Observation of exciton states in the magnetoabsorption spectra of lead telluride

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A low-voltage electroabsorption has been observed in lead telluride in a magnetic field. This electroabsorption sets in after a threshold is reached, goes through a maximum at $E_0^* \approx 1$–3 V/cm, and decays to zero at $E_0 \gg E_0^*$. This behavior is attributed to the appearance of exciton states in a magnetic field, which are then destroyed by impact ionization in the electric field.

The formation of shallow bound states in PbTe is extremely unlikely because of the exceptionally high static dielectric constant and the small effective masses. The binding energy of a hydrogen-like bound state is correspondingly less than 2×10^{-7} eV, so that it is easily disrupted, e.g., by a thermal process or as a result of screening by free carriers.

The situation is changed substantially upon the imposition of a magnetic field H, which "one-dimensionalizes" the relative motion of the electron and the hole under the condition $\beta = (a/L)^2 \gg 1$ [a is the Bohr radius of the exciton, and $L = (cos\hbar/eH)^{1/2}$ is the magnetic length]. In the case of one dimensional motion, we know[1] that a discrete state forms in an arbitrarily shallow potential well.

We have studied heteroepitaxial layers of PbTe on BaF_2 with an N-type conductivity, an electron density of $(2$–$5)\times10^{16}$ cm^{-3}, and a mobility $\sim 5\times10^5$ cm^2/(V·s) at 4 K. Using a diffraction monochromator (with a helium-neon laser) and a superconducting solenoid at $T = 2$ K, we detected oscillations in the edge absorption in the photon energy interval 0.19–0.49 eV. We observed up to 30 relatively sharp peaks in the absorption, which are evidence of the attainment of large values of $\omega\tau$ ($\omega_{cy}^c \tau_0 = 150$–$200$, where τ_0 is the mobility relaxation time, and ω_{cy}^c is the electron cyclotron frequency).

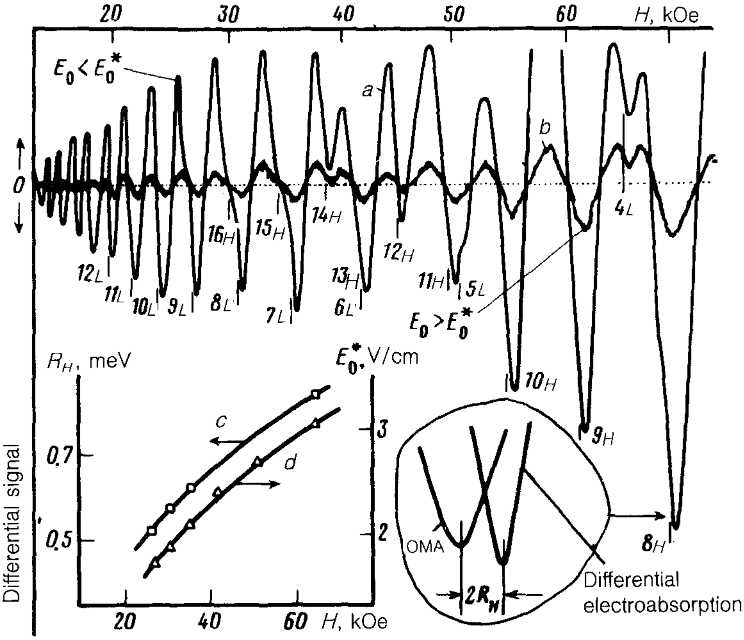

FIG. 1. Signal of differential electroabsorption of $PbTe/BaF_2$ for $E_0 < E_0^*$ and $E_0 > E_0^*$ versus the magnetic field ($H \| \langle 111 \rangle$, $\lambda = 3.39\ \mu m$, $T = 2$ K, $E_1 = 0.2$ V/cm). E_0: *a*—3 V/cm; *b*—10 V/cm ($\Omega = 1$ kHz). The labels L and H on the extrema mean "light" and "heavy" series, characterized by effective transverse masses m^*_{c,v_1} and by masses of the intersection of the ellipsoids with the plane perpendicular to the magnetic field direction, respectively. The numbers are the Landau quantum number l for the main selection rules, $\Delta l = 0$. The inset at the right compares in larger scale fragments of the electroabsorption spectrum with the spectrum of the oscillatory absorption at $E = 0$ near an extremum. This inset is drawn to explain how R_H is determined experimentally. The inset at the left shows the exciton rydberg (c) and E_0^* (d) versus the magnetic field.

