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Two-Dimensional Semimetal–Insulator Transition in HgTe-Based Quantum Wells Induced by a Longitudinal Magnetic Field

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A metal–insulator transition in a two-dimensional semimetal based on HgTe quantum wells is discovered. The transition is induced by a magnetic field applied parallel to the plane of the quantum well. The threshold behavior of the activation energy as a function of the magnetic-field strength and an abrupt reduction of the Hall resistance at the onset of the transition suggest that the observed effect originates from the formation of an excitonic insulator.

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In 1961, N. Mott [1] analyzed the dependence of the properties of a semimetal on the concentration of electrons and holes and found that, for a certain threshold value of this parameter, screening of the electron–hole Coulomb interaction decreases, so that the formation of bound electron–hole pairs becomes energetically favorable. In other words, according to Mott, a decrease in the charge-carrier concentration in such a system should result in the transition from a semimetallic to an insulating state, which he called excitonic insulator. Subsequently, a number of different possible mechanisms responsible for this kind of transition have been suggested [2–5]. It should be mentioned that no convincing experimental evidence for the existence of this interesting and important effect has been obtained since then. This situation stems from the fact that, until now, experimentalists have had no system where such a transition can occur and may be observed by transport measurements. Conventional three-dimensional semimetals, like Bi, Sb, and HgSe, are not suitable, since there is no possibility for varying the concentration of electrons and holes in a controllable way in this case; meanwhile, two-dimensional semimetals, where an electrostatic gate could be used for this purpose, were lacking. As a result, for more than half a century, achievements in this field were limited to just a few reports on indirect and not very convincing observation of the excitonic insulator in such systems as Bi_xSb_{1-x} [6] and $TmSe_{0.45}Te_{0.55}$ [7]. The situation has changed since the discovery of a two-dimensional semimetal in 18- to 21-nm-thick quantum wells based on HgTe [8–10]. In this system, which has an inverted energy spectrum, coexistence of electrons and holes of low densities (below 10^{11} cm^{-2}) and high mobilities of both electrons ($\mu_n = (3–6) \times 10^5$ cm^2/(V s)) and holes ($\mu_p = (3–10) \times 10^4$ cm^2/(V s)) is possible. It has been shown that the overlap Δ between the conduction band (whose minimum is located at the center of the Brillouin zone) and the valence band (whose maxima are shifted towards the edge of the Brillouin zone) and, thus, the semimetallic state itself appear owing to the tensile strain in the quantum-well layer caused by the lattice-constant mismatch between HgTe and CdTe. The value of Δ depends on the orientation of the quantum well. In particular, $\Delta(013) \approx 5$ meV and $\Delta(100) \approx 1$ meV. Evidently, a semimetal with any desired ratio of the electron and hole concentrations, including the most interesting case of charge neutrality ($N_s = P_s$), can be implemented upon the variation of the gate voltage in such a system. However, a careful study of the temperature dependence of the resistivity of this two-dimensional semimetal in zero magnetic field did not reveal any evidence of the transition to an insulating state even for the overlap value of about 1 meV and $N_s = P_s \approx 10^{10}$ cm^{-2} [9]. This is not surprising if we consider the ratio of the electron–hole Coulomb interaction energy E_c to the overlap Δ. For the above concentration and the dielectric constant of HgTe equal to 20, an estimate yields $E_c/\Delta \le 1$, which is far from being sufficient to guarantee the formation of bound electron–hole pairs. However, if the overlap is somehow reduced, the ratio E_c/Δ can be increased and the likelihood of the electron–hole pairing enhanced. One such possibility is the application of a magnetic field in the plane of the quantum well, which affects the orbital motion of electrons and holes and, thus, may cause the bands to shift apart, bringing about a reduc-

