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Optical anisotropy in GaAs/Al$_x$Ga$_{1-x}$As multiple quantum wells under thermally induced uniaxial strain

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The effect of thermally induced in-plane uniaxial strain on the optical properties of a GaAs/Al$_x$Ga$_{1-x}$As multiple quantum well (MQW) has been studied in detail. The strain was produced by bonding the MQW thin films to LiTaO$_3$, a transparent substrate which possesses a direction-dependent thermal expansion coefficient. At temperatures different from the bonding temperature we have observed an anisotropy in the optical properties of the MQW due to the strain-induced lowering of its in-plane fourfold rotation symmetry. The anisotropic absorption and birefringence for light incident normal to such a MQW structure have been determined and compared to a theory involving the mixing of the valence subbands.

Although the layered pattern in a semiconductor multiple quantum well (MQW) breaks the full cubic symmetry of the host materials, these structures reserve a fourfold or threefold rotation symmetry about a growth axis normal to (100)- or (111)-oriented substrates, respectively. A uniaxial stress applied in the plane of the structure further reduces this rotation symmetry, mixing[1,2] the heavy- and light-hole bands and creating an anisotropy in the in-plane components of the dielectric function in the spectral region near the band gap of the MQW. While such an anisotropy also exists in bulk semiconductors under uniaxial stress,[1] the strong excitonic features[3] in MQW absorption spectra which persist even at room temperature enhance the anisotropic optical properties and allow the manipulation of these properties in normal incidence devices. Previous optical studies[2,4–6] of MQW's in which the uniaxial stress was applied externally using a stress apparatus have concentrated primarily on the determination of strain-induced shifts in electronic energy levels associated with the lowering of symmetry rather than measurement of the anisotropy in the optical constants of the material, partially due to the difficulties involved in preparing a thin transparent sample for absorption measurements in a stress apparatus. In this paper we report the realization of a thermally controllable built-in uniaxial strain in the plane of a MQW structure bonded to a transparent substrate and present direct measurement of the anisotropy in the complex refractive index. The anisotropic absorption and birefringence for light incident normal to such a MQW structure have been determined and compared to theory.

Two *p-i*(MQW)-*n* structures grown on (100) GaAs have been used in this study. The *i* region for sample *A* consists of a 100-period, nominally 100-Å GaAs/60-Å Al$_{0.2}$Ga$_{0.8}$As MQW, while for sample *B* it consists of a 100-period, nominally 150-Å GaAs/50-Å Al$_{0.1}$Ga$_{0.9}$As MQW. A 500-Å AlAs sacrifice layer necessary for epitaxial lift-off[7] was grown below the active layer. The lift-off thin films were bonded using a suitable UV-curing optical cement[8,9] at a temperature T_0 (300 K for sample *A* and 375 K for sample *B*) to LiTaO$_3$, a transparent substrate which possesses a direction-dependent thermal expansion coefficient.[10] This substrate was cut such that the linear thermal expansion coefficient a_y matches that of the MQW (6.2×10^{-6}/°C), while its orthogonal counterpart a_x (16.2×10^{-6}/°C) does not. At a temperature $T\neq T_0$ a thermally induced in-plane uniaxial strain of

$$\epsilon_{xx}(T)=\int_{T_0}^{T}[a_x(T)-a_{\mathrm{MQW}}(T)]dT \tag{1}$$

can therefore be produced.

Shown in Fig. 1 are the absorption spectra at $T=200$, 300, and 400 K for sample *A*. The solid (open) circles are for absorption of light polarized along the x (y) direction, and the peaks labeled $11H$ and $11L$ are for heavy- and light-hole exciton transitions, respectively. At $T=T_0=300$ K the circles lie along the same curve, while at $T\neq T_0$ the absorption α_x is significantly different from α_y near the exciton peaks. The data therefore indicate the presence of an anisotropy in absorption $\Delta\alpha=\alpha_x-\alpha_y$ due to thermally induced uniaxial strain.

