Magneto-Optical Properties of Highly Anisotropic Holes in HgTe/CdTe Superlattices

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Far-infrared magneto-optical experiments have been performed on a *p*-type HgTe/CdTe superlattice with a small effective band gap. The angular dependence of the hole-cyclotron-resonance spectra reveals that the effective mass is 2 orders of magnitude heavier in the growth direction than transverse to it. These results provide evidence for a large valence-band offset. In addition, a tentative identification of hole spin resonance has been made. Evidence is presented which shows that the superlattice band structure can be substantially modified by the application of modest magnetic fields.

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Experimental studies of free-carrier transport along the growth direction in semiconductor superlattices have been predominantly limited to high-electric-field–driven tunneling of well-bound carriers through larger band-gap barriers. It is only recently that GaAs/AlGaAs superlattices were prepared which permitted the observation of electron cyclotron resonance involving transport through[1] (or specular reflection from[2]) the barriers. In these experiments an electron mass anisotropy ratio (effective mass along the growth direction divided by the in-plane effective mass) of less than 2 was reported.[1] Here we report magneto-optical measurements on a superlattice composed of an inverted-band, zero-gap semiconductor, HgTe, and a large band-gap semiconductor, CdTe. The experiments, performed in a magnetic field regime where the semiclassical cyclotron orbit radius, $r_0 = (\hbar/eB)^{1/2}$, was substantially larger than the superlattice period of 127 Å, showed well-developed hole-cyclotron-resonance absorption lines for orbits both perpendicular and parallel to the growth direction. The data yield a hole mass anisotropy ratio of 280. The results which are described below provide new insights into this novel superlattice system.

The HgTe/CdTe superlattice studied here was one member of a well-characterized set of samples.[3] It was grown by molecular-beam epitaxy on a (100) CdTe substrate after the growth of a 4000-Å $Cd_{0.85}Hg_{0.15}Te$ buffer layer. The superlattice consisted of 200 double layers of 78-Å-wide HgTe wells and 49-Å-wide $Cd_{0.85}Hg_{0.15}Te$ barriers. (Both the buffer layer and the barrier layers contain about 15% HgTe because the Hg-source shutter was open during the entire growth process.) Conductivity and Hall measurements at low temperatures indicated that the superlattice had an energy gap of less than 5 meV and was *p* type with hole density of the order of 10^{15} cm^{-3} and hole mobility of nearly 300000 cm^2/V s at 4.2 K. Earlier far-infrared magneto-optical experiments were performed on an *n*-type superlattice with different well and barrier thicknesses (or different energy gap) with growth along a (111) direction.[4] Thus the behavior we describe below was not observed. The present experiments were performed with use of far-infrared radiation from an optically (CO_2 laser) pumped molecular-gas laser and both superconducting and Bitter solenoidal magnets. The radiation was directed by light-pipe optics onto an area of about 8 mm^2 of the sample. The light-pipe system was placed in a He-exchange-gas enclosure which was immersed in liquid He. For selected laser frequencies, the transmission of the sample was measured as a function of magnetic field.

Figure 1 shows the magneto-absorption spectra for three laser frequencies in the Faraday geometry where

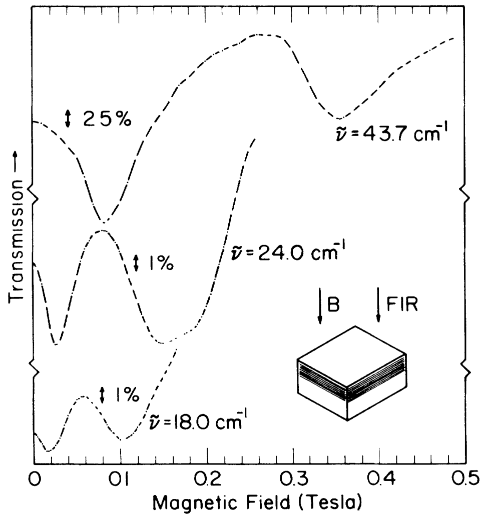

FIG. 1. Faraday-geometry magneto-absorption data for the HgTe/CdTe superlattice at 4.2 K. Since the spectra were recorded with two different analog systems, they were redrawn at 0.005 or 0.01 T intervals.

