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PAPER

Anomalously large resistance at the charge neutrality point in a zero-gap InAs/GaSb bilayer

W Yu[1], V Clericò[2], C Hernández Fuentevilla[2], X Shi[1,11], Y Jiang[3], D Saha[4], W K Lou[5], K Chang[5], D H Huang[6], G Gumbs[7], D Smirnov[8], C J Stanton[4], Z Jiang[3], V Bellani[9,10], Y Meziani[2], E Diez[2,12], W Pan[1,12], S D Hawkins[1] and J F Klem[1]

1 Sandia National Laboratories, Albuquerque, NM 87185, United States of America
2 NANOLAB, Nanotechnology Group, Universidad de Salamanca, E-37008 Salamanca, Spain
3 School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, United States of America
4 Department of Physics, University of Florida, Gainesville, FL 32611, United States of America
5 SKLSM, Institute of Semiconductors, Chinese Academy of Sciences, 100083 Beijing, People's Republic of China
6 Air Force Research Laboratory, Space Vehicles Directorate, Kirtland Air Force Base, Albuquerque NM 87117, United States of America
7 Department of Physics and Astronomy, Hunter College of the City University of New York, New York, NY 10065, United States of America
8 National High Magnetic Field Laboratory, Tallahassee, FL 32310, United States of America
9 Department of Physics, University of California at Berkeley, Berkeley, CA 94720, United States of America
10 Department of Physics, University of Pavia, I-27100 Pavia, Italy
11 Present address: Department of Physics, The University of Texas at Dallas, Richardson, TX 75080, United States of America.
12 Authors to whom any correspondence should be addressed.

E-mail: enrisa@usal.es and wpan@sandia.gov

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Abstract

We report here our recent electron transport results in spatially separated two-dimensional electron and hole gases with nominally degenerate energy subbands, realized in an InAs(10 nm)/GaSb(5 nm) coupled quantum well. We observe a narrow and intense maximum (∼500 kΩ) in the four-terminal resistivity in the charge neutrality region, separating the electron-like and hole-like regimes, with a strong activated temperature dependence above $T = 7$ K and perfect stability against quantizing magnetic fields. We discuss several mechanisms for that unexpectedly large resistance in this zero-gap semi-metal system including the formation of an excitonic insulator state.

Semi-classical electron band theory provides a unified theme to characterize materials that we deal with daily. In an insulator, such as SiO_2 used in every computer chip, the valence band is filled and the conduction band is empty. The energy gap between the conduction and valence band edges is large and as such the conductivity is zero even at room temperature. In a metal, such as gold, the energy gap between the conduction band and valence band is zero, there are mobile carriers and the conductivity is finite even at zero temperature. Semiconductors, such as silicon, are between these two limits, and have a non-zero energy gap. In semiconductors, at high temperatures electrons are excited to the conduction band from the valence band due to thermal excitations, resulting in a finite conductivity. As temperature decreases, the number of thermally excited carriers decreases exponentially and the material becomes an insulator. This semi-classical electron band theory has witnessed tremendous successes for nearly a century, forming the foundation of almost all modern technologies, such as transistors, LEDs, solar cells, etc.

More than 50 years ago, Mott made a seminal observation on the anomaly at the transition from a metal to a semiconductor [1]. Later on, Knox and co-workers [2] developed this idea and argued that, if in a semiconductor (which at low temperature is insulating) the binding energy of the excitons (E_B) exceeds the energy gap (E_g), the conventional insulating ground state would be unstable against a new phase, dubbed excitonic insulator, which originates from the formation of an exciton condensate. The low temperature behavior of conductivity for an excitonic insulator was theoretically predicted by Jerome and co-workers [3] and many other studies, both theoretical and experimental, have been performed afterwards [4–21]. Although experimental evidence on the existence of this unusual insulating state has been reported [7], no completely conclusive results have been obtained so far.

