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# Magnetic activation of bipolar plasmas in HgTe-CdTe superlattices

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It is shown theoretically that in semimetallic HgTe-CdTe superlattices, there is a critical magnetic field above which minority carriers with density proportional to $B - B_{\rm crit}$ are expected to coexist with majority carriers in the zero-temperature limit. Experimental confirmation of the magnetically activated bipolar plasma is provided by low-temperature magneto-optical data showing the emergence of minority holes in an $n$-type superlattice whenever $B > B_{\rm crit}$.

Since the recent resolution of controversy concerning the valence-band offset in HgTe-CdTe superlattices,[1] it has become apparent that a number of distinctive features in the band structure of that system are directly manifested in observable properties. These include an extreme nonparabolicity of the valence band,[2,3] "mass broadening,"[2] a double semiconductor-semimetal-semiconductor transition as the well thickness is varied,[2,4,5] and double-hole cyclotron resonance,[6,7] all of which have been correlated with specific aspects of the experimental magneto-transport and magneto-optical data. Most of these properties are either directly or indirectly related to interactions between the HH1 band, which is nearly dispersionless in the growth direction $k_z$, and the $E1$ band, which has strong dispersion in $k_z$. In this paper we demonstrate that the anticrossing of the two bands in semimetallic superlattices has another consequence which is, to our knowledge, unique in solid-state physics: the magnetic activation of a bipolar plasma whose density increases linearly with field when $B$ exceeds a certain critical value, $B_{\rm crit}$. Dramatic experimental confirmation of the effect is provided by low-temperature magneto-optical data showing the emergence of minority holes in an $n$-type superlattice whenever $B > B_{\rm crit}$.

Electron and hole Landau levels (without collision broadening)[8] as a function of $k_z$ are illustrated in Fig. 1, for a semimetallic HgTe-CdTe superlattice with well and barrier thicknesses $d_W = 74$ Å, $d_B = 39$ Å at a fixed field of 0.1 T. (See Ref. 9 for a detailed discussion of HgTe-CdTe band structures in the presence of a magnetic field.) All levels above and including $-1'E$ are electron states, while all levels below and including $1H$ are hole states. However, the levels 0 (which has the strong dispersion of the $E1$ band) and $-2'$ (which is nearly dispersionless like the HH1 band), anticross at an intermediate wave vector $k_{zc}$ and change their character at the crossing point (the approach of the two levels is indeterminately close).

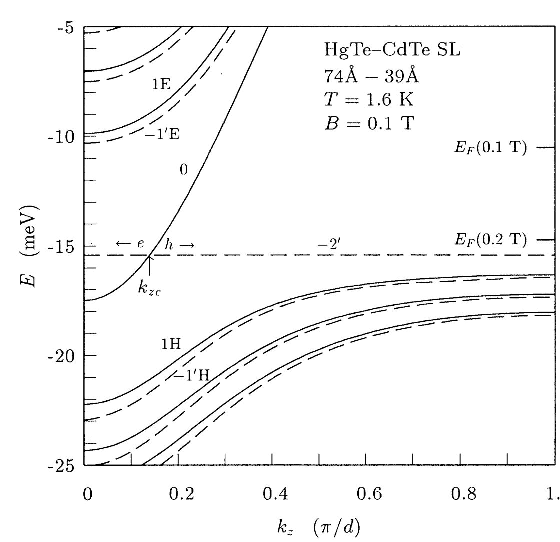


FIG. 1. Landau levels vs growth-direction wave vector at $B = 0.1$ T in a [100]-oriented semimetallic HgTe-$Hg_{0.15}Cd_{0.85}Te$ superlattice with $d_W = 74$ Å, $d_B = 39$ Å (including strain and assuming a valence-band offset of 350 meV). Allowed magneto-optical transitions can only connect two solid or two dashed levels. The position of Fermi energy (taking $N_D - N_A = 6 \times 10^{14}$ cm$^{-3}$) is indicated, along with $E_F$ relative to $-2'$ at the critical field (0.2 T).

 

That is, when $k_z < k_{zc}$ the 0 level is a valence band and $-2'$ is a conduction band, whereas the roles are reversed when $k_z > k_{zc}$.

