RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 44, NUMBER 16 15 OCTOBER 1991-II

Externally generated piezoelectric effect in semiconductor microstructures

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(Received 10 May 1991; revised manuscript received 30 May 1991)

We report a study of the effects of large, external uniaxial stress (T) along [100] and [110] on the optical properties of a strained layer (001) $In_{0.21}Ga_{0.79}As/GaAs$ single quantum well. For $\mathbf{T}\parallel[110]$ we have observed a redshift of several peaks and an increase in the intensities of several "symmetry-forbidden" transitions; effects not seen for $\mathbf{T}\parallel[100]$. This phenomenon is due to an electric field along [001] induced by the piezoelectric coupling for $\mathbf{T}\parallel[110]$.

Recently there has been considerable interest in the properties of strained layer quantum wells (QW's) and superlattices (SL's), such as $In_xGa_{1-x}As/GaAs$ with a [111] growth axis.[1-4] Such structures have large internal fields generated by the piezoelectric effect. These internal electric fields substantially change the electronic structure and optical properties of (111) QW's and SL's and can lead to large nonlinear optic and electro-optic effects. These fields cause a tilting of the energy bands and create a redshift of the optical transition energies [quantum-confined Stark effect (QCSE)] and changes in the oscillator strength.[3] Goossen *et al.* have reported a room-temperature exciton blueshift with an applied voltage in a (111) $In_{0.1}Ga_{0.9}As/GaAs$ *p-i-n* multiple-quantum-well modulator.[4] Because of symmetry considerations such strain-generated electric fields are not allowed in (001) strained layer systems.[1]

In this paper we report a piezoelectric effect generated in a (001) strained $In_{0.21}Ga_{0.79}As/GaAs$ single quantum well (SQW) by an external stress (T) along [110]. We have measured the effects of large $\mathbf{T}\parallel[110]$ (~ 18 kbar) as well as $\mathbf{T}\parallel[100]$ (~ 8 kbar) on the optical properties of the SQW. Using photoreflectance[5,6] (PR) at 300 K, we have studied the stress-induced changes in the energies and intensities of a number of intersubband transitions. For $\mathbf{T}\parallel[110]$ we have observed a redshift of a number of peaks and a dramatic increase in the amplitudes of several "symmetry-forbidden" "heavy-hole" features. This was not seen for $\mathbf{T}\parallel[100]$. We interpret this phenomenon as being due to an electric field along [001] induced by the piezoelectric coupling for $\mathbf{T}$ along the lower symmetry [110] direction. In contrast to the piezoelectric fields induced in (111) strained layer systems[1,2] the effect reported in this paper can be (i) externally tuned in a contactless manner and (ii) observed in lattice-matched microstructure systems such as (001) and (111) $GaAs/Ga_{1-x}Al_xAs$.

The SQW was fabricated by molecular-beam epitaxy in a Varian Gen-II system. The sample consisted of a 0.5-μm GaAs buffer on an undoped (001) substrate, the $In_{0.21}Ga_{0.79}As$ SQW and a 1-μm GaAs cap. All layers are undoped. The high quality of the interface of this sample is indicated by the fact that at 10 K the linewidth of the fundamental conduction to heavy-hole excitonic transition is only 2 meV.[7] This value is close to the theoretical limit for alloy scattering and hence contains no contribution from interfacial roughness.[7] The PR apparatus has been described in the literature.[8] The pump beam was the 633-nm line of a 5-mW He-Ne laser chopped at 200 Hz.

Shown in Fig. 1(a) is the PR spectrum (solid line) of the sample at 300 K for $\mathbf{T}=0$. The dashed line is a least-squares fit to a first-derivative Gaussian line-shape (FDGL) function.[5,6] The obtained energies are denoted by arrows at the top of the figure. We have identified the origins of these various features $mnH(L)$ by comparison with an envelope-function calculation, including