In recent years, new electronic materials, topological insulators, have been attracting increasing interest thanks to the possibility of hosting new exotic states of matter [22, 23]. Among them the InAs/GaSb double-quantum wells (DQWs) are of particular interest, as they can readily be integrated within current semiconductor processing technologies. In this material system, the top of the valence band of GaSb is 0.143 eV higher than the bottom of the conduction band of InAs [24]. Due to the quantum confinement effect, the alignment of E_0 (the lowest electron subband in the conduction band) and H_0 (the highest hole subband in the valence band) can be tuned by varying the wells' thickness (an alternative way is represented by application of an electrical field [25]). For a given thickness of the GaSb QW, the bilayer is a conventional semiconductor provided that the thickness of the InAs QW is sufficiently small to keep E_0 above H_0 [26]. Above a critical thickness of the InAs QW, a quantum spin Hall (QSH) phase is realized [27] due to the inversion between the electron and the hole ground levels. Recently new signatures for the inverted phase in InAs/GaSb were studied [28, 29], as well as edge transport in the trivial phase [30]. However, little is still known about the transport properties at the critical thickness, which corresponds to the phase boundary between the normal insulator (NI) and the QSH insulator.

In this paper, we report on electrical transport experiments performed in InAs/GaSb DQWs in the three regimes, i.e. normal, critical and inverted. An unexpectedly huge resistance peak is observed in the charge neutrality region (CNR) in a sample where the E_0 and H_0 subbands almost perfectly touch each other at $k = 0$, when a semi-metallic state is nominally expected. We propose that this huge resistance is due to the formation of an excitonic insulator phase at the charge neutrality point (CNP), in our critical thickness device.

In figure 1(a) we plot the evolution of the calculated band structures of the InAs/GaSb DQW for three different values of the InAs QW thickness d, corresponding to the normal, critical and inverted regimes. We found that for $d < 10$ nm, $E_g > 0$, signaling a normal semiconductor band structure, while for $d > 10$ nm, $E_g < 0$, indicating the band-inverted regime of the DQW. At $d = 10$ nm $= d_c$ (critical thickness) we obtain $E_g = 0$, which corresponds to the boundary between the normal and inverted band structures. Our assignment of these three regimes has also been confirmed by recent infra-red measurements in magnetic fields [31]. In figure 1(b), we report the schematics energy band profiles [26] of the samples in the three regimes. In the following, we also provide experimental results from two different methods to distinguish samples from normal, critical or inverted regimes confirming the eight-band $\mathbf{k} \cdot \mathbf{p}$ results showed in figure 1(a).

Our main results are plotted in figure 1(c), where we show the four-terminal resistance measured as a function of gate voltage (V_g) in three typical samples, for which the InAs QW thickness is 9 nm (sample A), 10 nm (sample B), and 13 nm (sample C), respectively. The CNP peak is centered in each sample at $V_g = -0.60$ V (sample A), $V_g = -0.53$ V (sample B), and $V_g = -0.70$ V (sample C) and in the figure the gate voltage is normalized so that the CNP corresponds to $V_g^* = 0$. In all three samples a resistance peak, centered at the CNP, separates two highly conductive regions associated to positively ($V_g^* < 0$ V) and negatively charged carries ($V_g^* > 0$ V). The sign of the carriers in the two regimes was confirmed by Hall measurements at a finite magnetic field. Most strikingly, for $d = d_c = 10$ nm, where the electron and hole subbands are degenerate (middle panel of figure 1(a)) and a semi-metal phase is expected, the four-terminal resistance reaches an overwhelmingly large value ~530 kΩ in the CNR (figure 1(c), the middle panel). Measurements with both constant current and constant voltage bias were carried out to confirm the value of this resistance peak. In contrast, in $d = 9$ and 13 nm DQWs, where the band gap is either positive or negative, the resistance in the CNR assumes smaller values: in the normal regime (figure 1(c), the left panel), the resistance at the CNP is ~400 kΩ, while in the inverted regime (figure 1(c), the right panel), the resistance is ~60 kΩ. In the following, we will concentrate on the transport properties of this anomalous insulating state detected in sample B. By comparing our experimental data with previous studies, we propose that such high resistance state in our critical thickness sample is probably due to the formation of an excitonic insulator phase.

