Optica Applicata, Vol. XXIX, No. 3, 1999

Photoreflectance spectra of MOVPE-grown $In_xGa_{1-x}As/GaAs$ MQW — the temperature dependence

Grzegorz Sęk, Jan Misiewicz

Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50–370 Wrocław, Poland.

Damian Radziewicz, Ryszard Korbutowicz, Marek Tłaczała

Institute of Microsystem Technology, Wrocław University of Technology, ul. Janiszewskiego 11, 50–370 Wrocław, Poland.

Strained $In_xGa_{1-x}As/GaAs$ multiple quantum well (MQW) structure grown by metal-organic vapour phase epitaxy (MOVPE) has been investigated by photoreflectance (PR) spectroscopy. Both, the heavy and light hole related confined transitions have been observed. On the basis of theoretical calculations, in the envelope function formalism, including strain effects and exciton binding energy we have found that the existence of type II light hole exciton in our type I MQW system has to be considered. The temperature dependence (92 – 300 K) of heavy hole (direct) and light hole (indirect) transition has been discussed in terms of semiempirical Varshni and Bose–Einstein expressions.

1. Introduction

The lattice constant of $In_xGa_{1-x}As$ does not match that of GaAs. If the thickness is below a critical value, lattice mismatch can be accommodated by elastic strain and thus the growth of dislocation-free structures can be achieved. For thin layers grown pseudomorphically, the strain induces a significant change in the electronic band structure. The strain shifts the edges of conduction and valence bands. As a result, the positions of the subband in the quantum well are affected, so do the energies of the optical transitions between the conduction and valence subbands. The electrons and heavy holes are confined in the $In_xGa_{1-x}As$ layers forming a type I heterostructure, and because of the strain, the light holes may be confined in the $In_xGa_{1-x}As$ or GaAs layers, giving respectively a type I [1], [2] or type II [3] – [7] system depending on the band offset ratio.

Modulation spectroscopy, particularly photoreflectance, has become a very powerful technique to study a large number of quantized states in a MQW structure. In the PR (contactless form of electromodulation) modulation of the built-in electric field in the sample is caused by photoexcited electron–hole pairs created by a pump source (laser or other light source) which is chopped at frequency f_m. This procedure results in sharp derivative-like spectral features in the region of intersubband transitions [8], [9]. In general, the normalized change in the reflectivity measured in the PR experiment is related to the modulated dielectric function $\varepsilon = \varepsilon_1 + i\varepsilon_2$ by [10]

$$\frac{\Delta R}{R} = \alpha(\varepsilon_1, \varepsilon_2)\Delta\varepsilon_1 + \beta(\varepsilon_1, \varepsilon_2)\Delta\varepsilon_2 \tag{1}$$

where α and β are the Seraphin coefficients. The quantities $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ are the changes in the real and imaginary parts of the dielectric function, respectively, induced by the periodic modulating electric field created by the pump beam. It has been shown that for bound states such as excitons or the confined states of a quantum well, the change of the dielectric function $\Delta\varepsilon$ exhibits a first-derivative spectrum. For excitons the dielectric function will have either a Lorentzian or Gaussian profile depending on whether the broadening is homogeneous or inhomogeneous, respectively. Moreover, there is strong experimental evidence for the excitonic character, even at room temperature, of the transitions associated with carrier quantum confinement [11], [12] and for a Gaussian broadening, more appropriate than a Lorentzian one, of such transitions at high temperatures ($T \geqslant 77$ K), [9], [13].

2. Experimental

The $In_{0.115}Ga_{0.885}As/GaAs$ MQW sample was grown by MOVPE technique on (100) oriented, semi-insulating GaAs substrate. The growth was performed under atmospheric pressure and at 670 °C temperature of the substrate in the system equipped with AIX-200 R&D horizontal Aixtron reactor. The structure consisted of 300 nm thick buffer followed by five periods of $In_{0.115}Ga_{0.885}As/GaAs$ layers and capped with 80 nm thick undoped GaAs layer. The $In_{0.115}Ga_{0.885}As$ and GaAs layer thicknesses were 10 and 80 nm, respectively.