The statistical properties of the carrier populations are governed by the requirement of charge neutrality,

$$n - p = N_D - N_A, \tag{1}$$

where $N_D$ and $N_A$ are the donor and acceptor concentrations. The electron and hole densities as a function of magnetic field and Fermi level $E_F$ are given by

$$n = \frac{eB}{2\pi^2\hbar}\sum_j \int_0^{\pi/d} dk_z f_j(k_z, B)\ ,$$
$$p = \frac{eB}{2\pi^2\hbar}\sum_j \int_0^{\pi/d} dk_z [1 - f_j(k_z, B)], \tag{2}$$

where the sums are over conduction or valence states, $f_j$ is the Fermi distribution function,

$$f_j = \frac{1}{e^{(E_j - E_F)/k_B T} + 1}, \tag{3}$$

and $E_j(k_z, B)$ is the energy of level $j$.

Consider the superlattice whose band structure is illustrated in Fig. 1 at $T = 1.6$ K and assuming a net donor density of $N_D - N_A = 6 \times 10^{14}$ cm$^{-3}$ (the same parameters will be employed below in fitting the experimental magneto-optical data). In the low-field limit, $E_F$ must lie above many Landau levels in the conduction band since the density of states per level is proportional to $B$. This naturally precludes the presence of any significant hole concentration at low $B$. However, the carriers occupy progressively fewer levels as the field is increased. Figure 1 illustrates that at $B = 0.1$ T the Fermi energy is 5 meV above the conduction-band minimum, i.e., the electron portion of the $-2'$ level along with the intermediate-$k_z$ portion of 0 ($k_{zc} \leq k_z \leq 0.25$) and small-$k_z$ states in $-1'E$ and $1E$ are adequate to account for the required electron density. When $B$ is increased further, one eventually reaches a critical field $B_{\rm crit}$ at which the density of states in $-2'$ is large enough to accommodate the entire electron population. The Fermi level at $B = B_{\rm crit}$ ($\approx 0.2$ T in this example) therefore moves to within a few $k_B T$ of the conduction-band minimum, as is shown in the figure.[10] If one then increases the field beyond the critical value, the electron portion of $-2'$ becomes partially unoccupied because the density of states is greater than that required to give $n$. However, this automatically implies that the hole portion of $-2'$ must be partially occupied, since the two portions are at the same energy. Electrons and holes therefore coexist in the zero-temperature limit whenever $B > B_{\rm crit}$.

The critical field is easily evaluated from Eqs. (1)–(3), accounting for the fractional apportionment of the $-2'$ level between conduction and valence states:

$$B_{\rm crit} = \left(\frac{2\pi\hbar d}{e}\right)\frac{N_D - N_A}{k_{zc}/(\pi/d)}, \tag{4}$$

where the same expression may be used for $p$-type semimetallic superlattices if $N_D - N_A$ is replaced by $N_A - N_D$ and $k_{zc}/(\pi/d)$ is replaced by $1 - k_{zc}/(\pi/d)$. Increasing $N_D - N_A$ increases $B_{\rm crit}$ since more electrons must be accommodated in the $-2'$ level, while increasing $k_{zc}$ has the opposite effect because more states are then available at a given field. The minority hole concentration at low $T$ is found to have the temperature-independent form

$$p \approx 0, \quad B < B_{\rm crit},$$
$$p = \frac{k_{zc}}{\pi/d}\left(1 - \frac{k_{zc}}{\pi/d}\right)\frac{e}{2\pi\hbar d}(B - B_{\rm crit}), \quad B > B_{\rm crit}, \tag{5}$$

which may also be used for the minority electron density in $p$-type superlattices. We thus predict that the application of a field $B > B_{\rm crit}$ to a semimetallic HgTe-CdTe superlattice at $T = 0$ results in the generation of a bipolar plasma whose concentration increases proportionately to $B - B_{\rm crit}$ (the dependence is not strictly linear because $k_{zc}$ varies with $B$). This increase continues until the field becomes large enough to shift the 0 level entirely above $-2'$ for all $k_z$ ($k_{zc}$ vanishes at the semimetal-to-semiconductor transition[9]). Since the superlattice is no longer semimetallic in the high-field limit, minority carriers freeze out at low $T$ as in a conventional semiconductor.

