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Optical properties of InGaAs/GaAs quantum wells with different distance from Si-delta-doping layer

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$In_{0.22}Ga_{0.78}As/GaAs$ single quantum wells with different distance from a delta doped layer have been investigated by using contactless electroreflectance (CER) spectroscopy. The oscillator strength of optical transitions and the value of the built-in electric field have been determined from CER spectra. Obtained results have been compared with theoretical calculations preformed in the framework of the effective mass approximation. In order to accurately find the wavefunctions of electrons and holes confined in the quantum well embedded in the built-in electric field, the time-dependent Schrödinger equation has been solved.

Keywords: quantum well, contactless electroreflectance, built-in electric field, delta-doping.

1. Introduction

Contactless electroreflectance (CER) spectroscopy [1, 2], 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 [3–6]. 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 probes the ground state only. 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 a very small oscillator strength like nominally parity forbidden ones.

Semiconductor structures with quantum wells (QW) are very important components of semiconductor devices. The distance between surface and QW has a strong influence on the optical properties of QW due to an existence of surface electric fields. In case of InGaAs QWs with delta-doping layers we have a situation that the built-in electric field changes strongly the profile of the QW and energy levels. CER spectroscopy is the experimental method which can be used in the investigations of the optical transitions in QWs as well as in the built-in electric fields. In our work, we have applied this technique to determine the built-in electric field, the energy and intensity of QW transitions in a set of $In_{0.22}Ga_{0.78}As$/GaAs QWs embedded in homogeneous electric field which arises between sample surface and Si delta-doping layer. In our investigations, we have found that the intensity of the optical transitions for investigated samples does not follow the well-known selection rules which are characteristic of rectangular QWs. The intensity of the optical transitions was obtained from CER spectra and compared with theoretical calculations. These calculations were performed using effective mass approximation for rectangular QWs in electric field. We have determined the value of the built-in electric field from the analyses of Franz–Keldysh oscillations (FKO) observed in CER spectra.

2. Experimental details

There are many types of modulation techniques depending on the source of modulation. In photoreflectance (PR) [7, 8] the modulation is caused by photo-injected electron-hole pairs which modulate the built-in electric fields of the microstructure. In CER measurement the sample is placed between two capacitor plates and built-in electric fields are modulated by an external one. In the contactless electroreflectance measurement the top electrode was made of a transparent Cu grating and kept at a distance of 0.2 mm from the sample surface, while the sample back side was fixed on the cuprum electrode. A maximum peak-to-peak alternate voltage of 0.9 kV was applied. Phase sensitive detection of the CER signals was made using a lock-in amplifier. Other relevant details of the experimental set-up have been described in [7–10]. All the measurements were performed at room temperature.

Samples used in this study were grown by metal-organic vapor phase epitaxy (MOVPE) on a semi-insulating GaAs substrate. The active region is composed of a 100 Å thick $In_{0.22}Ga_{0.78}As$ QW with GaAs barriers. Sample *A* was grown without

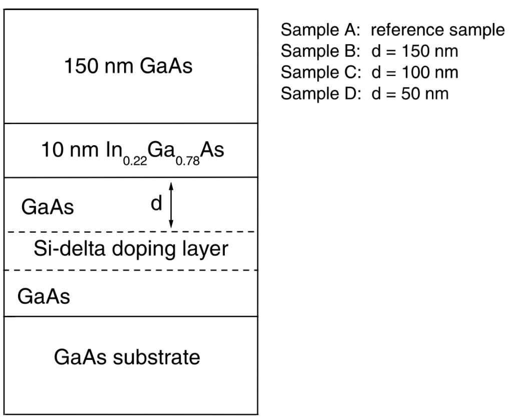

Fig. 1. Layer structure of the samples.

Si delta-doping layer. Samples *B*, *C*, *D* contain Si delta-doping layer in different distance from the QW. The distance is 150, 100 and 50 nm for sample *B*, *C* and *D*, respectively. The layer structure of the samples is shown in Fig. 1.

