InAs/GaAs QUANTUM DOTS COVERED BY GaAsSb STRAIN REDUCING LAYER

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Abstract
We have prepared and studied InAs/GaAs quantum dots (QDs) by the Metalorganic Vapour Phase Epitaxy in Stranski-Krastanow self-organized growth mode at temperature 510 °C and covered by GaAsSb strain reducing layer (SRL). We found out that for higher temperature (510 °C) the Sb incorporation into the SRL is decreased. Two explanations are suggested: first the higher strain on the apex of bigger QDs, second increased Sb surfacing on the growth surface. However, unincorporated surfacting Sb atoms also prevent QDs dissolution. Increased QD size together with decreased Sb incorporation helped us to obtain type I [1] QD structure with long wavelength emission at 1400 nm.

Keywords: Quantum dot, InAs, strain reducing layer, GaAsSb

1. INTRODUCTION
Quantum dots (QDs) are objects with all three dimensions comparable to the Bohr radius of the Wannier exciton, which are characteristic for their discrete (atomic-like) energy levels [2, 3, 4] and high electron-hole wavefunctions overlap. Self-assembled InAs QDs prepared on the GaAs substrate can evince luminescence in regions 1300 and 1550 nm, which is very promising for optoelectronic devices such as high-performance lasers and laser diodes, detectors, solar cells, single-photon sources and quantum information processors. Reaching these wavelengths is essential for achieving minimal attenuation of silica low-loss fibres and may be facilitated by covering the QDs with GaAsSb strain reducing layer (SRL). The main tasks of SRL are to reduce the strain inside QDs, to conserve their height and shape and to prevent their dissolution, which results in the demanded photoluminescence (PL) redshift. SRL also changes the electron and hole localization: depending on the amount of Sb in GaAsSb, the hole may be localized in the QD (type I heterostructure, less than about 14% of Sb [1]) or outside the QD in the SRL (type II, more than 14% of Sb); the electrons are in both cases inside the QD [5].

2. EXPERIMENTAL
All samples with QDs were prepared by low-pressure Metalorganic Vapour Phase Epitaxy (LP MOVPE) on the Aixtron 200 apparatus in Stranski-Krastanow growth mode. TMIn, TEGa, AsH\textsubscript{3}, TBAs and TESb were used as precursors. First, a semi-insulating GaAs substrate cut along the 100 plain is placed in the reactor. To remove the surface oxide layer, the substrate is heated at 700 °C and then two GaAs buffer layers are grown to improve the surface homogeneity, the first one grows at temperature 650 °C and is about 180 nm thick, the second one grows at 510 °C till the thickness of 10 nm. The prepared substrate is covered by about 2 monolayers of InAs, which has about 7% larger lattice parameter than GaAs. The strain between these two materials enables forming of QDs by self-organization. To cover the QDs, GaAsSb SRL with different Sb composition profile may be grown. The whole structure is then covered by a capping layer (usually 100 nm GaAs). During the growth the structure is being monitored by Reflectance Anisotropy Spectroscopy.
To study the structure features, PL measurements were performed by semiconductor laser (line 670 nm) and monochromator with Ge detector with standard lock-in technique at room temperature. AFM measurements were performed by NT-MDT NTEGRA Prima in tapping mode with simultaneous detection of phase signal; tip with radius 10 nm was used.

3. THEORETICAL PREDICTIONS

Using GaAs$_{1-x}$Sb$_x$ as SRL causes redshifting the PL maximum of a QD sample, because varying Sb content changes the band structure and so the carrier confinement potential (by shifting the hole localization). GaAsSb represents similar energy barrier for electrons in QDs as GaAs [6]. The band alignment depends on the amount of Sb in GaAs$_{1-x}$Sb$_x$ SRL; for small Sb concentration (x smaller than about 0.14 [1]), both electrons and holes are localized in the QD, which is called type I band alignment. The electron and hole wave functions overlap is high, which accelerates the charge carriers recombination and increases its rate. For x higher than 0.14, the formation of type-II band alignment was reported [5] with electrons in the QD and holes in the SRL (probability of finding the hole inside the QD is smaller than 20%), as a consequence of different band structure and strain distribution. The charge carriers wave functions overlap is reduced and the Coulomb energy of the electron-hole pair is decreased.

The transition between these two confinement types changes gradually and in the range around x=0.14, both types of band alignment might be achieved for the same Sb concentration just by tailoring the QD size and GaAs$_{1-x}$Sb$_x$ SRL thickness. With growing x (from 0.1 to 0.22 [1]), the emission energy red shift has been observed, more pronounced in the type II band alignment area. This is a result of smaller energetic distance between electron and hole ground states (lower QD’s ground state energy for electrons and higher for holes) as a consequence of lower strain [7]. Simultaneously, the smaller overlap of charge carriers ground state wave functions causes a low emission intensity and increases the probability of excited states emission. Higher Sb content also prevents In atoms from intermixing the capping layer more efficiently, which causes forming bigger QDs and subsequently decreases the PL peak full width at half maximum.