To compare experimental result with theory, we have performed a calculation for $k_\parallel=0$ in which the effect of strain[11] has been treated as a small perturbation of the Luttinger-Kohn Hamiltonian[12] for the unstressed MQW structure. For this case the strain Hamiltonian in the spin-$\frac{1}{2}$ basis for the conduction band and the spin-$\frac{3}{2}$ basis for a valence band in which the spin-orbit interaction has been neglected is given by a 4×4 matrix comprised of 2×2 block diagonal matrices

$$H_\epsilon=\begin{bmatrix}\frac{1}{2}[\Delta E_{\mathrm{QW}}+\Delta E_s'(1-2\gamma)] & (\sqrt{3}/2)\Delta E_s\\ (\sqrt{3}/2)\Delta E_s & -\frac{1}{2}[\Delta E_{\mathrm{QW}}+\Delta E_s'(1-2\gamma)]\end{bmatrix}, \tag{2}$$

with $\Delta E_{\mathrm{QW}}=E_{\mathrm{HH}}-E_{\mathrm{LH}}>0$, $\Delta E_s=b(\epsilon_{xx}-\epsilon_{yy})$, and $\Delta E_s'=b(\epsilon_{xx}+\epsilon_{yy})$, where E_{HH} and E_{LH} are the band edges of the heavy-hole and light-hole subbands, respectively, ϵ_{ii} is the strain in the i direction ($i=x,y,z$), and b is the shear deformation potential[13] corresponding to the tetragonal deformation of the host material. The strain in the z direction is related to the in-plane strain by $\epsilon_{zz}=\gamma(\epsilon_{xx}+\epsilon_{yy})$, where $\gamma=S_{12}/(S_{11}+S_{12})$ and S_{11} and S_{12} are elastic compliances for GaAs.[13] The zero of energy has been chosen at $\Delta E_H+(E_{\mathrm{HH}}+E_{\mathrm{LH}})/2$, where ΔE_H is the shift in the energy levels due to the hydrostatic component of the strain. From the resulting mixed valence-band wave functions we calculated the dipole matrix elements for interband transitions and obtained an analytic expression for the anisotropic absorption:

$$\Delta\alpha/\alpha_0=\pm 2\sqrt{3}\sin(2\phi)/[2\pm\cos(2\phi)]\ , \tag{3}$$

where $\alpha_0=(\alpha_x+\alpha_y)/2$ is the unpolarized absorption, plus and minus signs are used for heavy- and light-hole excitonic contributions, respectively, and

$$\phi=\arctan[\sqrt{3}\eta/(1+\sqrt{1+3\eta^2})]\ . \tag{4}$$

The parameter $\eta=\Delta E_s/[\Delta E_{\mathrm{QW}}+(1-2\gamma)\Delta E_s']$ is the ratio of the strain energy due to in-plane tetragonal deformation to the strain modified heavy-hole–light-hole splitting, and provides a measure of the strength of the perturbation of the MQW energy levels as well as of the magnitude of the mixing of the valence-band wave functions. Using the $\Delta E_{\mathrm{QW}}=10$ meV obtained from room-temperature absorption measurements we found $\Delta\alpha/\alpha_0=0.26$ (-0.55) and -0.76 (1.4) for heavy- and light-hole excitonic absorption, respectively, at $T=200$ K (400 K). From the sign of $\Delta\alpha$ we determined that the MQW is under compressive stress for $T<T_0$, and tensile stress for $T>T_0$.