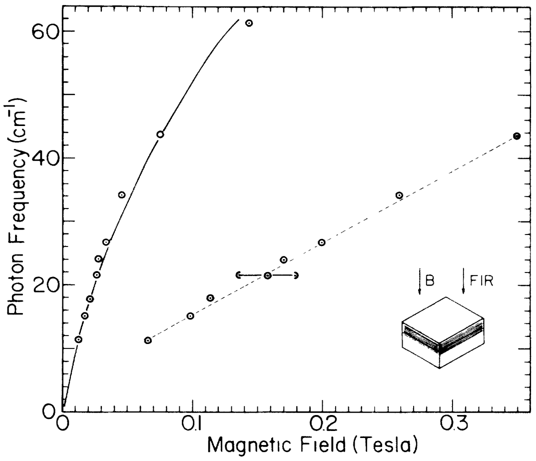

FIG. 2. A compilation of Faraday-geometry data for the HgTe/CdTe superlattice. The solid curve was calculated as described in the text. The dashed line, provided as a visual aid, shows that the high-field line has a nonzero energy intercept at zero field. The horizontal bar indicates the doubletlike behavior in the 18–24-cm^{-1} region.

the cyclotron orbit is parallel to the HgTe/CdTe layers. Through the use of a circular polarizer at $\tilde{\nu}=43.7$ cm^{-1} (a linear polarizer followed by a quartz quarter-wave plate) and a field-reversible superconducting magnet, it was found that *both* of the absorption lines of Fig. 1 occurred in the sense of circular polarization for which hole cyclotron resonance is allowed. However, as will be shown subsequently, only the lower-field line has been identified as hole cyclotron resonance. Using the relation $\hbar\omega_{\text{laser}}=\hbar\omega_c=eB_c/m^*$ at the resonant absorption field B_c, we find that the effective mass, m^*, of the hole subband is exceptionally light, of the order of $0.0011m_e$. It should be noted that even at resonant fields as low as 0.02 T (200 G), a cyclotron absorption line is observed. This implies that $\omega_c\tau$ is comparable to 1 even at this low field. By our fitting the data with Lorentzian line shapes, the scattering time τ is found to be 0.3 ps and the mobility about 300 000 cm^2/V s. These results confirm the observation[3] of high hole mobility in small-effective-gap HgTe/CdTe superlattices and show that it is due to a very light in-plane effective mass.

The data for the Faraday-geometry experiments are summarized in Fig. 2. It should be noted that the high-frequency, low-field line which has been identified as hole cyclotron resonance shows substantial curvature which is evidence of band nonparabolicity. For comparison, the solid curve was generated by use of bulk k^*p theory with a momentum matrix element of 18.5 and a spin-orbit splitting of 1.0 eV (suitable for bulk HgCdTe alloys)[5] and adjustment of the energy gap to 9 meV for best fit. It is only provided to indicate the amount of nonparabolicity. Critical comparison to theory requires correlation with detailed magnetic-field-dependent superlattice band-structure calculations.

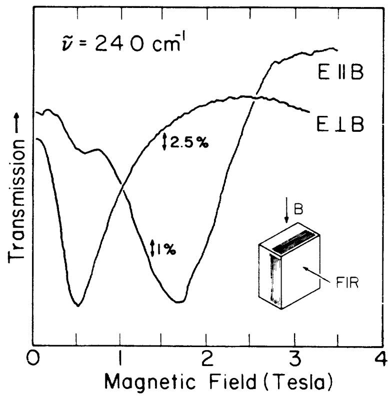

FIG. 3. Voigt-geometry magneto-absorption data for the HgTe/CdTe superlattice at 4.2 K.

