Optica Applicata, Vol. XXXV, No. 3, 2005

Optical properties of InGaAsP quantum well for infrared emission investigated by modulation spectroscopy

ARTUR PODHORODECKI[1*], JANUSZ ANDRZEJEWSKI[1], MARCIN MOTYKA[1], ROBERT KUDRAWIEC[1], JAN MISIEWICZ[1], JACEK WÓJCIK[2], BRAD J. ROBINSON[2]

[1]Institut of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

[2]Centre for Electrophotonic Materials and Devices, Department of Engineering Physics, McMaster University, Hamilton, Ontario, L8S 4L7 Canada

[*]Corresponding author: A. Podhorodecki, artur.p.podhorodecki@pwr.wroc.pl

Modulation spectroscopy, *i.e.*, photoreflectance (PR) and contactless electroreflectance (CER) are very powerful techniques to investigate optical properties of nanostructures. These techniques together with photoluminescence spectroscopy were used for investigation of optical properties of InGaAsP quantum well with infrared emission at 1.55 μm. Samples used in this study were grown by gas source molecular beam epitaxy (MBE) on *n*-doped (100) InP substrate. Based on the numerical calculations the origin of observed optical transitions has been explained and the energy structure of the investigated samples has been proposed.

Keywords: photoreflectance, quantum well.

1. Introduction

Photonic integrated devices based on InGaAsP multiple quantum wells (MQWs) structures are of particular importance due to the dramatic increase in demand for long wavelength optical communication. Currently, InGaAsP/InP quantum well structures are used for a variety of optoelectronic devices, such as electro-optic modulators for fiber optic communication [1], solar cells [2], infrared detectors [3] or lasers for operation near the 1.55 μm wavelength region. This value is important from the telecommunication point of view, especially because it is a telecommunication window, with characteristic minimal dispersion and absorption in silica glass fiber, which enables more data to be sent at longer distances.

Modulation spectroscopy, as an optical (*i.e.*, contactless and non-destructive) spectroscopy, has been proven to be a very powerful technique for studying

semiconductor low-dimensional structures [4–7]. The derivative nature of this experimental method enables observation of a large number of sharp spectral features including those related to excited state transitions in low-dimensional structures, in contrast to common emission-type experiments such as photoluminescence (PL), which usually probe only the ground state.

Its success comes from the fact that it is a very effective and highly sensitive absorption-type experiment which allows investigating both ground and excited state related optical transitions, including those with very small oscillator strength like nominally parity forbidden ones. The method remains effective in the case of full device structure as, *e.g.*, multilayer QW-based semiconductor laser structure [6, 7] gives signal from all parts of the structure.

There are many types of modulation techniques, depending on the source of modulation. In photoreflectance (PR) [8] the modulation is caused by photo-injected electron-hole pairs which modulate the built-in electric field of the microstructure. A common problem associated with PR is the unwanted signal that enters the detector due to the scattered pump light and/or its generated photoluminescence. In consequence, the poor signal-to-noise ratio is observed and in some cases the observation of PR signal is not possible or it is disturbed.

Contactless electroreflectance (CER) spectroscopy [9] utilizes a capacitor-like system consisting of a thin, transparent, conductive coating, which serves as one electrode. A second electrode, consisting of a metal strip, is separated from the first electrode by insulating spacers. The sample is placed between those two capacitor plates and built-in electric fields are modulated by external field. In this case unwanted PL signal is not observed but in some cases, *i.e.*, full laser structure, when the quantum well is surrounded by doped layers, which gives high internal electric field, PR can be a more effective technique than CER.

This work presents an experimental investigation of InGaAsP/InGaAsP QW of 1.55 μm wavelength emission. Contactless electroreflectance, photoreflectance and photoluminescence spectroscopy have been used to explain the origin of the optical transitions. The advantages of electroreflectance as compared to photoreflectance and photoluminescence spectroscopy have been shown.

