Tunnel injection structures based on InGaAs/GaAs quantum dots: optical properties and energy structure

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Abstract. The limited speed of direct modulation due to the significant population of hot carriers in quantum dots (QD) is a major drawback of the application of QD based lasers in fibre optics telecommunication. One of the most promising methods of alleviating this problem is the design of tunnel injection (TI) structures, where already cold carries are injected by means of tunnelling through a thin barrier from an adjacent quantum well (QW) directly to the QD ground state. We have investigated the properties of TI structures consisting of an In$_{0.6}$Ga$_{0.4}$As quantum well and a layer of self-assembled In$_{0.5}$Ga$_{0.5}$As/GaAs quantum dots versus the properties a reference QD sample. Photoreflectance spectroscopy is applied to determine the energies of optical transitions in this complex system. The obtained energies are then used to verify the reliability of the calculations in the 8 band $kp$ model, which take into account the realistic geometry of the dots, influence of the strain and the coupling between the dot layer and the injector quantum well. Finally, time resolved photoluminescence (PL) experiment is performed at low temperature and its results are related to the acquired structure of confined levels. The influence of the tunnelling process on PL rise and decay times is explained.

1. Introduction
Layers of self-assembled quantum dots (QD) are already used as active material in semiconductor lasers. Devices that are based on them offer, as was both predicted theoretically and confirmed experimentally, improvements to some of the operating parameters, when compared to still more common quantum well (QW) lasers. This concerns a low threshold current [1, 2] and high temperature insensitivity [3-5]. Due to the large inhomogeneous broadening of QD emission they can also be tuned in a wide range of wavelengths [6]. However, there are still problems that need to be overcome to push the performance characteristics of the QD lasers further, for instance, the existence of the large population of hot carriers occupying QD excited states or wetting layer, which limits the speed of modulation. In order to deal with that issue, tunnel injection (TI) [7-10] system has been proposed, where an additional QW, separated by a thin barrier from QD layer, is put into the structure. If the QW is properly designed, the lowest lying levels confined in it, especially electron levels, should have

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energies similar to the energies of electrons confined in QDs. Then the carriers trapped by the QW would very fast thermalise to the QW ground state and tunnel directly to the QD ground state, either resonantly or with the assistance of phonons, usually lateral optical. This process should be much faster than the thermalisation in a QD itself, which can suffer from the phonon bottleneck problem. Moreover, due to a bigger volume, QW can trap more carriers than QDs and wetting layer, thus the TI structure can have higher efficiency of emission.

In this paper we use photoreflectance (PR) spectroscopy, which is one of the absorption-like modulation techniques proven highly effective for the investigations of low dimensional semiconductor structures [11, 12], even complex ones, such as TI structures [10, 13], to study the optical transitions of three samples, two consisting of one layer of In$_{0.6}$Ga$_{0.4}$As QDs separated by a thin barrier from In$_{0.4}$Ga$_{0.6}$As QW and a reference sample without the injector QW. The measurement results are compared with the results of numerical calculations in an 8-band kp model (similarly as in Ref. [14]), which takes into account the realistic geometry of the dots and strain distribution. The calculations are necessary in order to determine the energies of levels confined in the system, since the experiment gives only the total energy of transition. Finally, a time resolved photoluminescence (TRPL) experiment is carried out and the determined rise and decay times of emission are discussed in the light of established energy structure.

2. Experiment

2.1. Investigated structures

The samples are molecular-beam-epitaxy grown on an n doped GaAs (100) substrate. The reference sample contains a layer of In$_{0.6}$Ga$_{0.4}$As QDs with the nominal thickness of 1.8 nm, surrounded by 15 nm of GaAs and embedded in an AlGaAs/GaAs superlattice. In TI structures A an B, beside the 15 nm GaAs layer and the layer of QDs grown in the same conditions as in the reference structure, an additional injector QW is inserted, separated by a 2 nm GaAs barrier from the QDs layer. In the case of sample A, this QW consists of a 15 nm thick In$_{0.2}$Ga$_{0.8}$As material, in the sample B the QW is 7 nm wide, with the 30 % of In.