The PR measurements at near-normal incidence were performed in the 1.3–1.6 eV range with energy step and spectral resolution below 1 meV. The standard experimental apparatus [14], [15] (see Fig. 1) consisted of a 150 W halogen lamp filtered by a double-grating GDM1000 monochromator as a probe source. The modulating beam came from a 15 mW He-Ne laser ($\lambda = 632.8$ nm) mechanically chopped at frequency of 120 Hz. The laser intensity was reduced to about 1 mW/cm^2 by using a neutral density filter to avoid a photovoltaic effect and heating of the sample. The reflected light was detected by a Si photodiode whose output was fed into a Stanford SR530 lock-in amplifier. Both ac and dc outputs were digitized and stored in a PC microcomputer which also controlled the monochromator step. The sample was mounted on the cold finger of a continuous-flow refrigerator coupled with a programmable temperature controller, allowing measurements in the 80–300 K temperature range.

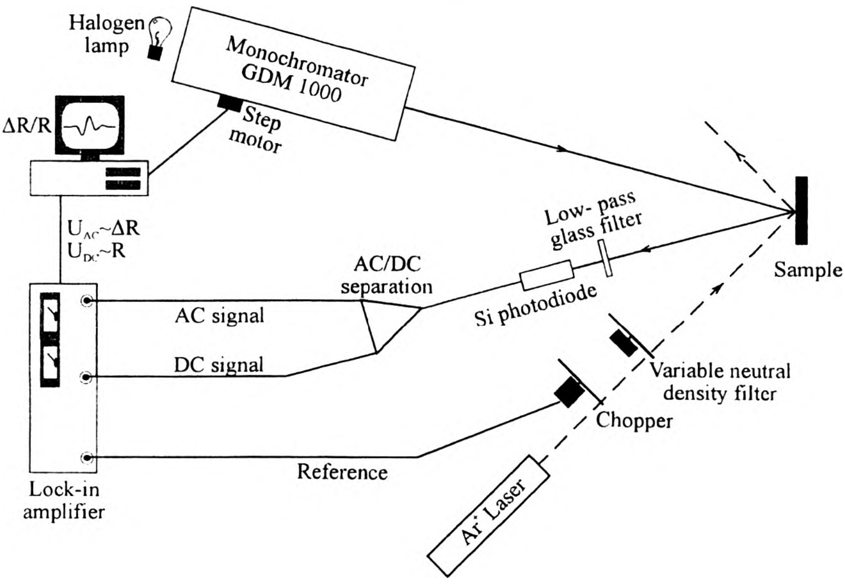

Fig. 1. Scheme of the set-up for photoreflectance measurements.

3. Results and discussion

Figure 2 shows the room temperature PR spectrum of the investigated MQW. Three transitions are observed. The feature near the energy of 1.42 eV is related to the band gap transition in GaAs material. The other two features are related to transitions involving confined states in MQW. The transitions are interpreted as 11H and 11L, where notation *mn*H(L) means the transition between *m*-th conduction and *n*-th valence subbands. The experimental energies were obtained from the fitting procedure for the first derivative of Gaussian lineshape, the most appropriate form of PR resonance for excitonic transitions in quantum wells [9]. In order to interpret the transitions obtained, theoretical calculations were performed on the basis of the envelope function approximation including strain effects [16], [17]. In the $In_{0.115}Ga_{0.885}As/GaAs$ system, the thickness of $In_{0.115}Ga_{0.885}As$ layer should be smaller than 180 Å to obtain good quality layers [18], where the lattice mismatch is totally accommodated by elastic strain. In this limit, for our structure, only the $In_{0.115}Ga_{0.885}As$ layers are strained and the GaAs layers can be taken to be unstrained. Because of the thick GaAs barriers (800 Å) also any miniband dispersion effects (superlattice effects) were neglected. The valence band offset (Q_v) was treated as a parameter and was estimated from the best agreement between experiment and theory for 11H transition, including exciton binding energy of 8 meV [3], [19]. The value of Q_v was determined to be 0.33, being a very well acceptable value in the literature [4], [5], [20], [21]. This value implies that the light hole transition has to be of type II, which was reported previously for this structure [6], and gives the light hole exciton binding energy of 3 meV, being in good agreement with that reported