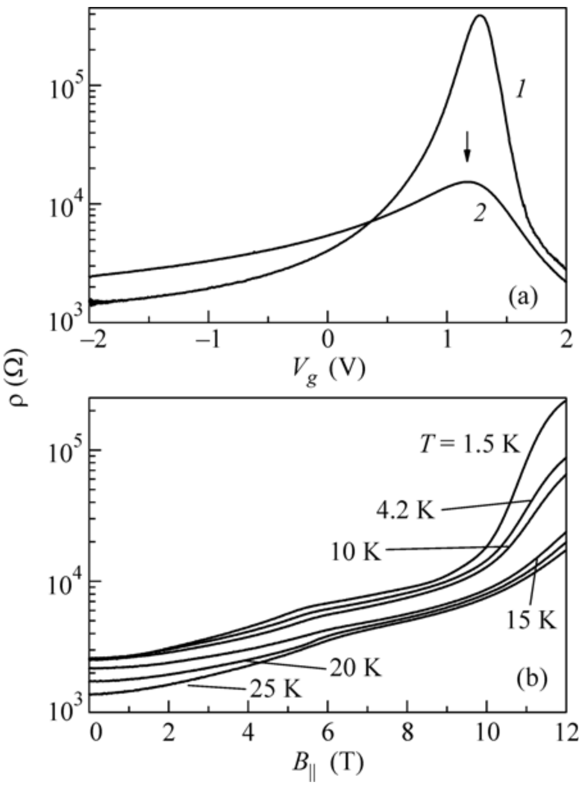

Fig. 1. (a) Dependences $\rho_{xx}(V_g)$ for $B_{\parallel} = 12$ T and temperature T = (*1*) 1.5 and (*2*) 30 K. The arrow indicates the position of the curve peak, corresponding to the charge neutrality point ($N_s = P_s$), which occurs at $V_g = 1.173$ V. (b) Dependence $\rho_{xx}(B_{\parallel})$ for T = 25, 20, 15, 10, 4.2, and 1.5 K and $V_g = 1.173$ V.

tion in both the overlap and carrier concentration. This idea is tested experimentally in the present study.

The samples investigated are 20.5-nm-thick HgTe quantum wells of (100) orientation grown by molecular-beam epitaxy. Details on the growth process and the structure of the grown samples can be found in [11]. As was shown in [10], at the charge neutrality point, the carrier concentrations in these quantum wells are $N_s^0 = P_s^0 = (1.2–1.5) \times 10^{10}\ \text{cm}^{-2}$. From these data, we can estimate the overlap between the bottom of the conduction band and the top of the valence band, which is responsible for the formation of a semimetallic state. The overlap is rather small (as was mentioned above, it is on the order of 1 meV), which is the reason we chose these quantum wells for the experiment.

Standard Hall bars were fabricated for magnetotransport measurements; their width was 50 μm and the spacing between the voltage probes was 100 and 250 μm. Ohmic contacts were obtained by indium alloying. A TiAu metallic gate was evaporated onto a double insulator layer grown on the semiconductor surface at 100°C and consisting of 100 nm of SiO_2 and 200 nm of Si_3N_4. The resulting structure actually represents a field-effect transistor where the conductivity of the two-dimensional channel in the HgTe quantum well is controlled by the voltage V_g applied to the gate [11]. Magnetotransport measurements with these samples were carried out at temperatures between 1.5 and 4.2 K in magnetic fields up to 12 T using a conventional phase-sensitive detection scheme operating in the frequency range of 6–32 Hz. The current was 1–10 nA, which ensured that carrier heating was avoided.

Previously, the properties of this system in a perpendicular magnetic field were investigated in detail both in the semiclassical field range [10] and in the regime of the quantum Hall effect [12].

Figure 1a shows the dependences $\rho_{xx}(V_g)$ measured in a parallel field of 12 T at temperatures of 30 and 1.5 K. A clearly developed peak can be seen in these dependences for the gate voltage $V_g = 1.173$ V, which corresponds to the charge-neutrality point. Note that the result obtained is independent of whether the magnetic field is oriented parallel or perpendicular to the pulling current. The height of the peak increases from 15 kΩ at $T = 30$ K to about 200 kΩ at 1.5 K, which is a direct indication of an insulating behavior at 12 T. Figure 1b shows the $\rho_{xx}(B_{\parallel})$ dependences for different temperatures and the gate voltage corresponding to the charge-neutrality point. Analyzing this dependence, one can see three regions characterized by different behaviors of $\rho_{xx}(B_{\parallel})$, which correspond to the magnetic fields below 6 T, from 6 to 9 T, and above 9 T. In the first region, a weak quasi-linear growth of the resistivity is observed. In a magnetic field of 6 T, there is an inflection point, above which the growth slows down. Finally, in the region above 9 T, an abrupt exponential increase in $\rho_{xx}(B_{\parallel})$ takes place. Note that this behavior is observed for all of the samples investigated.

