MOVPE PREPARED SELF−ORGANISED InAs/GaAs MONO− and MULTILAYER QUANTUM DOT STRUCTURES: MAGNETO−PHOTOLUMINESCENCE STUDY of ELECTRONIC TRANSITIONS

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1. Introduction

Self−assembled InAs quantum dots (QDs) in GaAs prepared by Stranski−Krastanow growth mode exhibit very strong quantum confinement effects with delta−function−like density of states. QDs in the laser active layer can improve the performance of semiconductor lasers. Lower threshold current density, better temperature dependence of threshold current, suppressed loss mechanisms (Auger recombination and intervalence band absorption) and higher optical power can be achieved using QDs in the active region of semiconductor lasers.

In the InAs/GaAs QD system emission wavelength 1.3 µm, suitable for optical communications, can be obtained. Problem to obtain 1.3 µm electroluminescence in MOVPE prepared QD lasers [1] is connected with recombination in these QDs which goes from higher excited states giving thus shorter wavelength. Increase of energy separation of the ground and excited states in QDs can solve this problem [2]. We have tried to find technological parameters, which can affect it.

The photoluminescence (PL) and magneto−photoluminescence (MPL) were used as tools revealing the electronic transitions in these structures [3 − 5].

2. Experimental

InAs QDs in GaAs matrix have been prepared in an AIXTRON 200 machine by LP−MOVPE on SI GaAs Cr doped (100) oriented substrates [6]. Precursors used for the growth of GaAs and InAs layers were TMGa, TMIn and AsH_3. Prior to growth, substrate temperature was increased up to 800°C for 5 minutes under arsine flow. The structures were grown under total pressure 70 hPa and total flow rate through the reactor 8 slpm. The first GaAs buffer layer was grown at four times higher growth rate at temperature 650°C, then the temperature was decreased to 500°C for the rest of the structure (the second GaAs buffer layer, InAs QD layers, GaAs separation layers and GaAs capping layer). All InAs layers were grown under the same conditions: 50 ml/min H_2 through TMIn bubbler, V/III ratio 85 and time of growth 9 seconds. The growth interruptions after the InAs layer growth, for the QD formation, were 30 sec. The slightly decreasing growth rate in the direction of gas flow in our reactor was used for fine optimisation of the WL thickness.

Optical properties of QDs were studied by PL and MPL. Ar laser (line 2.41 eV) was used as an excitation source; PL was detected by a Ge detector using standard lock−in technique. MPL measurements were performed in the Faraday and/or Voigth configurations in the range up to 28 T at liquid nitrogen temperature.

3. Results and discussion

The PL and MPL spectra were measured on samples, with different number of QD layers in the structure and different thickness of GaAs separation layers as shown in Table 1.

Sample	***A***	***B3***	***B7***	***C3***	***C5***	***C7***
Number of layers	1	3	7	3	5	7
Spacer thickness [nm]	−	7.5	7.5	3.75	3.75	3.75

Tab. 1: Parameters of QD samples.

A possible way to increase the wavelength of QD PL corresponding to the recombination from the QD ground state is to increase the size of QDs. The size of QDs is effectively increased in structures with stacked QDs [7]. An advantage of these structures is the increased size of QDs with retained high QD density [8]. The increase of the size of QDs with the number of QD layers is demonstrated in a TEM picture of sample B7 (Fig. 1).

