Quantum Hall Effect near the Charge Neutrality Point in a Two-Dimensional Electron-Hole System

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We study the transport properties of HgTe-based quantum wells containing simultaneously electrons and holes in a magnetic field B. At the charge neutrality point (CNP) with nearly equal electron and hole densities, the resistance is found to increase very strongly with B while the Hall resistivity turns to zero. This behavior results in a wide plateau in the Hall conductivity $\sigma_{xy} \approx 0$ and in a minimum of diagonal conductivity σ_{xx} at $\nu = \nu_p - \nu_n = 0$, where ν_n and ν_p are the electron and hole Landau level filling factors. We suggest that the transport at the CNP point is determined by electron-hole "snake states" propagating along the $\nu = 0$ lines. Our observations are qualitatively similar to the quantum Hall effect in graphene as well as to the transport in a random magnetic field with a zero mean value.

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The quantum Hall effect (QHE) of a two-dimensional (2D) electron gas in a strong magnetic field is one of the most fascinating quantum phenomena discovered in condensed matter physics. Its basic experimental manifestation is a vanishing longitudinal conductivity $\sigma_{xx} \approx 0$ and a quantization of the Hall conductivity $\sigma_{xy} = \nu \frac{e^2}{h}$, where ν is the Landau level (LL) filling factor [1]. The discovery of a 2D electron-hole system in graphene at a finite magnetic field has started a series of studies on the properties of the special state realized when the densities of the electrons and holes are equal, called the charge neutrality point (CNP) [2–4]. In a strong magnetic field the QHE near the CNP reveals a plateau in σ_{xy} with $\nu = 0$ currently associated with the resolution of the spin or the valley splitting of the lowest LL [3,4]; however, the longitudinal resistivity ρ_{xx} at $\nu = 0$ demonstrates different behavior in various but otherwise quite similar samples: in some samples ρ_{xx} shows a rapid divergence at a critical field and, with the temperature decreasing, saturates at a value much larger than the resistance quantum h/e^2 [4], while in the others it decreases with lowering the temperature [3]. The QHE behavior near the CNP has attracted much theoretical interest and several microscopic mechanisms that might be responsible for these phenomena have been proposed [3,5], however no final quantitative conclusion has been drawn up yet.

Graphene remained a unique 2D system with described properties when recently a new 2D system showing similar properties has been discovered. It has been shown [6] that a two-dimensional semimetal exists in undoped HgTe-based quantum wells with an inverse band structure and the (013) surface orientation.

In this Letter we report the results of our study of the transport properties of the HgTe-based quantum wells near the CNP. At filling factor $\nu = 0$ (CNP) our system goes into a high resistivity state with a moderate temperature dependence markedly different from a thermally activated behavior expected when there is an opening of a cyclotron gap in the density of states. We suggest that at the CNP the 2D electron-hole gas in our HgTe quantum wells is not homogeneous due to the random potential of impurities. The random potential fluctuations induce smooth fluctuations in the local filling factor around $\nu = 0$. In this case the transport is determined by special class of trajectories, the "snake states" [7] propagating along the contours $\nu = 0$. The situation is very similar to the transport of two-dimensional charge carriers moving in a spatially modulated random magnetic field with zero mean value [8]. We especially emphasize that our results may be equally relevant to the composite fermions description of the half-filled LL [9] and quantum Hall effect in graphene at Dirac point [2–4].

Our HgTe quantum wells were realized on the basis of undoped CdHgTe/HgTe/CdHgTe heterostructure grown by means of MBE at $T = 160$–$200\,^\circ$C on GaAs substrate with the (013) surface orientation. The details of the growth conditions are published in [10]. The section of the structure under investigation is schematically shown in Fig. 1. For magnetotransport measurements 50 by 100 μm Hall bar samples have been fabricated on top of these quantum wells by standard photolithography. The ohmic contacts to the two-dimensional gas were formed by the in-burning of indium. To prepare the gate, a dielectric layer containing 100 nm SiO_2 and 200 nm Si_3Ni_4 was first grown on the structure using the plasmochemical method. Then, the TiAu gate was deposited. The density variation with gate voltage was 8.7×10^{14} m^{-2} V^{-1}. The magnetotransport measurements in the described structures were per-

