Magnetic-field-induced electron localization in $Cd_xHg_{1-x}Te$ due to potential fluctuations

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A model is proposed which ascribes the peculiarities of the galvanomagnetic properties of semimetal and semiconductor $Cd_xHg_{1-x}Te$ crystals to localization of electrons in the fluctuation potential. The important role of acceptors in the localization of electrons in semimetallic samples is demonstrated. In contrast to previous work, part of the measurements are carried out at an ultrahigh frequency ($\omega = 2 \cdot 10^{11}\ s^{-1}$). Experiments performed with $Cd_xHg_{1-x}Te$ samples of various composition at $T = 1.4$–$30\ ^\circ K$ and $B \lesssim 80$ kG are in agreement with the model proposed and confirm its predictions.

It is well known (Ref. 1–5) that the galvanomagnetic properties of crystals of $Cd_xHg_{1-x}Te$ at helium temperatures exhibit a number of peculiarities which manifest themselves primarily through a sharp increase in the resistances (both longitudinal and transverse) of these crystals, and an equally abrupt falloff in their Hall conductivity, starting at some magnetic field B_c. The natural explanation of this effect involves localization of conduction electrons in a strong magnetic field; however, the mechanism and character of this localization have not yet been clearly elucidated.

In semimetallic samples of $Cd_xHg_{1-x}Te$, electron localization is associated with magnetic freezeout on localized acceptor levels, which emerge from the conduction band in a strong magnetic field (Ref. 1). However, this process by itself should lead to the "wrong" type of conductivity, i.e., p-type, in $Cd_xHg_{1-x}Te$, since hopping conductivity on acceptors has a hole-like character. To date, p-type conductivity has never been observed in these materials.

For semiconducting crystals, the following conductivity mechanisms have been proposed: Wigner crystallization of the electron gas (Ref. 2), magnetic freezeout on donors (Refs. 3 and 4), or localization in "troughs" of the potential contour (i.e., potential fluctuations; see Ref. 5). All these mechanisms except the last one are suspect at the present time because they (or their consequences) are found to be in contradiction with experimental data: the observed localization occurs at temperatures that are too high and fields that are too weak for Wigner crystallization, and freezeout on donors is also a high-field effect (Ref. 5). As for the mechanism proposed in Ref. 5, i.e., localization of electrons in potential fluctuations, it must be regarded purely as a hypothesis whose correctness is supported solely by the fact that the experimentally determined value of the field B_c is considerably smaller than the field needed to produce magnetic freezeout on donors. We note here that the experiments reported in Ref. 5 were carried out on semiconducting samples only, all of which were of the same composition ($x = 0.2$), and hence the question of what mechanism causes localization in semimetallic samples remains open.

In this work we describe and analyze experiments whose results are naturally explained on the basis of magnetic-field-induced localization of electrons in potential fluctuations, both for semiconducting and semimetallic crystals of $Cd_xHg_{1-x}Te$. In contrast to Ref. 5, our experiments not only broaden the class of samples which have been investigated, but also make use of a novel experimental technique (performing measurements at ultra-high frequencies), which allowed us to detect (and correlate with the results of DC measurements) the different components of the high frequency conductivity tensor and the dielectric permeability. All this permitted us to arrive at a much more reliable and detailed picture of the mechanism by which the electrons are localized, and to elucidate (in the case of the semiconducting samples) the important role of acceptors in this process.

EXPERIMENTAL RESULTS

In addition to standard galvanomagnetic measurements carried out on crystals of $Cd_xHg_{1-x}Te$ for various compositions (see Table I) in the temperature range $1.4\ ^\circ K$ to $30\ ^\circ K$, and for magnetic fields up to 80 kG, we also investigated the propagation of high-frequency electromagnetic waves ($\lambda \approx 8$ mm) with two differernt directions of circular polarization (in a magnetic field, these are helicon and ordinary waves; see Ref. 6). These waves propagate according to the following dispersion relation (magnetic field is in the z-direction):

$$\frac{k^2c^2}{\omega^2} = \varkappa \pm \frac{4\pi}{\omega}\sigma_{yx}(\omega) + i\frac{4\pi}{\omega}\sigma_{xx}(\omega), \qquad (1)$$

in which $\omega \approx 2\times 10^{11}\ sec^{-1}$ and k are the frequency and wave number. $\varkappa$ is the dielectric permeability, and σ_{yx}, σ_{xx} are components of the conductivity tensor. Having measured the phase and amplitude of waves which have passed through a crystal, we can determine the absolute values of $\varkappa(\omega), \sigma_{yx}(\omega), \sigma_{xx}(\omega)$ and their field dependences (Ref. 7).

