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Linear Birefringence in GaAs/AlAs Multiple Quantum Wells

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Transmission spectroscopy has been used to investigate the in-plane linear birefringence of GaAs/AlAs multiple quantum wells (MQWs) with symmetric wells/barriers from 20/20 to 70/70 Å. Varying optical thicknesses of the samples have been used to measure a reference value of the birefringence. While the resonant part in the dispersion of the birefringence has been attributed to the contribution from the confined electronic gaps, a nonresonant background birefringence has been analyzed as a function of the MQW period and explained by the presence of local fields.

In quantum well (QW) structures based on III–V zincblende semiconductors and grown along a [001] direction, the original cubic T_d point group of the bulk is reduced to D_{2d} and the system becomes uniaxial. As a result, the electronic band structure is modified along with other fundamental characteristics of the carriers, such as an anisotropy of the electron g-factor and effective masses. The anisotropy appears also in the optical properties and the QW structures become birefringent. This effect reveals itself in the fact that the two principal components of the refractive index, $n_\perp$ and $n_\parallel$, for electromagnetic waves polarized in-plane and along the QW-growth direction ($\hat{\mathbf{z}}$), respectively, become different.

At present, linear birefringence in semiconductor microstructures is a subject of great practical interest due to the potential application of this effect in frequency converters [1]. Linear birefringence has been studied in low-dimensional systems using various experimental techniques [2 to 10]. It has been found that in QWs, $n_\parallel$ and $n_\perp$ depend on the frequency of the light ω and they show a resonant dispersion when approaching a direct gap from below [11]. In this paper we report on studies of the birefringence in GaAs/AlAs multiple quantum wells (MQWs) with different periods using standard techniques of in-plane transmission of the light between crossed polarizers in the frequency range between the fundamental gaps of the MQWs and that for the GaAs substrate [8 to 10].

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Structures with GaAs/AlAs MQWs were grown by molecular beam epitaxy (MBE) on (001) GaAs substrates. Samples with symmetric GaAs wells/AlAs barriers of 20/20, 30/30, 40/40, 50/50, 60/60, and 70/70 Å have been studied. As described in Refs. [8, 9], the MQWs were confined between two $Al_{0.7}Ga_{0.3}As$ layers of ≈1.5 μm each, producing a waveguiding effect for propagation along the planes ($\mathbf{k}_{\text{light}} \perp \hat{\mathbf{z}}$). The MQWs themselves were made thick enough (about 1.2 μm along $\hat{\mathbf{z}}$) to minimize the waveguide induced birefringence with respect to the intrinsic birefringence of the MQWs [8]. Samples with parallel opposite surfaces were prepared by cleaving; their length, along which light is transmitted, was $d \approx 1$ mm in the [110] direction. Wedge samples were also prepared by mechanical polishing with an angle between two opposite surfaces of ≈1°. The cross-polarized in-plane transmission of a halogen lamp was detected with either a SPEX-1404 double monochromator or a DILOR spectrometer equipped with a photomultiplier and a CCD detector, respectively (see Refs. [8 to 10] for additional details). Spectra were obtained at both room and liquid helium temperatures in the energy range between the fundamental gaps of the GaAs substrate (≈1.38 eV at 300 K) and that of the MQWs. Transmission measurements were performed with two linear crossed polarizers, oriented at 45° with respect to the MQWs $\hat{z}$-axis to minimize stray-light.

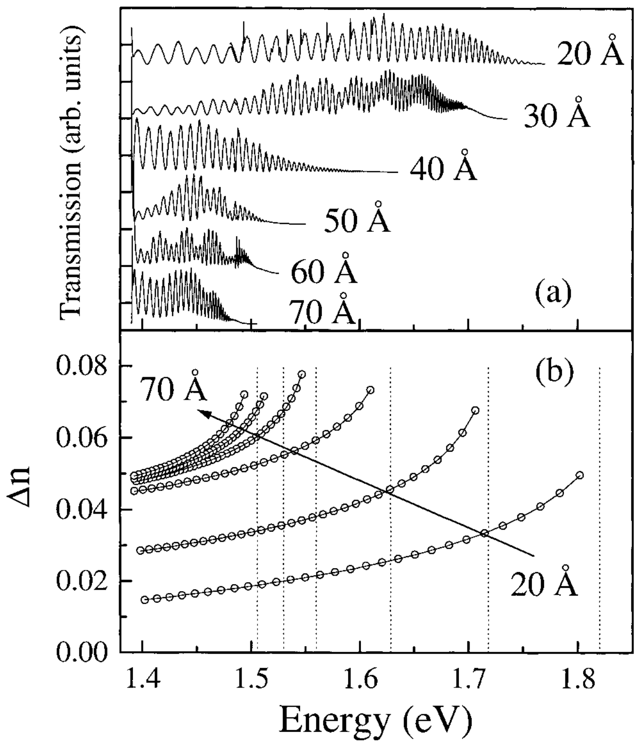

Fig. 1. a) In-plane transmission through crossed polarizers for samples with $d = 1$ mm and different well widths (shown next to the spectra) at $T = 300$ K. The birefringence oscillations disappear at the gaps of the MQWs which, owing to the different confinements, shift to higher energies for structures with smaller QW widths. b) Experimental birefringence dispersions (symbols) in MQWs with different periods. The solid lines represent fits to the experimental points with Eq. (3). The positions of the fundamental gaps are shown with dashed vertical lines

