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Metal-insulator transition in a HgTe quantum well under hydrostatic pressure

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The 2D semimetal in a 20 nm (100) HgTe quantum well is characterized by a comparatively low overlap between the conduction and the valence bands induced by lattice mismatch. In the present paper we report the results of transport measurements in this quantum well under hydrostatic pressure of 14.4 kbar. By applying pressure we have further reduced the band overlap, thereby creating favorable conditions for the formation of the excitonic insulator state. As a result, we observed that the metallic-like temperature dependence of the conductivity at lowering temperature sharply changes to the activated behavior, signalling the onset of an excitonic insulator regime.

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A few years ago the 2D semimetal has been realized in 20 nm wide HgTe-based quantum wells [1]. A semimetal is a degenerate Fermi system with two types of charge carriers of different sign (electrons and holes) that co-exist in the same coordinate space (in the same quantum well) and both participate in charge transport. The observation of a 2D semimetal in HgTe Quantum Wells (QWs) opens up new possibilities for experimental study of some long standing problems. One of these is the exciton insulator (EI) state, first theoretically predicted by Mott in 1949 [2–4]. It has been shown that a semiconductor having a narrow band gap G or a semimetal with an equal number of electrons and holes becomes unstable under certain conditions with respect to the pairing of electrons and holes. Such pairing produces a system with a spectrum similar to that of a superconductor, with a characteristic energy gap Δ that is determined at $T=0$ by the binding energy E_B of the pairs ($E_B = m^* e^4/2\kappa^2\hbar^2 \equiv R_y^*$, $(m^*)^{-1} = (m_e^*)^{-1} + (m_h^*)^{-1}$).

The EI phase diagram is shown in Fig. 1a. As can be seen from the diagram the EI formation is impossible when the gap/overlap is larger than the exciton binding energy E_B. The EI formation is facilitated by a small gap in a semiconductor or bands overlap in a semimetal. The largest EI gap ($\Delta_{00} \sim E_B$) is expected

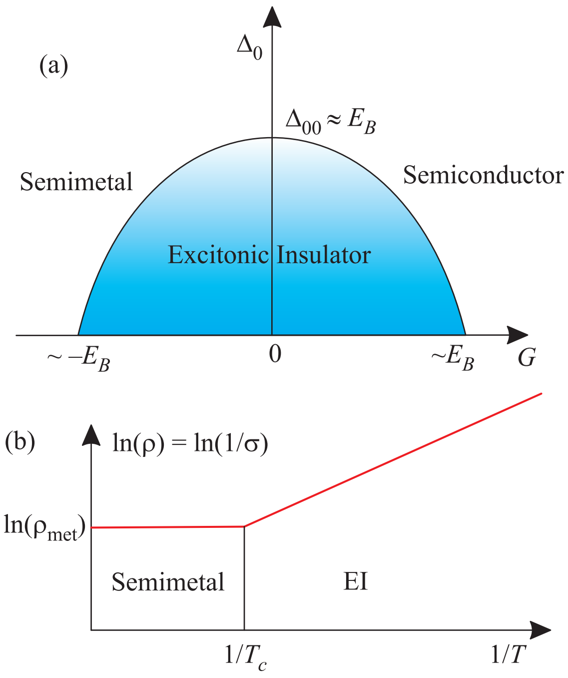

Fig. 1. (a) – Phase diagram of EI, Δ_0 is the zero temperature EI gap, G is the semiconductor gap (on the right) or the semimetal bands overlap (on the left), E_B is the electron-hole binding energy. (b) – $\rho(T)$ dependence for semimetal to EI transition