The experimental results can be summarized as follows: there exists a value of magnetic field $B = B_c$ (characteristic for each sample) at which $\sigma_{xx}(0) = \sigma_{yx}(0)$. As B traverses the region around B_c, various material parameters undergo more or less abrupt variations (see Fig. 1):

1) For $B \approx B_c$ an abrupt decrease in $\sigma_{yx}(0)$ takes place;

2) For $B \gtrsim B_c$ an exponential component appears in the temperature dependence of $\sigma_{yx}(0)$ (see Figs. 2, 3);

3) For $B \lesssim B_c$ $\sigma_{yx}(0) = \sigma_{yx}(\omega)$, $\sigma_{xx}(0) = \sigma_{xx}(\omega)$; for $B \gtrsim B_c$ this equality ceases to hold, while

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TABLE I. Parameters for samples of $Cd_xHg_{1-x}Te$, studeid at $T = 4.2$ °K.

№№	1	2 [4]	3	4	5
x	0	0,08	0,125	0,14	0,14
n, 10^{15} см$^{-3}$	2,25	1,5	0,89	0,19	2,1
μ, 10^5 см^2/V·s	1,17	1,8	7,9	4,5	1,4
N_I, 10^{15} см$^{-3}$	8,2 [1]	10^{1} [1]	3,8 [1]	3,2 [1]	15
$K_{eff}=N_A^-/N_D$	0,57 [1]	0,74 [1]	0,62 [1]	0,88 [1]	0,75
$K=N_A/N_D$	$0,79<K<1$ [2]	>1 [2]	0,95 [2]	0,94 [2]	$K=K_{eff}$

№№	6	7	8	9	10
x	0,167	0,17	0,176	0,18	0,18
n, 10^{15} см$^{-3}$	0,6	0,3	0,14	0,71	0,78
μ, 10^5 см^2/V·s	1,7	30	6,1	5,5	4,1
N_I, 10^{15} см$^{-3}$	1,8	1,0	1,2 [3]	2,9 [3]	4
$K_{eff}=N_A^-/N_D$	0,94	0,54	0,81	0,60	0,70
$K=N_A/N_D$	$K=K_{eff}$	$K=K_{eff}$	$K=K_{eff}$	$K=K_{eff}$	$K=K_{eff}$

[1] N_I = computed for $B < B_c$.
[2] Computed for $B > B_c$ with the help of data from high-frequency measurements.
[3] Obtained for $\varkappa = 18$.
[4] In sample No. 2, where $N_A > N_D$, a sign change in $\sigma_{yx}(0)$ is observed; the electrons are localized not in the fluctuations but on acceptor levels.

$$|\sigma_{yx}(\omega)-\sigma_{yx}(0)|/\sigma_{yx}(\omega)\sim|\sigma_{xx}(\omega)-\sigma_{xx}(0)|/\sigma_{xx}(\omega)\sim 1;$$

4) For $B \approx B_c$ the value of $\varkappa(\omega)$ exhibits a jump (see Fig. 1);

5) For $B > B_c$, in certain samples of n-$Cd_xHg_{1-x}Te$ the Hall constant changes its sign, whereas for other (similar) samples this does not happen.

