Optical properties of InAs quantum dots embedded in InGaAs/AlGaAs/GaAs structures with different capping layers

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Abstract. The InAs quantum dots (QDs) embedded in Al₀.₃₀Ga₀.₇₀As/ InGaAs/ Al₀.₃₀Ga₀.₇₀As structures and covered by strain reduced AlGaInAs capping layer have been investigated in as grown state by means of a photoluminescence method. Three types of QD structures with different QD capping layers: GaAs (#1), Al₀.₁₀In₀.₁₅Ga₀.₇₅As (#2) and Al₀.₄₀In₀.₁₅Ga₀.₄₅As (#3) are compared. It is revealed that the QD emission in the structure with Al₀.₁₀In₀.₁₅Ga₀.₇₅As capping is characterized by the highest PL intensity of the ground state (GS) band and smaller the full with at half maximum (FWHM), compared to #1 and #3 structures. The variation of the GS emission peak versus temperature has been monitored within the range of 10-500K for the as grown film states and compared with shrinkage of the energy bandgaps in the InAs and GaAs bulk crystals. The results show that the efficiency of Ga/Al/In intermixing in #2 and #3 is less than in #1. Finally, the peculiarities of PL spectra of the studied QD structures have been analyzed and discussed.

1. Introduction

Self-assembled semiconductor quantum dots (QDs), grown by the molecular beam epitaxy (MBE), has been studied extensively in recent years with special attention to lasers [1,2], photodiodes and solar cells [3-5], tunnelling diodes [6,7], optical amplifiers and switches [8,9], memories [10] and light emitting diodes (LED)[11]. An established way of QD growth is by Stranski - Krastanov (S-K) mode [12]. Furthermore, the lattice mismatch between InAs-GaAs layers is very large (7%), so that the effects of lattice mismatch are significant. For this reason, in order to decrease this mismatch, the strain reduced Layers (SRL) such as InGaAs, AlGaAs, InAlGaAs [13-16] as the QD capping layers, have been very interesting for researchers. The SRL layer improves electrostatic confinement by modifying the potential barriers for electrons in the QD ground states [17]. In this case, a low threshold current density and a reduced dark current can be obtained. Furthermore, AlGaInAs prevents the diffusion of In atoms from the QDs at growth temperatures, thereby maintaining the size and quality of QDs. InAlGaAs as a capping layer promises the high temperature operation and favours to the shift of the QD emission peak to

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the telecommunication wavelength of 1.30 µm [18]. These superior features are promising for QD laser applications in optical communication systems.

The photoluminescence (PL) study versus temperature provides useful information on the optical properties, which is of considerable practical and theoretical interest. The PL intensity decrease in InAs/InGaAs QDs, is attributed to the thermal escape of the carriers (electrons and holes) from the QDs into the wetting (WL) or QW layers, or in the GaAs barrier, followed by the carrier recombination through non-radiative centres [19-26]. The insertion of additional layers of AlAs[27], InAlAs[28,29], AlGaAs[30,31] or InAlGaAs into the InGaAs/GaAs quantum wells leads to enlarging the potential barriers for the exciton thermal escape from the quantum dots.

The comparative study of PL spectra of InAs QDs embedded in the GaAs-based structures with different capping layers versus temperatures allows a deep understanding of the operating and design peculiarities, as well as showing the advantages of capping layers used.

2. Experimental Details

A set of QD structures was grown by molecular beam epitaxy (MBE) in a V80H reactor using the solid sources on the 2-inch semi-insulating GaAs substrate (001). The InAs QDs, were self-organized on the $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ (#1 and #2) and $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ (#3) buffer layers (1nm) from an equivalent of 1.575 InAs monolayers (ML). The InAs ML was grown with a growth rate of 0.05 ML / s. Then InAs QDs were covered by the first capping quantum well (QW) layer (7.5 nm) at 510 °C, as well as by the second layer of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ (100nm), AlAs (10nm) and GaAs (2nm) layers at 610 °C (figure 1). Three QD structures were investigated with different first capping layers, such as: i) GaAs (#1), ii) $\text{Al}_{0.1}\text{In}_{0.15}\text{Ga}_{0.75}\text{As}$ (# 2) and iii) $\text{Al}_{0.4}\text{In}_{0.15}\text{Ga}_{0.45}\text{As}$ (# 3). PL spectra were monitored using a spectrometer SPEX 500M with a Ge detector at the excitation by a 532nm light wavelength from a solid-state laser V-5 COHERENT Verdi with an excitation power 500 W/cm². To PL measurement in the temperature range of 10-500K, the QD structures were mounted in a closed-cycle He cryostat.

![Figure 1. Schematic design of QD structures on the GaAs substrate (001).](image)

3. Results and Discussion

PL spectra of the QD structures #1, #2, #3 measured at different temperatures are presented in figures 2, 3 and 4, respectively. The PL spectra consisting the four overlapping PL bands related to the recombination of excitons located at the ground state (GS), first (1ES), second (2ES) and third (3ES) excited states in QDs (figures 2-4). PL parameters: GS, 1ES peak positions, energy between them (ΔE(GS-1ES)), PL intensity ratio (IGS/I1ES) and the full width at half maximum (FWHM) of GS bands are summarized in table 1.
Figure 2. PL spectra of the structure #1 measured at different temperatures.