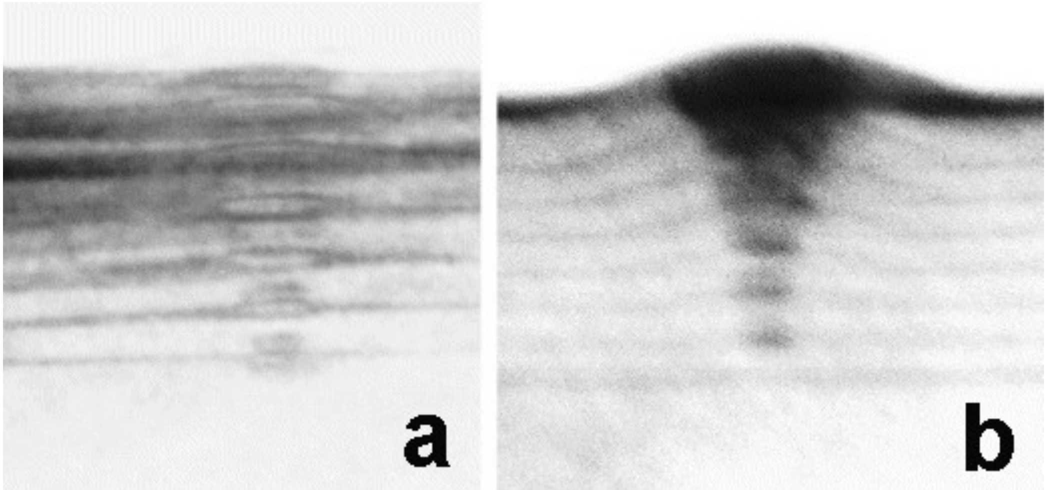

Fig. 1: TEM images of 7 QD layers − B7 sample (a, b − different location) with the spacer thickness 7.5 nm.

The accompanying decrease of the energy of quantum states can be seen from the PL spectra of samples with 1, 3, 5 and 7 QD layers (Fig. 2a).

Ground state transitions (marked by arrows) dominate for low excitation power, while for high excitation power excited state transitions become dominant (see sample C5 Fig. 2a).

The inset shows the dependence of the energy of the ground state on the number of QD layers. The decrease of the energy of the ground state can be explained by the increase of the height of QDs with increasing number of layers or lower strain in multi−layer structures. QDs in the upper layers are formed predominantly on the hillocks created by QDs in the lower layers. Curvature of these hillocks can decrease the strain in QDs and so deepen the potential well inside QDs.

The existence of well resolved PL maxima for multilayer QD samples (except C7) may be explained by the relaxation of electrons and holes to the lowest energy states due to interaction of vertically correlated QDs. The luminescence is thus originated from QDs of similar size.

In the case that thicker spacers between QD layers are used in the structure the energy separation of the ground and excited states is increased as can be seen from the comparison of PL spectra of samples B3 and C3 (Fig. 2b). The energy difference between the ground and the first excited states is for sample B3 higher (92 meV) than for sample C3 (76 meV), despite the fact that the energy difference between energy levels should decrease with decreasing energy of the ground state (with the height of QDs). This fact is very important for the design of 1.3 µm QD lasers.

To explain the dependence of the separation of energy levels in QDs on the thickness of spacers we tried to compare TEM pictures of structures with 3.75 and 7.5 nm thick spacers (Figs. 1 and 3). The main difference between these two structures seems to be in the shape of QDs. This has to be confirmed by measurement with atomic resolution.

The vertically correlated QDs with thicker spacers (B3) seem to be more flat. The strain inside flat QDs should be similar to the strain in QWs and also effective masses of electrons and holes can be similar to those in QWs: m_e* in the z (growth) direction would be closer to the effective mass in InAs while in the xy plane (plane of QDs) to the effective mass in GaAs. The strongest quantization takes place in the z direction, where the flat QDs can have lower m_e*. This may be one possible reason for the increased energy separation of quantum states. The higher reduced effective mass in x and y directions in QDs with thicker spacers was confirmed by lower diamagnetic shift and excited state splitting observable in MPL spectra of sample B3 (Fig. 4).