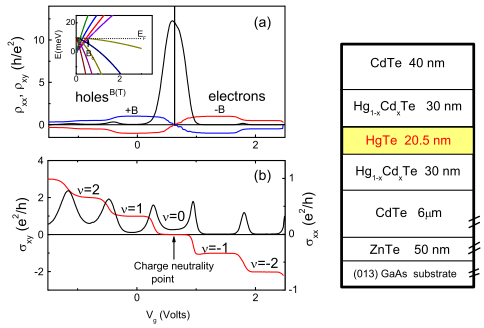

FIG. 1 (color online). Top-schematic view of the sample. (a) Diagonal ρ_{xx} (black) and Hall ρ_{xy} (blue, red) resistivities as a function of the gate voltage at fixed magnetic field $B = 2.8$ T. Hall resistivity is shown for different signs of the magnetic field. Inset: Landau level fan diagram for the electron and hole subbands. Notice that the last Landau levels from each set of subband cross at a finite B_c-field. E_F is the Fermi level at the charge neutrality point. (b) Diagonal σ_{xx} (black, right axis) and Hall σ_{xy} (red, left axis) conductivities as a function of the gate voltage at the same magnetic field, $T = 90$ mK. Arrow indicates the position of the charge neutrality point, when $n_s = p_s$.

formed in the temperature range 0.050–4.1 K and in magnetic fields up to 7 T using a standard four point circuit with a 2–3 Hz ac current of 0.1–1 nA through the sample, which is sufficiently low to avoid the overheating effects. Several samples from the same wafer have been studied.

When a large positive voltage is applied to the gate, the usual increase of the electron density is observed. At lower gate voltages there is a coexistence of electrons and holes with close densities [6]. Finally, for large negative voltages the Fermi level goes deep into the valence band and the sample becomes p conductive. The density of the carriers at CNP without magnetic field was $n_s = p_s \approx 5 \times 10^{10}$ cm^{-2}, the corresponding mobility was $\mu_n = 250\,000$ cm^2/V s for electrons and $\mu_p \approx 25\,000$ cm^2/V s holes. These parameters were found from comparison of the Hall and the longitudinal magnetoresistance traces with the Drude theory for transport in the presence of two types of carriers [6]. In magnetic field the energy spectrum of electrons and holes is quantized and, naively, the LL fan diagram consists of two sets of overlapping LLs, as shown in Fig. 1. Above some critical magnetic field B_c it is expected that a zeroth LL gap will open in the spectrum after the last hole and electron LLs cross each other.

Figure 1(a) shows the longitudinal ρ_{xx} and Hall ρ_{xy} resistivities as a function of the gate voltage at fixed magnetic field. Pronounced plateaus with values $\rho_{xy} = -h/\nu e^2$ are clearly seen at $\nu = -2, -1, 1, 2$ accompanied by deep minima in ρ_{xx} on electron and hole sides of the dependence. Surprisingly, when V_g is swept through the charge neutrality point the longitudinal resistivity shows a large maximum, whereas ρ_{xy} goes gradually through zero from h/e^2 ($-h/e^2$) value on the electron side to $-h/e^2$ (h/e^2) value on the hole side. Indeed, ρ_{xx} is symmetric, and ρ_{xy} is antisymmetric in B. Figure 1(b) shows the conductivities σ_{xx} and σ_{xy} as a function of the gate voltage calculated from experimentally measured ρ_{xx} and ρ_{xy} by tensor inversion. Standard quantum Hall effect plateaux $\sigma_{xy} = e^2\nu/h$ accompanied by minima in σ_{xx} are clearly visible. We note, however, that the steps in σ_{xy} on the holes side are not completely flat and the minima in σ_{xx} are not very deep due to a lower hole mobility. Notice that the height of the peaks in σ_{xx} is very close to $e^2/2h$ for all LLs as expected for conventional QHE. The most intriguing QHE state is observed at the charge neutrality point at $\nu = 0$. Figure 1(b) shows that σ_{xy} has a flat zero value quantum Hall plateau around CNP, while σ_{xx} displays a pronounced minimum. Both the minimum and the plateau at CNP strongly depend on the magnetic field and the temperature. Figure 2 demonstrates the evolution of σ_{xx} and σ_{xy} with temperature (a) and magnetic field (b) when the system is driven from n type to p type. Indeed, all QHE states become more pronounced with T decreasing and B increasing, especially the plateau and the minimum on hole side closest to the CNP. The position of all the minima, except the minima at $\nu = 0$, shifts with magnetic field, as a result of the increase in the LLs degeneracy.