First, we observed that the maximum value of R_{xx} shows very weak temperature dependence at low T (see figure 2). We note here that this low temperature saturation behavior is different from the insulating state at the CNP in the single layer graphene [32]. On the other hand, this weak temperature dependence seems to be a generic feature in InAs/GaSb heterostructures [26, 33–36], whether in the normal, critical, or inverted band regimes. The exact origin of this anomalous temperature dependence is not understood and requires more detailed studies. The high-T regime ($T > 7$ K) is properly described by an activated behavior $R_{xx}^{\mathrm{CNP}} \propto e^{\Delta/2k_B T}$. The best fit of R_{xx}, shown in figure 2(b), gives an estimated energy gap $\Delta = 2.08 \pm 0.10$ meV. Temperature dependence measurements of R_{xx}^{CNP} were also carried out in sample A and sample C, and the results are shown in figure S2 of the supplementary information (SI) is available online at stacks.iop.org/NJP/20/053062/mmedia. The energy gap in normal semiconducting sample A (~3.3 meV) is quite different from that found in other normal semiconducting InAs/GaSb bilayers. For example in [26] the authors report an energy gap of ~0.5 meV, which is value is six times smaller than that measured in our sample. On the other hand, the value of the R_{xx} peak

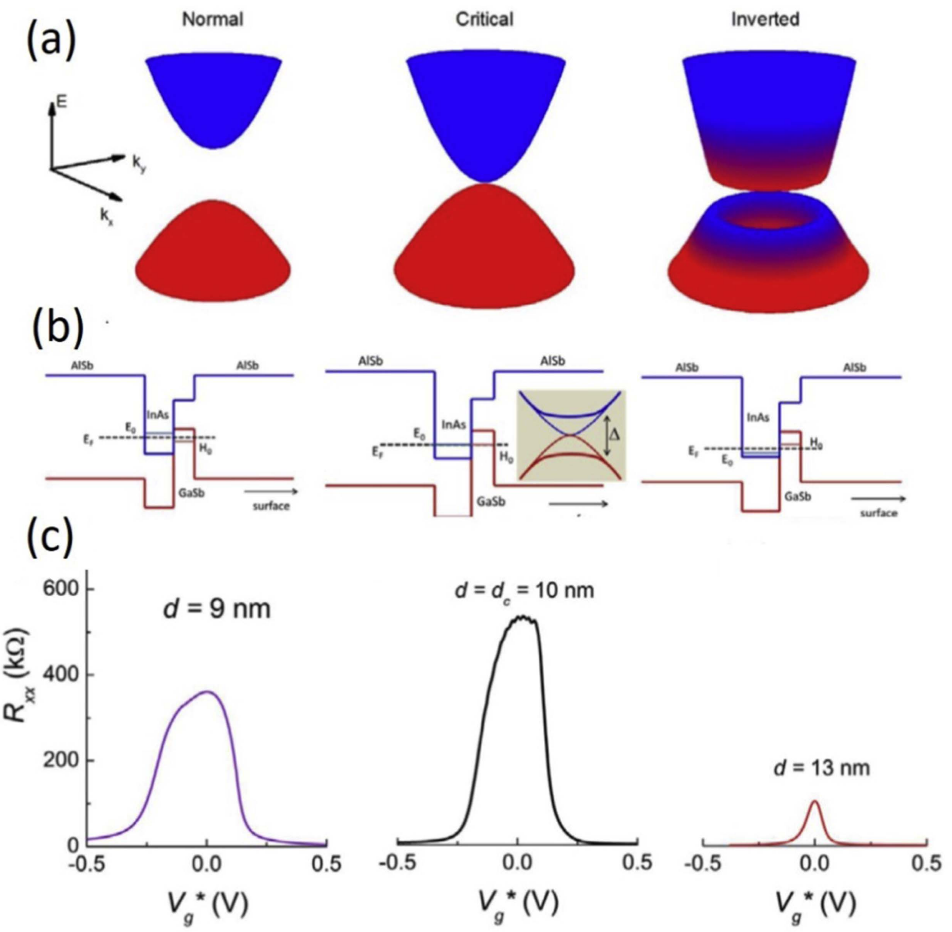

Figure 1. Band structures and four-terminal resistance of InAs/GaSb. (a) Band structures of the InAs/GaSb DQWs calculated using the eight-band $\mathbf{k}\cdot\mathbf{p}$ method (supplementary information) for three typical configurations: (left, sample A) $d = 9$ nm, (middle, sample B) $d = 10$ nm, and (right, sample C) $d = 13$ nm. (b) Shows schematic band profiles for samples A–C, respectively. E_0 is the lowest electron subband in the conduction band and H_0 the highest hole subband in the valence band. E_F is the Fermi level, at the charge neutrality point. The shaded inset in the middle panel shows the opening of the energy gap (Δ) due to the formation of an excitonic insulator phase. (c) Displays four-terminal resistance as function of gate voltage, measured at $T = 500$ mK, in samples A–C, respectively. The gate voltage is normalized so that the gate voltage at the CNP is zero ($V_g{}^* = V_g - V_g^{CNP}$).