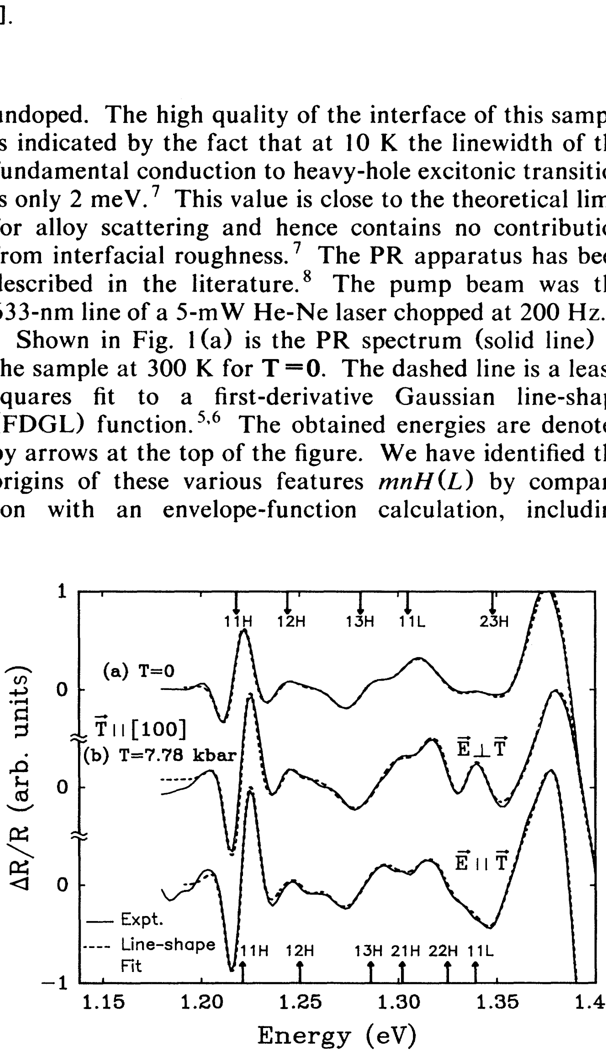

FIG. 1. (a) Experimental photoreflectance spectra (solid line) at 300 K for $T=0$. The dashed line is a least-squares fit to a FDGL function. (b) Experimental photoreflectance spectra (solid line) at 300 K for $T=7.78$ kbar along [100] for $\mathbf{E}\perp\mathbf{T}$ and $\mathbf{E}\parallel\mathbf{T}$. The dashed lines are least-squares fits to a FDGL function.

strain.[1,9,10] The notation $mnH(L)$ denotes a transition from the mth conduction to the nth valence subband of heavy- (H) or light- (L) hole (out-plane) character. The best overall fit was obtained for an In composition of 21% and a well width of 105 Å.[7] These values are also in agreement with x-ray measurements.[7] The lowest-lying feature is the "symmetry-allowed" $11H$ transition. At about 1.30 eV there is a structure which actually contains two oscillators, i.e., $11L$ and $22H$, both of which are symmetry allowed. The remaining features in the spectra are due to symmetry-forbidden transitions such as $12H$, $13H$, and $23H$. Although $13H$ is symmetry forbidden it is "parity allowed" because of the finite depth of the well.[11] The presence of $12H$ and $23H$ is probably due to a small built-in electric field in the sample. The large feature starting at around 1.38 eV corresponds to the direct gap of the GaAs cap/substrate/buffer.

The solid lines in Fig. 1(b) are the PR spectra at 300 K for a stress of 7.78 kbar along [100] for light with the electric-field vector **E** polarized perpendicular ($\perp$) and parallel ($\parallel$) to the external stress **T**. The dashed lines are least-squares fits to the FDGL function. The obtained energies are indicated at the bottom of the figure.

A comparison of Figs. 1(a) and 1(b) shows that the energies of the heavy-hole transitions ($11H$, $12H$, $13H$), are relatively insensitive to the external stress while $11L$ has shifted to higher energies and is seen only for $\mathbf{E}\perp\mathbf{T}$. The stress and polarization dependence of the various transitions are similar to that observed for (001) GaAs/$\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ multiple quantum wells for $\mathbf{T}\parallel[100]$.[1,12–14]

