Photoinduced reflection of light from a single CdTe/CdMnTe quantum well with a piezoelectric internal field

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A photoinduced change in refractive index has been observed and studied in strained CdTe/CdMnTe quantum-well heterostructures grown on CdZnTe substrates in the (111) orientation. The effect stems from a shift of resonant frequencies and from a change in the oscillator strengths of exciton transitions. It reaches a maximum for exciton transitions between the first electron quantum-well subband and the second hole quantum-well subband. © *1995 American Institute of Physics.*

The existence of a strong piezoelectric field in strained heterostructures was pointed out comparatively recently, first by theoreticians[1,2] and then by experimentalists.[3–6] A piezoelectric internal field can greatly alter the band structure and optical properties of strained heterostructures. It not only causes shifts of resonant frequencies of optical transitions but may change the shape of wave functions, selection rules, oscillator strengths, the Coulomb interaction of carriers, etc. A piezoelectric internal field can be modulated by applying an external field or through photogeneration of electron–hole pairs. This modulation possibility opens up some extensive opportunities for applications of strained heterostructures in electrooptics and nonlinear optics. In this letter we are reporting the observation and study of a huge change in the optical refractive index in the vicinity of a forbidden exciton transition between the ground electron subband e_1 and the second quantum-well subband of a heavy hole, hh_2, in a CdTe/CdMnTe single quantum well.

The undoped CdTe/Cd$_{1-x}$Mn$_x$Te ($x = 17\%$) heterostructures with a single quantum well were grown by molecular beam epitaxy on Cd$_{1-y}$Zn$_y$Te ($y = 4\%$) substrates in the (111) orientation. The width of the quantum well was varied from 50 to 150 Å. A stress arises in such structures because of the difference between the lattice constants of CdTe and CdMnTe. If the structure is grown in the (111) direction, this stress gives rise to a piezoelectric field, which is directed along the axis of the structure.[2] The strength of this field depends on the difference between lattice constants, on the thicknesses of the barrier layers, and on the thicknesses of the wells. In our case it is 0.75 mV/Å.

We studied reflection and photoluminescence spectra and the changes in the reflection spectra of these structures during auxiliary illumination of the samples in the region above the exciton resonance.

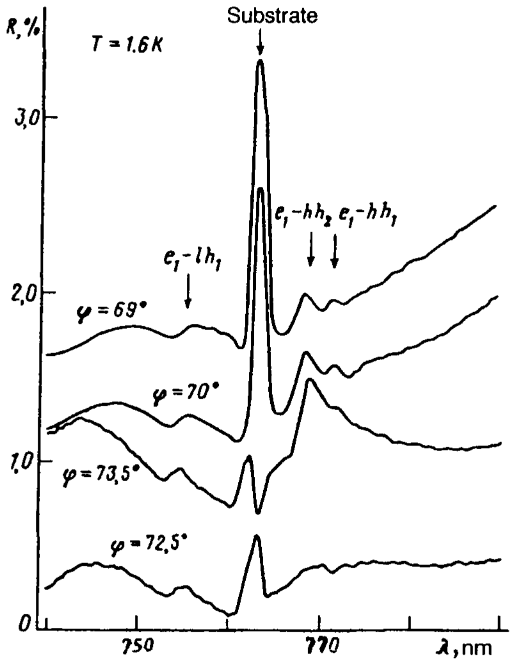

FIG. 1. Reflection spectra in the region of exciton resonances of a CdTe/$Cd_{0.83}Mn_{0.17}Te$ heterostructure with a single quantum well 97 Å wide in p-polarization for four angles of incidence of the light near the Brewster angle ($\varphi_{Br}=73°$). The arrows mark exciton transitions between the first electron quantum-well subband (e_1) and several hole quantum-well subbands in the quantum well: the first heavy-hole subband (hh_1), the second heavy-hole subband (hh_2), and the first light-hole subband (lh_1).

To suppress the background reflection from the surface of the sample to the maximum extent, and to bring out the signal from the single quantum well, we recorded ordinary reflection spectra at an angle of incident close to the Brewster angle of 73°.

In studies of photoinduced reflection it is often difficult to eliminate the effect of the photoluminescence signal, which may have the same frequency as the reflection signal. In order to suppress the contribution of photoluminescence to the reflection spectrum during the auxiliary illumination, we measured the polarized component of the reflection signal. The light beam incident on the sample was linearly polarized, and the degree of linear polarization of the signal from the sample was analyzed. Since the photoluminescence signal was not polarized, it did not contribute to the measured spectrum.