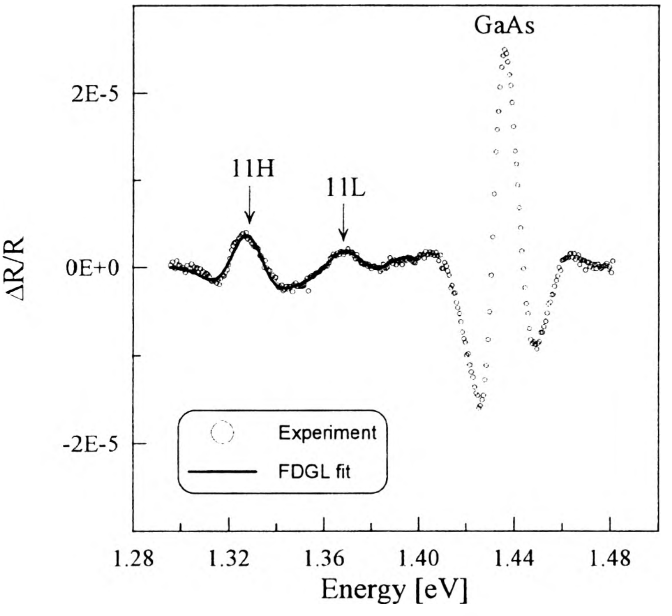

Fig. 2. Room temperature PR spectrum of $In_{0.115}Ga_{0.885}As/GaAs$ MQW. Open circles — experiment, solid line — fit according to the first derivative of Gaussian lineshape.

in [3]. The values of transition energies for the case of room temperature are presented in Tab. 1. The material parameters used in the calculations have been taken after ADACHI [22], [23] and are summarized in Tab. 2. For the ternary alloy $In_xGa_{1-x}As$ they were linearly interpolated between the corresponding values of the binary compounds.

Table 1. The comparison of experimental and theoretical transition energies for room temperature. In parenthesis, the values of exciton binding energies taken in the calculations are shown.

Transition	Experimental transition energy [eV]	Theoretical transition energy [eV]
11H	1.328	1.327(8)
11L	1.371	1.371(3)

Table 2. Values of the material parameters used in the calculations. C_{ij} — elastic stiffness constants, a, b — deformation potentials.

Material	Band gap [eV]	Lattice constant [Å]	C_{11} [10^{11}dyn/cm^2]	C_{12} [10^{11}dyn/cm^2]	a [eV]	b [eV]
InAs	0.354	6.0584	8.33	2.53	−5.80	−1.80
GaAs	1.424	5.6533	11.88	5.32	−9.80	−1.76