Figure 3 shows magneto-absorption spectra for the Voigt geometry where the cyclotron orbits require hole transport through the superlattice barriers. (The orbit diameter at 0.5 T is about 720 Å compared to the superlattice period of 127 Å.) In this geometry, the absorption spectra for $E\perp B$ and $E\parallel B$ are found to be very different. The low-field line is identified as a cyclotron resonance transition since it occurs in the $E\perp B$, cyclotron-resonance–active sense of polarization. Conversely the high-field line at 1.7 T in $E\parallel B$ is clearly not a cyclotron resonance transition. (The weak structure at 0.5 T in $E\parallel B$ may be due to leakage of $E\perp B$ radiation through the linear polarizer.) A compilation of Voigt-geometry data is shown in Fig. 4. Whereas the $E\perp B$ cyclotron resonance transition varies linearly with field at low frequencies and has a zero-frequency intercept at zero magnetic field, the $E\parallel B$ high-field line has zero splitting at magnetic field of 0.7 T.

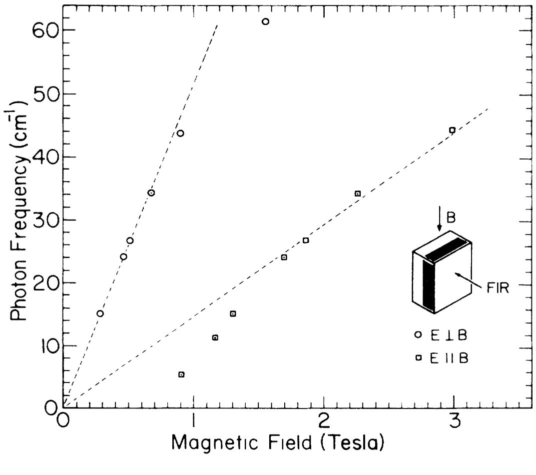

FIG. 4. A compilation of Voigt-geometry data for the HgTe/CdTe superlattice. The dashed lines are provided as visual aids.

In order to establish the relationship of the absorption lines observed in the Faraday and the Voigt geometries, the dependences of these lines have been studied as functions of the angle between the magnetic field and the growth direction. The position of the low-field line as a function of angle could be modeled by our assuming that the hole constant-energy surface was ellipsoidal. In this case, the cyclotron-resonance effective mass is given by[6]

$$[1/m_r(\theta)]^2 = \cos^2\theta/m_x^2 + \sin^2\theta/m_x m_z\ ,$$

where m_x and m_z are the effective masses in the superlattice layers and in the growth direction, respectively, and θ is the angle between the field and the growth direction. As a result of band nonparabolicity, the mass anisotropy m_z/m_x given by the constant-energy ellipsoid decreases with increasing energy. To obtain a lower limit on the mass anisotropy at the band edge, mass values from the Faraday and Voigt data are selected from Figs. 2 and 4 at a photon frequency of 24 cm^{-1}. From these values and the expression for m_r, $m_z = 0.30m_e$ is obtained with m_z/m_x of 280.

The experimental determination of a reliable value for m_z/m_x has been shown to have significant implications for the HgTe/CdTe superlattice band structure.[7] This relationship can be understood by consideration of an unstrained, lattice-matched superlattice such as GaAs/AlGaAs. In this case, the band with heavy-hole character along the growth direction lies higher in energy than the band with light-hole character along the growth direction. However, in analogy to stressed Ge,[8] the heavy-hole band has light-hole dispersion for motion in the superlattice plane, i.e., $m_z/m_x > 1$, while the opposite condition applies for the light-hole band, i.e., $m_z/m_x < 1$. Recent band-structure calculations for the HgTe/CdTe superlattice have shown, however, that for small valence-band offset of order 0–40 meV, the effects of lattice-mismatch–induced strain raises the light-hole band above the heavy-hole band.[7,9] Calculations predict that in the presence of strain a valence-band offset of greater than 150 meV is required[3] for quantum-well confinement to raise the heavy-hole band above the light-hole band. Therefore, since our mass-anisotropy results demonstrate that the heavy-hole band is the topmost valence band, our data support a large value for the valence-band offset.