2. Experimental details

Samples used in this study were grown by gas source molecular beam epitaxy (MBE) on *n*-doped (100) InP substrates. The structure investigated is shown schematically in Fig. 1. The active region is composed of a 55 Å thick $In_{0.72}Ga_{0.28}As_{0.56}P_{0.44}$ (QW1) which lies between two 150 Å thick $In_{0.72}Ga_{0.28}As_{0.87}P_{0.13}$ layers which together with QW1 layer create a 355 Å thick quantum well (QW2) (see Fig. 1). This gives an emission from QW1 at 1576 nm wavelength as determined by room temperature PL. This "partial" structure is completed with upper and lower undoped InP claddings and $In_{0.72}Ga_{0.28}As_{0.87}P_{0.13}$ bulk-like layers (BL).

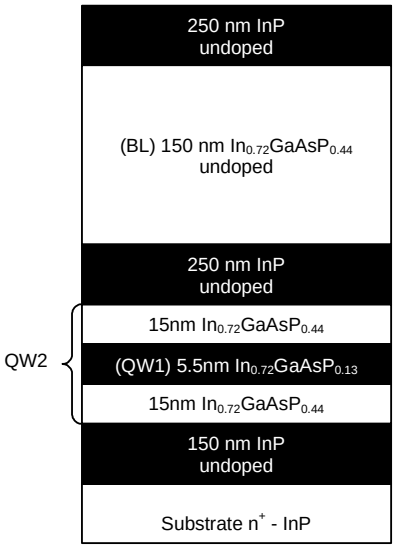

Fig. 1. Schematic structure of InGaAsP quantum well.

Photoreflectance measurements were performed in the so-called bright configuration with a conventional experimental set-up, with a halogen lamp (150 W) as a probe light source, a 0.55 m monochromator and InGaAs *p-i-n* photodiode was applied for obtaining the PR and CER spectra. For PR, a YAG laser with 532 nm emission line was used as the pump beam. The probe and pump beams were defocused to a diameter of 2 mm and the power of modulated beam was about 15 mW. In the CER experiment, the top electrode consisted of a transparent conducting ATO layer on quartz, which was kept at a distance of 0.1 mm from the sample surface while the sample itself was fixed on the bottom cuprum electrode. A maximum peak-to-peak alternating voltage of 0.9 kV was applied. Phase sensitive detection of the PR and CER signals was made using a lock-in amplifier. Other relevant details of the experimental set-up have been described in [4, 6]. All measurements were performed at room temperature.

3. Experimental results and discussion

Figure 2**a** shows PL spectrum of InGaAsP QW structure recorded at room temperature. The line shape of the emission peak of the fundamental transition is asymmetric with a tail at high energy side, which is typical of free carriers recombination at room temperature [10–12]. Beside fundamental transition from quantum well region, two additional weaker and broad transitions are observed. The first one at 1256 nm is attributed to the radiative recombination from QW2 region and the second one from InP layer. At this point, it can be concluded that for such a high luminescence intensity (five times stronger than photoreflectance) it will be very difficult to obtain high quality PR signal. Indeed, as can be observed from Fig. 2**a**, the signal-to-noise ratio in the case

of PR spectra is poor. For this reason, investigation of the optical properties of the InGaAsP QW1 will be based on the electroreflectance spectrum shown in Fig. 2**b**. However, comparing these two spectra, *i.e.*, photoreflectance and electroreflectance, it can be concluded that observed features in both cases are the same. But in the case of CER, the signal-to-noise ratio is high, due to the absence of PL signal, and the features are more clear, especially for the features associated with the InP layer and $In_{0.72}Ga_{0.28}As_{0.56}P_{0.44}$ bulk layer. Figure 2**b** shows CER spectra of InGaAsP QW1 structures together with the fitting curves. CER spectrum exhibits more details than PL spectrum where only one peak from QW1 region, related to the ground state transition is observed. In CER spectrum, besides resonances related to the QW1, features associated with the $In_{0.72}Ga_{0.28}As_{0.56}P_{0.44}$ (QW2), $In_{0.72}Ga_{0.28}As_{0.56}P_{0.44}$ bulk layer (BL) and InP layer are observed. CER resonances related to InGaAsP QW1 could be analyzed using the low-field electromodulation Lorentzian line shape functional form [8]

