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Optical methods used to optimise semiconductor laser structures with tunnel injection from quantum well to InGaAs/GaAs quantum dots

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We present the results of optical measurements performed on structures consisting of an InGaAs quantum well (QW), separated by a thin barrier from a layer of self-assembled InGaAs quantum dots (QDs). Such a kind of design is called a tunnel injection structure, because its functionality is based on the tunnelling of carriers from a QW to QDs, preferably with the assistance of optical phonons. In this approach, the injector QW serves as a reservoir of the carriers (due to much higher efficiency of carrier collection) and alleviates the problem of long relaxation times needed for carriers to reach the QDs ground state. In order to investigate the structures several complementary experimental techniques are applied. Photoreflectance, an absorption-like modulation spectroscopy, gives the information about the optical transitions and the electronic structure. The temperature evolution of photoluminescence allows emission efficiency and carrier losses to be determined. Photoluminescence excitation probes directly the carrier transfer from QW to the dots. The interpretation of the results is supported by the calculations in the envelope function formalism. It has been found out that the wavefunction position of the lowest lying levels depends on the QW parameters and thus different regimes of tunnelling are proposed.

Keywords: quantum dots, optical properties, lasers, tunnel injection.

1. Introduction

Tunnel injection (TI) structures [1–9] have been designed in order to improve the properties of semiconductor lasers based on self-assembled quantum dots (QDs), usually for the telecom applications. Quantum dot lasers besides having several well-known advantages, both predicted theoretically and confirmed experimentally, such as a low threshold current [10, 11], low temperature sensitivity [12–14] and wide spectral tunability [15], suffer from the low carrier collection efficiency and from the problem of "hot carriers", *i.e.*, the majority of carriers in the system occupy excited states in the dots, states in the wetting layer (WL) and bulk-like barrier material. Hot carriers severely limit the speed of modulation in laser devices, because of the long relaxation times needed first in order to capture the carrier by the QD and second, to relax to the QD ground state (GS). This is especially important for electrons, as holes relax faster [16]. One of the approaches is to add an additional quantum well (QW) to the system, separated by a thin barrier from the QDs layer. It will act as an effective carrier reservoir, because the carrier collection of QW is much higher than in the case of QDs. Moreover, if the QW is appropriately chosen, so that its GS transition energy differs from the GS energy of QDs by the energy of lateral optical (LO) phonon, the carriers will tunnel from the QW directly to the QW GS (hence the name tunnel injection), avoiding the long relaxation processes in the QDs. Both the relaxation to the QW GS and the phonon assisted tunnelling are fast, thus the overall time needed for the carrier to reach the QDs GS is greatly reduced.

It this paper, we present investigation of the optical properties of several TI structures, consisting of $\mathrm{In_{0.6}Ga_{0.4}As}$ QDs and $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ QW, with varying In content and well width. The electronic structure of the samples is determined by photoreflectance (PR), an absorption-like modulation spectroscopy technique which is highly sensitive to optical transitions in semiconductor heterostructures [17, 18] and which has been previously applied to other TI structures [7–9]. Numerical calculations in the framework of envelope function approximation [19] are then performed in order to interpret measured energies of optical transitions and thus to resolve the positions of levels confined in the complex quantum mechanically coupled system consisting of QW, WL and QDs. The photoluminescence (PL) spectroscopy is used to probe the emission properties of the structure investigated, finally the photoluminescence excitation (PLE) measurement is performed in order to directly confirm the transfer of carriers from QW to QDs. The results obtained from the emission-like experiments are explained in the framework of the electronic structure determined previously and conclusions on the prospects of applying TI are formulated.

2. Experiment

2.1. Structures under investigation

The samples are molecular-beam-epitaxy grown on *n* doped GaAs (100) substrate. Sample A is the reference containing the layer of $\mathrm{In_{0.6}Ga_{0.4}As}$ QDs with the nominal thickness of 1.8 nm, surrounded by 15 nm of GaAs and embedded in AlGaAs/GaAs superlattice. Samples B, C, D and E are TI structures, in which between 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 thin barrier from the QDs layer. In the case of sample B, this QW consists of a 15 nm thick $\mathrm{In_{0.2}Ga_{0.8}As}$ material, and the barrier of 2 nm thick GaAs; in sample C the QW is the same and the separation layer contains 0.5 nm GaAs/1 nm $\mathrm{Al_{0.33}Ga_{0.66}As}$/0.5 nm GaAs;

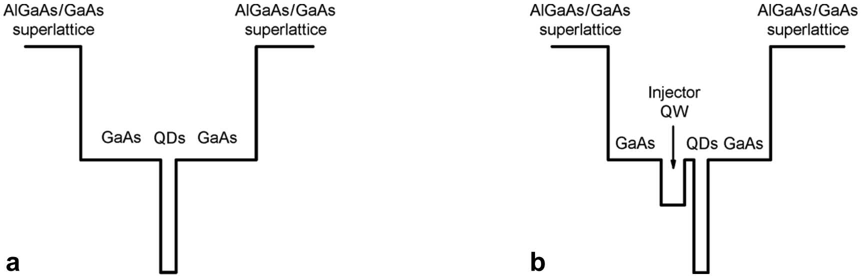

Fig. 1. Schematics of conduction band minimum for reference (**a**) and tunnel injection (**b**) samples.

samples D and E include 7 nm thick InGaAs QWs separated again by 2 nm of pure GaAs, with the In content in the well being 25% and 30%, respectively. The schematic of conduction band minimum is shown in Fig. 1.

2.2. Experimental setup

Photoreflectance is measured in a standard bright configuration setup, with the pump beam provided by the 514 nm line of an Ar^+ laser, the probe beam obtained from a tungsten halogen lamp, and detection supplied by an InGaAs photodiode combined with a 0.55 m focal length monochromator. Further details can be found in [20, 21]. The PL is measured in a similar setup, but with an InGaAs linear array used as a detector. The excitation light in the PLE experiment is provided by a tunable Ti:sapphire laser and detected also by an InGaAs linear array detector. Low temperature measurements are carried out in continuous-flow helium cryostat.

2.3. Photoreflectance results and numerical calculations

The results of room temperature PR experiment are shown in Fig. 2. The spectral range is chosen so that only transitions which are of interest in this paper (below GaAs band gap) are presented. The superlattice related part of the spectra, which does not affect the electronic structure of the active region under investigation, is out of interest in this paper. The obtained spectra can be divided into two distinct parts, depending on the origin of observed transitions. The lowest energy transition (1.05–1.1 eV) visible for all samples is attributed to the GS transition in the QDs. Its low intensity and large broadening is characteristic of PR resonances connected with self-assembled dots and is explained by the small volume of QD material and large inhomogeneous distribution of dot sizes and contents. The GS energy of QDs varies between samples, indicating some differences of average QD sizes. Since the growth of the self-assembled dots is driven by the strain, these differences are related to the different strain distribution in the samples, which may be explained by the fact the dots are grown on the top of the injector QW and barrier, which vary for each sample. Several stronger and narrower resonances visible at higher energies for the TI structures originate from the 2D part of the structure, *i.e.*, the coupled system of the injector and WL. The lowest energy state of this system shifts with the changes in the well width and content, the difference

when the GS wavefunction is localized in the dots, the tunnelling must be assisted by phonon, which might be beneficial from the point of view of a laser performance. Finally, the PLE experiment directly confirmed an efficient transfer of carriers from the injector QW to the dots.

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