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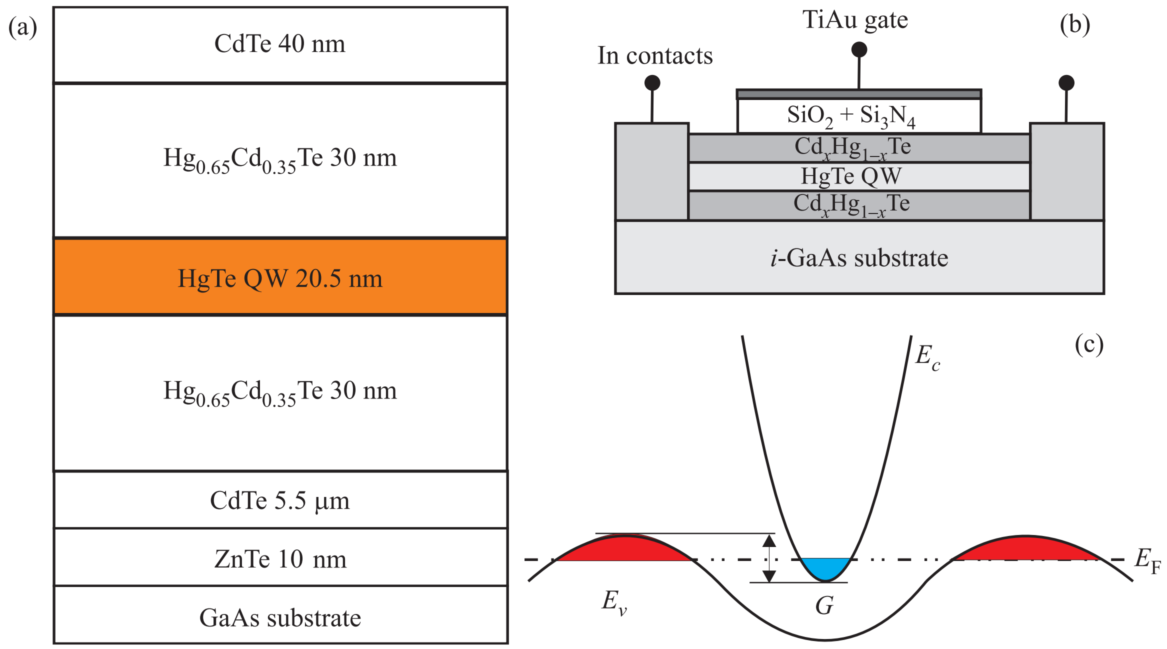

Fig. 2. (a) – Layer structure of (100) HgTe QW. (b) – The cross section of the samples studied. (c) – The semimetal energy band diagram

when the semiconductor gap or the semimetal bands overlap is equal to zero. For the intermediate values of G the EI gap Δ_0 varies between 0 and $\sim E_B$ according to the diagram. Once the temperature goes below $T_c \sim \Delta_0$ the EI gap opens up in the energy spectrum. With the temperature decreasing the gap asymptotically approaches its zero temperature limit Δ_0. In the case of the semimetal to EI transition the metallic transport intrinsic to a semimetal will be replaced by an activated transport once the temperature decreases below T_c: $\sigma \sim \exp(-E_A/kT)$, where the activation energy E_A is a function of Δ and G. Therefore, the observation of a $\rho(T)$ dependence like the one shown in Fig. 1b is generally considered to be the primary signature of the semimetal – EI transition [5].

Despite the fact that the concept of the EI has been proposed quite a long time ago, so far there has been little convincing experimental evidence of its existence, mostly limited to measurements conducted on 3D bismuth-antimony alloy samples in strong magnetic fields [5]. Also, an attempt has been made recently to observe a magnetic field induced exciton insulator state in a HgTe QW [6]. Major interest however is in the observation of the zero field exciton insulator state, rather than the magnetic field induced one.

To this end the 2D semimetal system in HgTe QW is an excellent candidate, provided the energy bands overlap could be reduced below the exciton binding energy. In this respect the 20 nm HgTe QW with the (100) surface orientation looks especially promising. Indeed, it has a low energy bands overlap of about 1.2–1.5 meV, which, nevertheless, needs to be further reduced since the estimated exciton binding energy is 0.7 meV in HgTe. The HgTe film is stretched due to a slight difference in the lattice constants of CdTe ($a = 0.648$ nm) and HgTe ($a = 0.646$ nm). The $k{-}p$ energy spectrum calculations show that it is the strain that produces the band overlap [7–9]. Therefore, application of the hydrostatic pressure to the sample may partially compensate the strain and reduce the overlap below $E_B = 0.7$ meV.

