Quantum Hall effect near the charge neutrality point in two-dimensional electron-hole system

G.M.Gusev,$^1$ E.B.Olshanetsky,$^{1,2}$ Z.D.Kvon,$^2$ N.N.Mikhailov,$^2$ S.A.Dvoretsky,$^2$ and J. C. Portal$^{3,4,5}$

1Instituto de Física da Universidade de São Paulo, 13596-170, São Paulo, SP, Brazil
2Institute of Semiconducter Physics, Novosibirsk 630090, Russia
3LNCMI-CNRS, UPR 3228, BP 166, 38042 Grenoble Cedex 9, France
4INSA Toulouse, 31077 Toulouse Cedex 4, France and
5Institut Universitaire de France, 75005 Paris, France

(Dated: March 31, 2010)

We study the transport properties of HgTe-based quantum wells containing simultaneously electrons and holes in 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 $\sigma_{xy}$ at $\nu = \nu_p - \nu_n = 0$, where $\nu_n$ and $\nu_p$ are the electron and hole Landau filling factors. We suggest that the transport at the CNP 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 random magnetic field with zero mean value.

PACS numbers: 71.30.+h, 73.40.Qv

Keywords:

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 the condensed matter physics. Its basic experimental manifestation is a vanishing longitudinal conductivity $\sigma_{xx} \approx 0$ and a quantization of the Hall conductivity $\sigma_{xy} = \nu e^2/h$, where $\nu$ is the Landau filling factor [1]. The discovery of a 2D electron-hole system in graphene at a finite magnetic field has put a beginning to a series of studies of the properties of the special state realized when the densities of the electrons and holes are equal, the charge neutrality point (CNP) [2,3]. In a strong magnetic field the QHE near the CNP reveals a plateau in $\sigma_{xy}$ with $\nu = 0$ currently associated with the resolution of the spin or the valley splitting of the lowest Landau level (LL) [3,4]. However, the longitudinal resistivity $\rho_{xx}$ at $\nu = 0$ demonstrates different behavior in various but otherwise quite similar samples: in some samples $\rho_{xx}$ shows a rapid divergence at a critical field and, with the temperature decreasing, saturates at a value much larger than the quantum of resistance [5], while in the others it decreases with lowering the temperature [5]. 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 [5,6], 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 [7] that a two-dimensional semimetal exists in undoped HgTe-based quantum wells with an inverse band structure and a (013) surface orientation.

In this paper 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 the Landau 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" propagating along the contours $\nu = 0$. The situation is very similar to the transport of two-dimensional particles moving in a spatially modulated random magnetic field with zero mean value [10]. We especially emphasize that our results may be equally relevant to the composite fermions description of the half-filled Landau level [11] and quantum Hall effect in graphene at Dirac point [12].

Our HgTe quantum wells were realized on the basis of undoped CdHgTe/HgTe/CdHgTe heterostructure grown by means of MBE at T=160-200 C on GaAs substrate with the (013) surface orientation. The details of the growth conditions are published in [12]. The section of the structure under investigation is schematically shown in Fig. 1. For magnetotransport measurements 50$\mu$m by 100$\mu$m 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$_3$Ni$_4$ was first grown on the structure using the plasmochemical method. Then, the TiAu gate was deposited. The density variation with gate voltage was $8.7 \times 10^{13} m^{-2} V^{-1}$. The magnetotransport measurements in the described structures were performed in the temperature range 0.050-4.1 K and in magnetic fields up to...
are clearly seen at ν field. Pronounced plateaux with values as a function of the gate voltage at fixed magnetic 
mínima in \( \rho \) ing mobility was \( \mu \) µlence band and the sample becomes p-conductive. The 
negative voltages the Fermi level goes deep into the va-
tron and holes with close densities [8]. Finally, for large 
At lower gate voltages there is a coexistence of elec-
ples from the same wafer have been studied.