We used the simulation software Nextnano$^3$ to predict the transition of QD structure from type I to type II for QDs with different size but same aspect (height/width ratio) of 1/3. The GaAsSb SRL thickness of 5 nm was the same for all simulations. The results are shown in Fig. 1.

![Fig. 1 Photoluminescence energy as a function of GaAsSb SRL composition for several QD sizes. Type I / type II transition for QDs of different size is marked by grey line.](image)

To distinguish between type I and type II heterostructure, the line direction is used. The break point shows the switch between these two types. As can be seen from Fig. 1, the switch occurs for about 13% to 15%.
For smaller QDs, the heterostructure becomes type II for less Sb in GaAsSb SRL; for 2 nm QDs the threshold amount is about 13%, while for 8 nm QDs it is 15%.

Another simulation represents the dependence of the hole probability density on GaAs\(_{1-x}\)Sb\(_x\) composition. Without SRL or with small content of Sb in GaAsSb, the holes are localized in the QDs. For raising amount of Sb in SRL, the highest hole probability density moves upwards (towards the SRL) and out of the centre of QD. We can see in Fig. 2 that for 25% of Sb in GaAsSb, the holes are completely localized in SRL. Irrespective of the Sb content, the electrons are still localized inside QDs.

**Fig. 2** Hole probability density for 5 nm InAs QD with 5 nm thick GaAsSb SRL with different amount of Sb.

### 4. RESULTS AND DISCUSSION

#### 4.1 Growth temperature

One of the main parameters influencing the structure properties is the growth temperature of QDs. All the compared structures have the same growth parameters (except of the temperature) and 3 monolayers of GaAs as a capping layer, which conserves the QDs and keeps them measurable for the AFM; using a thicker capping layer would make the imaging of QDs impossible.

From AFM measurements it is obvious that for higher growth temperature the resulting QDs are bigger (in both lateral dimension and height), as Fig. 3 proves. For 470 °C, QDs are too small (they evince short PL wavelength), while for 530°C they are too big and the strain in QDs relaxes mainly in dislocations, which decreases the PL intensity. Considering these results, the optimal growth temperature was set to 510 °C, which enables growth of the biggest QDs without formation of large objects.

The influence of QD size (temperature while growing QDs) on PL is shown in Fig. 4. The most intensive PL maxima in the region of 1300 nm are evinced by samples with QDs grown at 490 °C and 510 °C, which is in accordance with the AFM measurements.

Another comparison of samples with the same composition but different QD growth temperature is in Fig. 5. Both samples are covered by GaAsSb SRL and exhibit PL on longer wavelengths compared to structures without SRL in Fig. 4. The combination of ideal growth temperature and Sb content in SRL redshifted the PL maximum to 1399 nm.
4.2 The incorporation of antimony into GaAsSb SRL

The main tasks of GaAsSb SRL are to reduce strain inside QDs, to prevent QDs dissolution and hereby to conserve height and aspect ratio of QDs thanks to surfacting Sb. To achieve these results while preserving type-I transition, the rate of antimony incorporated into the SRL is very important.

We have investigated the incorporation of Sb in the thick GaAsSb layer grown without QDs. As can be clearly seen from Fig. 6, the amount of Sb is highest near the sample surface (depth 2 nm) for both samples 1 and 2. That proves the assumption that Sb has been surfacting during the layer growth. In comparison, both gallium and arsenic have constant incorporation rate, which also means homogeneous composition of the layer without gradient.

For structures with QDs, the Sb incorporation is significantly influenced by the strain, because it grows on the places where the lattice constant of strained InAs is most similar to the lattice constant of relaxed GaAsSb. We simulated the strain in an uncapped QD using Nextnano³ software and found out its strong dependence on the QD size. Bigger QDs evince higher strain on their apex, as Fig. 7 proves.
The GaAsSb lattice constant is proportional to the Sb content; for small rate the Sb is more likely to grow on the sides of QDs, where the lattice constants of GaAsSb and less strained InAs are similar. If the Sb content in SRL is increased, the GaAsSb lattice constant is bigger and Sb surfacts mainly over the top of QDs with high lattice constant of strained InAs.

This assumption was proved by AFM measurements in Fig. 8 and Fig. 9 for two QD samples with different Sb content in SRL: 10% and 20%. For lower content of Sb, the SRL grows more on the QD sides and its occurrence over the middle of the dot is small. For higher Sb content, the GaAsSb preferential growth places are close to the top of QD, which is obvious from side profiles in Fig. 9.

5. CONCLUSIONS

According to the simulation, the type I / type II transition for smaller QDs occurs for lower Sb content in GaAsSb SRL; 13% of Sb for 2 nm QDs, 15% of Sb for 8 nm QDs. For higher content of Sb, the hole states move towards SRL and the heterostructure becomes type II. The antimony surfacts during the GaAsSb growth. Increasing the QD growth temperature causes forming of bigger QDs, which redshifts their photoluminescence spectrum; the optimal growth temperature was found to be 510°C. Longest achieved wavelength for high QD growth temperature and decreased Sb incorporation into the SRL was 1399 nm (measured at room temperature) while preserving type I transition.

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LITERATURE