In the present paper we report the results of transport measurements for a 2D semimetal in 20 nm (100) HgTe QW under a hydrostatic pressure of about 14.4 kbar. We observed that the metallic-like temperature dependence of the conductivity at lowering temperature sharply changes to the activated behavior, signalling the onset of an excitonic insulator regime.

The (100)-oriented 20 nm HgTe QWs were grown by a modified MBE technology (for fabrication details see [1, 10] and the references therein). The schematic layer structure of the QW is shown in Fig. 2a. On top of this structure conventional Hall bars provided with electrostatic top gates were fabricated, their cross section shown schematically in Fig. 2b. The gate enables us to vary the density of holes and electrons in the QW in a wide range. The energy band spectrum in the well (see

Fig. 2c) allows for a simultaneous presence of electrons and holes in various proportions including the so called charge neutrality point (CNP) – where there are equal number of electrons and holes. The sample was placed in the non-magnetic piston-cylinder clamp pressure cell filled with polyethylsiloxane pressure transmitting liquid [11]. The pressure of $P = 16$ kbar was created and fixed at room temperature. The cell was then slowly cooled to ensure hydrostatic conditions. The low temperature pressure value $P = 14.4$ kbar was determined *in-situ* using the superconducting transition temperature of the tin gauge[2)]. Measurements were carried out at temperatures 1.3–100 K using the standard lock-in technique. The signal frequency was 6–12 Hz and the driving currents were of the order 1–10 nA to avoid heating effects.

Below the transport properties of a 20 nm (100) HgTe QW under a hydrostatic pressure of 14.4 kbar are discussed. To illustrate the effect of pressure a comparison is made with corresponding measurements performed earlier in similar samples with no pressure applied [8].

Fig. 3a shows our major result – striking temperature dependence of the sample resistance under pressure of 14.4 kbar. Gate voltage here corresponds to CNP, where the electron and hole densities are equal. Sample resistance clearly shows exponential growth that starts abruptly once the temperature descends below ≈ 10 K (see inset to Fig. 3a). This temperature dependence is completely different from the one measured with no pressure applied. The latter is shown on Fig. 3b. In this case on lowering the temperature from 10 down to 0.2 K the resistivity displays a weak variation around $3k\Omega/\square$. From ≈ 4 to ≈ 2 K this variation is probably due to a modified temperature dependent electron-hole scattering peculiar for the 2D semimetal [10] evolving to a weak localization behavior for lower temperatures.

More information about pressure effects on the sample properties could be obtained from the $\rho(V_g)$ dependences. In Fig. 4 we present $\rho(V_g)$ curves, taken at a set of temperatures with no pressure applied (a) and under hydrostatic pressure of 14.4 kbar (b). The curves in Fig. 4a are typical for all 20 nm HgTe QWs with a 2D semimetal and have been discussed in detail in previous publications [1, 7, 8]. At high positive gate biases, when the quantum well is populated with high mobility electrons, the resistivity is low, for example, $\rho \sim 60\Omega/\square$ at 4.2 K (see the red curve in Fig. 4a). As the bias (V_g) is reduced the resistivity increases reaching the maximum of 3 $k\Omega/\square$ in the vicinity of the charge neutrality point where the electron and hole densities are equal. As V_g becomes negative the well is increasingly populated with holes, the resistance decreases and levels off at values $\approx 1\,k\Omega/\square$ that are higher than the corresponding values on the electron side due to the lower hole mobility.