at low temperature reported in [26] is one order of magnitude larger than ours. The physical origin for these discrepancies is not known at present and more detailed studies are under course.

In figure 3(a) we plot the longitudinal (σ_{xx}) and Hall (σ_{xy}) conductivities, measured at $B = 7$ T and $T = 100$ mK. Quantized plateaus at filling factors $\nu = 1$ and $\nu = 2$ (as well as at all higher values in the standard integer Quantum Hall sequence, here not shown) are clearly developed for both electrons and holes. In the vicinity of the CNP, an additional plateau at $\sigma_{xy} = 0$ is observed; a similar quantized plateau was reported for an inverted InAs/GaSb sample in [37], as well as for a degenerate HgTe quantum well in [38]. In figure 3(b), we show the two-dimensional density of charge carriers for electrons n and holes p as a function of V_g. The experimental points (red and black open circles) were obtained from the position of the integer quantum Hall plateaus at several different magnetic fields, while the continuous lines are linear best fits. The lines of the fits cross at $V_g = -0.55$ V and at $n_0 = p_0 = -1.1 \times 10^{10}$ cm^{-2} (which corresponds to the CNP condition $n + p = 0$). We note here that the obtained electron and hole densities at the CNP are the lowest reported, indicating a high quality of our sample. Figure 3(c) shows the normalized magnetoresistance $(R_{xx}(B) - R_{xx}(0))/R_{xx}(0)$ in the CNR at $T = 100$ mK: zero magnetoresistance is observed up to $B = 7$ T. Such stability under quantizing magnetic field extends also to its temperature dependence, as shown in the inset of figure 2(b). Indeed, we observed little differences between the data collected in the range 0 T $< B <$ 7 T. These observations strongly differ from those reported for the insulating state at the CNP in [37], where a huge magnetoresistance accompanied by strong B-induced strengthening of the T-dependence was reported. In the Supplementary Information (figure S3) we have addressed this point carefully, by comparing the results for the critical sample with the normal and inverted ones where a larger dependence is observed. In the SI we also report other measurements on samples in different regimes. We study the parallel magnetic field dependence in figure