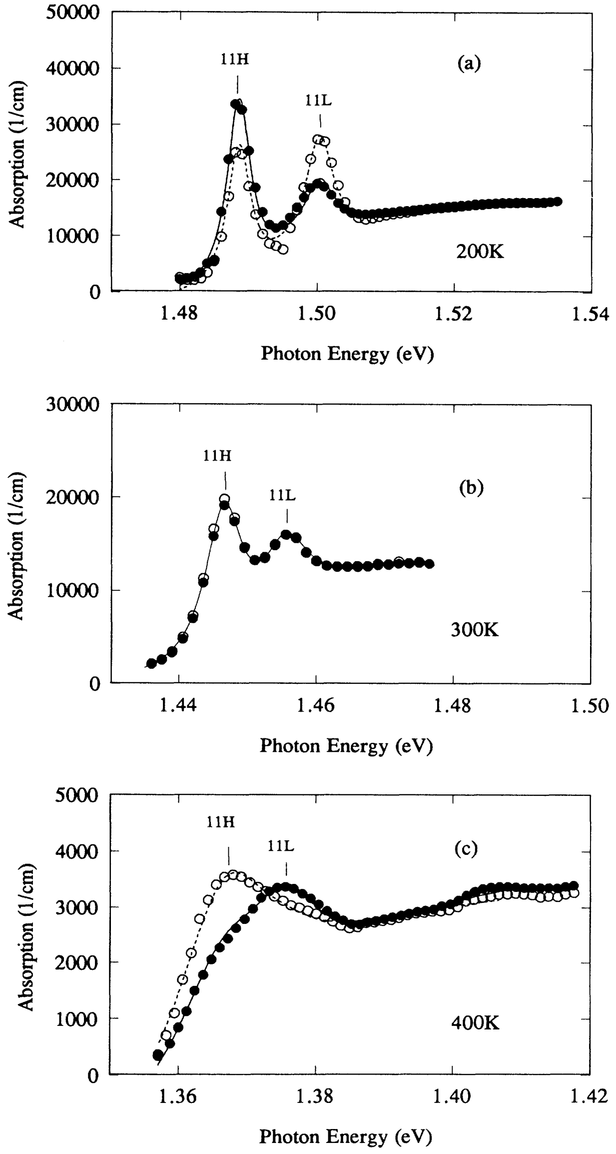

FIG. 1. Absorption spectrum for sample A at (a) 200 K, (b) 300 K, and (c) 400 K; α_x (solid circles) and α_y (open circles) represent absorption of light polarized parallel and perpendicular, respectively, to the axis of the in-plane uniaxial strain; solid and dashed lines are fits to α_x and α_y described in the text.

A least-squares fit to the room-temperature absorption data was performed which incorporated Lorentzian line shapes for the excitons and broadened two-dimensional densities of states for the continua:

$$\alpha_j(E,E_j,\Gamma_j,E_j^{\mathrm{ex}})=\mathrm{Im}\{A_j(E-E_j+i\Gamma_j)^{-1}+B_j\ln[\Gamma_j+i(E-E_j-E_j^{\mathrm{ex}})]\}\ . \tag{5}$$

where $j=1,2$ stands for heavy (light) hole to conduction transitions, A_j and B_j are the amplitudes for the exciton and continuum contributions, E is the photon energy, Γ_j is the broadening parameter, E_j is the exciton transition energy, and E_j^{ex} is the exciton binding energy. Taking E_j^{ex} as 8 (7.5) meV (Ref. 14) for heavy (light) -hole excitons, we have achieved an excellent fit to the data in Fig. 1(b) by employing a sum of the heavy- and light-hole absorption coefficients:

$$\alpha(E)=\sum_{j=1,2}\alpha(E,E_j,\Gamma_j,E_j^{\mathrm{ex}})\ . \tag{6}$$

For the absorption data at $T\neq T_0$, we include the anisotropic effect $\Delta\alpha/\alpha_0$ in Eq. (6) as

$$\alpha_{x,y}(E)=\sum_{j=1,2}\alpha(E,E_j,\Gamma_j,E_j^{\mathrm{ex}})[1\pm\tfrac{1}{2}(\Delta\alpha/\alpha_0)_j]\ , \tag{7}$$

and fit the α_x, and α_y simultaneously, with a plus (minus) sign for x (y) polarization. In this model the anisotropy for transitions between a particular hole band and the conduction band is taken as its $k_{\parallel}=0$ value. Although this approximation is only valid when $k_{\parallel}$ is near the zone center or the transition energy is not too far away from the exciton peak, the fits to α_x and α_y shown in Figs. 1(a) and 1(c) using the values of $\Delta\alpha/\alpha$ calculated from Eq. (4) are in excellent agreement with the experimental data. This indicates that the primary contribution to the anisotropic absorption comes from the mixing of heavy- and light-hole bands near $k_{\parallel}=0$.

We have also measured the birefringence $\Delta n = n_x - n_y$ at various temperatures. In these experiments the incident light was linearly polarized at 45° with respect to the x and y axes. To separate the phase difference associated with Δn in the MQW from that produced by the $LiTaO_3$ substrate, an orthogonally oriented identical piece of $LiTaO_3$ was placed against the substrate, resulting in a cancellation of the substrate-induced phase difference. A Soleil-Babinet phase compensator and polarizer were then used to analyze the transmitted light. While $\Delta n/n$ is significantly smaller than $\Delta\alpha/\alpha_0$, it remains clearly measurable for the temperatures T and T_0 employed in these experiments. Figure 2(b) (circles) shows the measured Δn values as a function of photon energy for sample B at 200 K. They are in good agreement with the ones (solid line) calculated from the Kramers-Kronig relations using the $\Delta\alpha$ measured in this sample [Fig. 2(a)]. This indicates that the birefringence is also the result of anisotropic in-plane strain.