3. Experimental results and discussion

Figure 2 shows CER spectra of investigated structures recorded at room temperature. In these spectra we can observe an oscillating-like feature at 1.424 eV which is related to the optical transition through the band gap of GaAs bulk-like (thick) layer. The FKO are typically observed in absorption type spectra of bulk materials in an electric field. The value of the built-in electric field of investigated samples was determined from FKO period. A plot of $(4/3\pi)[(E_n - E_g)/(\hbar\Theta)]^{3/2}$ [11] against the extreme number *n* should be a straight line, as can be seen in Fig. 3. From the slope of this line it is possible to obtain the electro-optic energy of an electron with mass equal to the reduced effective mass μ in the direction of electric field *F*. The electrooptic energy is defined as

$$(\hbar\Theta)^3 = \frac{e^2\hbar^2F^2}{2\mu}. \tag{1}$$

The electric field values determined by using the above method are equal to $F = 16.7$, 25.1, 31.1 and 43.2 kV/cm for sample *A*, *B*, *C* and *D*, respectively.

Bellow GaAs resonance one can see lines associated with QW transitions. In this study, we have focused on the two lowest energy transitions which are the fundamental QW transitions (between the first heavy hole and the first electron subbands (11H) and the first parity forbidden one, *i.e.*, occurring between the second heavy hole and the first electron subbands (21H)). The properties of PR lines related to both of them have

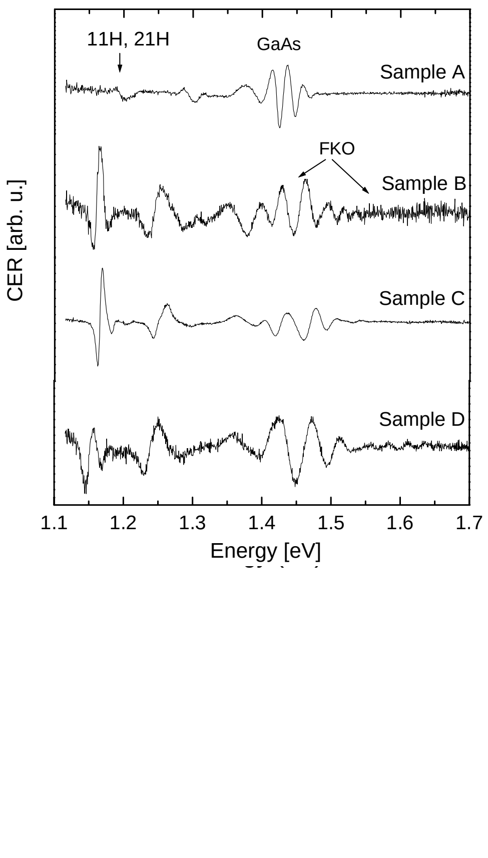

Fig. 2. Contactless electroreflectance spectra for all samples.

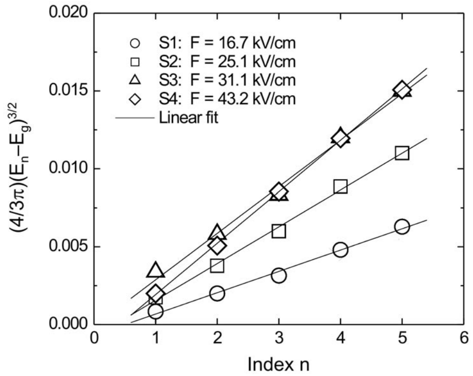

Fig. 3. Built-in electric field determined from FKO period.

been derived using the low-field electromodulation Lorentzian line shape functional form fitting procedure [7, 12]

$$\frac{\Delta R}{R}(E) = \mathrm{Re}\left[\sum_{j=1}^{n} C_j \exp(i\vartheta_j)\left(E - E_j + i\Gamma_j\right)^{-m_j}\right] \tag{2}$$

where n is the number of the optical transition and spectral function 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 the transitions, respectively. We assumed that $m = 3$, which corresponds to one electron absorption in two-dimensional systems. Examples of fitting curves are shown by dotted line in Fig. 4 together with the modulus of individual resonances associated with 11H and 21H transitions. The modulus of the PR spectra was obtained using the following equation:

$$|\Delta\rho(E)| = \frac{|C|}{\left[\left(E - E_0\right)^2 + \Gamma^2\right]^{m/2}}. \tag{3}$$