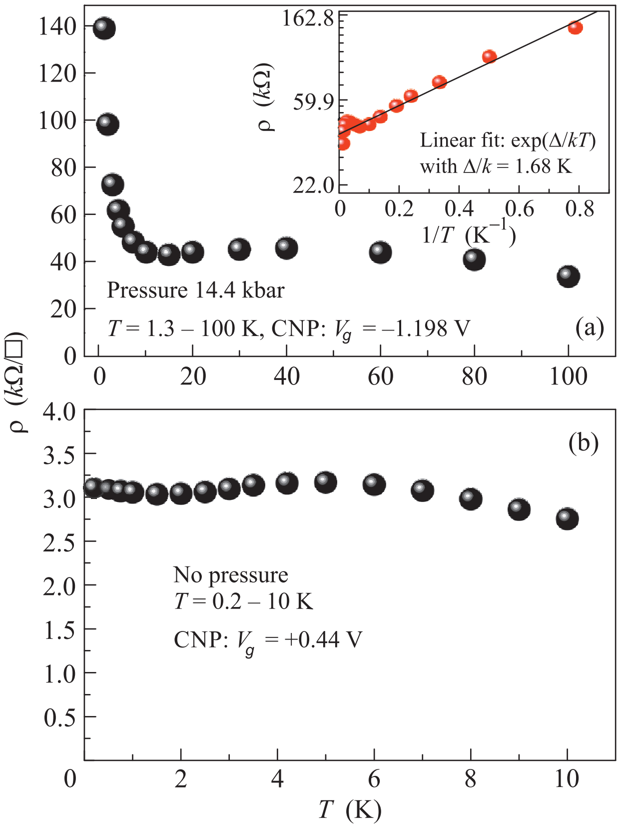

Fig. 3. Resistance versus temperature at the charge neutrality point ($N_s = P_s$). (a) – Under pressure of 14.4 kbar. (b) – No pressure applied to the sample

As one can see in Fig. 4b the hydrostatic pressure of 14.4 kbar has a dramatic effect on the sample behavior. Although the overall shape of the $\rho(V_g)$ dependence is qualitatively preserved, the resistivity values have grown considerably for all the gate voltages in the range. In particular, for a given temperature of 4.2 K, the sample under pressure shows $\approx 1.1\,k\Omega$ instead of $60\,\Omega$ at high positive bias on the electron side and $14\,k\Omega$ instead of $1\,k\Omega$ at high negative bias on the hole side compared to the normal conditions (see red curve on Fig. 4b). Most dramatically the $\rho(V_g)$ behavior changes in the vicinity of the CNP. Whereas at ambient pressure it grows gradually as temperature decreases, under pressure, the $\rho(V_g)$ peak starts growing exponentially with

[2)] Due to a low thermal expansion of both the cell and pressure medium the quoted pressure of 14.4 kbar refers to the temperature range below 20 K. At higher temperatures, the pressure value in the cell might be slightly elevated.