A possible explanation for the origin of the high-field absorption line is suggested by Fig. 3. Intraband magneto-optical studies of InSb have demonstrated that free-electron spin resonance can be observed in the $E \parallel B$ Voigt geometry for certain crystallographic orientations of the sample with respect to the magnetic field.[10] Under these conditions, the normal magnetic dipole spin resonance matrix element is substantially enhanced by an electric dipole contribution due to inversion asymmetry of the sample.[11] In addition, earlier observations of electron spin resonance in HgCdTe alloys[12] and InSb (Ref. 13) attributed the absorption to an electric dipole contribution due to conduction-band nonparabolicity. In these latter experiments, the transition was only observed in the electron-cyclotron-resonance–inactive sense of circular polarization of the Faraday geometry. Since a small-gap HgTe/CdTe superlattice has both dramatic band nonparabolicity and enhanced inversion asymmetry compared to a HgCdTe alloy, a strong spin resonance line such as observed here is to be expected. For the foregoing reasons, the high-field line is identified as hole spin resonance. While g values of the order of 200 for the Faraday geometry and 30 for the Voigt geometry can be inferred from the data, it is obvious that the field-dependent splittings in both geometries are complicated and require additional experimental study. A recent calculation of spin splitting in a superlattice predicts zero splitting at finite field,[14] as we observe in Fig. 4.

Another possible approach to understanding our results which should be considered is the phenomenon of tilted-orbit cyclotron resonance.[15] As observed in bulk semiconductors with multiple ellipsoids not all aligned with principal axes along the field direction, elliptically polarized real-space currents lead to the breaking of the usual cyclotron-resonance selection rules. In addition, as the field orientation is changed, light-mass Fermi-surface cross sections become heavy, and vice versa. However, since we have observed no evidence for this tendency nor for the tilted-orbit selection rules, this mechanism can be ruled out. (Of course, our data at angles between Faraday and Voigt may have tilted-orbit selection rules.)

The strong band nonparabolicity and anisotropy obtained from the hole cyclotron resonance and the anomalous character of the spin resonance line position demonstrate the importance of magnetic-field–dependent band-structure calculations which include spin effects. Theoretical in-plane dispersion relations at zero field[11] predict that in small-gap HgTe/CdTe superlattices such as the present one, the light-hole mass region extends only over $E(k_x) = 10$–20 meV below the band edge. At larger values of k_x, the in-plane dispersion reflects a much heavier mass. This prediction has been substantiated by our failure to observe light-hole cyclotron resonance above the CdTe restrahlen band (photon energies of about 30 meV). In this spectral region, we observed a series of intersubband transitions with heavy-mass behavior. We therefore looked for heavy-mass cyclotron resonance at high fields and low frequencies. Starting at about 5 T, a broad, strong electron absorption line developed with $m^* = 0.21m_e$ at 10 T. In agreement with theory, we conclude that free-carrier effective masses are strongly affected by magnetic fields as low as 0.2 T and that even qualitative features of the superlattice band structure are profoundly modified by fields of 5–10 T.

Transport experiments on small-gap superlattices have shown evidence for high-mobility intrinsic electrons at temperatures as low as 15 K.[3] Band structures calculated for a 350-meV valence-band offset predict that the zone-center electron and hole masses should be "mirrors" of each other. When the present sample was heated to about 20 K, two absorption lines appeared in the electron-active sense of circular polarization at the same field magnitudes as the previously described hole cyclotron and spin resonances. However, the identification that these lines are due to light electrons should be considered tentative because of the imperfect separation of hole-active and electron-active cyclotron and spin resonance transitions by the circular polarizer and because the selection rules may depend on temperature.

In summary, the dispersion relations for a heavy-hole subband in a small-gap HgTe/CdTe superlattice have been established through the use of intraband magnetoabsorption spectroscopy. The measurements demonstrate that the superlattice has highly anisotropic, 3D-like dispersion. The anisotropy leads us to conclude that large valence-band offsets are appropriate for HgTe/CdTe superlattices. Detailed analysis of the data requires magnetic-field–dependent superlattice band-structure calculations which include spin.

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