Figure 3. PL spectra of the structure #2 measured at different temperatures.
Figure 4. PL spectra of the structure #3 measured at different temperatures.

The PL spectra of different QD structures measured at 10 K are shown in figure 5 for comparison. The GS emission peak shift to a low energy from 1.133 eV in #1, 1.067 eV in #2 up to 1.043 eV in #3 structures (figure 5). Three different factors impact on the energy between GS and 1ES states: i) elastic stress, ii) height of potential barriers and iii) QD sizes. The energy ΔE(GS-1ES) between GS and 1ES states is estimated as: 56 (#1), 66 (#2) and 68 (#3) meV. The elastic stresses at the QD interface and the value of potential barrier in #2 are smaller than in #1. In this case the bigger value (66 meV) in #2, compared to 56meV in #1, testifies to the smaller QD sizes in #2. In contrary, in the structure #3 the elastic stresses at the QD interface is smaller, but the value of potential barrier is higher significantly, compared to #1 and #2. The latter leads to increasing the energy between GS and 1ES peaks in #3 (table 1).

Figure 5. PL spectra of studied QD structures measured at 10K.
Table 1. GS an 1ES parameters of QD emission at 10K in studied QD structures.

| Samples | Capping layer          | GS [eV] | 1ES [eV] | ΔE(GS-1ES) [meV] | I<sub>GS</sub>/ I<sub>1ES</sub> | FWHM- [meV] |
|---------|------------------------|---------|----------|------------------|-----------------|-------------|
| #1      | GaAs                   | 1.133   | 1.189    | 56               | 0.85            | 63          |
| #2      | Al<sub>0.10</sub>In<sub>0.15</sub>Ga<sub>0.75</sub>As | 1.067   | 1.133    | 66               | 1.29            | 48          |
| #3      | Al<sub>0.40</sub>In<sub>0.15</sub>Ga<sub>0.45</sub>As | 1.043   | 1.111    | 68               | 0.78            | 53          |

The deconvolution procedure, which allows estimating the FWHM of elementary PL bands of the Gaussian shape, has been applied to the analysis of GS, 1ES and 2ES states. The FWHMs of GS emission bands have been estimated as: 63 (#1), 48 (#2) and 53 (#3) meV (Table 1). The structure #1 is characterized by the highest FWHM, which means a greater dispersion of QD sizes and/or the QD material composition, compared to #2 and #3. The latter can be the result of intermixing the Ga and In atoms at the capping QW/QD interface. Note, that the smaller ration I<sub>GS</sub>/ I<sub>1ES</sub> in #3, compared with #1 and #2, can be attributed to the smaller QD density in #3. The latter may be the results of the different alloy composition used for the buffer 2 layer in #3.

The PL spectra have been measured at different temperatures (figures 2, 3 and 4) with the aim to analyze the QD material compositions in studied QD structures. The GS emission peaks shift to lower energy versus temperature (figure 6) due to the shrinkage of QD energy bandgap at higher temperatures. The temperature effect on the energy bandgap can be modelled using well known Varshni formula [32]:

$$E(T) = E_0 - \frac{\alpha T^2}{T + \beta}$$  \[1\]

where $E_0$ is the bandgap at $T = 0$K, $\alpha$ and $\beta$ are the fitting Varshni thermal coefficients. The red lines in figure 6 present the Varshni fitting results for #1, #2 and #3 structures. Varshni fitting parameters obtained for the structures #1, #2 and #3 have been summarized in Table 2. The comparison of Varshni fitting parameters for QDs with those in the bulk InAs and GaAs crystals (Table 2) shows that the coefficients $\alpha$ and $\beta$ in #2 and #3 are closer to those in InAs in comparison with $\alpha$ and $\beta$ in #1. Therefore, the Ga/In atom intermixing at the QWs/QD interface occurs more efficiently in #1 than in #2 and #3. At the same time, the GS peak positions in #2 and #3 structures have been detected at lower energies (Table 2), compared with #1. The presence of aluminium in the capping QW layers is responsible for a low atom inter-diffusion in #2 and #3. The lower chemical bond energy for In-As and Ga-As bonds, compared with this value for Al-As, causes the significant Ga/In atom inter-diffusion in #1 and less efficient Ga/In/Al intermixing in #2 and #3 [35]. Because the structure #3 has a higher amount of Al (40%) in a capping QW, compared with the Al content (10%) in #2, the fitting parameters for #3 are very similar to those in the bulk InAs (Table 2).