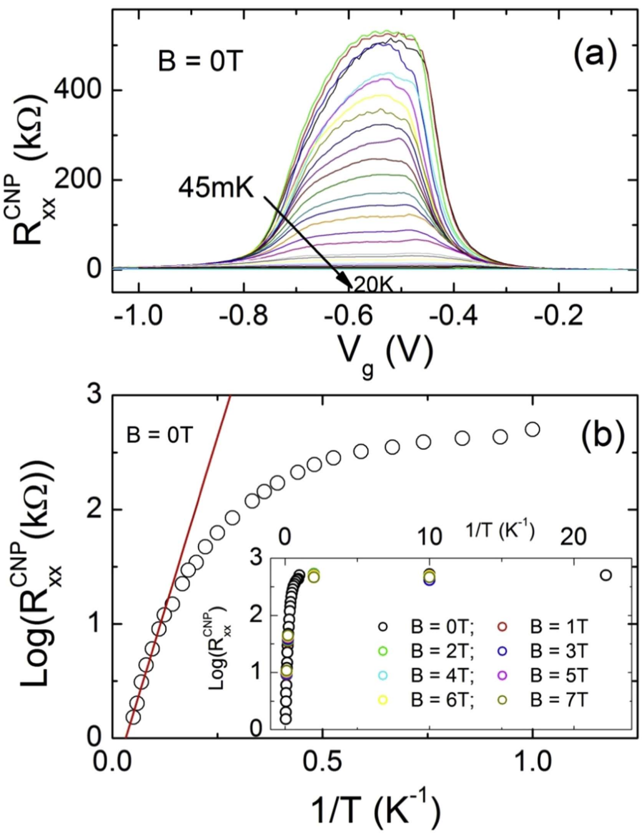

Figure 2. Longitudinal resistance of the critical sample. (a) Longitudinal resistance R_{xx} as a function of gate voltage V_g for increasing temperatures at $B = 0$ T, measured in sample B. (b) maximum of R_{xx} in the CNR as a function of $1/T$. The red line is a fit to $R_{xx}^{CNP} \propto e^{\Delta/2k_BT}$, obtained for the data at $T > 7$ K, which provides the estimation of the energy gap Δ reported in the text. The inset shows the temperature dependent data of R_{xx}^{CNP} at various magnetic fields.

S4. In figure S5, we use another method for identifying the three different regimes (normal, critical and inverted) proposed by Büttner *et al* [38].

The main result of this paper is the observation of an unexpectedly huge resistance peak in the CNR in a sample where the E_0 and H_0 subbands almost perfectly touch each other at $k = 0$, and a semi-metallic state is nominally expected. Based on this observation, we propose that that the large resistance in the CNR in our critical sample is probably due to the formation of an excitonic insulator phase. When the Fermi level is tuned to the CNP, excitons will form by the attractive Coulomb interactions between residual electrons and holes, whose densities are vanishingly small. At the critical thickness d_c, the band energy gap is almost zero and, thus, smaller than the exciton binding energy E_B, realizing the condition $E_g < E_B$. As predicted more than 50 years ago [1], the excitons under this condition condense, giving rise to an energy gap, which is responsible for the large resistance peak in the CNR. Away from the critical thickness, for $d < 10$ nm, a normal gap $E_g > E_B$ appears (see figure S1(b) in the SI). For $d > 10$ nm, the energy band structure becomes inverted. Due to strong interactions between electrons and holes, a mini gap (Δ) is formed at a finite k. At the band edges, the two types of carries coexist. As a result, E_B is much reduced [14]. Consequently the condition $E_B < \Delta$ prevents the formation of exciton condensation. Furthermore, the value of $4n_0a_u^2$ reached in our critical thickness sample also supports the formation of an excitonic insulator phase [14], being a_u the Bohr radius. Using the values quoted in [39], i.e., effective mass of $m_e = 0.023\ m_0$ for electrons in InAs and $m_h = 0.33\ m_0$ for holes in GaSb, and an effective dielectric constant $\kappa \sim 15$, the calculated Bohr radius is $a_u \sim 36.9$ nm. With $n_0 = 1.1 \times 10^{10}$ cm^{-2}, $4n_0a_u^2 \sim 0.6 < 1$, condition at which an excitonic condensed phase was shown to be thermodynamically stable [14]. Finally, the existence of an excitonic insulator phase in the critical sample is consistent with recent theoretical calculations [21], where the excitonic insulator phase is shown to be stable for samples with zero band gap and strong inter-layer interactions.