In the rest of the Letter we will focus on the magnetoresistance behavior at the CNP. Figure 3 shows a sharp increase in the resistivity ρ_{xx} with magnetic field at the CNP at different temperatures. It is worth noting that all the resistivity curves show a steplike feature $\rho_{xx} \sim h/4e^2$ visible at $B_c \approx 1.4$ T. The resistivity shows no temperature dependence below B_c, while above 1.4 T ρ_{xx} increases the more rapidly the lower the temperature. Indeed such temperature dependence may indicate activated behavior due to the opening of a zeroth gap, as expected from the simple energy diagram shown in the Fig. 1. Surprisingly, we find that the profile of $\rho(T)$ does not fit the activation form $\rho(T) \sim \exp(\Delta/2kT)$, where Δ is the activation gap. The Inset to Fig. 3 shows that $\rho(T)$ starts to deviate strongly

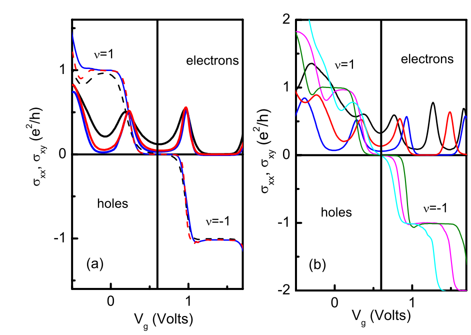

FIG. 2 (color online). (a) Diagonal σ_{xx}(solid lines) and Hall σ_{xy}(dashed lines) conductivities as a function of the gate voltage at fixed magnetic field $B = 2.8$ T and at the different T (mK) : 850 (black), 250 (blue), 90 (red). (b) Diagonal σ_{xx} (solid lines) and Hall σ_{xy} (dashed lines) conductivities as a function of the gate voltage at the different values of the magnetic field $B(T)$: 1.5 (black), 2 (red), 2.5 (blue), $T = 50$ mK. Vertical line indicates CNP.

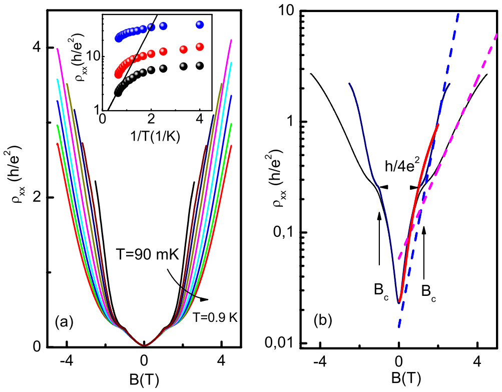

FIG. 3 (color online). (a) Magnetoresistivity at CNP for different temperatures. Insert: the resistivity as a function of the inverse temperature at a fixed magnetic field $B(T)$: 4 (black), 6 (red), 7 (blue). The solid line in the insert is a fit of the data with an Arrenius function with $\Delta = 0.3$ meV (b) Magnetoresistivity at CNP for two temperatures (90 and 900 mK). Magenta and blue dashed straight lines are fits of the data with the function $\rho(T) \sim \exp(\Delta/2kT)$. Red solid curve is the fitting obtained using the theoretical approximation [12] describing snake state percolation in quasiclassical random magnetic field regime.