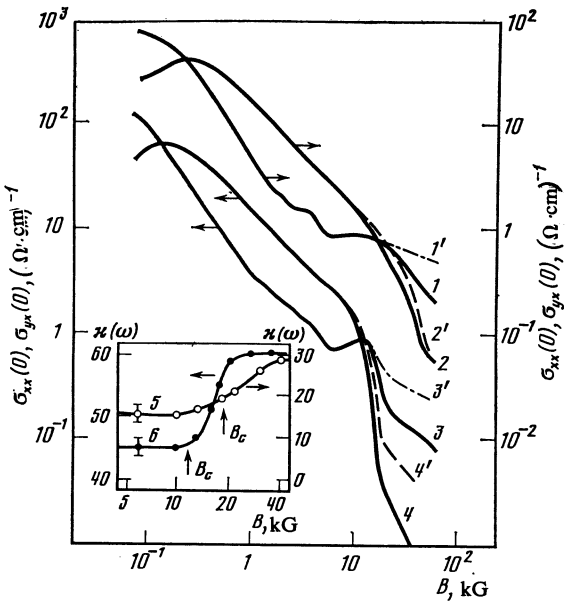

FIG. 1. Dependence of $\sigma_{xx}(0)$ (curves 1, 3), $\sigma_{yx}(0)$ (curves 2, 4), $\sigma_{xx}(\omega)$ (curves 1′, 3′), $\sigma_{yx}(\omega)$ (curves 2′, 4′) on magnetic field at $T = 4.2$ °K. The inset shows the dependence of $\varkappa(\omega)$ (measured at a frequency of 2×10^{11} sec^{-1}) on magnetic field at $T = 4.2$ ° K. Curves 1, 1′, 2, 2′, 5 were obtained from sample No. 10, curves 3, 3′, 4, 4′, 6 from sample No. 3.

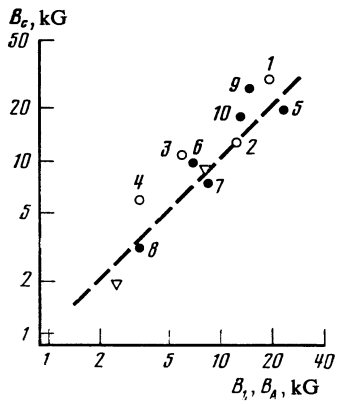

FIG. 2. Experimental values of B_c at $T = 4.2$ °K compared with calculated values of B_l (●) and B_A (○). The figures next to each point are sample numbers. Points ▽ are calculated from data given in Ref. 5.

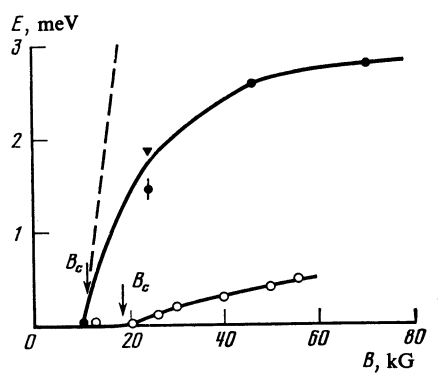

FIG. 3. Dependence of the activation energy for conductivity $\sigma_{yx}^{(1)}(0)$ on magnetic field for samples No. 10 (○) and No. 3 (●). For $B < B_c$, $E = 0$. The point (▼) is determined from the temperature dependence of $\sigma_{xx}^{(1)}(0)$ for sample No. 3. The dashed line shows the calculated magnetic-field dependence of the energy gap between the acceptor level and the bottom of the conduction band for $B > B_c$.

DISCUSSION

All the peculiarities enumerated above can be explained on the basis of the assumption that for all the semiconducting and semimetallic crystals investigated in which $N_D > N_A$, there occurs at a field $B = B_c$ a transition from metallic conductivity to activated conductivity. This transition is due to localization of electrons in "troughs" formed by the potential contour, and is connected with the presence of large number of charged impurities (donors and acceptors), and possibly with fluctuations in composition. Electron localization in these potential fluctuations can occur at considerably lower fields than those necessary to cause magnetic freezeout on discrete impurities.

The field at which this localization in impurity potential fluctuations begins is given by the expression (Refs. 5, 8):

$$B_l \approx 3\pi^2 \frac{\hbar c}{e} \frac{a^{1/3} n^{7/6}}{N_I^{1/3}} \quad (N_I = N_D + N_A^-), \tag{2}$$

in which $a = \hbar^2 \varkappa / me^2$ is the Bohr radius of an electron localized on an isolated donor and n, N_D and N_A are the concentrations of electrons, donors and acceptors[1)].