Fig. 1a shows the in-plane crossed-polarized transmission spectra for GaAs/AlAs MQWs with different periods. For smaller well widths, the birefringence oscillations vanish at higher photon energies due to the larger electronic gaps produced by confinement. The overshoot in the transmission intensity at $\approx 1.385\,\text{eV}$ corresponds to the gap of the GaAs substrate [8, 9]. The incident light beam with $\mathbf{k}_{\text{light}} \parallel [110]$ and polarization at 45° with respect to $\hat{\mathbf{z}}$ consists of two in-phase polarized electromagnetic waves along $\hat{\mathbf{x}}' = [1\bar{1}0]$ and $\hat{\mathbf{z}} = [001]$, respectively. The oscillations in Fig. 1 result from the phase difference between these two waves at the output face of the sample, acquired by the presence of the birefringence $\Delta n = (n_\perp - n_\parallel)$. The maxima in the spectra are determined by the requirement that this phase difference should be equal to an integer multiple M of λ,

$$\Delta n(\lambda)\, d = M\lambda\,, \tag{1}$$

where $\lambda = 2\pi c/\omega$ is the wavelength of the light in vacuum. The crossed-polarized transmitted intensity in Fig. 1 is expected to be represented by [8, 9]

$$I(\lambda) \sim \sin^2\left(\pi\, \frac{\Delta n(\lambda)\, d}{\lambda}\right). \tag{2}$$

The sign of the birefringence is known from previous studies [8]: $(n_\perp - n_\parallel) > 0$. In order to obtain the dispersion of $\Delta n(\lambda)$, we need at least one calibration point for Δn^0 at λ_0 for each sample. This is equivalent to the determination of the specific order M in Eq. (1) corresponding to λ_0. Such calibration values were measured by means of light transmission between crossed polarizers in samples with variable d values. The wedge samples were continuously displaced with the misoriented opposite surfaces in the direction perpendicular to both, the light beam and the entrance slit of the spectrometer. As a result, we were able to probe different parts of the same structure with continuously varied values of d. The measured phase shift of the transmitted light intensity, which can be written as $\varphi(\delta d) = \pi(\Delta n(\lambda)/\lambda)\,\delta d$, was found to be perfectly linear as a function of the thickness variation δd. It allowed the determination of the dispersion of the birefringence $\Delta n(\lambda)$ in the whole measured spectral range with high accuracy.

The birefringences so obtained are shown in Fig. 1b for several MQWs with different periods. For all samples, Δn increases when the energy approaches the fundamental gap of the structures shown by the vertical dashed lines. For thinner wells (20/20 and 30/30), a strong decrease in the overall magnitude of $\Delta n(\omega)$ is observed. This tendency demonstrates that, in spite of the larger splitting between light- and heavy-hole subbands in the valence band, the small-period MQWs become more optically isotropic in comparison with wide-period MQWs. The experimental data were fitted with [8, 10]

$$\Delta n(\omega) = \Delta n_{\text{bg}} - \Delta n_{\text{gap}} \ln\left[1 - \left(\frac{\omega}{\omega_{\text{g}}}\right)^2\right], \tag{3}$$

where the first and second terms represent, respectively, the dispersionless background contribution and the resonant part, which reveals a logarithmic singularity at the lowest direct-gap ω_{g}. This equation is actually the textbook example of birefringence in the transparency region for a solid with a two-dimensional singularity in the lowest direct gap [11]. In Fig. 1b these fits are shown by solid lines together with the experimental data. The values of the fundamental gaps (ω_{g}) for the MQWs with different periods