Figure 2 shows the results of employing Eqs. (1)–(3) to calculate $n$ and $p$ vs $B$ for two different superlattices: $d_W = 74$ Å, $d_B = 39$ Å (as in Fig. 1) and $d_W = 81$ Å, $d_B = 39$ Å (whose band structure is similar to that in Fig. 1 except that the crossing point $k_{zc}$ is farther to the right, at $\approx 0.5\pi/d$). In both cases, we again assume $N_D - N_A = 6 \times 10^{14}$ cm$^{-3}$. The figure illustrates that while the minority hole density at $T = 1.6$ K essentially vanishes in the limit of zero magnetic field, there is a

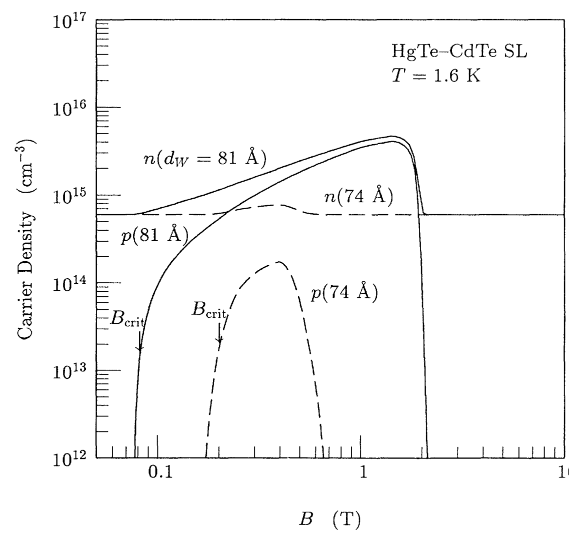


FIG. 2. Theoretical electron and hole densities vs magnetic field at $T = 1.6$ K, for HgTe-CdTe superlattices with $d_W = 74$ Å (dashed) and 81 Å (solid curves). In both cases, $d_B = 39$ Å and $N_D - N_A = 6 \times 10^{14}$ cm$^{-3}$.

dramatic increase as soon as $B$ exceeds $B_{\rm crit}$. The critical field is smaller in the 81-Å superlattice because of the larger $k_{zc}$ [see Eq. (4)]. In that case, the roughly linear increase of $n$ and $p$ with $B - B_{\rm crit}$ continues well beyond the point where the minority hole density exceeds the background doping level. At 1.8 T an energy gap finally opens up between the 0 and $-2'$ levels, and $p$ drops rapidly to zero. The maximum hole density is seen to be much lower in the 74-Å superlattice, because the semimetal-to-semiconductor transition occurs at $B \approx 0.5$ T, only 0.3 T beyond $B_{\rm crit}$. Nonetheless, the magnetic activation is predicted to produce minority hole concentrations large enough to be observable experimentally. Bipolar densities larger than those shown in Fig. 2 should be achievable in superlattices for which the semimetal-to-semiconductor transition occurs at fields greater than 1.8 T, i.e., in structures with larger $d_W$ or smaller $d_B$.

We next present experimental magneto-optical data which fully substantiate the predicted magnetic activation of minority carriers. Using an apparatus which has been described previously,[11] magneto-transmission measurements were performed at a series of discrete far infrared (FIR) laser wavelengths between 103 and 229 $\mu$m. The present data were acquired with the optical beam and magnetic field parallel to the superlattice growth direction, and all measurements employed radiation which was circularly polarized, either in the electron cyclotron resonance active (CRA) sense or in the electron cyclotron resonance inactive (CRI) sense. The 100-period HgTe-CdTe superlattice was grown by molecular beam epitaxy at 195 °C onto a [211] CdTe substrate with no buffer layer. Nominal well and barrier thicknesses obtained from x-ray satellite peaks were 75 and 36 Å. Magneto-transport and earlier magneto-optical measurements on this superlattice were reported previously as data for Sample 5 from Ref. 12. Since those results showed the superlattice to be semimetallic with a small $k_{zc}$ as in Fig. 1, the parameters used to obtain that figure are employed in the magneto-optical calculations discussed below.[13] The analysis of the magneto-transport data implied a net electron concentration of $9.6 \times 10^{14}$ cm$^{-3}$, which is in reasonable agreement with the value $6 \times 10^{14}$ cm$^{-3}$ obtained from the fit to the magneto-optical data.[14]