from the Arrenius exponential law and at low temperature and high magnetic field ρ_{xx} it almost saturates. Therefore we may conclude that the observed T dependence is not related to the opening of the gap at the CNP and another mechanism is responsible for this behavior. Another important indication of the existence of a gap at CNP would be an exponential increase of ρ_{xx} with B. Note that the energy gap at CNP is determined by equation $\Delta = \hbar\omega_c^e/2 + \hbar\omega_c^p/2 - \Delta_0$, where $\hbar\omega_c^{e,p}$ is the cyclotron energy of electron or hole, $\omega_c^{e,p} = \frac{eB}{m_{e,p}c}$ is the cyclotron frequency, $m_{e,p}$ is effective mass, $\Delta_0 \approx 5$ meV is the overlap of the conduction and valence bands [6]. Taking into account the effective masses $m_e = 0.025m_0$, $m_p = 0.15m_0$ meV at CNP, we obtain $\Delta > 7.4$ meV at $B > 3$ T.

Figure 3 shows the comparison of the magnetoresistivity at the CNP with equation $\rho(T) \sim \exp(\Delta/2kT)$, taking into account the linear dependence of the gap Δ on the magnetic field. The increase of ρ_{xx} with B is qualitatively consistent with the opening of the gap, however, the value of Δ is found to be smaller than expected by more than a factor of 30. Moreover, we observe a reduction of the gap with lowering the temperature, which seems very unlikely. Therefore, a closer inspection of the $\rho_{xx}(B)$ data raises further doubt as to the existence of a gap at $\nu = 0$ filling factor.

To understand this anomalous behavior at CNP in the two-dimensional electron-hole system static disorder should be taken into account, i.e., the fluctuations of the local filling factor around $\nu = 0$ induced by the smooth inhomogeneities. Notice that at $B > B_c$ the opening of the gap at $\nu = 0$ leads to depopulation of the levels, and the system turns into a conventional insulator with $n_s = p_s \rightarrow 0$. From a simple argument this occurs when $\hbar\omega_c^e/2 + \hbar\omega_c^p/2 = \Delta_0$. For $\Delta_0 \approx 5$ meV we obtain $B_c = 1.4$ T, which agrees well with the position of the plateaulike feature in $\rho_{xx}(B)$ dependence, shown in Fig. 3.

Fluctuations of the local filling factor ν near zero leads to the formation of percolation paths along the $\nu = 0$ contours. A remarkable point to be noted is the possibility of a conducting network formed of such contours, since the coupling between two adjacent percolating cluster occurs through the critical saddle points, as shown in Fig. 4 [11,12]. The conductivity is realized by the electrons and holes moving along $\nu = 0$ lines and in quasiclassical regime have a trajectories of a snake-type, which is shown in Fig. 4. We emphasize the similarities in the description of the conductivity of an electron-hole system at the CNP and the transport of two-dimensional electrons in a random magnetic field with zero mean value [11–13].

Propagation of the snake-type trajectories along the $\nu = 0$ contours and their scattering at the saddle points may explain the large magnetoresistance at the CNP in Fig. 3. The analytical solutions for the model [12] have been obtained for two distinct regimes corresponding to a small and a large amplitude of the random magnetic field (RMF). In the limit of a small RMF at $\alpha \ll 1$, where $\alpha = d/R_c$, d is the correlation radius of the potential fluctuations, $R_c = \hbar k_F/m_{e,p}\omega_c$ is the Larmour radius, k_F is the Fermi wave number, the conductivity is given by $\sigma_{xx} = e^2/h(k_F d/4\alpha^2)$. Weak disorder regime $\alpha \ll 1$ in our case corresponds to the regime of a small amplitude random magnetic field. Figure 3(b) shows the results of the comparison of our data and the theory of percolation via the snake states. We obtain an excellent agreement with parameter $d = 0.06$ μm, which seems very reasonable. Note that the classical Drude model predicts quadratic positive magnetoresistance $\Delta\rho_{xx}/\rho_0 = \mu_n\mu_p B^2$ and large positive Hall resistance $\rho_{xy} = B/ne$ for homogeneous electron-hole system at CNP in the case $\mu_n \gg \mu_p$ and $n = n_s = p_s$ [6]. Our magnetoresistance data and observation of the $\rho_{xy} \approx 0$ are inconsistent with this prediction. We attribute such difference to the inhomogeneity of the e-h system, as we mentioned above. The model [12] also predicts a crossover from weak to strong RMF at $\sigma_{xx} \sim h/4e^2$, which corresponds to the features indicated in