According to Ref. 8, relation (2) is correct if $n < N_I / (N_I a^3)^{1/5}$ that is for a sufficiently high level of compensation $K = N_A/N_D > [(N_I a^3)^{1/5} - 1]/[(N_I a^3)^{1/5} + 1]$, which is also characteristic of $Cd_x Hg_{1-x} Te$ crystals (see Table I). In the absence of strong compensation, magnetic freezeout on donors would have to begin at a field B_1 which is determined by the condition (Ref. 8)

$$N_D \lambda_1^2 a / \ln(a/\lambda_1) \approx (0{,}25)^3, \tag{3}$$

where $\lambda_1 = (c\hbar/eB_1)^{1/2}$. From (2) and (3) (for $K \geqslant 0.5$) we find

$$B_1 \geqslant 4 (na^3)^{1/6} B_l \approx 4 B_l, \tag{4}$$

that is $B_1 \gg B_l$.

A very important property of $Cd_x Hg_{1-x} Te$ should be noted here: in crystals of semimetallic composition the acceptor level lies in the conduction band for $B = 0$, and if the concentration of electrons is small enough to ensure that $\varepsilon_F^0 \leqslant \varepsilon_A^0$ (ε_F^0, ε_A^0 are the Fermi energy and acceptor ionization energy corresponding to $B = 0$), the acceptors will be totally (or at any rate partially) neutral. Therefore the effective compensation level satisfies $K_{\text{eff}} = N_A^-/N_D \ll K$, and the amplitude of potential fluctuations is not so great; hence, there is no reason to expect that the onset of electron localization in potential fluctuations can be described by formula (2). However, as the magnetic field increases, the bottom of the conduction band rises, and for a certain field B_A the acceptor level emerges from the conduction band. At this field, part of the electrons become trapped on acceptors, the compensation increases abruptly from K_{eff} to $K = N_A/N_D$, and localization of electrons (those which still remain in the conduction band) takes place in the newly-emerged potential fluctuations.

In semimetallic samples Nos. 1–4, $\varepsilon_F^0 \approx \varepsilon_A^0$ for $B = 0$. This confirms that the values of ε_A^0 determined with the help of such relations are in good agreement with the data given in Ref. 9. The field B_A at which the acceptor level emerges from the conduction band can be determined with the help of the following expression:

$$^1/_2 \varepsilon_g [(1 + 4P^2/3\varepsilon_g^2 \lambda_A^2)^{1/2} - 1] = \varepsilon_A^0 \approx \varepsilon_F^0, \tag{5}$$

in which $\lambda_A = (c\hbar/eB_A)^{1/2}$, P is the momentum matrix element (Ref. 10) and E_g is the energy gap between the Γ_8 and Γ_6 bands. In semimetallic sample No. 5 (which is near in composition to the transition to the semiconducting state) $\varepsilon_F^0 > \varepsilon_A^0$ for $B = 0$. In it $K = K_{\text{eff}}$ even for $B = 0$, and the emergence of the acceptor level from the conduction band does cause the compensation level or potential contour to vary. In this case, electron localization occurs, just as in the semiconducting samples, at the field B_l.

Thus, in the model under investigation here the critical field B_c for semiconducting crystals must coincide with the field B_l, while for semimetallic crystals, depending on the relation between ε_F^0 and ε_A^0, it coincides either with the field B_A (for $\varepsilon_F^0 \leqslant \varepsilon_A^0$) or with the field B_l (for $\varepsilon_F^0 \geqslant \varepsilon_A^0$). A comparison of experimental and theoretical values of the critical field presented in Fig. 2 for various samples (also shown there are points taken from Ref. 5) demonstrates good agreement between theory and experiment[2)].