$$\frac{\Delta R}{R}(E) = \mathrm{Re}\left[\sum_{j=1}^{n} C_j e^{i\vartheta_j}\left(E - E_j + i\Gamma_j\right)^{-m_j}\right] \tag{1}$$

where n is the number of optical transitions and spectral functions used in the fitting procedure, C_j and ϑ_j are the amplitude and phase of the line shape, and E_j and Γ_j are the energy and the broadening parameter of transitions, respectively. We assumed that $m = 3$, which corresponds to one electron absorption in two dimensional systems. The fitting curves are shown by the bold line in Fig. 2**b** together with the modulus of the individual resonance (Fig. 2**c**) obtained according to the following equation:

$$|\Delta\rho(E)| = \frac{|C|}{\left[\left(E - E_0\right)^2 + \Gamma^2\right]^{m/2}}. \tag{2}$$

It is worth noting that the plot of the modulus of individual resonances helps to state whether or not the fit is correct. Therefore, we selected Lorentzian line-shape which gives a simple formula for the modulus. It is well known that the Gaussian line-shape is more appropriate at room temperature. However, our experience with the fitting shows that both Lorentzian and Gaussian lines give the same transition energy within experimental error.

We have found that the part of CER spectrum related to InGaAsP QW1 (from 0.75 to 0.95 eV) could be satisfactorily fitted by three resonances. The identification of the resonances was possible on the basis of calculations within the framework of the usual envelope function approximation [13]. Parameters used in calculation have been assumed after [14].

On the basis of the calculations, it has been concluded that only one electron state is confined in the QW1 and three (one) states are confined in the heavy (light) hole

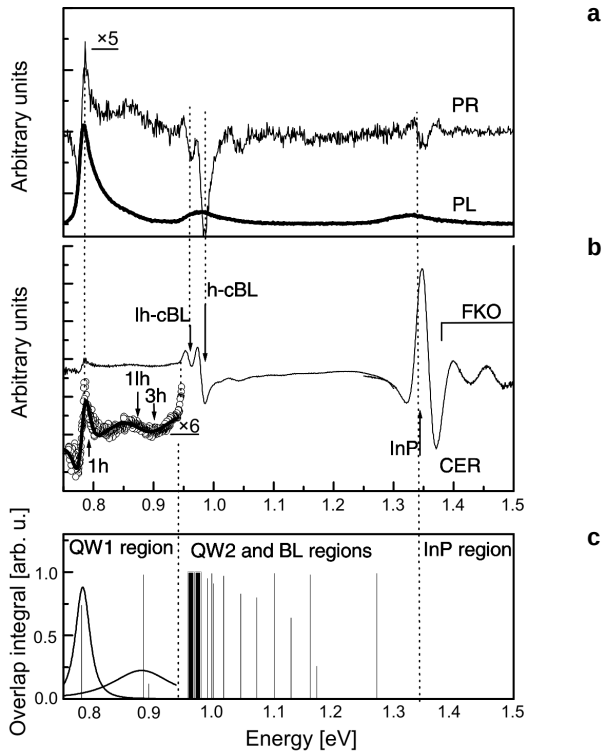

Fig. 2. Room temperature photoreflectance, luminescence (**a**), and electroreflectance spectra of InGaAsP QW structure (**b**); theoretical (vertical lines) and experimental (Lorentzian lines) optical transitions intensities (**c**).

QW1. The notation *h*(*l*)*m*-*e*1 indicates a transition between the *m*-th valence state of heavy hole (or light hole) and the first electron state. The numerical results obtained with calculated potential (see Fig. 3) are presented in Fig. 2.