To detect bound states, we use electric fields: a static field E_0 and an alternating field, with an amplitude E_1, at the frequency $\Omega = 1$ kHz. The results show that even an extremely weak static electric field, $E_0 = 2$–8 V/cm, caused a significant quenching of the oscillations (by $\sim 25\%$), but this quenching reaches saturation in strong fields. The imposition of an alternating component of the field makes it possible to detect a large differential signal (Fig. 1), whose dependence on the static component E_0 goes through a maximum at $E_0^* = 1.5$–3.1 V/cm and then falls off to zero as E_0 is raised further. This effect of the electric field may be evidence that the field causes a decay of certain weakly bound states, whose significant contribution to the fundamental absorption allows us to identify these states as being related to diamagnetic excitons. The nature of the structural features observed near the cyclotron-resonance line in PbTe in the long-wave part of the IR spectrum has recently become the subject of some discussion in the literature.[2,3] Levis *et al.*[2] interpret their experimental data, also obtained from heteroepitaxial layers of $PbTe/BaF_2$, as evidence for the observation of shallow bound states at impurities or vacancies in a magnetic field. McKnight and Drew[3] argue that these structural features belong to a dielectric anomaly in PbTe. Our own data seem to be evidence in favor of the conclusions of Levis *et al.*,[2] since there are similarities in the conditions for the existence of exciton states and shallow impurity states.

According to Bychkov,[1] the binding energy in a shallow potential well $u(r)$ in a strong magnetic field is

$$R_H = -\frac{m}{8h}\frac{1}{L^4}(\int u(r)d^3r)^2$$

and increases in proportion to H^2. An estimate of R_H for $\mathbf{H}\|\langle 111\rangle$ from this expression shows that even in the extreme case in which the screening radius of the Coulomb potential is on the order of the lattice constant at $H\approx 100$ kOe the binding energy is $R_H\approx 10^{-4}$ eV.

Experiments with various experimental configurations, with various samples, suggest that the main reason for the decay of the exciton states in PbTe in an electric field is their impact ionization by free charge carriers. In this case, we perceive a definite analogy with the cases of InSb in a magnetic field[4] and germanium,[5] where the ionization of donors or the destruction of excitons by impact ionization occurs at electric fields in the same range.

Unfortunately, a direct calculation of the binding energy from E_0^* for impact ionization would require a detailed account of the changes in the energy distribution of the carriers; the presence of the magnetic field would complicate such calculations.

There is the possibility of obtaining an independent estimate of R_H by comparing the electromodulation spectrum with the ordinary spectrum. Since the modulation occurs in such weak electric fields only by virtue of the exciton contribution, while the total absorption is determined primarily by transitions to the continuum above the Landau levels, it may be assumed that the slight shift of the peaks which does occur is due primarily to the binding energy. According to D'yakonov *et al.*,[6] this shift would be on the order of $2R_H$ in the case of strong screening. The estimates of R_H found in this manner are shown in the inset in Fig. 1 as a function of the magnetic field, along with the behavior of E_0^* as a function of the magnetic field. The binding energy increases slowly as a function of the magnetic field and has a value of $(5–8)\times 10^{-4}$ eV for 20–60 kOe, in agreement with calculations based on the model of diamagnetic excitons,[7] if we choose the effective dielectric constant to be $\kappa_0^{\mathrm{eff}}\approx 130$. The reason for such a pronounced change in κ_0 might be sought in the frequency dependence of the lattice polarizability of PbTe. We see that by choosing an appropriate scale factor (el_0^*) we can bring the curves of R_H and E_0^* versus H essentially into coincidence. The lower boundary on the mean free path here is $l_0^{*\min}\approx 2.7\ \mu$m.

Putting all these results together, we can say that we have detected exciton states under these experimental conditions from the interband magnetoabsorption even in such a narrow-gap $[\epsilon_g(0) = 0.19$ eV$]$ semiconductor crystal as PbTe, where the effective masses are very small $[m_{c1}^*(0)\approx m_{v1}^*(0)\approx 0.02m]$, and the dielectric constant is unusually large $(\kappa_0\approx 1000)$.

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