Next, let us consider the temperature dependence of the resistivity at the charge-neutrality point, which is shown in Fig. 2a. It is clearly seen that, in magnetic fields from zero to 10 T, this dependence exhibits semimetallic behavior. Then, in a narrow range of magnetic fields, the character of this dependence changes to insulating. The measured temperature dependences were fitted by Arrhenius curves $\rho(T) \approx \exp(-\Delta_A/k_B T)$ with a different activation energy Δ_A for each value of the parallel magnetic field. The inset in Fig. 2b shows examples of such fits for parallel fields of 12, 11, and 10 T. The magnetic-field dependence of Δ_A obtained in this way is plotted in Fig. 2b. According to this figure, in parallel fields $B_{\parallel} < 10$ T, the resistivity of the system under study exhibits semimetallic behavior, characterized by a nearly zero activation energy. For $B_{\parallel} > 10$ T, a transition into an insulating state takes place, with the activation energy increasing abruptly in a narrow range of magnetic fields (about 1 T) and then approximately leveling off at $\Delta_A \approx 1.7$ K in fields $B_{\parallel} > 11$ T.

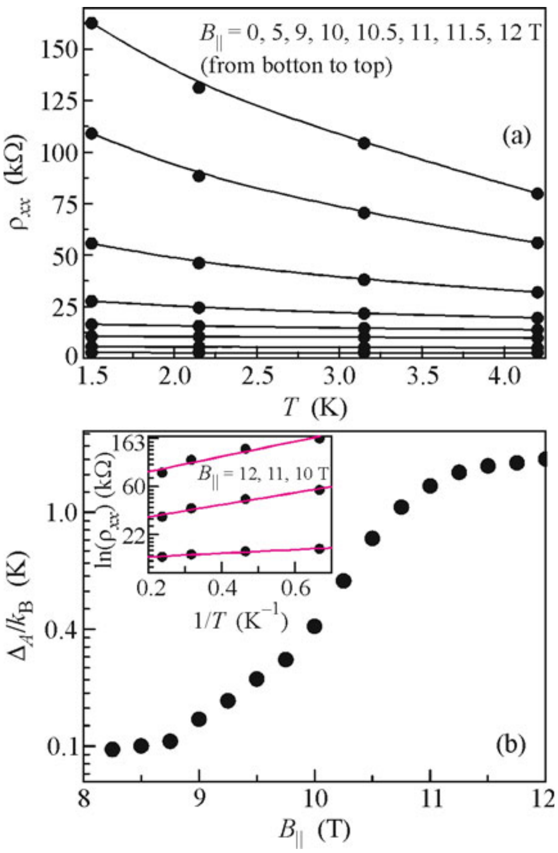

Fig. 2. (a) Temperature dependence of the resistivity in the range of 1.5–4.2 K for different values of the parallel magnetic field (lines are drawn through experimental points to guide the eye). (b) Energy gap Δ at the charge-neutrality point ($N_s = P_s$) for different values of the parallel magnetic field in the range of 8–12 T. Inset: approximation of the temperature dependences corresponding to parallel magnetic fields of 12, 11, and 10 T by Arrhenius curves.

Let us discuss the results obtained. The effect of the longitudinal field on the resistivity of a one-component two-dimensional electron system has been widely investigated in relation to the issue of the nature of the metal–insulator transition in this system [13, 14]. The behavior of $\rho_{xx}(B_{||})$ that we observe in the first two magnetic-field regions is qualitatively similar to that observed for a two-dimensional hole gas in an AlGaAs/GaAs heterojunction [15], where the longitudinal magnetoresistance is described satisfactorily by the Zeeman splitting of the two-dimensional subband [16]. However, the exponential growth of the resistivity taking place in fields $B_{||} > 9$ T does not occur in that case and is observed for the first time in the present study. The simplest explanation for this effect can be given by assuming that a gap opens in the energy spectrum upon the application of a longitudinal magnetic field. However, this interpretation is inconsistent with the rapid quasi-leveling-off of the magnetic-field dependence of the activation energy. An alternative explanation can be associated with the

