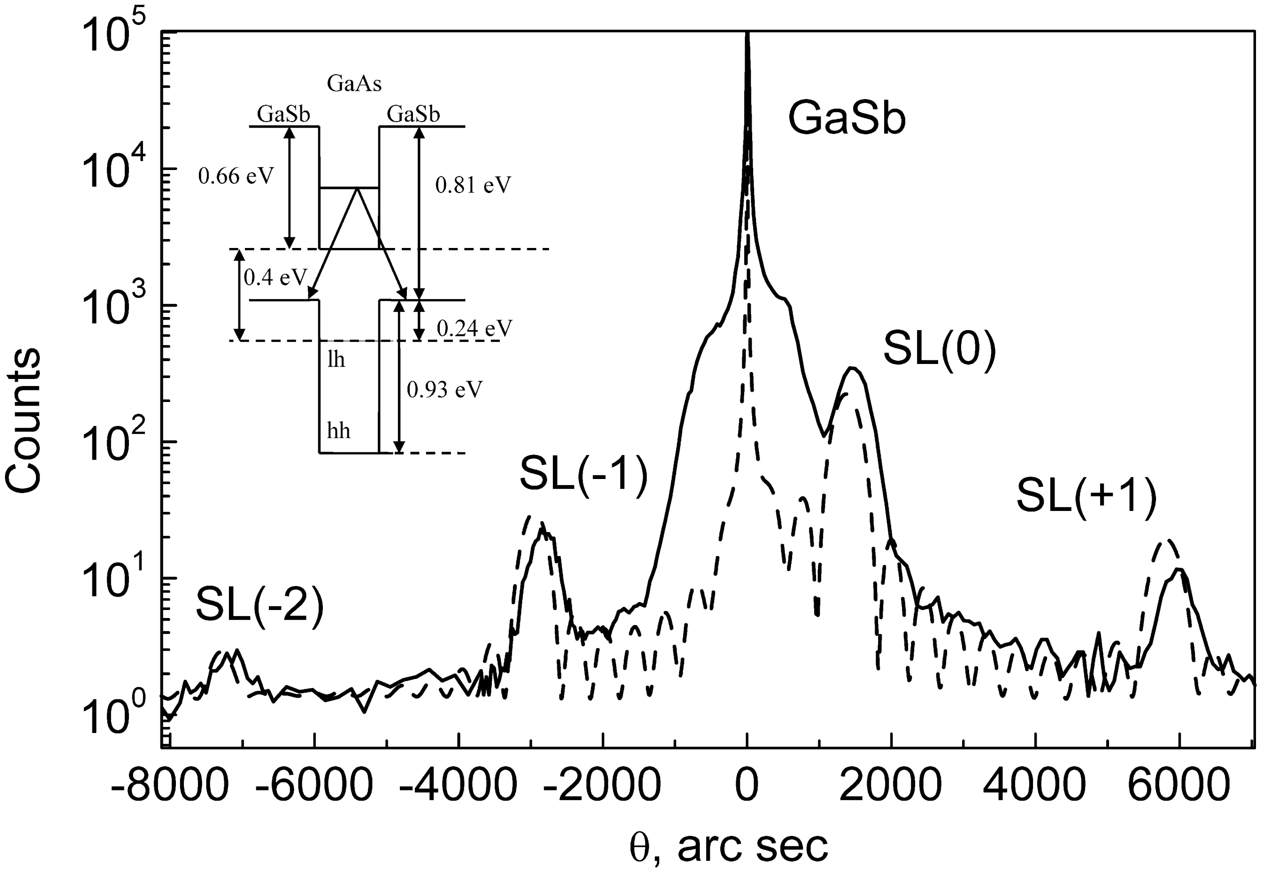

Fig. 1 XRD θ–2θ rocking curves for the SL sample: experimental (solid curve) and simulated using with a Gaussian-like broadened distribution of As atoms with 4.5 ML FWHM (dashed curve). The inset shows the schematic diagram of band line-ups and optical transitions for tensile strained GaAs in unstrained GaSb.