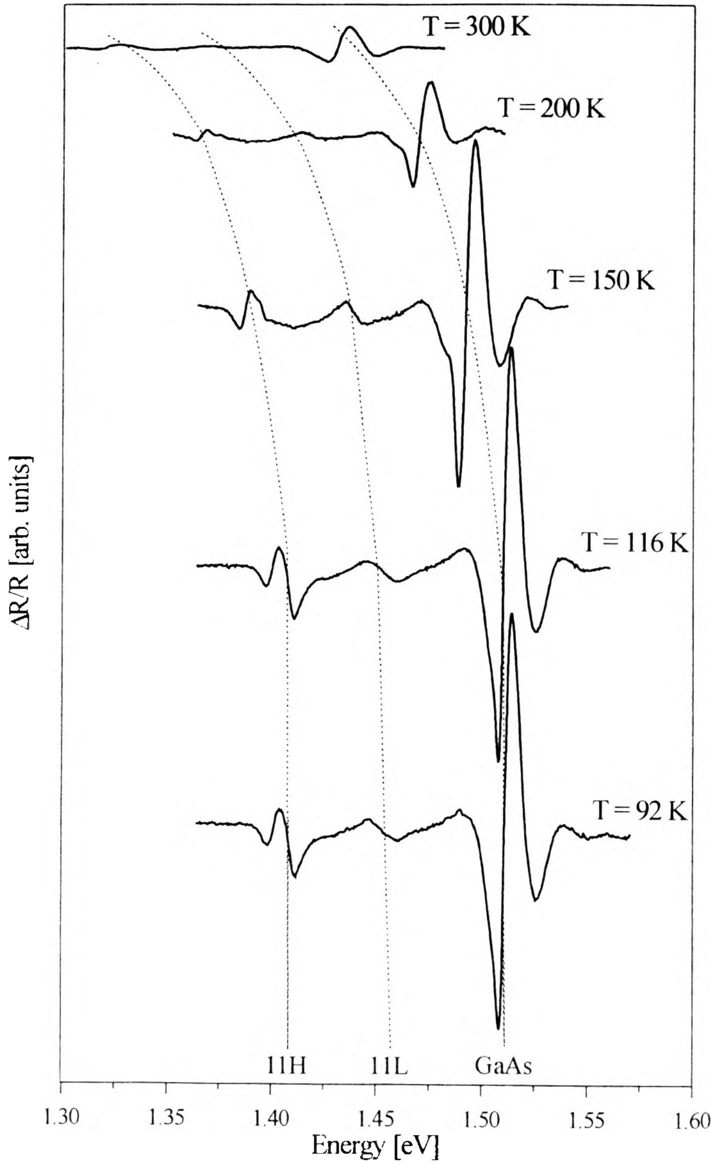

Fig. 3. PR spectra of $In_{0.115}Ga_{0.885}As/GaAs$ MQW as a function of temperature in the range 92 – 300 K.

In Figure 3, the temperature dependence of PR spectrum of the investigated MQW is shown, in the temperature range 92 – 300 K. With the temperature increase a natural decrease of PR amplitude and the red shift of energy are observed for all features. For analysing the temperature dependence of energy of transitions in MQW, a plot of transition energy versus temperature is also presented in Fig. 4. This temperature dependence was analysed in terms of semi-empirical Varshni and

Bose–Einstein expressions. The solid lines are least-squares fits to the Varshni relation (after [9])

$$E(T) = E_0(0) - \alpha T^2/(\beta + T). \tag{2}$$

Table 3. Values of the parameters of $E(T)$ dependence from Eqs. (2) and (3).

Transition	$E_0(0)$ [eV]	α [10^{-4}eV/K]	β [10^{-4}eV/K]	E_B [eV]	a_B [meV]	Θ_B [K]
11H	1.423	5.7	195	1.469	49	203
11L	1.471	6.0	181	1.519	53	206

The values of $E_0(0)$, α and β obtained for both confined transitions are listed in Tab. 3. The values of α and β for our sample were found to be similar to those for bulk GaAs [24] and $In_xGa_{1-x}As$ with various x [24], [25]. This shows that the main influence of the temperature on the energy of the confined transitions in MQW (direct 11H as well as indirect 11L) is through the temperature dependence of the band gap of the constituent material in the well.

