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Exciton-Induced Dispersion of Electroreflectance in a GaAs/AlAs Quantum Well Structure at Room Temperature

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Observed electroreflectance spectra for a GaAs/AlAs quantum well structure show very clear exciton-induced features at room temperature. A maximum rate for the field-induced modulation of refractive index, $\Delta n/n/E$ in each quantum well is deduced to be 4 %/10^5V/cm at a photon energy close to excitonic gap. Such a large variation in refractive index is attributed to excitonic transitions.

Since the first observation of field-induced quenching of photoluminescence from an AlGaAs quantum well (QW) structure[1], field effects on optical properties of QW structures have been attracting a great deal of attentions. The field effects with a favorable high speed switching capability may play an important role for a unique and sophisticated combination of optics with microelectronics in near future. A couple of field-effect devices such as a light emitter[2], an optical loss modulator[3], an electro-optic bistable device[4] and a total-internal-reflection switch[5] were proposed and/or demonstrated. Previously, efforts have been mainly concentrated on investigations of field-induced changes in luminescence and absorption coefficient of QW structures. Experimental data on field-induced variations in refractive index of QW structures are, also, quite important for designing field-controlled optical devices, such as the total-internal-reflection switch[5], in which the refractive index changes are made use of. Recently, the electro-optic coefficients of an AlGaAs multi-quantum well (MQW) structure have been measured at a fixed photon energy, 50 meV far below excitonic gap[6]. Electroreflectance (ER) measurements for QW structures[7),8] are quite interesting from the point of view of understanding the field-induced variations in the refractive index over a wide wavelength range, particularly, involving the excitonic gap. In this paper, we shall report ER spectra of a GaAs/AlAs MQW structure, associated with the n=1 (fundamental) transitions, at intermediate fields and at room temperature, demonstrating very clear exciton-induced features of the variations in refractive index, and resulting in a maximum rate, $\Delta n/n/E$= 4 %/10^5V/cm, for the field-induced modulations of refractive index in each quantum well at a photon energy near electron-to-heavy hole excitonic gap. This is the first assignment of field-induced variations in refractive index of QW structures at excitonic gap energies.

The ER measurements were performed with normal incidence configuration for Schottky

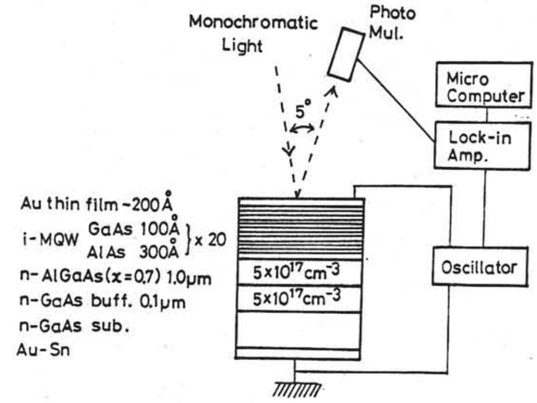

Fig.1 Sample configuration and experimental arrangements.

barrier samples with a 20 periods MQW structure consisting of 100 Å GaAs wells and 300 Å AlAs barriers as shown Fig.1. A monochromated light source with a power density of 1.5×10^{-4} W/cm^2 was used. The n-doped $Al_{0.7}Ga_{0.3}As$ ($\sim$1.0 μm) and the undoped MQW structure were sequentially grown on an n-type GaAs substrate by molecular beam epitaxy. Electron couplings between the adjacent wells in the MQW structure might be neglected because of the thick AlAs barriers. The MQW structure can be regarded as a collection of uncoupled quantum wells. The very thin ($\sim$200 Å) Au film was deposited on the top surface of the MQW structure to form a Schottky contact. A reverse bias voltage applied to the Schottky diode results in electric field, perpendicular to the heterojunction plane, across the MQW structure. It was confirmed with capacitance-voltage measurements that the depletion layer spread over the MQW structure for reverse bias voltages, larger than 2 volts corresponding to an electric field of 3×10^4 V/cm.