When a large positive voltage is applied to the gate, 
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 suffi-
ciently low to avoid the overheating effects. Several sam-
ple 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 elec-
trons and holes with close densities. Finally, for large 
negative voltages the Fermi level goes deep into the va-
lence band and the sample becomes p-conductive. The 
density of the carriers at CNP without magnetic field 
was \( n_s = p_s \approx 5 \times 10^{10} \text{cm}^{-2} \), the mobility corresponding 
impedance was \( \mu_n = 250000 \text{cm}^2/\text{Vs} \) for electrons and 
\( \mu_p \approx 25000 \text{cm}^2/\text{Vs} \) holes. These parameters were found 
from comparison of the Hall and the longitudinal magne-
toresistance traces with the Drude theory for transport in 
the presence of two types of carriers. In magnetic field 
the energy spectrum of electrons and holes is quantized 
and, naively, the LL fan diagram consists of two sets of 
overlapped LLs, as shown in figure 1. Above some criti-
cal 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 \( \rho_{xx} \) and Hall \( \rho_{xy} \) resistivities as a function of the gate voltage at fixed magnetic 
field. Pronounced plateaux with values \( \rho_{xy} = -\hbar/ve^2 \) 
are clearly seen at \( \nu = -2, -1, 1, 2 \) accompanied by deep 
minima in \( \rho_{xx} \) on electron and hole sides of the depen-
dence (here \( \nu = \nu_p - \nu_n \) -is the differential filling fac-
tor). Surprisingly, when \( V_g \) is swept through the charge 
neutrality point the longitudinal resistivity shows a large 
maximum, whereas \( \rho_{xy} \) goes gradually through zero from 
\( h/e^2 \) value on the electron side to \( -h/e^2 \) value on the hole side. Indeed, \( \rho_{xx} \) is symmetric, and 
\( \rho_{xy} \) is antisymmetric in B. Fig.1b shows the conductiv-
ities \( \sigma_{xx} \) and \( \sigma_{xy} \) as a function of the gate voltage 
calculated from experimentally measured \( \rho_{xx} \) and \( \rho_{xy} \) by 
tensor inversion. Standard quantum Hall effect plateaux 
\( \sigma_{xy} = e^2/2h \) accompanied by minima in \( \sigma_{xx} \) are clearly 
visible. We note, however, that the steps in \( \sigma_{xy} \) on the 
holes side are not completely flat and the minima in \( \sigma_{xx} \) 
are not very deep due to a lower hole mobility. Notice 
that the height of the peaks in \( \sigma_{xx} \) is very close to \( e^2/2h \) 
for all Landau levels as expected for conventional QHE. 
The most intriguing QHE state is observed at the charge 
neutrality point at \( \nu = 0 \). Figure 1b shows that \( \sigma_{xx} \) has a 
flat zero value quantum Hall plateau around CNP, while 
\( \sigma_{xy} \) 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 \( \sigma_{xx} \) and \( \sigma_{xy} \) with temperature (a) and 
magnetic field (b) when the system is driven from n-type 
to p-type. Indeed, all QHE states become more pro-
nounced 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.
netoresponse behaviour at the CNP. Figure 3 shows a sharp increase in the resistivity $\rho_{xx}$ with magnetic field at the CNP at different temperatures. It is worth noting that all the resistivity curves show a plateaux-like feature $\rho_{xx} \sim h/4e^2$ visible at $B_c \approx 1.4T$. The resistivity shows no temperature dependence below $B_c$, while above 1.4 T $\rho_{xx}$ increases the more rapidly the lower the temperature. Indeed such temperature dependence may indicate activated behaviour due to the opening of a zeroth gap, as expected from the simple energy diagram shown in the Figure 1. Surprisingly, we find that the profile of $\rho(T)$ does not fit the activation form $\rho(T) \sim \exp(\Delta/2kT)$, where $\Delta$ is the activation gap. Insert to figure 3 shows that $\rho(T)$ starts to deviate strongly from the Arrenius exponential law and at low temperature and high magnetic field $\rho_{xx}$ 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 behaviour. The important indication of the existence of the gap at CNP may be the exponential increase of $\rho_{xx}$ with $B$. Note that the energy gap at CNP is determined by equation $\Delta = \hbar \omega_{c,p}$, where $\hbar \omega_{c,p}$ is the cyclotron energy of electron or hole, $\omega_{c,p} = eB/m_{e,p}$ is the cyclotron frequency, $m_{e,p}$ is effective mass, $\Delta_0 \approx 5meV$ is the overlap of the subbands $\mathbf{3}$. Taking into account the effective masses $m_e = 0.025m_0$, $m_p = 0.15m_0$ meV at CNP, we obtain $\Delta > 7.4meV$ at $B > 3T$.

**Figure 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.

Figure 3 shows the comparison of the magnetoresitivity at the CNP with equation $\rho(T) \sim \exp(\Delta/2kT)$, taking into account the linear dependence of the gap $\Delta$ on the magnetic field. The increase of $\rho_{xx}$ with $B$ is qualitatively consistent with the opening of the gap, however, the value of $\Delta$ is found to be smaller by more than a factor of 30. Moreover, we found the reduction of the deduced 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 quantum Hall effect 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 $\omega_{c,e}^p - \omega_{c,p}^e = \Delta_0$. For $\Delta_0 \approx 5meV$ we obtain $B_c = 1.4T$, which agrees well with the position of the plateau-like feature in $\rho_{xx}(B)$ dependence, shown in figure 3.

Fluctuations of the local filling factor $\nu$ 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 figure 4 [13, 14]. The conductivity is determined by the electrons and holes that move along $\nu = 0$ lines and in quasiclassical regime have a trajectories of a snake type, which is
shown in figure 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 13 13.