Let us move on to the temperature dependence on the conductivity tensor. Within the context of the model under investigation here, the conductivity for $B > B_c$ should be determined by free electrons which are thermally excited into states above the mobility edge, and also electrons (for $N_D > N_A$) or holes (for $N_D < N_A$) which are localized either in potential fluctuation troughs or on acceptors, and which participate in hopping conductivity. In this case, according to the two-band model,

$$\sigma_{yx}(0) = \sigma_{yx}^{(1)}(0) + \sigma_{yx}^{(2)}(0), \quad \sigma_{xx}(0) = \sigma_{xx}^{(1)}(0) + \sigma_{xx}^{(2)}(0), \tag{6a}$$

where

$$\sigma_{yx}^{(1)}(0), \sigma_{xx}^{(1)}(0) \propto T^{n/2} \exp(-E/kT), \tag{6b}$$

$$\sigma_{yx}^{(1)}(0) = nec/B \gg \sigma_{xx}^{(1)}(0), \quad \sigma_{yx}^{(2)}(0) \ll \sigma_{xx}^{(2)}(0). \tag{6c}$$

Here, the subscripts 1, 2 refer to free and localized carriers respectively, E is the activation energy for the process of thermal excitation of electrons to states above the mobility edge[3)]. For $N_D > N_A$, $\sigma_{yx}^{(2)}(0) > 0$, while for $N_D < N_A$ $\sigma_{yx}^{(2)}(0) < 0$. In particular, this model explains when the sign of the Hall coefficient remains the same and when it changes (after it drops suddenly around $B \approx B_c$) with increasing magnetic field, which is observed for $B > B_c$ in various samples [for example, the change of the sign of $\sigma_{yx}(0)$ in sample No. 2]. In addition, it also provides a natural explanation of the origin of so-called "heavy" electrons (Ref. 9)—these are precisely the electrons which are localized in the potential fluctuation troughs and which contribute to the current through hopping conductivity.

In semiconducting crystals, once the electrons are localized in the potential fluctuations, their activation energy E smoothly increases for $B > B_l$ with increasing magnetic field, attaining a value (in the case of impurity potential fluctuations; see Ref. 8) of

$$E \approx e^2 N_I^{2/3} / \varkappa n^{1/3} \tag{7}$$

(for $B \leqslant B_l$, $E = 0$). The interval ΔB_l of field over which a

noticeable change in E occurs is determined by the condition $\varepsilon_F(B_l + \Delta B_l) \sim \gamma/2$ where γ is the mean value of the fluctuating potential, coinciding in order of magnitude with (7). Taking into account that $\varepsilon_F(B_l) \sim \gamma$ (by definition of B_l), while in the quantum limit $\varepsilon_F \alpha n^2/B^2$ (see e.g. Ref. 6), we find $\Delta B_l \sim 1/2B_l$ (at ~ 10 kG for sample No. 10, see Fig. 3).

Applied to semimetallic samples, this particular localization mechanism predicts that the activation energy should initially increase rapidly from zero (in a field $B \approx B_A$); its subsequent variation should be rather slow, continuing up to a field whose magnitude is given by relation (7). The point is that so long as the electrons are being captured by acceptors which are emerging from the conduction band, the rate of change of the activation energy is determined by the motion of the acceptor level, i.e., by the expression

$$E(B) \approx \frac{\varepsilon_g}{2}\left[\left(1+\frac{4P^2}{3\varepsilon_g^2\lambda^2}\right)^{1/2}-1\right]-\varepsilon_A^0, \quad \lambda^2=\frac{c\hbar}{eB} \quad (B>B_A). \tag{8}$$

Subsequently, while the acceptor level is passing through the band of fluctuations, the Fermi level moves much more slowly. The field interval ΔB_A over which a rapid change in E takes place is determined by the condition $E(B_A + \Delta B_A) \approx \gamma/2$. Hence, $\Delta B_A \sim (\gamma/2\varepsilon_A^0) B_A$ (this is ~ 5 kG for sample No. 3; see Fig. 3). It is natural to suppose that the transition from rapid to slow variation of E occurs within a range of fields for which the activation energy E is different from zero. This field coincides with the one at which $\sigma_{xx}(0) = \sigma_{yx}(0)$ for those samples in which the dependence of E on B was measured. Therefore [taking into account that in the absence of localization, i.e., for free carriers, $\sigma_{xx}(0) < \sigma_{yx}(0)$] we choose to determine the field B_c in this way for all samples. We note, however, that the considerations described above give rise to a variation of σ_{xx}, σ_{yx} and $\varkappa$ only over a rather narrow region of B around the transition field (see Fig. 1).