2.2. Experimental setup

Photoreflectance is measured in a standard bright configuration setup, with the pump beam provided by the 532 nm line of a frequency doubled yttrium-aluminium-garnet laser, the probe beam obtained from a tungsten halogen lamp, and the detection supplied by an InGaAs photodiode combined with a 0.55 m focal length monochromator. Further details can be found in [15]. For the time resolved PL measurements, the 800 nm line from a high power mode-locked Ti:Sapphire laser is used as a nonresonant excitation source and a Hamamatsu streak camera equipped with a Peltier cooled S1 photocathode and combined with a 0.25 m focal length monochromator as a detection system. Low temperature measurements are carried out in a continuous-flow helium cryostat.

3. Experimental results and calculations

![Figure 1. Room temperature PR spectra of reference QD sample and TI samples A and B in the region of lowest energy transitions. Arrows indicate the energies of optical transitions relevant for this paper.](image)
Figure 1 shows PR spectra measured at room temperature for all samples, at the region of lowest energy transition. In the reference sample only one weak (due to small total volume of QDs) and broad (due to the broad distribution of QDs sizes and contents) transition can be seen, attributed to the QD ground state. In TI samples, beside analogical transition, slightly shifted in energy because of a different strain distribution governing Stranski-Krastanov growth mode and coupling with injector QW, more PR resonances at higher energies are visible, attributed to the transitions between levels confined in the complex QW+QD system. In this paper we will concentrate only on two QW+QD transitions in sample A and one in sample B, because they are primarily involved in the tunnelling process.

In the next step the 8 band kp model is used in order to calculate the energy structure of investigated samples. The details of the model can be found in [14], material parameters were taken after [16]. Figure 2 presents calculated energies of a few lowest lying electron levels confined in the conduction band potential, projected onto the cross-section of the potential in the growth direction, with the strain effect included. The reference QDs were used as a test of the model. Good agreement between calculated transition energies and energies obtained from high excitation PL measurements (not shown here) has been obtained. Only electron levels are discussed, since there are many hole levels confined, and separation between consecutive levels is on the order of a single meV, thus at room temperature holes can be treated as having a quasi-continuous band. The results obtained for TI structures indicate that in the sample A first two electron levels are confined in QD, only the third level is smeared over entire QW+QD system, whereas in the sample B it is the case of already the second one.

Figure 2. Calculated cross-sections of realistic confining potentials in conduction band (including the effect of strain) in the growth direction, at room temperature, for a) reference sample, b) TI sample A and c) TI sample B. Horizontal lines indicate energies of electron levels discussed in the paper.

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Figure 3. Time-resolved PL spectra for reference sample (open triangles), TI sample A (filled circles) and TI sample A (filled squares), measured at 5 K, with moderate excitation power (100 µW). Solid lines are fits by the exponential decay formulae.
Finally, the time resolved photoluminescence was measured at low temperature, at moderate excitation power density of 80 mW/cm². In order to determine the rise and decay times of emission, fits with exponential function were performed. The results for the reference sample are ~40 ps rise time (with the setup response time ~30 ps) and 1.2 ns decay time, which is typical for such QDs. Surprisingly, almost identical times were obtained for TI structure A. On the other hand, both the rise time and the decay time for sample B were found to be longer (~100 ps and ~2 ns, respectively). This difference can be explained by the determined energy structure. In the TI sample B the tunnelling occurs to the QD ground state, thus it determines the relevant times of emission, because QW feeds the carriers directly to the emitting state. In the sample A the tunnelling occurs to higher state in the dot, thus the rise and decay times are governed by the relaxation processes within the dot, which are approximately the same as in the reference sample.

4. Conclusions

Photoreflectance measurement results, followed by the calculations in an 8 band kp model involving realistic dot geometry and strain distribution, lead to the determination of the energy structure of TI samples, containing an InGaAs QW and a layer of self-assembled InAs/GaAs QDs. The obtained diagram of confined energy levels was used to explain the differences in rise and decay times between TI structures with various injector wells and QD reference sample. It was found that the time characteristics of emission depend on the fact, if the tunnelling occurs directly to QDs ground state or to QDs excited state.

Acknowledgments

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