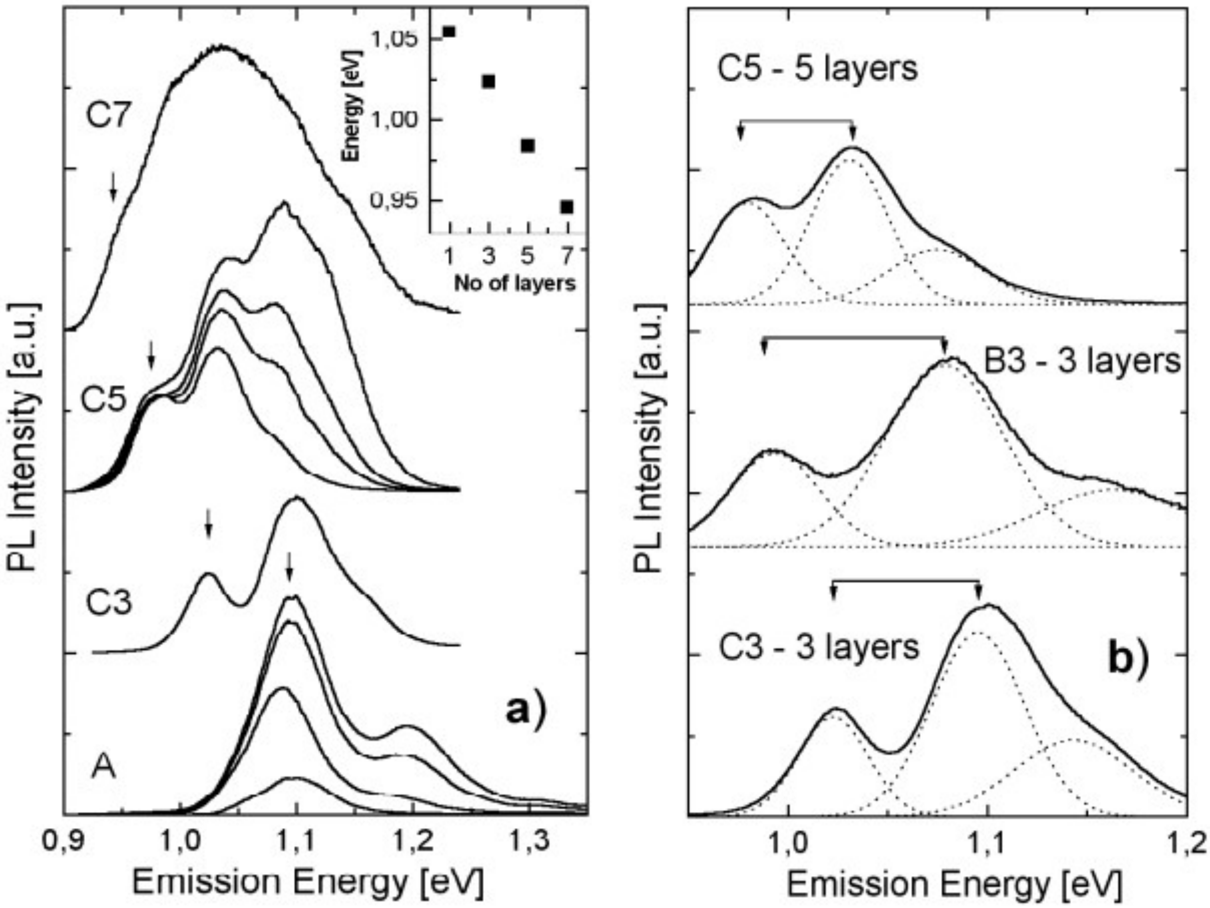

Fig. 2: a) PL spectra of QD samples with different number of QD layers at 77 K. PL spectra of samples A and C5 were measured for several intensities of excitation. Transitions between ground states are marked by arrows. The dependence of emission energy of the ground state transition on the number of QD layers is shown in the inset. b) Comparison of PL spectra of 3 QD layer samples (B3, C3) with different thickness of spacer layers and comparison of PL spectra of samples with the same thickness of spacer layers and different number of QD layers (C3, C5).

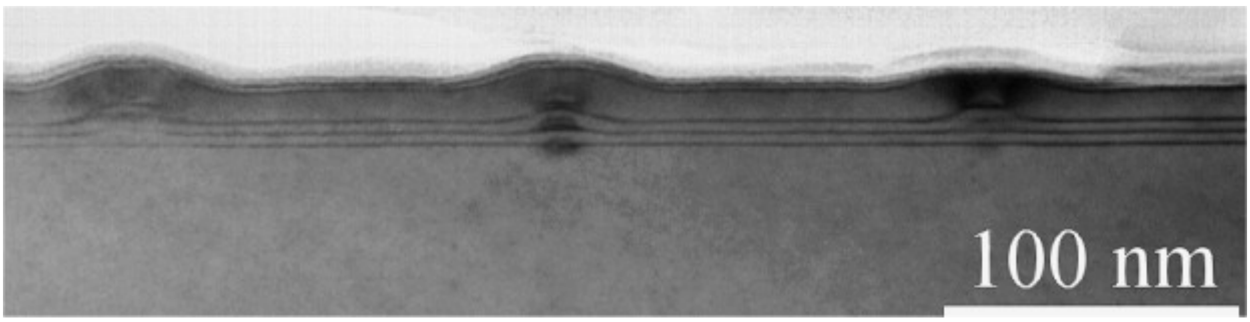

Fig. 3: TEM image of 3 QD layers − C3, with spacer thickness 3.75 nm.