In Fig. 4 the temperature dependence of $\sigma_{yx}(0)$ is shown for semiconducting sample No. 10 for various values of $B \geqslant B_c$. It is clear that over a significant portion of the temperature interval investigated this dependence is well-

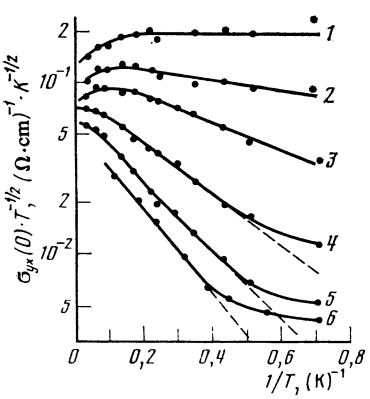

FIG. 4. Temperature dependence of $\sigma_{yx}^{(1)}(0)$ for sample No. 10 for various values of magnetic field B in kG: 1—20; 2—25; 3—30; 4—40; 5—50; 6—54.

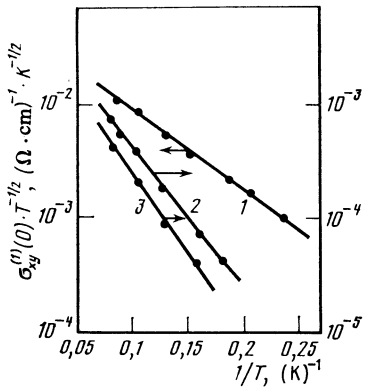

FIG. 5. Temperature dependence of $\sigma_{yx}(0)$ for sample No. 3 for various values of magnetic field B in kG: 1—25; 2—40; 3—70.

described by an expression of type (6b). On this basis, we assume that in the range of fields for which a linear dependence was observed, we have $\sigma_{yx}(0) = \sigma_{yx}^{(1)}(0)$ and that the slope of this linear portion of the curve gives the activation energy $E(B)$. The deviation from strict linearity which is observed for strong magnetic fields in the low-temperature region is connected with the relative growth of the contribution $\sigma_{yx}^{(2)}(0)$ to $\sigma_{yx}(0)$ and in principle allows one to determine the magnitude of $\sigma_{yx}^{(2)}(0)$, which is found to be $\sim 3\times 10^{-3}$ $(\Omega\cdot\text{cm}^{-1})$ for $T \approx 1.4$ °K and $B \approx 50$ kG. This value of $\sigma_{yx}^{(2)}(0)$ is considerably smaller (for higher temperatures or in lower fields) than the typical value $\sigma_{yx}^{(1)} = 10^{-2}$–$10^{-1}$ $(\Omega\cdot\text{cm})^{-1}$ measured in sample No. 10. The situation is quite different for semimetallic sample No. 3, where for $T < 4$ °–6 °K (in the magnetic-field-dependent region) $\sigma_{yx}^{(2)}(0) \gg \sigma_{yx}^{(1)}(0)$. Therefore, separating $\sigma_{yx}^{(1)}(0)$ from $\sigma_{yx}(0)$ for this sample is found to be possible only at rather high temperatures. The corresponding temperature dependence is shown in Fig. 5.

The dependences $E(B)$ found with the help of Figs. 4, 5 are shown in Fig. 3; the absolute value of E agrees with the estimate $E \approx 1$–2 meV, obtained with the help of (7). It is clear (in agreement with what was said earlier), that the dependence $E(B)$ for semimetallic sample No. 3 has at first an almost discontinuous character [hence $E(B) \approx E_A(B)$], and subsequently (just as for semiconducting sample No. 10) is found to become significantly smoother. This smooth variation is considerably slower than the rate of motion of the acceptor level (see above), indicating that the localization of the electrons does not occur on acceptors.

It is also clear that (for $B \gtrsim 20$ kG) $E \gg kT$ for sample No. 3 and $E \leqslant kT$ for sample No. 10. That is, in this case in sample No. 3 $\sigma_{yx}^{(1)}(0) < \sigma_{yx}^{(2)}(0)$, while in sample No. 10 $\sigma_{yx}^{(1)}(0) \gg \sigma_{yx}^{(2)}(0)$ (see above).