As a remark, we would like to mention a recent theoretical study of the charge transport in two-dimensional disordered semimetals by Knap *et al* [40]. In that work it was found that electron and hole puddles, due to smooth fluctuations of the potential, are responsible for a large resistance peak in the CNR measured in HgTe QWs by Olshanetsky *et al* [41]. First, we point out that the HgTe QW structure considered in [41], 20 nm wide, is far from the critical thickness of 6.3 nm in the HgTe QW [38]. As a result, the conduction and valence bands

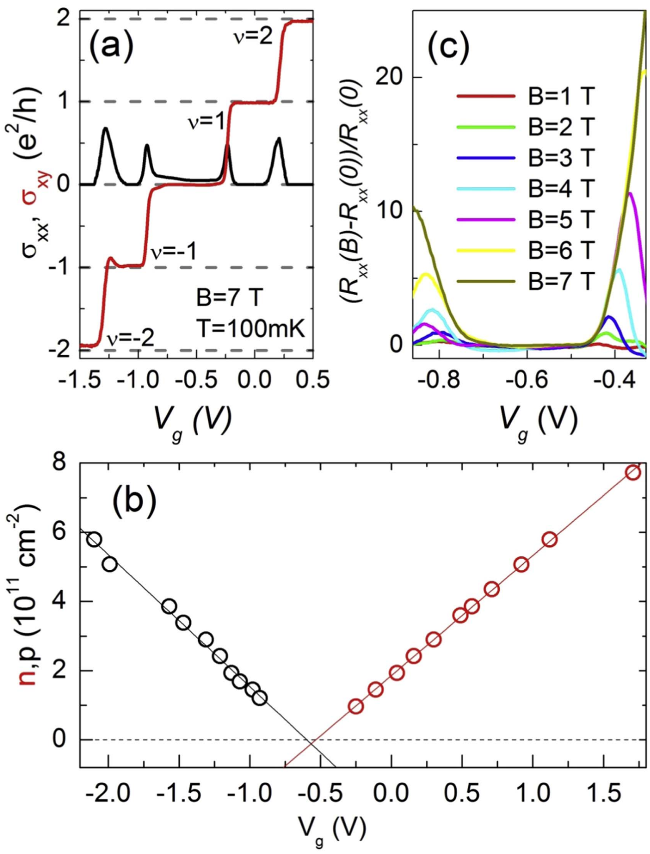

Figure 3. Magnetotransport properties of the critical sample. (a) Longitudinal (σ_{xx}) and Hall (σ_{xy}) conductivities as a function of V_g, measured at $B = 7$ T. (b) Two-dimensional charge density for electrons n and holes p as a function of V_g. (c) Normalized magnetoresistance $(R_{xx}(B) - R_{xx}(0))/R_{xx}(0)$ in the CNR, for increasing magnetic fields. All the data were acquired at $T = 100$ mK.

overlap is much greater than the gap estimated in our critical sample. Second, in [41] the authors found that the resistance at the CNP increases monotonically with decreasing temperature (figure 3 in [41]), a behavior different from what we have observed. R_{xx} shows relatively strong magnetic field dependence in [41] at the temperature considered, which, again, is very different from our observation (see figure 3(c)). Recent work, did not found enhancement in the resistance at the CNP [42, 43], however the presence of enhancements is markedly dependent on the distance from the critical regime.

Finally, in a recent work on InAs/GaSb double-quantum wells [44], the authors also reported on the observation of an excitonic insulating phase, by gating the residual electron and hole density at the CNP towards the diluted regime, which is naturally realized in our nominally zero-gap system. Notably, the activation gap as measured in their most diluted regime matches our value of Δ.

In summary, we have reported our electrical transport results in spatially separated two-dimensional electron and hole gases with nominally degenerate energy subbands, realized in an InAs(10 nm)/GaSb(5 nm) coupled quantum well. An unexpectedly huge resistance peak was observed in the CNR, where a semi-metallic state should be nominally expected. We propose that that such unexpectedly large resistance in this zero-gap semi-metal system is probably due to the formation of an excitonic insulator state.

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ORCID iDs

E Diez https://orcid.org/0000-0001-7964-4148

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