The MPL was measured on our samples (Fig. 4) to clarify whether the peaks with higher energy in PL spectra of samples with stacked QDs originate from smaller QDs in lower layers or whether it is the PL of excited states in the upper QD layers. The s−like states in Faraday configuration exhibit always only a small diamagnetic shift. The p− or d−like states are splitted into two or three peaks in the case that they are sufficiently occupied by carriers. In case that p− or d−like states are not occupied enough, only the branch with lower energy can be seen in MPL and so the decrease of peak energy with increasing magnetic field can be observed. The splitting of the MPL peaks under higher magnetic fields or the decrease of the peak energy for insufficiently occupied QDs is the evidence of p− and d−like QD states in the upper layer in our samples.

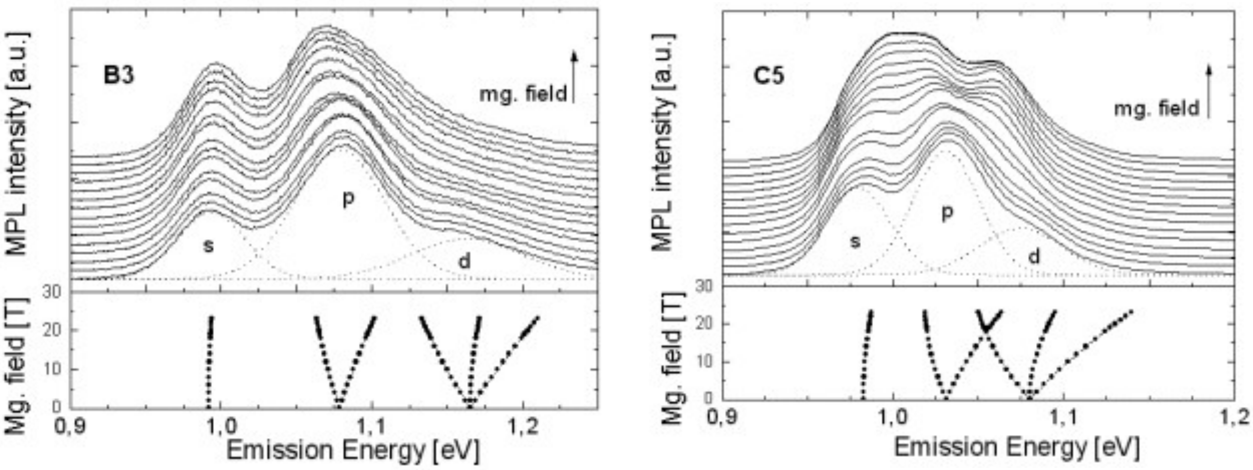

Fig. 4: Top − Evolution of MPL spectra with increasing magnetic field from 0 T to 23 T for samples B3 (left) and C5 (right), measured at 77 K. Bottom − Positions of s−, p−, d− energy levels as a function of magnetic field calculated according to a simple one particle Fock−Darwin model for two−dimensional electrons confined in a parabolic well [9] with effective masses 0.06 m_0 for C5 and 0.07 m_0 for B3 samples, respectively.

4. Conclusion

The influence of the number of QD layers and spacer thickness on the PL and MPL spectra was studied. Our PL spectra reveal the overlapping of electron wave functions of vertically stacked QDs and relaxation of electrons and holes to the lowest energy states.

We have confirmed the red shift of PL maxima with the number of QD layers accompanied by lower energy separation between them.

The energy separation of the ground and excited states is increasing with increasing thickness of the GaAs spacer layers between QD layers. This fact is important for the design of 1.3 µm QD lasers.

Acknowledgement

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