Figure 1 shows spectra of the p-polarization reflection of a CdTe/$Cd_{0.83}Mn_{0.17}Te$ structure with a single quantum well 97 Å wide. These spectra were recorded at three angles of incidence near the Brewster angle at $T=1.6$ K. There is a clearly defined structural feature with a wavelength of 7631 Å, which corresponds to reflection from the $Cd_{0.96}Zn_{0.04}Te$ substrate. There are also three weaker features in the reflection spectrum, at wavelengths of 7555, 7660, and 7750 Å. The positions of the quantum-well levels for electrons and holes have been calculated with the parameter values $m_e=0.096m_0$, $m_{hh}=1.0m_0$, $\Delta E_v=0.15\Delta E$, and $m_{lh}=0.2m_0$ (Ref. 8). The results show that these struc-

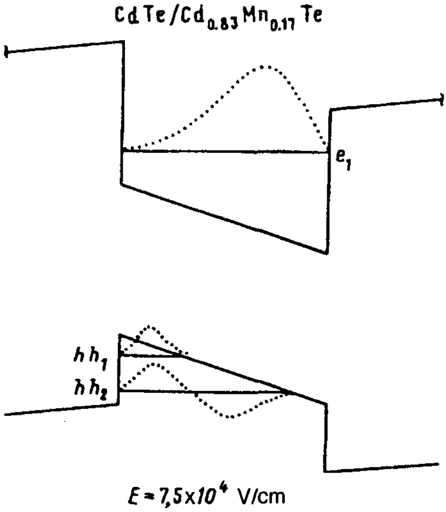

FIG. 2. Energy-band diagram and sketch of the wave functions in the test structure.

tural features can be associated with exciton transitions between the first quantum-well subband of an electron (e_1), on the one hand, and three other quantum-well subbands, on the other: that of a light hole (lh_1), the second heavy-hole subband (hh_2), and the first heavy-hole subband (hh_1), respectively. We also observed lines corresponding to these transitions in the photoluminescence spectrum of the test sample. However, the photoluminescence intensities of these transitions were sharply different from those of the corresponding lines in the reflection spectrum. The most intense line in the photoluminescence spectrum was that associated with the e_1–hh_1 transition; the e_1–hh_2 line was weaker by a factor of 4; and the photoluminescence from the substrate was not observed at all. These differences in intensities are due to differences in the populations of these states.

In the absence of an internal electric field, the e_1–hh_2 transition is forbidden. This transition becomes allowed in an electric field, while the probability for the e_1–hh_1 transition, in contrast, decreases. It can be seen from the reflection spectrum (Fig. 1) that the amplitude of the reflection line and thus the oscillator strength for the e_1–hh_2 transition are significantly greater than those for the e_1–hh_1 transition. The reason is the larger overlap integral of the wave functions for the e_1 and hh_2 (Fig. 2).

Using the results of Ref. 9 to analyze the reflection line for the e_1-hh_2 transition, we can determine parameters of the exciton transitions such as the resonant frequency ω_0, the damping $\hbar\Gamma$, and the longitudinal–transverse splitting $\hbar\omega_{LT}$, which describe the dielectric constant in the vicinity of the exciton resonance:

$$\epsilon(\omega)=\epsilon_0-\frac{\epsilon_0\omega_{LT}}{\omega_0-\omega-i\Gamma}. \tag{1}$$

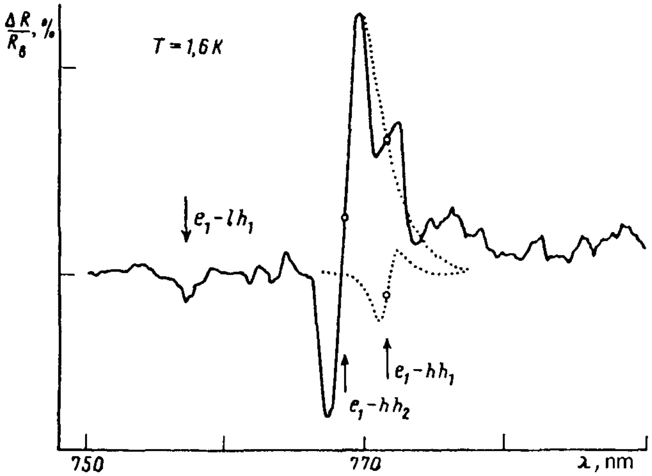

FIG. 3. Normalized spectrum of the photoinduced reflection of the test structure, $\Delta R(\omega)/R_b=(R_1(\omega)-R_0(\omega))/R_b$, where $R_0(\omega)$ is the reflection spectrum in the case of normal incidence without the auxiliary illumination, $R_1(\omega)$ is the reflection spectrum in the case of auxiliary illumination with a HeNe laser, and R_b is the background reflection far from the exciton resonance. The arrows mark the corresponding exciton transitions. The dotted curve is the result of a decomposition of the original spectrum into components associated with the e_1-hh_1 and e_1-hh_2 transitions, with the parameter values given in the text proper.