Figure 3 shows experimental magneto-transmission spectra for both polarizations at $T = 1.6$ K. The CRA spectra for all six photon energies are dominated by a strong electron cyclotron resonance minimum (which corresponds to an effective mass of only $\approx 0.002 m_0$). By contrast, the structure in the CRI spectrum for the lowest photon energy (5.41 meV) is barely discernible. However, with increasing frequency the lower-field CRI feature,[15] whose position $B_r$ is comparable to the electron cyclotron field, grows rapidly until at 12.0 meV its line intensity is nearly as large as that of the CRA resonance. The increase is particularly abrupt for photon energies between 8.48 and 10.4 meV, i.e., where the magnetic field at resonance spans the narrow range between 0.16 and 0.20 T.

In order to verify that these observations are in agreement with the behavior expected when minority holes are magnetically activated, we compare the experimental magneto-transmission spectra with the results of a theoretical model. The calculation employs a recently developed formalism[9] which fully accounts for the HgTe-CdTe superlattice band structure. Dependences of the Landau levels on $k_z$ and $B$ were again calculated using the parameters discussed in connection with Fig. 1. Statistical considerations were also properly treated, using

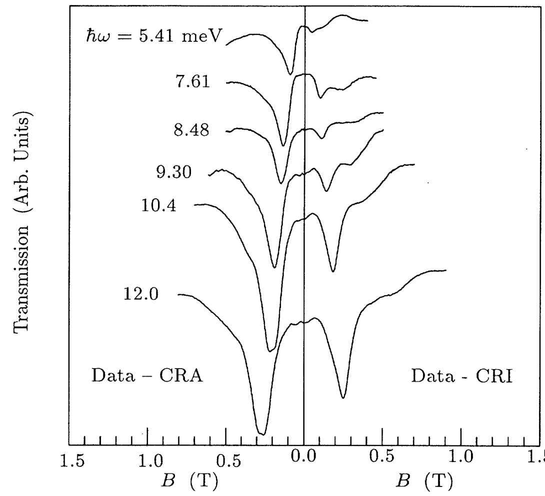


FIG. 3. Experimental CRA and CRI transmission spectra vs magnetic field at $T = 1.6$ K, for a HgTe-CdTe superlattice at six different FIR photon energies.

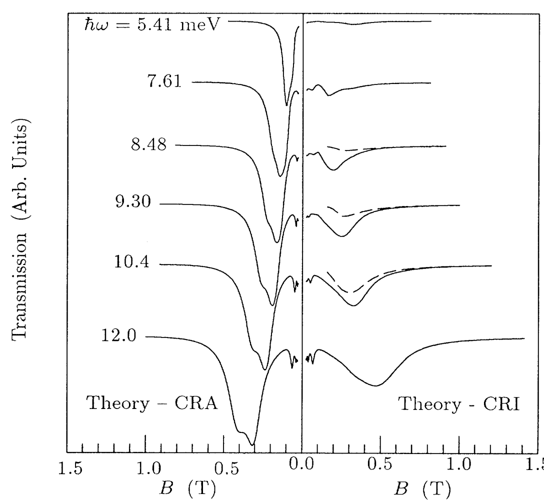


FIG. 4. Theoretical CRA and CRI transmission vs magnetic field at $T = 1.6$ K for six different FIR photon energies. The calculation assumes $N_D - N_A = 6 \times 10^{14}$ cm$^{-3}$ for all solid curves and $1 \times 10^{15}$ cm$^{-3}$ for the three dashed curves. Identifying the minima, the CRA feature has contributions by $-2' \rightarrow -1'E$ (higher field) and $0 \rightarrow 1E$ (lower field), both due primarily to transitions near $k_z = 0$. The CRI spectrum is dominated by $-2' \rightarrow -1'H$, where the strong feature is due to transitions near $k_z = 0$. The higher-field CRI line, which is barely discernable at 7.61 meV in the theory but is somewhat better resolved in the experiment, is due to the same transition at $k_z \approx \pi/d$.

an independently derived Fermi energy whose variation with $B$ depends on the details of the band structure.