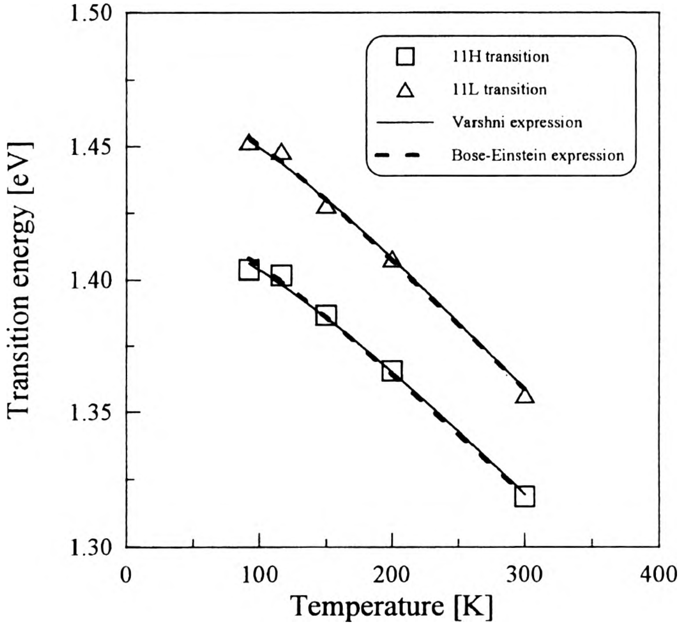

Fig. 4. Temperature dependence of energy of 11H (rectangles) and 11L (triangles) transitions. Solid line – fit according to the Varshni expression (Eq. (2)), dashed line – fit according to the Bose–Einstein expression (Eq. (3)).

The data were also fit to Bose–Einstein expression (dashed lines in Fig. 4) proposed by Lautenschlager *et al.* [26]

$$E(T) = E_B - a_B\{1 + 2/[\exp(\Theta_B/T) - 1]\tag{3}$$

where a_B represents the strength of the electron-average phonon (optical and acoustical) interaction and Θ_B corresponds to the average phonon temperature. Our numbers for E_B, a_B and Θ_B are given in Tab. 3. The parameters obtained by us are again similar to those of GaAs [24], $In_xGa_{1-x}As$ layers [24], [25] and quantum wells [27] for different indium content. Such a result confirms also that the temperature dependence of confined transitions is mainly through the temperature dependence of the energy gap of the quantum well material for both direct (11H) and indirect (11L) transitions. There is no influence of the confinement on the character of the temperature dependence of the given transition. One would also expect a difference in the temperature dependence of a direct and indirect exciton, but unfortunately this was not confirmed in our case, probably because of too small difference between temperature coefficients of GaAs barrier and $In_{0.115}Ga_{0.885}As$ well materials.

4. Conclusions

In this work, the $In_{0.115}Ga_{0.885}As$/GaAs MQW structure was investigated by using photoreflectance spectroscopy. There was found clear evidence for type II of light hole exciton in our type I (for heavy holes) MQW structure. We also obtained the valence band offset value of 0.33, which agrees very well with the previous reports. From the temperature dependence of 11H and 11L transitions some fundamental constants of electron–phonon coupling were derived. The parameters from temperature dependence appeared to be very similar to those of GaAs and $In_xGa_{1-x}As$ for different x values. No significant influence has been found of the carrier confinement and spatial character of the transition on the character of the temperature dependence. This study of the temperature variation of these excitonic transition energies shows that the main influence of temperature on quantized transitions is through the temperature dependence of the band gap of the quantum well material.

Acknowledgements — This paper was partly supported by Centre for Advanced Materials and Nanotechnology, Wrocław Universiy of Technology, Poland, and National Committee for Scientific Research (KBN), grant No. PB2-028.11.