Displayed by the solid lines in Figs. 2–4 are the experimental data for $\mathbf{T}\parallel[110]$ for 8.52, 15.8, and 17.6 kbar, respectively, for $\mathbf{E}\perp\mathbf{T}$ and $\mathbf{E}\parallel\mathbf{T}$. The solid lines are least-squares fits to the FDGL function. What is most significant about these spectra is the large change in the amplitude of the symmetry-forbidden $12H$ and $13H$ features in relation to the symmetry-allowed $11H$ (and $11L$) transition. This effect is not observed for $\mathbf{T}\parallel[100]$ (see Fig. 1). For the highest stresses there is also a considerable redshift of the heavy-hole peaks due to the quantum-confined Stark effect[13] related to the piezoelectric field. Those effects have not been observed in previous piezo-optical experiments on quantum wells because of the low stresses (~5 kbar) that were employed.[1,12,14,15] In Fig. 2 the polarization dependence of $11L$ is clearly evident. Another interesting aspect of Fig. 2 is that the lowest-lying heavy-hole features have split into doublets designated ($11H$, A) and ($12H$, B), respectively. A similar effect has been observed in a (001) GaAs/$\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ multiple-quantum-well structure for $\mathbf{T}\parallel[100]$.[14] Although the exact origin of the A and B peaks is not known they might be due to excited states (e.g., $2s$) of the $11H$ and $12H$ excitons or $\mathbf{k}\neq\mathbf{0}$ transitions.[14] These peaks are under further investigation.

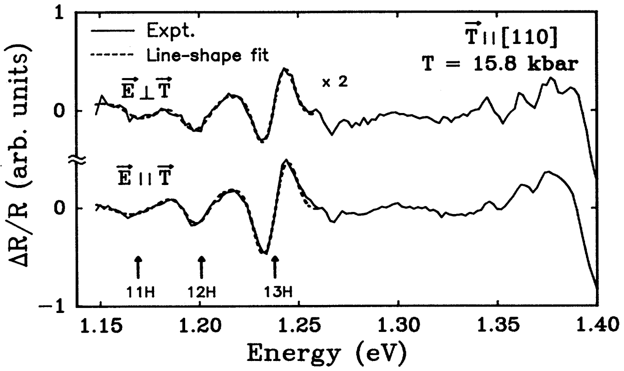

FIG. 3. Experimental photoreflectance spectra (solid lines) at 300 K for $T=15.8$ kbar along [110] for $\mathbf{E}\perp\mathbf{T}$ and $\mathbf{E}\parallel\mathbf{T}$. The dashed lines are least-squares fits to a FDGL function.

The stress-induced shifts in energy of the various features for $\mathbf{T}\parallel[100]$ are in good agreement with a theoretical calculation of the effects of the external stress on the electronic levels of the SQW implicitly including the coupling with the spin-orbit-split band.[16] However, a similar analysis is not able to explain the result for $\mathbf{T}\parallel[110]$.[16]

We interpret the above stress-induced redshifts and changes in the amplitudes of $11H$, $12H$, and $13H$ for $\mathbf{T}\parallel[110]$ as being due to an external piezoelectric effect along the [001] growth axis. For zinc-blende materials the off-diagonal strains produce a polarization field given by[1,17]

$$P_i^s = 2e_{14}\epsilon_{jk} \, , \qquad (1)$$

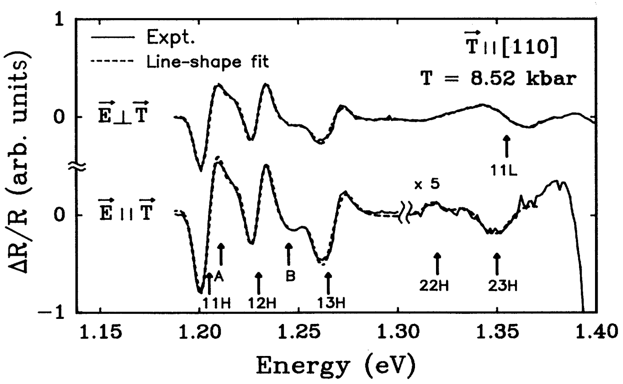

FIG. 2. Experimental photoreflectance spectra (solid lines) at 300 K for $T=7.60$ kbar along [110] for $\mathbf{E}\perp\mathbf{T}$ and $\mathbf{E}\parallel\mathbf{T}$. The dashed lines are least-squares fits to a FDGL function.