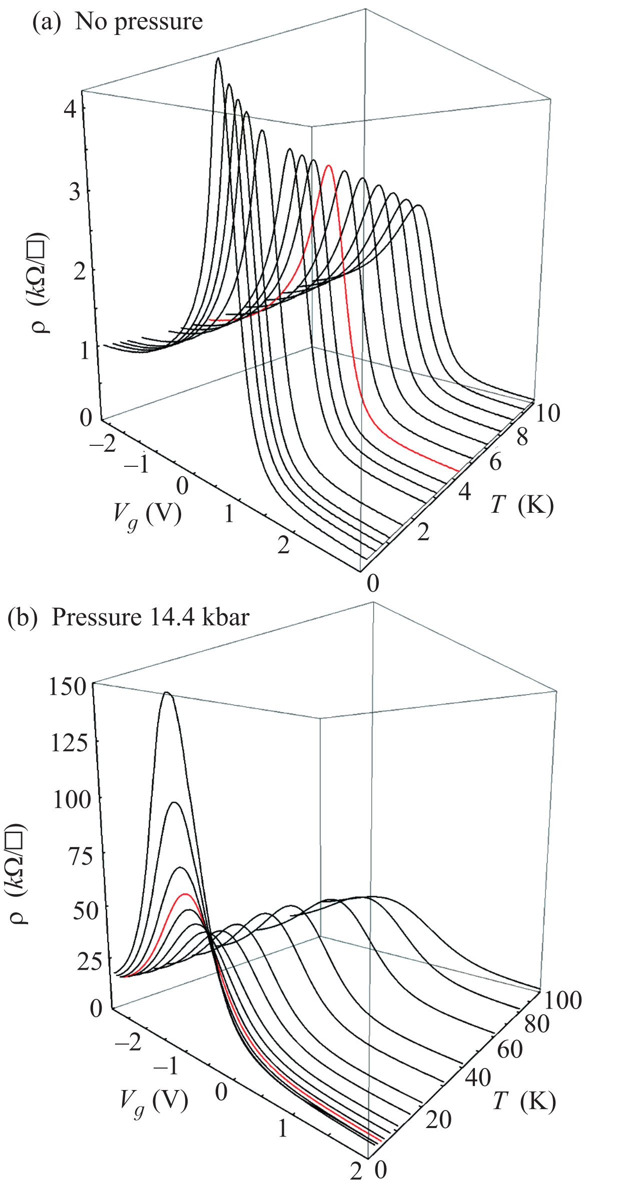

Fig. 4. (Color online) ρ versus V_g at different temperatures. (a) – No pressure applied, $T = 0.2$, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 4.2, 5, 6, 7, 8, 9, 10 K. (b) – Sample under pressure 14.4 kbar, $T = 1.3$, 2, 3, 4.2, 5.3, 7.4, 10, 15, 20, 30, 40, 60, 80, 100 K

$1/T$ (see the inset of Fig. 3a). The observed resistance change with pressure is reversible: when the pressure is removed the resistance returns to the original values.

What is peculiar about the data in Figs. 3a and 4b is that until the temperature descends below $T_c \approx 10$ K there is apparently no gap in the energy spectrum. Indeed, with the temperature decreasing from ≈ 100 K down to the point where the $\rho(T)$ dependence in Fig. 3a turns abruptly exponential (≈ 10 K), the sample resistance goes through a maximum at ≈ 40 K. Such behavior is clearly inconsistent with a gap being present in the energy spectrum at $T > 10$ K even if the temperature dependent contributions from phonon and impurity scattering are taken into account. Thus, a following conclusion may be made from the observed behavior. At temperatures from about 100 down to 10 K the system remains essentially semimetallic and there is no gap in the energy spectrum. Then, at about 10 K a gap opens up in the spectrum and the system becomes insulating with a corresponding activated resistance versus temperature dependence.

The described behavior is a clear evidence for a metal-insulator transition that occurs upon lowering temperature below a certain $T_c \approx 10$ K and resembling the anticipated semimetal – exciton insulator transition. There is one point, however, that needs to be mentioned. According to the theory one would expect the activation energy Δ to be close to the critical temperature T_c and both of them to be of the order of E_B. We find that while T_c is indeed close to $E_B \approx 0.7$ meV, the activation energy turns out to be about four times smaller. A disorder in the QW could be a possible reason for such a discrepancy but it would be expected to act similarly on both Δ and T_c. A theory that takes disorder into account is needed to explain the observed disagreement.

It is worth noting that among the different scenarios of the semimetal–EI transition there is one resembling the Bardeen–Cooper–Schrieffer theory of superconductivity which was first proposed by Keldysh and Kopaev [12] and later discussed in [13, 14]. However, this scenario requires systems with an equivalence of the electron and holes Fermi-surfaces which is not the case for the studied system.

In conclusion, the present experiment has been conceived as an attempt to observe the theoretically predicted transition from a 2D semimetal to the exciton insulator state. To this end a hydrostatic pressure was applied to the sample in order to reduce the already comparatively low bands overlap in the (100) 20 nm HgTe QW. The sample behavior under pressure is greatly altered. The most significant modification is the metal-insulator transition observed at the CNP at $T_c \approx 10$ K which is close to the estimated exciton binding energy $E_B \approx 8$ K. In our opinion the character of the observed transition is consistent with the theoretically predicted semimetal-exciton insulator transition (compare the $\rho(T)$ dependences in the insert to Fig. 3a and in Fig. 1b). The observed behavior is a signature of the collective exciton state occurring in the electron-hole system as the temperature is reduced below the binding energy.

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