Table 2. Varshni fitting parameters of QD structures and the bulk InAs and GaAs.

| Samples  | $E_0$ [eV] | $\alpha$ [meV/K] | $\beta$ [K] |
|----------|------------|------------------|-------------|
| #1       | 1.133      | 0.390            | 110         |
| #2       | 1.067      | 0.280            | 93          |
| #3       | 1.043      | 0.270            | 83          |
| InAs [33, 34] | 0.415     | 0.276           | 83          |
| GaAs [33, 34] | 1.519     | 0.540           | 204         |
4. Conclusions

Three QD structures with different capping QWs have been investigated using the photoluminescence and its temperature dependence. Three compositions for QD capping layers were compared: GaAs (#1), Al$_{0.10}$In$_{0.15}$Ga$_{0.75}$As (#2) and Al$_{0.40}$In$_{0.15}$Ga$_{0.45}$As (#3). The sample #2 shows the highest PL intensity and smaller FWHMs of PL bands (the more homogenous QD sizes), than these parameters in #1 and #3. The mentioned advantages in #2 were achieved due to the Al-based capping QW layer, the bigger mismatch and strain between WL and buffer 2 layers, the smaller mismatch at the QW/QD interface and better structure quality of capping QWs.

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References

[1] J Kim, C Lee, B Choi, H Kwack and C Lee, E Sim 2007 Appl. Lett. 90 153111
[2] Y Qiu, D Uhl, R Chacon and R Yang 2003 Appl. Phys. Lett. 83 1704
[3] R Attaluri, J Shao, K Posani, S Lee and A Stintz 2007 J. Vac. Sci. Technol. 25 1186
[4] T.V. Torchinskaya 1998 Opto-Electron. Rev. 6 121
[5] A Amtout, S Raghavan, P Rotella, G von Winckel and A Stintz 2004 J. Appl. Phys. 96 3782
[6] W Wang, Y Hou, D Xiong, N Li, W Lu, et al. 2008 Appl. Phys. Lett. 92 023508
[7] H Li, B. Kardyna, D Ellis, A Shields, et al. 2008 Appl. Phys. Lett. 93 153503
[8] L Padiha, A Neves, E Rodriguez and C Cesar 2005 Appl. Phys. Lett. 86 161111
[9] M Sugawara, H Ebe, N Hatori and M Ishida 2004 Phys. Rev. B 69 235332.
[10] M Geller, A Marent, T Nowozin, D Feise, K Potschke and N Akcay 2008 Physica E 40 1811
[11] D Bimberg and M Grundman 2001 Quantum Dot Heterostructures, Wiley & Sons 328
[12] I Stranski, L Krstanow and W Sitzungsber 1938 Abt. 2B 146 797
[13] F Chang, C Wu and H Lin 2003 Appl. Phys. Lett. 82 4477–4479
[14] J Tatebayashi, M Nishioka, Y Arakawa 2001 Appl. Phys. Lett. 78 3469–3471
[15] E Kim, Z Chen and A Madhukar 2001 Appl. Phys. Lett. 79 3341–3343
[16] Z Chen, E Kim and A Madhukar 2002 Appl. Phys. Lett. 80 2490–2492

Figure 6. The variation of GS peak positions versus temperatures in the structures #1, #2 and #3. Varshni fitting is shown by red lines.
[17] E Kim, Z Chen and A Madhukar 2001 Appl. Phys. Lett. 79 3341–3343
[18] M Park, O Kwon, W Han and K Lee, 2006 IEEE Photonics. Tech. Lett. 18 16
[19] T Torchynska, J Casas, E Velazquez, P Eliseev, A Stintz and R Peña 2003 Surf. Sci. 532 848
[20] Y Dai, J Fun, Y Chen, R Lin, S Lee and H Lin 1997 J. Appl. Phys. 82 4489
[21] C Kapteyn, M Lion, R Heitz, D Bimberg and A Kovsh 2000 Appl. Phys. Lett. 76 1573
[22] C Duarte, E da Silva, A Quivy, M da Silva and S Martini 2003 J. Appl. Phys. 93 6279
[23] X Meng, B Xu, P Jin, X Ye, Z Zhang and C Li 2002 J. Cryst. Growth 243 432
[24] L Seravalli, P Frigeri, M Minelli and P Allegri 2005 Appl. Phys. Lett. 87 063101
[25] T Torchynska, 2008 J. Appl. Phys. 104 (7) 074315
[26] T Torchynska and A Stintz 2010 J. Appl. Phys. 108 (2) 024316
[27] P Yu, J Leem, M Jeon, S Noh, J Lee, G Kim, S Kang and J Kim 2002 J. Appl. Phys. 91 5055
[28] H Liu, I Sellers, M Hopkinson and M Skolnick 2003 Appl. Phys. Lett. 83 3716
[29] K Chang, S Yang, R Hsiao, J Chen, L Wei, J Wang and J Chi 2005 J. Appl. Phys. 97 083511
[30] Z Zhang, B Xu, P Jin, X Meng, C Li, X Ye and Z Wang 2002 J. Appl. Phys. 92 511
[31] I Guerrero Moreno, T Torchynska and J Casas Espinola 2013 Physica E 51
[32] Y Varshni 1967 Physica 34 149
[33] http://www.ioffe.ru/SVA/NSM/Semicond/GaInAs/index.html
[34] K Takahashi, A Yoshikawa 2007 Wide Band gap Semiconductors, Springer Berlin