The first resonance associated with the *h*1-*e*1 transition is observed at 0.782 eV (theoretical 0.783 eV). The *h*2-*e*1 transition is forbidden, but due to the internal electric field and/or interface roughness selection rules can be broken and this transition can be observed. From theoretical considerations this transition is expected at 0.825 eV but oscillator strength calculated for this transition is almost equal zero, thus this transitions is absent in the CER spectra. The second resonance at 0.882 eV (theoretical 0.883 eV) is associated with *l*1-*e*1 transition and it merges with third resonance, at 0.901 eV (theoretical 0.892 eV), associated with the *h*3-*e*1 transition. As can be observed in Fig. 2**c**, presenting theoretically (vertical lines) as well as experimentally (Lorentzian lines) the oscillator strengths obtained for the observed optical transitions, dominant contribution in observed resonance comes from the light hole transition.

Features in the range from 0.95 to 1.35 eV are more complicated to explain. This is due to the fact that they could be a superposition of transitions of different nature (2D like and/or 3D like transitions) associated with $In_{0.72}Ga_{0.28}As_{0.87}P_{0.13}$ BL and from

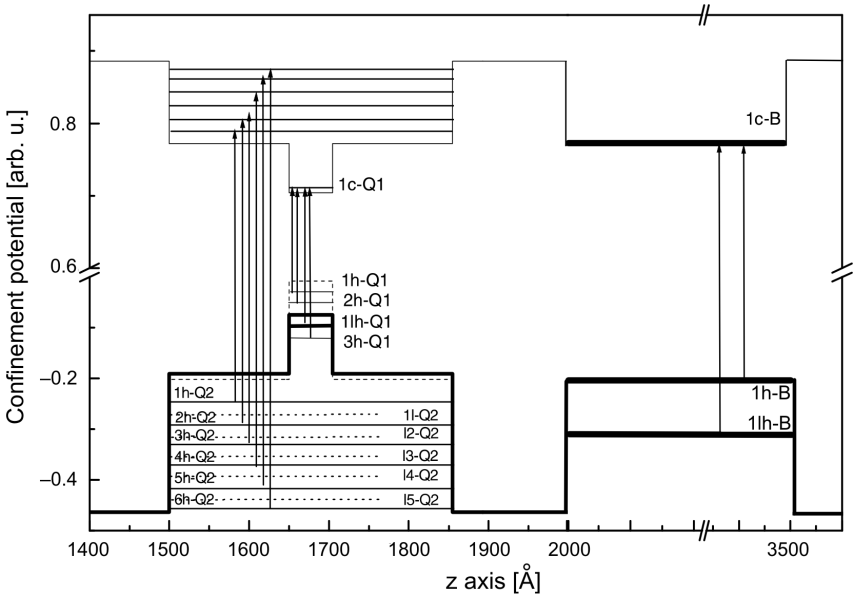

Fig. 3. Calculated confinement potential and energy levels obtained theoretically for three different quantum wells: for well defined quantum regime (L_z = 55 A), for quasi-quantum regime (L_z = 355 A), and for quasi-bulk regime (L_z = 1500 A).

QW2. However, two transitions at 0.962 eV and 0.974 eV have been attributed to the light hole and heavy hole transitions, respectively, associated with the bulk $In_{0.72}Ga_{0.28}As_{0.87}P_{0.44}$ layer. As can be observed from Fig. 2**c**, the oscillator strengths for these transitions (two bold lines) are equal. These transitions can also merge with *l*1-*e*1 (theoretically 0.997eV) and *h*1-*e*1 (theoretically 0.992 eV).

Also from Fig. 2**b**, the transition associated with InP substrate can be observed together with the Franz–Keldysh oscillations.

4. Conclusions

In this work, InGaAsP quantum well structure has been investigated using electroreflectance, photoluminescence and photoreflectance spectroscopy. Based on the numerical calculations the origin of the observed optical transition has been explained. The advantages of electroreflectance in comparison with photoreflectance have also been presented.

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Received June 6, 2005