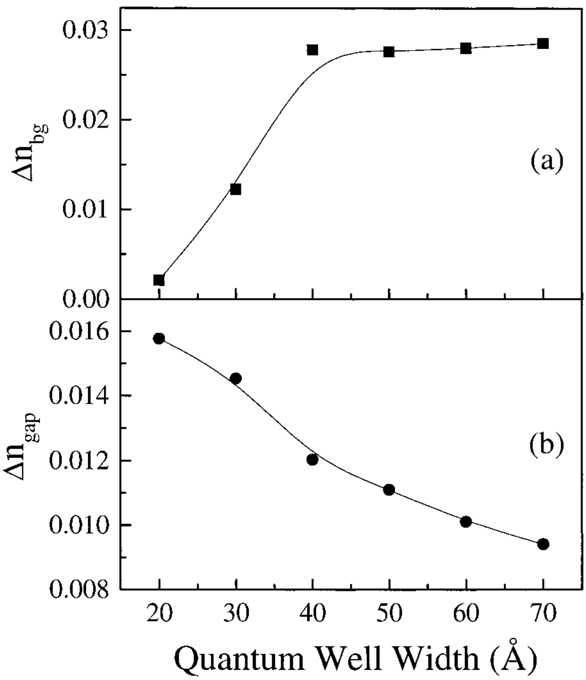

Fig. 2. Parameter of Eq. (3) vs. well-widths: a) Δn_{bg} and b) Δn_{gap}. Note the strong decrease of Δn_{bg} in the 20/20 and 30/30 samples. The solid lines are a guide to the eye

were determined experimentally from the transmission spectra (see Fig. 1a). As expected, there is a continuous increase of the gap energies with decreasing well widths due to the stronger confinement.

Fig. 2a,b shows the variation of the parameters Δn_{bg} and Δn_{gap} in Eq. (3). The strong decrease of the background birefringence Δn_{bg} was observed for well widths below 40 Å. Several reasons can be adduced to explain the observed drop in the background birefringence in MQWs with small periods (see Ref. [10] for further details). One plausible explanation is the vanishing influence of local fields in the ultrathin MQWs. Indeed, the background birefringence contribution from local fields in a layered structure is proportional to the contrast of the dielectric functions between barriers (AlAs) and wells (GaAs). For GaAs/AlAs MQWs, a simple estimate based on effective medium theory [7] gives $\Delta n_{bg} \approx 0.04$ for this contribution. When the period of the structure becomes comparable to the lattice constant ($\approx$5 Å), the dielectric properties of the GaAs/AlAs MQWs should become similar to that of bulk $Al_{0.5}Ga_{0.5}As$ where local field corrections decrease to the negligible values found in bulk semiconductors. A reduction of Δn_{bg} of the order of $\approx$0.04 is, accordingly, expected for thin QWs and this is in fair quantitative agreement with the experiment. These qualitative ideas can explain the observed behavior of Δn_{bg}, but a careful theoretical treatment is needed in order to confirm this conjecture.

The parameter Δn_{gap} shown in Fig. 2b demonstrates an increase of the strength of the resonance for thinner QWs. This magnitude is basically determined by the splitting between light- and heavy-hole subbands in the valence band, which increases with confinement but saturates for small well widths [10]. In order to demonstrate the resonant contribution of the fundamental gap to the dispersion, the temperature dependence of

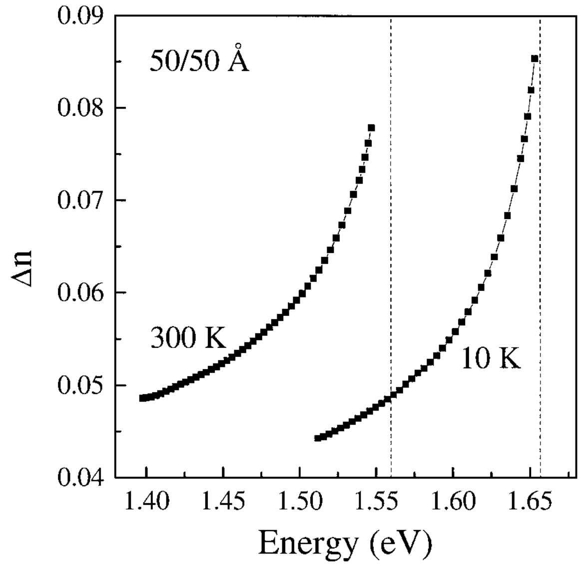

Fig. 3. Birefringence dispersion in the 50/50 Å structure at two different temperatures: 10 and 300 K. The temperature-induced shift of the position of the electronic gap (dashed vertical lines) upon cooling manifests itself as a shift towards high energies in the dispersion of the birefringence

the birefringence was measured for the 50/50 sample. Fig. 3 shows two curves for $\Delta n(\omega)$ taken at 10 and 300 K. As expected, the fundamental gap of the MQWs shifts to higher energies upon cooling, and causes a nearly *parallel* shift of the dispersion curve for the birefringence. The temperature-induced modifications in $\Delta n(\omega)$ can be used as an experimental demonstration of the fact that the dispersion of the birefringence comes from a resonance with the fundamental gap.

In conclusion, the linear optical birefringence has been studied in GaAs/AlAs MQWs using transmission spectroscopy. A significant change in the background birefringence for MQWs has been observed as a function of the period and attributed to the presence of local fields. The effect of temperature on the resonant part of the birefringence has been also presented.

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