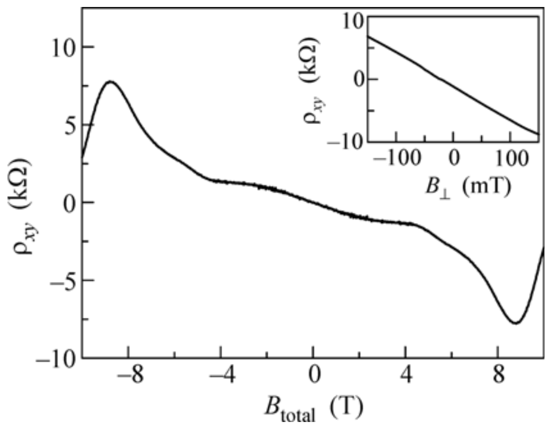

Fig. 3. Hall component of the resistivity versus the total magnetic field at the charge-neutrality point ($N_s = P_s$) for $T = 1.5$ K. Inset: the Hall resistivity at the charge-neutrality point versus the magnetic field with zero parallel component.

onset of the formation of bound electron–hole pairs and, thus, with the transition to an excitonic-insulator state.

In order to distinguish between these mechanisms of the metal–insulator transition, we measured the Hall effect originating from the presence of a small normal component of the magnetic field. It was impossible to determine the magnitude of this component accurately under our experimental conditions, but it did not exceed 1% and, thus, was about 0.1 T at most. In this field range, the Hall component of the resistivity tensor of the system under study behaves semiclassically [9]. At the charge-neutrality point, the slope of the Hall effect curve yields the electron concentration. The contribution of holes is negligible owing to their much lower (almost 30 times) mobility. The inset in Fig. 3 shows the dependence of the Hall resistance at the charge-neutrality point on the magnetic field in the absence of the parallel component. Figure 3 shows the dependence of ρ_{xy} on the total magnetic field (which, in this case, is almost equal to the parallel component) for both field directions. The antisymmetric behavior and nonlinearity of the $\rho_{xy}(B)$ dependence are evident. A more detailed analysis indicates that the slope of this dependence does not change up to $B \approx 2$ T, and, thus, the electron concentration is constant in this field range. Then, the slope decreases markedly, which is most probably associated with an increase in the band overlap caused by the Zeeman splitting. Next, at $B \approx 5$ T, the slope changes abruptly and rapid nonlinear growth of $\rho_{xy}(B)$ takes place. This is an indication of a decrease in the electron concentration, which originates from a reduction in the band overlap caused in this case by the action of the magnetic field on the orbital motion of electrons and holes. The most interesting behavior occurs at about 9 T. In this field, $\rho_{xy}(B)$ attains a maximum and then starts to decrease abruptly. The decrease in the Hall signal almost coincides with the onset of the exponential growth of $\rho_{xx}(B)$ (cf. Figs. 2b and 3). This behavior of $\rho_{xy}(B)$ rules out the "gap" origin of the observed metal–insulator transition. At the onset of the transition (corresponding to the maximum of $\rho_{xy}(B)$, the electron concentration is only a factor of 1.7 smaller than it is in zero magnetic field and, thus, the band overlap is still noticeable. Moreover, a further increase in the magnetic field does not lead to a continuing increase in $\rho_{xy}(B)$. On the contrary, an abrupt drop in ρ_{xy} occurs with the beginning of the exponential growth in $\rho_{xx}(B)$. Thus, the observed transition is better explained in terms of the second interpretation, i.e., understood as the transition to an excitonic-insulator state, characterized by an increase in the resistivity with decreasing temperature and the lack of the Hall effect, since only neutral particles are present in this state. Since the system under study features incongruent electron and hole Fermi surfaces, the observed transition is not related to the BCS mechanism [3]. It is determined by a simpler electron–hole pairing mechanism, where the formation of bound pairs takes place because the Coulomb interaction energy exceeds the kinetic energy of electrons and holes ($E_c/\Delta > 1$). For such a transition, the critical temperature, which is actually the value at which the activation energy levels off, depends on the ratio of the electron and hole effective masses [2]: $\Delta \approx (m_e/m_h)E_c$. For $m_e = 0.025m_0$ and $m_h = 0.15m_0$, we obtain $\Delta = 1.2$ K, which differs not too much from the experimentally determined value of Δ_A. However, one should not overestimate the significance of this agreement. The above estimate is fairly rough. A more meaningful comparison requires both the development of a theory taking into account the field-induced anisotropy of the electron and hole effective masses and further experiments. But, anyhow, the present experiments demonstrate that the two-dimensional semimetal in HgTe quantum wells represents a new interesting object for studying the metal–insulator transition and the role of interaction in this transition.

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