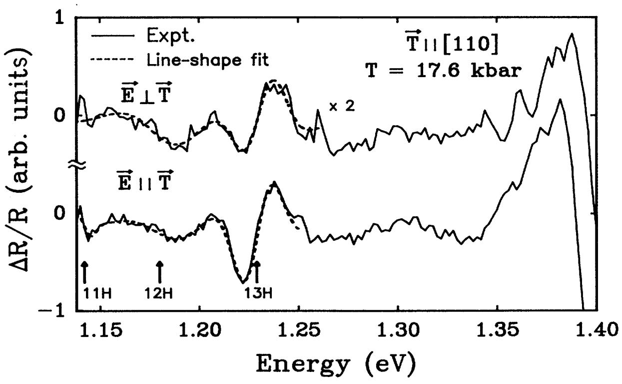

FIG. 4. Experimental photoreflectance spectra (solid lines) at 300 K for $T=17.6$ kbar along [110] for $\mathbf{E}\perp\mathbf{T}$ and $\mathbf{E}\parallel\mathbf{T}$. The dashed lines are least-squares fits to a FDGL function.

where P_i^s is the induced electrical polarization, e_{14} is the piezoelectric constant, and ϵ_{jk} is a symmetrized strain component. However, diagonal strains (e.g., ϵ_{xx}) do not induce a polarization (i.e., $e_{11}=0$) in these materials.[18] For T∥[110] the strain $\epsilon_{xy} = \frac{1}{4} S_{44}T$ and hence

$$P_z^s = \tfrac{1}{2} e_{14} S_{44} T \,, \tag{2}$$

where S_{44} is an elastic compliance constant. Thus there is an electric field, E_z, along [001], given by[1]

$$E_z = P_z^s/\kappa\epsilon_0 \,, \tag{3a}$$

$$E_z = e_{14} S_{44} T/2\kappa\epsilon_0 \,, \tag{3b}$$

where κ is the static dielectric constant and ϵ_0 is the permittivity of free space.

For $In_{0.21}Ga_{0.79}As$ the quantities $e_{14} = -1.36\times10^{-5}$ C/cm^2, $S_{44} = 1.81\times10^{12}$ dyn/cm^2, and $\kappa = 13.38$.[3] Hence for $T = 17.6$ kbar there is an electric field of $E_z = 1.85 \times 10^5$ V/cm along [001].

In order to confirm the above interpretation of the effects for T∥[110] we have performed a theoretical calculation including not only the effects of strain, similar to T∥[100], but also the influence of the stress-generated E_z on the energy levels (QCSE) and intensities of $11H$, $12H$, and $13H$.[16] The relaxation method[18] was employed to determine the QCSE and the overlap integrals (intensities) between the valence and conduction-subband wave functions. The relation between T and E_z was taken from Eq. (3b). At zero stress the overlap integrals (intensities) of the $11H$, $12H$, and $13H$ transitions are in the ratio 100:0:2. The nonzero amplitude of $13H$ is a consequence of the finite depth of the well.[11] At about 8 kbar the intensity of $11H$ has decreased, while $12H$ has increased so that they are approximately equal. The amplitudes of the three features are now in the ratio 40:40:15. As the stress increases these intensities continue to change so that at $T = 16$ kbar the ratio is 10:20:20, while at $T = 18$ kbar we find 7:15:20, i.e., the $13H$ transition is most intense. This general trend is in good agreement with the data of Figs. 2–4. Also the calculated QCSE was able to account for the observed redshifts.

In conclusion, we have studied the influence of large, external T∥[100] and T∥[110] on the energies and intensities of the quantum transitions in a (001) $In_{0.21}Ga_{0.79}As/GaAs$ SQW. For the latter configuration we have observed a significant redshift of $11H$, $12H$, and $13H$ as well as a dramatic increase in the intensities of several symmetry-forbidden features, an effect not seen for the former stress direction. This phenomenon can be explained in terms of the effects of an electric field generated along [001] due to the piezoelectric coupling for T∥[110]. A theoretical calculation of the electric field dependence of the energies (QCSE) and intensities of $11H$, $12H$, and $13H$ is in general agreement with the experimental results.

The authors H.Q. and F.H.P. wish to acknowledge the support of the IBM Shared University Research (SUR) program, the Olympus Corporation, National Science Foundation Grant No. ECS-8913321, and the New York State Science and Technology Foundation under its Centers for Advanced Technology program.

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