Figure 2 shows the room temperature ER spectra of the sample for a small modulating field of 6.25×10^3 V/cm and for various bias fields. The downward peaks have been assigned to the 1hh→1e and 1ℓh→1e excitonic transitions. Despite of significant red shifts of the peaks, the spectral shapes were not significantly changed with increasing field up to 1.2×10^5 V/cm. This indicates that excitons in the MQW structure are

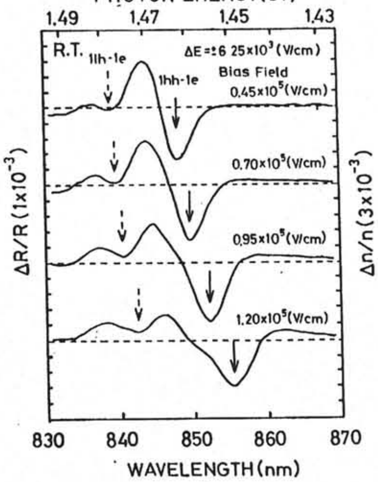

Fig.2 Electroreflectance spectra for a small modulating electric field and various bias fields at room temperature.

quite stable under the high field, perpendicular to the well plane, even at room temperature. With conventional formulations[9] for reflectance modulations due to refractive index- and absorption coefficient-variations, it was confirmed that the observed ER spectra are almost dominated by refractive index-variation over the wavelength range (830 $\sim$ 870 nm). Thus, the ER spectra permit us a rough estimation of the dispersion of refractive index-variations $\Delta n/n$ by the following procedure.

The dispersion of the reflectance is given by[9]

$$\Delta R/R = \alpha\Delta\varepsilon_1+\beta\Delta\varepsilon_2 \qquad (1)$$

assuming that the dielectric constant $\varepsilon=\varepsilon_1+i\varepsilon_2$ is modulated by amount of $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$. The coefficients α and β are expressed in a mixed notation,

$$\alpha = 2\gamma/(\gamma^2+\delta^2) \qquad (2)$$
$$\beta = 2\delta/(\gamma^2+\delta^2)$$
$$\gamma = n(n^2-3k^2-1) \qquad (3)$$
$$\delta = k(3n^2-k^2-1)$$

where n and k are the refractive index and the extinction coefficient in MQW structure. Now, let us assume that the absorption coefficient and the refractive index around the wavelength of the excitonic gap and the absorption coefficient variation and the refractive index variation $\Delta n/n$ by applied field are 10^4 cm^{-1}, 3.3, 5×10^3 cm^{-1} and 1 % which will be interpreted in what follows. In eq.(1), the influence of the second term on the reflectance variation $\Delta R/R$ is estimated to be below 10 % of the first term. Thus, the dispersion of the refractive index variation is approximately given by

$$\Delta n/n = [(n^2-1)/4n]\cdot(\Delta R/R)$$
$$= 0.75\Delta R/R \qquad (4)$$

The shifted energies of the downward peaks as functions of the bias field are shown in Fig.3. The theoretical field-induced shifts of the lowest subband (1hh→1e, 1ℓh→1e) free carrier- and excitonic-transition energies are, also, shown in the figure. The free carrier-transition energies were estimated by solving one-dimensional Schrödinger equation while the excitonic binding energies E_{ex} were estimated with variational technique for the trial exciton function[10),11)],

$$\phi_{ex}(\vec{r}) = [(2\pi)^{1/2}/\lambda]\cdot\exp(-r/\lambda). \qquad (5)$$

The observed peak shifts are reasonably explained

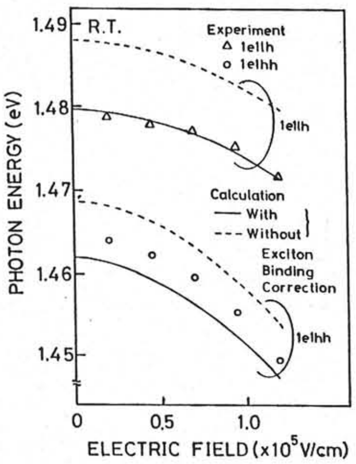

Fig.3 Downward peak shifts as a function of the bias field. Estimated transition energies are, also, shown.

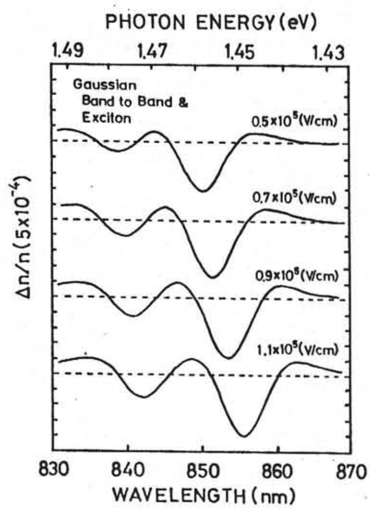

Fig.4 Estimated dispersions of field-induced variation in refractive index of the quantum well.

in terms of the excitonic transitions.