Propagation of the snake-type trajectories along the ν = 0 contours and their scattering at the saddle points may explain the large magnetoresistance at the CNP in figure 3. The analytical solutions for the model [14] 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 α << 1, where α = d/Rc, d is the correlation radius of the potential fluctuations, Rc = (4πkF/mc) is the Larmour radius, kF is the Fermi wave number, the conductivity is given by

\[ \sigma_{xx} = \frac{e^2 k_F d}{h 4\pi^2}. \]

Weak disorder regime α << 1 in our case corresponds to the regime of a small amplitude random magnetic field. Figure 3b 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 = 0.06µm, which seems very reasonable. Note that the classical Drude model predicts quadratic positive magnetoresistance Δρxx/ρ0 = μnμpB2 and large positive Hall resistance ρxy = B/2ne for homogeneous electron-hole system at CNP in the case μn >> μp and n = n0 = p0 8. Our magnetoresistance data and observation of the ρxy ≈ 0 are inconsistent with this prediction. We attribute such difference to the inhomogeneity of the e-h system, as we mentioned above. The model [14] also predicts a crossover from weak to strong RMF at \( \sigma_{xx} \sim h/4e^2 \), which corresponds to the features indicated in Figure 3b by arrows at \( B_c \). In a strong disorder regime α >> 1 the theory [14] 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 no direct comparison with the experiment in order to distinguish between all theses models would be possible without further theoretical and experimental works.

Finally we would like to discuss the similarity and the difference between other bipolar 2D system, such as graphene 4 6 and InAs/GaSb system 16, 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 in InAs and holes in GaSb 17. 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 behaviour in the quantum Hall regime. In 16 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 5, 6. 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 < Bc and compare it with the theoretical snake state model for a small amplitude random magnetic field regime. Above Bc the situation becomes very similar to graphene, except that the nature of the gap at ν = 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 ν = 0 plateau in \( \sigma_{xy} \) accompanied by a vanishing diagonal conductivity \( \sigma_{xx} \approx 0 \). However, we do not find a thermally activated temperature dependence in the longitudinal conductivity minimum, 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 ν = 0 lines. Our observations show that there is a common underlying physics in such phenomena as the ν = 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.

A financial support of this work by FAPESP, CNPq (Brazilian agencies), RFBI (09-02-00467a and 09-02-12291-off-m) and RAS programs "Fundamental researches in nanotechnology and nanomaterials" and "Condensed matter quantum physics" is acknowledged.

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 das Sarma et al 18.
1997).
[2] The Quantum Hall Effect, 2nd Ed., edited by Richard E. Prange and Steven M. Girvin (Springer-Verlag, New York, 1990). B. I.
[3] Halperin, Helv. Phys. Acta 56, 75 (1983).
[4] Z. Jiang, Y. Zhang, H. L. Stormer, and P. Kim, Phys. Rev. Lett. 99, 106802 (2007).
[5] D.A. Abanin, K.S. Novoselov, U. Zeitler, P.A. Lee, A.K. Geim, and L.S. Levitov, Phys. Rev. Lett. 98, 196806 (2007).
[6] J. G. Checkelsky, L. Li, and N. P. Ong, Phys. Rev. Lett. 100, 206801 (2008); J. G. Checkelsky, L. Li, and N. P. Ong, Phys. Rev. B 79, 115434 (2009).
[7] E. Shimshoni, H. A. Fertig, and G. V.Pai, Phys. Rev. Lett. 102, 206408 (2009);
[8] Z. D. Kvon et al., JETP Lett. 87, 502 (2008); E. B. Olshanetsky et al, JETP Letters, Vol. 89, 2903. (2009).
[9] J.E.Muller, Phys. Rev. Lett. 68, 385 (1992).
[10] A.G.Aronov, A.D.Mirlin, P.Wolff, Phys. Rev. B 49, 16609 (1994).

[11] Composite fermions: a unified view of the quantum Hall regime, edited by O. Heinonen, (World Scientific, 1998).
[12] N. N. Mikhailov et al., Int. J. Nanotechnology 3, 120 (2006)
[13] D.K.K.Lee, J.T.Chalker, D.Y.K.Ko, Phys. Rev. B, 50, 5272 (1994); D.K.K.Lee, J.T.Chalker, Phys. Rev. Lett., 72, 1510 (1994); S.C.Zhang, D.P.Arovas, Phys.Rev.Lett., 72, 1886 (1994).
[14] F.Evers, A.D.Mirlin, D.G.Polyakov, P.Wolff, Phys. Rev. B., 60, 8951 (1999).
[15] D.V.Khveshchenko, Phys. Rev.Lett., 77, 1817 (1996).
[16] R. J. Nicholas et al, Phys. Rev. Lett. 85, 2364 (2000); K. Takashina et al, Phys. Rev. B 68, 235303 (2003).
[17] M. J. Yang et al, Phys. Rev.Lett., 78, 4613 (1997); Y. Naveh and B. Laikhtman, Europhys. Lett., 55, 545 (2001))
[18] S. Das Sarma and Kun Yang, Solid State Commun. 149, 1502 (2009).