When $\Delta n \neq 0$ the transmitted light is elliptically polarized with the major axis of the ellipse rotated away from 45° due to the anisotropy in absorption. This rotation is given by

$$\tan[2(\Delta\theta + 45^\circ)] = \tan\{2\arctan[\exp(\Delta\alpha d/2)]\} \times \cos(2\pi\Delta n d/\lambda) , \tag{8}$$

where d is the thickness of the MQW, λ is the wavelength of the incident light, and $\Delta\theta$ is the rotation angle measured from 45°. Figure 2(c) shows the polarization state of the emergent light at various photon energies corresponding to extrema in the $\Delta\alpha$ and Δn spectra. In the transparent region of the spectra (point A) the output polarization state is the same as that of the incident light within experimental error. The transmitted light also remains linearly polarized at the peaks in the $\Delta\alpha$ spectrum (points C, E, and G), where $\Delta n \sim 0$, but the electric-field vector is rotated with respect to the initial polarization state. At the first heavy-hole exciton peak (point C) a rotation of $\Delta\theta \sim 32^\circ$ was observed. As the photon energy increases the major axis of the vibrational ellipse rotates in the opposite direction, reaching a value $\Delta\theta \sim -18^\circ$ at the light-hole exciton peak (point E). At higher energies $\Delta\theta$ returns to zero, becoming slightly positive ($\Delta\theta \sim 8^\circ$) at the second heavy-hole exciton peak (point G). For all other points in the neighborhood of the first heavy-hole and light-hole exciton peaks a significant birefringence was observed, with representative vibrational ellipses corresponding to the polarization states of the extrema in Δn (points B, D, and F) shown in the figure.

Creation of a controllable built-in uniaxial strain and the concomitant breaking of in-plane rotation symmetry in MQW structures may have many applications. We have designed a high-contrast MQW light modulator[15] based upon the polarization rotation due to anisotropic absorption of light impinging at normal incidence to the surface of the structure. Moreover, when the strain in the MQW is along an axis other than ⟨100⟩ a piezoelectric field is generated which has been predicted[16] to create larger nonlinear optical properties. Special designs of the cut of the $LiTaO_3$ substrate can achieve different anisotropic in-plane strains not available in many external stress apparatuses. For example, one can design a cut such that $\epsilon_{xx} = -\epsilon_{yy}$, which results in an absence of hydrostatic stress. With different designs of stress the mixing of the valence bands as well as the dynamics of hot hole relaxation can be studied in detail.

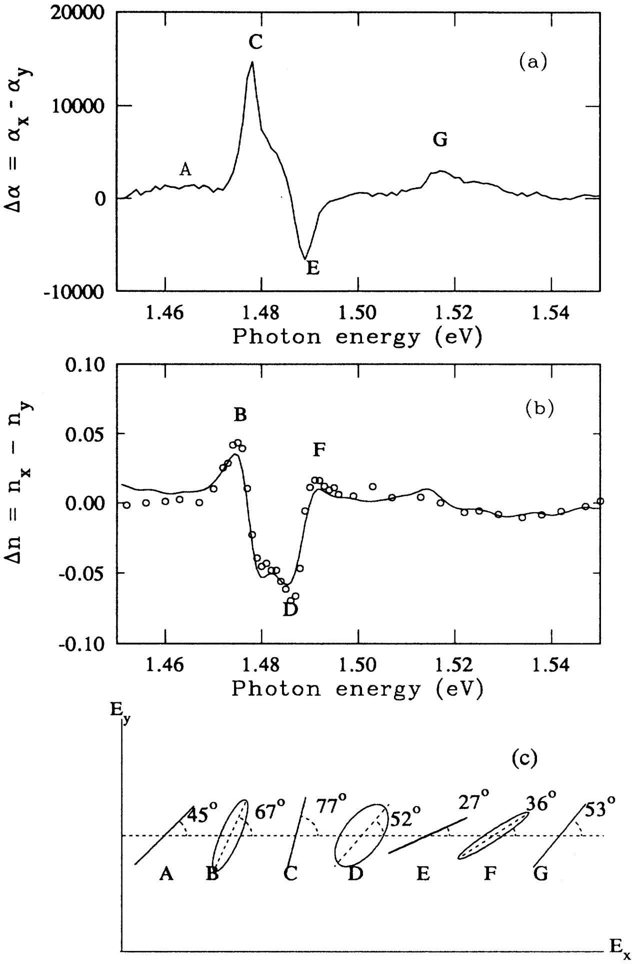

FIG. 2. (a) Anisotropic absorption $\Delta\alpha$ from sample B as a function of photon energy. (b) Measured (circles) and calculated (line) birefringence Δn from sample B as a function of photon energy. (c) Illustration of the vibrational ellipses for the electric-field vector of the transmitted light from sample B at various photon energies.

In summary, we have demonstrated the realization of a thermally induced in-plane uniaxial strain which breaks the in-plane rotation symmetry of a MQW structure. We have observed anisotropic absorption and birefringence for light incident normal to the structure. The experimental result is in excellent agreement with theory.

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