As a result, we find the following values for the e_1-hh_2 exciton transition: $\hbar\omega_0=1.620$ eV, $\hbar\Gamma=2.7$ meV, and $\hbar\omega_{LT}=0.6$ meV. The oscillator strengths of the other transitions are much lower.

The value of $\hbar\omega_{LT}$ for the e_1-hh_2 transition thus varies from zero in the absence of an electric field to 0.6 meV in the piezoelectric field of our structure. We would thus expect a pronounced change in the refractive index when the internal electric field is screened by photogenerated carriers. To investigate this possibility we studied spectra of the photoinduced reflection of light during auxiliary illumination of the structure above the exciton resonance in the single quantum well. Figure 3 shows a normalized spectrum of the photoinduced reflection, $\Delta R(\omega)/R_b=(R_0(\omega)-R_1(\omega))/R_b$, where $R_0(\omega)$ is the reflection spectrum in the absence of the auxiliary illumination, $R_1(\omega)$ is the reflection spectrum in the case of illumination with a HeNe laser at 6328 Å and an intensity of 10 W/cm^2, and R_b is the background reflection coefficient. Note the huge value of the photoinduced-reflection signal, $\Delta R/R_b=15\%$, at a relatively low level of the illumination. This value of the signal corresponds to a change $\sim 10\%$ in the refractive index. In addition to the clearly defined photoinduced-reflection signal associated with the e_1-hh_2 transition, we see structural features in the spectrum associated with the e_1-hh_1 and e_1-lh_1 transitions, but their contributions to the photoinduced-reflection spectrum are considerably smaller.

At a phenomenological level, the spectrum of the photoinduced reflection from a heterostructure with a single quantum well can be described in the same way as an ordinary reflection spectrum, under the assumption that the auxiliary illumination leads to a change in the dielectric constant through a change in exciton parameters. According to Refs. 9 and 10, the exciton component of the reflection of a structure with a single quantum well is proportional to the function

$$f(x,\Phi)=\frac{\omega_{LT}}{\Gamma}\,\frac{\sin(\Phi)+x\cos(\Phi)}{1+x}, \quad x=\frac{\omega_0-\omega}{\Gamma}. \tag{2}$$

For small changes in $f(x,\Phi)$, the frequency dependence of the photoinduced-reflection signal is

$$\Delta R\propto \frac{\partial f}{\partial \omega_0}\Delta\omega_0+\frac{\partial f}{\partial \omega_{LT}}\Delta\omega_{LT}+\frac{\partial f}{\partial \Gamma}\Delta\Gamma. \tag{3}$$

The lineshape of the $\Delta R(\omega)$ signal depends on the phase shift Φ as the light propagates from the surface of the sample to the quantum well and back. It is found by analyzing the original reflection spectrum[9] $R_0(\omega)$. In our structure, we found $\Phi=\pi/2+2\pi N$ from the reflection spectrum.

The spectrum of the photoinduced reflection, $\Delta R/R_b$, is thus described by the parameters, $\hbar\omega_{LT}$, $\hbar\Gamma$, $\hbar\omega_0$, and Φ, which are found from an analysis of the ordinary reflection spectrum, and by the changes in these parameters due to the illumination: $\Delta\omega_0$, $\Delta\omega_{LT}$, and $\Delta\Gamma$. Since the spectra of the derivatives $\partial f/\partial\omega_0$, $\partial f/\partial\omega_{LT}$, and $\partial f/\partial\Gamma$ are different, it is possible to distinguish the contributions to the photoinduced-reflection signal by changing the corresponding parameters. Fitting the calculated spectrum of photoinduced reflection to the measured spectrum, we found relative values of the changes in the exciton parameters during the auxiliary illumination (for the e_1-hh_2 transition we found $\Delta\omega_0/\Gamma=0.1$, $\Delta\omega_{LT}/\omega_{LT}=0.25$, and $\Delta\Gamma/\Gamma=0$). We were also able to decompose the spectra for the e_1-hh_2 and e_1-hh_1 transitions and to determine the contribution of the e_1-hh_1 transition to the photoinduced reflection. This contribution turned out to be much smaller than the e_1-hh_2 contribution. It can also be seen from an analysis of the $\Delta R(\omega)/R_b(\omega)$ spectrum that while the oscillator strength of the e_1-hh_2 transition increases in an electric field, the strengths of the e_1-hh_1 and e_1-lh_1 transitions decrease.

Let us summarize. 1) A change has been observed in the optical refractive index in the region of exciton resonances in a heterostructure with a single quantum well with a piezoelectric internal field during auxiliary illumination of the structure. This effect has been explained in terms of a modulation of the electric field as it is screened by the photogenerated carriers. 2) The magnitude of the photoinduced change in the refractive index reaches a maximum for the e_1–hh_1 exciton transition, which is forbidden in the absence of an electric field. 3) It has been established that the change in the refractive index is caused by a shift of the resonant frequencies of the exciton transitions and also by changes in oscillator strengths.

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