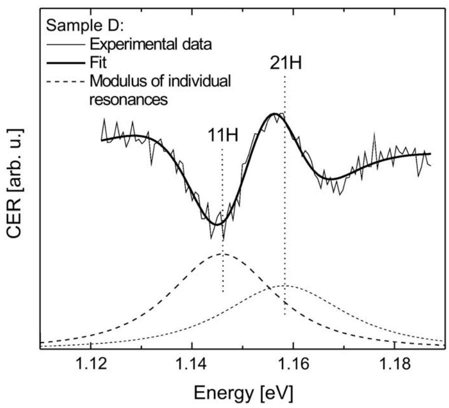

Fig. 4. Fit and resonance associated with 11H and 21H transitions for sample *D*.

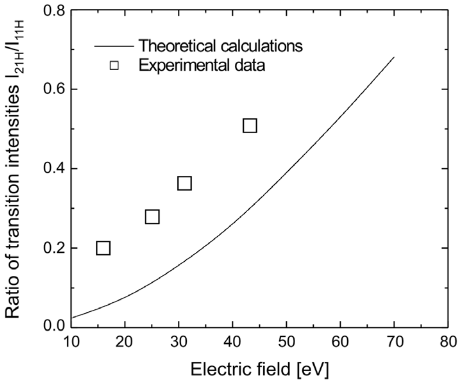

Fig. 5. Ratio of intensity of 21H transition to intensity of 11H transition as a function of electric field.

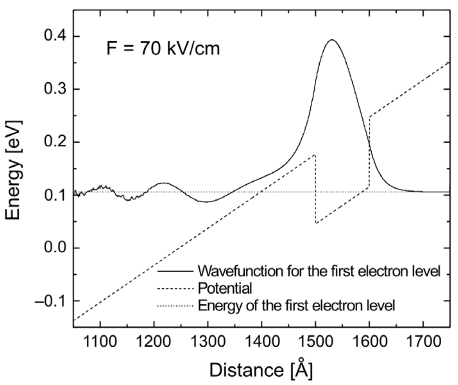

Fig. 6. Wavefunction for the first electron level (solid line), shape of QW potential (dashed line) and the energy of the first electron level (dotted line) obtained on the basis of theoretical calculations performed for a InGaAs/GaAs QW under the electric field of 70 kV/cm.

The integrated intensity of the modulus corresponds to transition intensity. It is worth to notice that the plot of the modulus of individual resonances helps to decide if the fit is correct. Intensities of 11H and 21H transitions were determined from CER spectra and compared with theoretical calculations. Calculations were performed in the framework of the effective mass approximation for rectangular QWs in electric field. We have solved the problem of QW embedded in electric field. When a QW system is subjected to electric field the energy levels become shifted. Moreover, in the presence of even the smallest electric field, there are no strictly confined states in the system [13, 14]. There are many methods which describe properties of QWs as a function of an applied field [15, 16]. We used a method of ZAMBRANO and ARCE [16] which is based in principle on integration of time-dependent Schrödinger equation. We have calculated the overlap integral for optical transitions and hence derived a number which is proportional to the intensity of optical transition.

Figure 5 shows a ratio of 21H and 11H transition intensities as a function of the built-in electric field. The intensity of 21H transition increases with increasing value of the electric field. As it is seen, the experimental data is in good agreement with theoretical calculation results. An example of calculated wave function for the first electron level for QW embedded in the electric field of 70 kV/cm is shown in Fig. 6.

4. Conclusions

A set of InGaAs/GaAs quantum wells with different distance from Si delta-doping layer was investigated. Our results have shown that electric field significantly influences the optical transitions. It has been observed that with the increase in the electric field the intensity of 11H transition decreases while the intensity of 21H transition increases.