microscopy (TEM) in cross-section geometry using a Philips EM-420 microscope at 100 kV. It is well known that (200) reflections are chemically sensitive for face-centered cubic materials and can be used to detect composition variations.[11] Fig. 2 shows dark-field images of the single-layer GaAs/GaSb samples of different intended GaAs thickness with all images obtained under the same conditions. A transformation of the intrinsic morphology with the increase in the GaAs insertion thickness is clearly evident. The image of the submonolayer insertion shows as a dark stripe without any traces of clustering (Fig. 2a). Upon increasing the thickness, the image reveals the formation of extended islands showing a noticeable strain field (Fig. 2b). The sizes of these islands are raised in the growth direction with further increase in the GaAs thickness that is seen in Fig. 2c as the enlargement of dark haloes near the islands. The lateral size and the height of the islands are estimated as about 10 and 3 nm, respectively. Finally, one can see the extended defects near some islands that evidences the onset of a relaxation process in the structure upon 2 MLGaAs insertion (Fig. 2d).

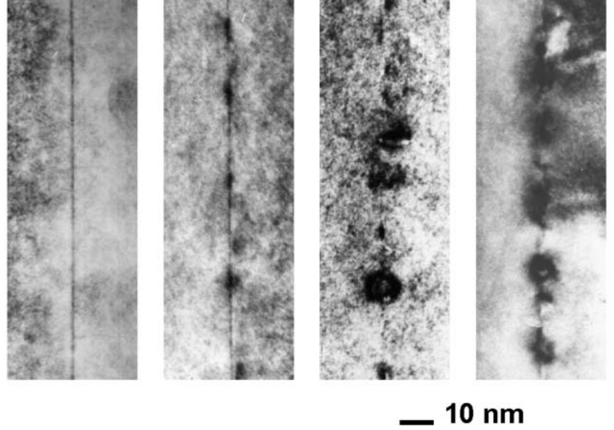

Fig. 2 Cross-section g[002] dark-field TEM images of single-layer GaAs/GaSb samples with different nominal thicknesses of a GaAs layer: (a) 0.8 ML; (b) 1.2 ML; (c) 1.5 ML; (d) 2.0 ML.

The structures with thin GaAs layers exhibit PL at low temperatures. Fig. 3 displays the PL spectra measured at 80 K at low excitation conditions (1 W cm^{-2}) in the single layer samples with varying GaAs thickness. All the spectra show a peak at 0.8 eV due to the band-to-band transitions in bulk

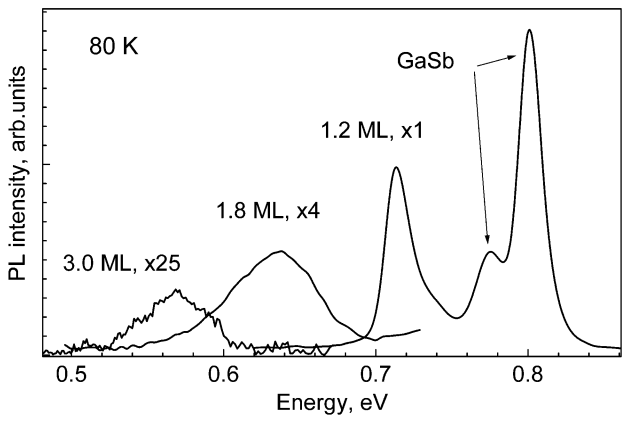

Fig. 3 Low excitation PL spectra in single-layer GaAs/GaSb samples with different nominal thicknesses of a GaAs layer.

GaSb, accompanied by a 0.775 eV peak attributed to donor–deep native acceptor recombination, and another peak, with the peak energy related to the GaAs thickness as deduced from the XRD measurements and extrapolating the GaAs deposition time. As the thickness increases from 1.2 to about 3.5 ML the peak shifts from 1.7 to 2.3 μm. Simultaneously, the peak undergoes some broadening, and its maximum intensity progressively decreases. The integrated intensity remains almost constant up to the nominal thickness of about 2–2.5 ML, and then it abruptly decreases in thicker layers.