An important supplementary argument for using the model under investigation here, i.e., electron localization in the potential fluctuation "troughs" (and not on discrete centers) is connected with the results of conductivity measurements at high frequency (see Fig. 1), which show that only for $B < B_c$ do the values of the components of static and high frequency conductivities coincide[5]. For $B \gg B_c$ they differ, and we always have $\sigma_{yx}(\omega) > \sigma_{yx}(0)$ (see Fig. 1). Evidently this is connected with the fact that the spatial dimen-

sions of the potential fluctuation troughs which localize the electrons are rather large (larger than the localization region for electrons on discrete centers). Consequently, these electrons behave as if they were "free" in the high-frequency electric field, and hence can make a contribution to the high-frequency conductivity[6]. (We remark that in our experimental situation $\hbar\omega \ll E$, and so it is impossible to excite electrons with radiation in the ultra-high- frequency band.)

The polarization of electrons localized in potential fluctuation troughs can also bring about an increase in the high-frequency dielectric permeability. One must therefore expect a more or less abrupt rise in $\varkappa(\omega)$ for $B = B_c$; this is also observed in the experiment (see the inset in Fig. 1). In those samples in which no transition was observed over the range of fields investigated, $\varkappa(B)$ falls monotonically (see Ref. 7). To summarize, the entire ensemble of experimental data indicates that in crystals of $Cd_x Hg_{1-x} Te$ localization of electrons in a magnetic field takes place (in semiconducting samples entirely, in semimetallic samples at any rate partially) in potential fluctuation troughs. This mechanism also explains the peculiarities in the galvanometric behavior of these crystals.

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[1)] The numerical coefficient in (2) is larger than that given in Ref. 5 by a factor of two. Usually expressions like (2) are obtained from the condition $\varepsilon_F \approx \gamma$, where ε_F is the Fermi level and γ is the mean amplitude of the potential fluctuations. However, one must also recognize that in this case the electron density of states is roughly two times smaller than when potential fluctuations are absent, because the peaks of these fluctuations occupy approximately half the sample volume. Experiments show (see below) that the conductivity σ_{yx} first acquires an activated character in the field B_l determined by (2), while at a field $\sim 1/2\, B_l$ the reduction in free electron concentration is only beginning.

[2)] We have determined the value of N_D needed to calculate B_l with the help of the Brooks-Herring formula (for electron moblity at $B = 0$), in which we use a value of $\varkappa$ taken from Ref. 7 along with one we measured ourselves.

[3)] Here $\sigma_{yx}^{(1)}$, $\sigma_{xx}^{(1)}$ are determined by the electron concentration in states above the mobility edge; the factor $T^{1/2}$ in (6b) is connected with the temperature dependence of the effective density of states. The first relation in (6c) corresponds to magnetization of free electrons, while the second is derived in Ref. 11.

[4)] At low temperatures, $\sigma_{yx}(0) \approx \sigma_{yx}^{(2)}(0) \sim \exp(-E^{(2)}/kT)$ where $E = 0$; 0.03 and 0.09 meV corresponding to $B = 25$, 46 and 70 kG. Provided that $E^{(2)} \ll E$, we can find $\sigma_{yx}^{(1)}(0)$ in the higher temperature region where $\sigma_{yx}^{(1)} \gg \sigma_{yx}^{(2)}$ with the help of the relation $\sigma_{yx}^{(1)}(0) = \sigma_{yx}(0) - \tilde{\sigma}_{yx}^{(2)}(0)$, where $\tilde{\sigma}_{yx}^{(2)}(0)$ is the value of $\sigma_{yx}^{(2)}(0)$ extrapolated into this temperature region.

[5)] In controlled experiments on weakly compensated crystals of n-InSb ($N_D \approx 2N_A \approx 1.6 \times 10^{15}$ cm^{-3}), in which magnetic freezeout of electrons occurs onto discrete donors, no dependence of σ_{yx}, σ_{xx} on frequency (to the limits of experimental precision) is observed.

[6)] A similar mechanism for high-frequency conductivity connected with Maxwell-Wagner polarization operates in heterogeneous materials of powder type, and causes high-frequency losses in such materials (Ref. 12). It is effective when the size of the localization region is not small compared to the screening length and the period of the high-frequency field is comparable to the Maxwell relaxation time τ_M (in the case of our experiments, $\omega\tau_M \sim 1$).

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