Theoretical dispersions of the field-induced modulations of refractive index for a modulating field of 6.25×10^{3} V/cm are shown in Fig.4. The imaginary parts of dielectric constant caused by the excitonic- and free carrier-transitions were estimated and, then, their contributions to the real part of dielectric constant were obtained by Kramers-Krönig transformation of the imaginary parts. In the estimation of the free carrier contribution to the imaginary part, energy-dependent transition matrix elements[12] and line broadenings were taken into account. The contributions of free carrier-transitions to the imaginary part may be written for heavy hole (hh)-electron (e),

$$\varepsilon_i = \frac{e^2}{\varepsilon_0 m_0^2 \omega^2 \pi L_z \hbar^2} \sum_i^{e} \frac{3}{4} m_h \sum_j^{hh} M_{ij}^2 \int \left(1 + \frac{E_{ci}+E_{hj}}{E_{ci}+E_{hj}+E}\right) \cdot F(Eg+E_{ci}+E_{hj}+E-\hbar\omega)\,dE \tag{6}$$

and for light hole (ℓh)-electron,

$$\varepsilon_i = \frac{e^2}{\varepsilon_0 m_0^2 \omega^2 \pi L_z \hbar^2} \sum_i^{e} \frac{1}{4} m_\ell \sum_j^{\ell h} M_{ij}^2 \int \left(5 - 3\,\frac{E_{ci}+E_{hj}}{E_{ci}+E_{hj}+E}\right) \cdot F(Eg+E_{ci}+E_{hj}+E-\hbar\omega)\,dE \tag{7}$$

where m_h and m_ℓ are the reduced effective masses of hh-e and ℓh-e, and Eg, E_{ci} and E_{hj} are the energy gap and the quantized energies of hh and ℓh respectively. On the other hand, the contributions of the excitonic transitions may be written for heavy hole (hh) excitons,

$$\varepsilon_i = \frac{2\pi e^2}{\varepsilon_0 m_0^2 \omega^2 L_z} \frac{3}{2} M^2 |\phi_{exh}(0)|^2 \cdot \left|\int \psi_e(z)\psi_h(z)dz\right|^2 \cdot F(\hbar\omega_{exh}-\hbar\omega) \tag{8}$$

and for light hole (ℓh) excitons,

$$\varepsilon_i = \frac{2\pi e^2}{\varepsilon_0 m_0^2 \omega^2 L_z} \frac{1}{2} M^2 |\phi_{ex\ell}(0)|^2 \cdot \left|\int \psi_e(z)\psi_\ell(z)dz\right|^2 \cdot F(\hbar\omega_{ex\ell}-\hbar\omega) \tag{9}$$

where L_z denotes the thickness of the quantum well, and $(3M^2/2)$ and $(M^2/2)$ are the squared matrix elements relevant to heavy hole-to-conduction band and light hole-to-conduction band transitions, respectively[12]. $F(\hbar\omega_{ex}-\hbar\omega)$ is the Gaussian line shape function centered at the excitonic gap $\hbar\omega_{ex}$. The wave functions $\psi_e(Z)$, $\psi_h(Z)$ and $\psi_\ell(Z)$ are solutions of the one-dimensional Schrödinger equations for the quantum well subjected to the electric field. In the numerical estimation, the following numerical parameters, reasonable for the MQW structure, were used[13),14)]: the heavy hole effective masses $m_{h\perp}=0.34m_o$, $m_{h/\!/}=0.1m_o$, the light hole effective masses $m_{\ell\perp}=0.094m_o$, $m_{\ell/\!/}=0.21m_o$, 60:40 split ratio for band discontinuities in conduction and valence bands, the full width at a half-maximum of the Gaussian function =13 meV. With respect to both the shapes and modulation depths of the dispersion curves, the observed ER data shown in Fig.2 are satisfactorily fitted by the theoretical curves which are dominated at the excitonic gaps by the