The emission wavelength of the GaAs/GaSb structures remains well below the GaSb band gap for any GaAs thickness, which is consistent with the expected type II band line up. For the fully relaxed case, the valence band offset at the GaAs/GaSb interface is estimated as 0.8 eV, while the conduction band offset is 0.1 eV,[2] with electrons confined in GaAs and holes in GaSb. The inset in Fig. 1 demonstrates the expected band offsets for a pseudomorphic GaAs/GaSb QW structure, as estimated using the work of van der Walle.[12] A strong biaxial stress induced by the 7% lattice mismatch enhances the conduction band offset up to 0.66 eV and decreases the valence band offset down to 0.24 eV. Note that the lowest hole subband in a tensile stressed GaAs/GaSb QW is the light-hole one. The band line-ups are of type II and are independent of the degree of strain relaxation in the structure.

Pseudomorphic growth is expected for the GaAs layer with a thickness below a critical value. For a GaSb/GaAs heterostructure the critical thickness was obtained theoretically as 7 atomic layers.[13] This estimation is in good agreement with the experimentally determined threshold of the Stranski–Krastanov growth, which is between 0.75 and 1.2 nm of GaSb.[2] A similar critical thickness is anticipated for our samples, because the lattice mismatch, while being of different sign, has the same absolute value. However, both the fast decrease in the PL intensity (see Fig. 1) and the formation of defects (Fig. 3d) in the GaAs layers thicker than 2 ML (0.6 nm) suggest that for a tensile stressed GaAs/GaSb insertion the critical thickness is somewhat smaller than for a compressive stressed GaSb/GaAs structure.

At the low excitation power density used in these experiments, we were unable to find any conclusive evidence of two PL bands coming from the array of QDs and the wetting layer (WL), as commonly reported in the InAs/GaAs and GaSb/GaAs systems, confirming the absence of the conventional QD/WL system in our films. A realistic model of the structure geometry assumes in-plane inhomogeneity of the GaAs layers, *i.e.* the formation of islands, which are either thicker or enriched by As as compared to the average layer parameters. To check this idea we performed continuous wave (cw) PL measurements at high-power excitation. The rationale was that, at low excitation power densities, the cw PL reflects the recombination of thermalised carriers, *i.e.* of electrons and holes localised in the minima of the potential fluctuations. At larger excitation powers, the states localized in these fluctuations can be filled and/or screened by carriers, thus making it possible to detect recombination processes involving higher energy electron and hole states. Fig. 4 shows the PL spectra measured at different excitation power densities in a sample containing a single 1.2 ML thick GaAs layer. A single nearly symmetric low-energy emission band is seen at relatively weak excitation levels. With an increase in power we observe a peak shift to longer wavelengths due to sample heating, as also confirmed by the similar shift of the GaSb barrier related peak. Furthermore, at higher excitation levels, a short wavelength shoulder appears on the main band. This shoulder evolves with further power increase until it emerges as a second overlapping emission band with a comparable intensity. We interpret the observed two bands as due to lateral inhomogeneities within the GaAsSb alloy layer. In this case the lowest PL band reflects the recombination of carriers localized within the potential minima, most likely related to the As-rich islands. The higher energy band represents the recombination of non-equilibrium 2D carriers in the surrounding QW-like layer.

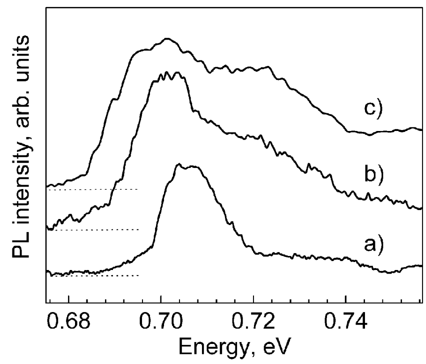

Fig. 4 PL spectra in a single-layer sample with 1.2 ML nominally thick GaAs, measured at different excitation power densities. The temperatures shown in the are estimated from the position of the bulk GaSb PL band: (a) 70 W cm^{-2}, $T = 20$ K; (b) 300 W cm^{-2}, $T = 80$ K; (c) 400 W cm^{-2}, $T = 90$ K.

In conclusion, we have presented optical and structural studies of a new type of a heterostructure combining a thin layer of GaAs in GaSb, in which GaAs is under tensile strain. The structure is characterized by a type II band offset and it emits bright PL in the spectral range of 1.7–2.3 μm, depending on the nominal thickness of the GaAs layers. The combined XRD and optical studies of a single layer and a SL with the 1.2 ML thick GaAs layers suggest an alloy character of the active region and considerable localization effects controlling the behavior of the recombining carriers.

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