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References

[1] AIGOUY L., HOLDEN T., POLLAK F.H., LEDENTSOV N.N., USTINOV W.M., KOPEV P.S., BIMBERG D., *Contactless electroreflectance study of a vertically coupled quantum dot-based InAs/GaAs laser structure*, Applied Physics Letters **70**(25), 1997, pp. 3329–31.

[2] MUNOZ M., GUO S., ZHOU X., TAMARGO M.C., HUANG Y.S., TRALLERO-GINER C., RODRIGUEZ A.H., *Contactless electroreflectance of CdSe/ZnSe quantum dots grown by molecular-beam epitaxy*, Applied Physics Letters **83**(21), 2003, pp. 4399–401.

[3] MISIEWICZ J., KUDRAWIEC R., MOTYKA M., ANDRZEJEWSKI J., GOLLUB D., FORCHEL A., *Photo- and contactless electro-reflectance spectroscopies of step-like GaInNAs/Ga(In)NAs/GaAs quantum wells*, Microelectronic Journal **36**(3-6), 2005, pp. 446–9.

[4] YIN X., POLLAK F.H., *Novel contactless mode of electroreflectance*, Applied Physics Letters **59**(18), 1991, pp. 2305–7.

[5] GAL M., SHWE C., *Novel contactless electroreflectance spectroscopy of semiconductors*, Applied Physics Letters **56**(6), 1990, pp. 545–7.

[6] YIN X., XINXIN-GUO, POLLAK F.H., PETTIT G.D., WOODALL J.M., CHIN T.P., TU C.W., *Nature of band bending at semiconductor surfaces by contactless electroreflectance*, Applied Physics Letters **60**(11), 1992, pp. 1336–8.

[7] POLLAK F.H., [In] *Handbook on Semiconductors*, T.S. Moss [Ed.], Vol. 2, Elsevier Science, Amsterdam 1994, pp. 527–635.

[8] MISIEWICZ J., SITAREK P., SĘK G., KUDRAWIEC R., *Semiconductor heterostructures and device structures investigated by photoreflectance spectroscopy*, Materials Science **21**(3), 2003, pp. 263–318.

[9] POLLAK F.H., *Contactless electromodulation and surface photovoltage spectroscopy for the nondestructive, room temperature characterization of wafer-scale III-V semiconductor device structures*, Materials Science and Engineering B: Solid State Materials for Advanced Technology **B80**(1-3), 2001, pp. 178–83.

[10] KUDRAWIEC R., GLADYSIEWICZ M., MOTYKA M., MISIEWICZ J., YUEN H.B., BANK S.R., WISTEY M.A., BAE H.P., HARRIS J.S. JR, Applied Surface Science, in press.

[11] SHEN H., POLLAK F.H., *Generalized Franz–Keldysh theory of electromodulation*, Physical Review B: Condensed Matter **42**(11), 1990, pp. 7097–102.

[12] ASPNES D.E., *Third-derivative modulation spectroscopy with low-field electroreflectance*, Surface Science **37**, 1973, pp. 418–42.

[13] BASTARD G., MENDEZ E.E., CHANG L.L., ESAKI L., *Variational calculations on a quantum well in an electric field*, Physical Review B: Condensed Matter **28**(6), 1983, pp. 3241–5.

[14] AUSTIN E.J., JAROS M., *Electronic structure of an isolated GaAs-GaAlAs quantum well in a strong electric field*, Physical Review B: Condensed Matter **31**(8), 1985, pp. 5569–72.

[15] JUANG C., KUHN K.J., DARLING R.B., *Stark shift and field-induced tunneling in* $Al_xGa_{1-x}As/GaAs$ *quantum-well structures*, Physical Review B: Condensed Matter **41**(17), 1990, pp. 12047–53.

[16] ZAMBRANO M.L., ARCE J.C., *Stark-resonance densities of states, eigenfunctions, and lifetimes for electrons in GaAs/(Al,Ga)As quantum wells under strong electric fields: an optical-potential wave-packet propagation method*, Physical Review B: Condensed Matter and Materials Physics **66**(15), 2002, pp. 155340–9.

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