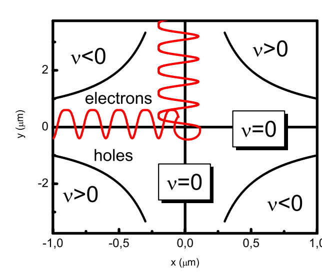

FIG. 4 (color online). (a) Schematic illustration of the electron-hole "snake state" percolation along $\nu = 0$ line at CNP in the strong magnetic field and geometry of the saddle point between adjacent percolation clusters.

Fig. 3(b) by arrows at B_c. In a strong disorder regime $\alpha \gg 1$ the theory [12] predicts that $\sigma_{xx} \sim \alpha^{-1/2}\ln^{-1/4}\alpha$, while the model [13] gives a different result. Not knowing which approximation is more realistic we find nevertheless that all models predict a fast increase of resistance with magnetic field in accordance with our observation. There is also one important observation to be made concerning the strong magnetic field approximation. We expect that with magnetic field increasing the density inhomogeneity domains will be eliminated at a critical magnetic field when the magnetic field length falls well below the typical domains size, and the snake states will be suppressed. For the estimation of the value of such critical magnetic field a more detailed theory is required. In this regime the transport should be dominated by variable range hopping between islands with the different filling factors. Another scenario in the strong magnetic field would be a joint contribution of the snake states, counter-propagating trajectories and variable range hopping to the transport. However, further theoretical and experimental work would be needed in order to distinguish between all these models.

Finally, we would like to discuss the similarity and the difference between other bipolar 2D system, such as graphene [2–4] and InAs/GaSb system [14], where the QHE has also been studied. In contrast both to our 2D *e-h* system in HgTe QW and to graphene the InAs/GaSb-based system is not a semimetal since there is a gap resulting from the hybridization of in-plane dispersions of electrons in InAs and holes in GaSb [15]. The electrons and holes are spatially separated by the heterostructure interface. Besides, so far there has been no demonstration of a state with equal electron and hole densities in InAs/GaSb [an analogue of the CNP in (013) HgTe QW]. All this results in a qualitatively different interpretation of the insulating behavior in the quantum Hall regime. In [14] a model was proposed which incorporates counter-propagating edge channels, while we suggest that in our system there are snake states propagating though the bulk of a disordered potential landscape. In contrast to the bipolar InAs/GaSb system, graphene shows a certain similarity with our system as far as the transport properties at the CNP in the QHE regime are concerned [3,4]. The main difference between our system and graphene is that there are neither electrons nor holes in graphene at the Dirac point in zero magnetic field, whereas the HgTe QWs are always populated with both types of carriers. It allows us to study the transport at $B < B_c$ and compare it with the theoretical snake state model for a small amplitude random magnetic field regime. Above B_c the situation becomes very similar to graphene, except that the nature of the gap at $\nu = 0$ may be different.

In conclusion, we have measured quantum Hall effect near the charge neutrality point in a system which contains electrons and holes. We have found that the QHE in this system shows a wide $\nu = 0$ plateau in σ_{xy} accompanied by a vanishing diagonal conductivity $\sigma_{xx} \approx 0$. However, we do not find a thermally activated temperature dependence in the longitudinal conductivity minima, which would be expected due to the opening of a gap in the energy spectrum in a conventional QHE. We attribute such behavior to a percolation of the snake-type trajectories along $\nu = 0$ lines. Our observations show that there is a common underlying physics in such phenomena as the $\nu = 0$ quantum Hall effect at the CNP, QHE in graphene at Dirac point and the transport in a random magnetic field with zero mean value.

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Note added.—During the preparation of this manuscript we became aware of a related work on the application of the random magnetic field model to transport in graphene by S. Das Sarma and Kun Yang [16].

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