References

[1] MENÉNDEZ J., PINCZUK A., WERDER D. J., SPUTZ S. K., MILLER R. C., SIVCO D. L., CHO A. Y., Phys. Rev. B **36** (1987), 8165.
[2] JOYCE M. J., XU Z. Y., GAL M., Phys. Rev. **B 44** (1991), 3144.
[3] MARZIN J. Y., CHARASSE M. N., SERMAGE B., Phys. Rev. B **31** (1985), 8398.
[4] JI G., HUANG D., REDDY U. D., HENDERSON T. S., HOUDRÉ R., MORKOÇ H., J. Appl. Phys. **62** (1987), 3366.
[5] PAN S. H., SHEN H., HANG Z., POLLAK F. H., ZHUANG W., XU Q., ROTH A. P., MASUT R. A., LACELLE C., MORRIS D., Phys. Rev. B **38** (1988), 3375.
[6] SĘK G., MISIEWICZ J., RADZIEWICZ D., TŁACZAŁA M., PANEK M., KORBUTOWICZ R., Vacuum **50** (1998), 199.
[7] MORAN M., DAWSON P., MOORE K. J., Solid State Commun. **107** (1998), 119.

[8] GLEMBOCKI O. J., SHANABROOK B. V., *Semiconductors and Semimetals*, Vol. 36, [Eds.] D. G. Seiler and C. L. Littler, Academic, New York 1992, p. 221.
[9] POLLAK F. H., *Handbook on Semiconductors*, Vol. 2, [Ed.] M. Balkanski, North-Holland, Amsterdam 1994, p. 527.
[10] SERAPHIN B. O., BOTTKA N., Phys. Rev. **145** (1966), 628.
[11] SHANABROOK B. V., GLEMBOCKI O. J., BEARD W. T., Phys. Rev. B **35** (1987), 2540.
[12] SHEN H., PAN S. H., POLLAK F. H., SACKS R. N., Phys. Rev. B **37** (1988), 10919.
[13] GLEMBOCKI O. J., Proc. SPIE **1286** (1990), 2.
[14] MISIEWICZ J., JEZIERSKI K., SITAREK P., MARKIEWICZ P., KORBUTOWICZ R., PANEK M., ŚCIANA B., TŁACZAŁA M., Adv. Mater. Opt. Electron. **5** (1995), 321.
[15] MISIEWICZ J., SĘK G., CIORGA M., SITAREK P., KANIEWSKA M., REGIŃSKI K., MUSZALSKI J., Electron. Technol. **29** (1996), 139.
[16] BASTARD G., Phys. Rev. B **25** (1982), 7584.
[17] BASTARD G., *Wave Mechanics Applied to Semiconductor Heterostructures*, Les Editions de Physique, New York 1988, p. 31.
[18] FITZGERALD E. A., *Properties of Lattice-Matched and Strained Indium Galium Arsenide*, [Ed.] P. Bhattacharaya, Vol. 8, Inspec, London 1993, p. 6.
[19] HOU H. Q., SEGAWA Y., AOYAGI Y., NAMBA S., ZHOU J. M., Phys. Rev. B **42** (1990), 1284.
[20] DUTTA M., PAMULAPATI J., *Properties of Lattice-Matched and Strained Indium Galium Arsenide*, [Ed.] P. Bhattacharaya, Vol. 8., Inspec, London 1993, p. 199.
[21] ARNAUD G., ALLEGRE J., LEFEBVRE P., MATHIEU H., HOWARD L. H., DUNSTAN D. J., Phys. Rev. B **46** (1992), 15290.
[22] ADACHI S., J. Appl. Phys. **53** (1982), 8775.
[23] ADACHI S., J. Appl. Phys. **58** (1985), R1.
[24] HANG Z., YAN D., POLLAK F. H., PETTIT G. D., WOODALL J. M., Phys. Rev. B **44** (1991), 10546.
[25] CHEN J. H., CHI W. S., HUANG Y. S., YIN Y., POLLAK F. H., PETTIT G. D., WOODALL J. M., Semicond. Sci. Technol. **8** (1993), 1420.
[26] LAUTENSCHLAGER P., GARRIGA M., LOGOTHETIDIS S., CARDONA M., Phys. Rev. B **35** (1987), 9174.
[27] CHI W. S., HUANG Y. S., QIANG H., POLLAK F. H., PETTIT D. G., WOODALL J. M., Jpn. J. Appl. Phys. **33** (1994), 966.

Received January 11, 1999