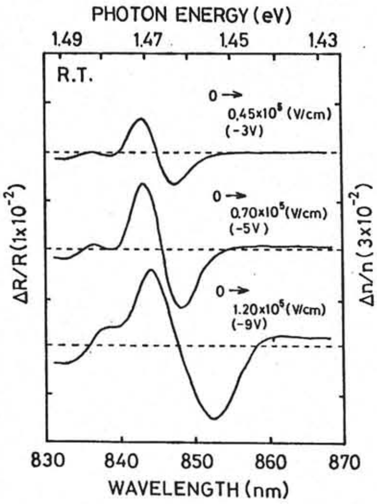

Fig.5 Electroreflectance spectra for large modulating fields at room temperature.

exciton contribution. In other words, the excitonic transitions are mainly responsible for the field-induced modulations of refractive index in the GaAs/AlAs MQW structure at room temperature. The experimentally obtained refractive index variation $\Delta n/n$ were about 4 times as large as theoretical ones. The theoretical results are sensitive to the line width. One of the reason of the discrepancy between the theory and the experiments may be uncertainty on the value of line width. Besides, the theoretical squared matrix elements on the basis of k•p perturbation theory may result in an underestimation, by a factor of 2[15),16)].

The ER spectra for large modulating fields are shown in Fig.5. The maximum variation in refractive index was deduced to be 1.1 % at a photon energy of 1.455 eV for the variation in electric field ($0 \rightarrow 1.2\text{x}10^5$ V/cm). From the consideration of volume-ratio of the well to barrier layers, it is concluded that the maximum variation in the MQW structure originates from a refractive index variation $\Delta n/n$ of 4.4 % in each quantum well. The obtained rate, $\Delta n/n/E \sim 3.7\text{x}10^{-9}$ m/V, for the field-induced variation of refractive index in each quantum well is thirteen times larger than a theoretical value on the basis of free carrier transitions in an InGaAsP/InP QW structure[5)]. This indicates an importance of excitonic transitions for field-induced refractive index-variations in the GaAs/AlAs MQW structure and a possibility of an optical switch much more efficient than the previous prediction[5)].

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References

1) E.E.Mendez, G.Bastard, L.L.Chang, L.Esaki, H.Morkoc and R.Fisher: Phys. Rev. **B-26** (1982) 7101.
2) M.Yamanishi and I.Suemune: Japan. J. Appl. Phys. **22** (1983) L22.
3) T.H.Wood, C.A.Burrus, D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard and W.Wiegmann: Appl. Phys. Lett. **44** (1984) 16.
4) D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard, W.Wiegmann, T.H.Wood and C.A.Burrus: Appl. Phys. Lett. **45** (1984) 13.
5) H.Yamamoto, M.Asada and Y.Suematsu: Electronics Lett. **21** (1985) 579.
6) M.Glick, F.K.Reinhert, G.Weimann and W.Schlapp: Appl. Phys. Lett. **48** (1986) 989.
7) M.Erman, J.B.Theeten, P.Frijlink, S.Gaillard, Fan Jian Hia and C.Alibert: J. Appl. Phys. **56** (1984) 3241.
8) C.Alibert, S.Gaillard, J.A.Brum, G.Bastard, F.Frijlink and M.Erman: Solid State Comm. **53** (1985) 457.
9) B.O.Seraphin: Semiconductors and Semimetals Vol.9, Chap.1, p.8-13, Academic Press (1972)
10) D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard, W.Wiegmann, T.H.Wood and C.A.Burrus: Phys. Rev. Lett. **53** (1984) 2173.
11) D.A.B.Miller, D.S.Chemla, T.C.Damen, A.C.Gossard, W.Wiegmann, T.H.Wood and C.A.Burrus: Phys. Rev. **B-32** (1985) 1043.
12) M.Yamanishi and I.Suemune: Japan. J. Appl. Phys. **23** (1984) L35.
13) R.C.Miller, D.A.Kleinman and A.C.Gossard: Phys. Rev. **B-29** (1984) 7085.
14) J.A.Brum and G.Bastard: Phys. Rev. **B-31** (1985) 3893.
15) E.O.Kane: J. Phey. Chem. Solids. **1** (1957) 249.
16) H.C.Casey Jr and M.B.Panish: Heterostructure Lasers, Part A, Chap.3, p.150-157, Academic Press (1978).