Results for the theoretical magneto-transmission are illustrated in Fig. 4. Although the calculated CRI resonance is somewhat broader than in the data of Fig. 3, we find that the main features of the two spectra are in excellent agreement. While the CRA minimum is strong at all photon energies,[16] theory predicts a negligible absorption of CRI-polarized radiation until the resonance field approaches the critical value. The solid curves were calculated assuming $N_D - N_A = 6 \times 10^{14}$ cm$^{-3}$, for which $B_{\rm crit} \approx 0.20$ T (the onset of CRI absorption begins at fields slightly below the critical value due to thermal broadening). The dashed curves show that the fit to the data is not as good if the net donor density is increased slightly, to $1 \times 10^{15}$ cm$^{-3}$. It is evident that the magnetic activation of minority holes, and hence the onset of CRI absorption, is then delayed until $B_r$ reaches a higher critical field: $B_{\rm crit} \approx 0.32$ T. If $N_D - N_A$ is increased further to $2 \times 10^{15}$ cm$^{-3}$, magnetic activation ceases to occur at all because the superlattice then passes through the semimetal-to-semiconductor transition before the critical field in Eq. (4) is reached. On the other hand, considerably stronger minority hole activation is expected in superlattices with larger $k_{zc}$ (see Fig. 2).

The magnetic activation of minority carriers in semimetallic HgTe-CdTe superlattices at fields above the critical value is apparently unique. Although electrons and holes coexist at zero temperature in indirect semimetals such as Bi,[17] in that case there is in no sense a magnetic activation of the plasma. Similarly, while the magnetic "boil off" of neutral acceptors in $Hg_{1-x}Mn_xTe$ leads to a considerable increase in the free carrier concentration with $B$,[18] that effect yields only a unipolar hole population rather than the bipolar plasma which results in the present system. Theory predicts that electron-hole concentrations in excess of $10^{16}$ cm$^{-3}$ should be attainable in semimetallic HgTe-CdTe samples with $k_{zc}(B=0) \approx \pi/d$. Activation of even higher densities may be possible within limited magnetic field ranges [such that $0 < k_{zc}(B) < \pi/d$] in thick-well superlattices from the "second semiconducting region."[2,4,5]

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[1] For a summary of evidence showing that the offset must be large, see J. R. Meyer, C. A. Hoffman, and F. J. Bartoli, Semicond. Sci. Technol. **5**, S90 (1990).

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[8] In the experiment discussed below, we estimate broadening by 2–3 meV. It should be noted that any partially filled narrow band displays semimetallic features, since the unfilled states may be treated as holes. However, at magnetic fields for which the cyclotron energy is larger than the bandwidth, this effect will not lead to minority-carrier cyclotron resonance, and does not account for the data in Fig. 3.

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[10] While the higher-order Landau levels spread farther apart at $B = 0.2$ T, the arrangement of 0 and $-2'$ is the same except that $k_{zc}$ moves slightly to the left.

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[13] The experimental conditions could not be reproduced exactly because the present band-structure formalism does not treat [211]-oriented superlattices in the presence of a magnetic field. However, as long as the crossing point $k_{zc}$ is accurately accounted for, the main features should not be very sensitive to orientation or to the small difference between assumed and measured $d_B$.

[14] The modest disagreement may be due either to our use of a band structure with $k_{zc}$ slightly too small or to error in the mixed conduction analysis induced by the change of the carrier densities with magnetic field.

[15] Besides the principal minimum at lower fields, the experimental CRI spectra contain a weak higher-field minimum as well. This is also present in the theoretical spectra at 5.41 and 7.61 meV, and is due to hole cyclotron resonance at $k_z \approx \pi/d$ (see Refs. 6, 7, and 9). In both experiment and theory this feature is relatively strongest at 7.61 meV, where $B_r < B_{\rm crit}$ for the lower-field line but $B_r > B_{\rm crit}$ for the higher-field resonance.

[16] Note that in both the theoretical and experimental spectra, the CRA minimum becomes resolved into a doublet as the photon energy is increased (the splitting of the experimental line becomes more obvious at slightly higher temperatures). This is because two different transitions contribute: $-2' \rightarrow -1'E$ and $0 \rightarrow 1E$.

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