SAND2016-11998C

Evidence for an Excitonic Insulator Phase in a Zero-Gap InAs/GaSb Bilayer

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Introduction

InAs/GaSb double quantum wells (DQWs) have been attracting increasing interest in recent years. In these structures the electron and hole sub-bands are localized in different quantum wells and their alignment can be tuned on the basis of the wells' thickness. The most studied regime, the topological insulator phase, appears in a material with a bulk band gap as an ordinary insulator, together with exotic topologically protected conducting states on their edges or surface [1]. In InAs/GaSb DQWs a quantum spin hall (QSH) phase has been predicted when the bands' inversion is realized above a critical thickness of the InAs layer (for a fixed thickness of the GaSb one) and several experimental results point at this phenomenology [2-8]. Little is known however about the transport properties at the critical thickness, which corresponds to the phase boundary between the normal insulator (NI) and the topological insulator (TI). Here we report on magnetotransport experiments performed on a InAs/GaSb double quantum well grown with critical thickness parameters, in which degenerate electron and hole sub-bands are expected. We observe a narrow and intense maximum (≈ 500 kΩ) in the four-terminal resistance 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. By comparing our experimental data of samples in different regimes (normal insulator, critical regime and topological insulator), we show that such unexpectedly large resistance in our nominally zero-gap semi-metal system is due to the formation of an excitonic insulator state[9][10]. Our results pave a new way to experimental study of this peculiar state of matter.

Three different regimes: an unexpected behaviour

Three different regimes appear depending on the alignment between the valence band of GaSb and the conduction band of the InAs.

Our samples were engineered to display all these three typical configurations, for this purpose a series of InAs/GaSb DQW samples, in which the thickness of InAs (d) was varied from 9 nm to 13 nm while the thickness of GaSb was fixed at 5 nm, were grown with the molecular beam epitaxy (MBE) technique.

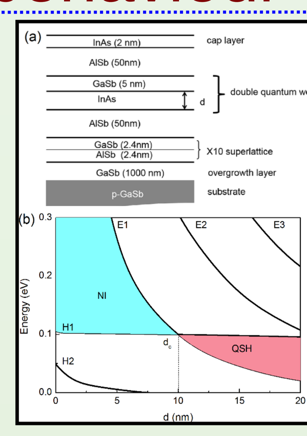


Figure 1: (a) Schematic structure of the InAs/GaSb DQW samples. (b) Evolution of the electron and hole subbands as a function of the InAs thickness d, calculated using the 8-band k·p method. The critical thickness dc, corresponding to the boundary between the normal and inverted band structures, is found to be dc = 10.03 nm.

Unexpected large R_{xx} in critical sample!

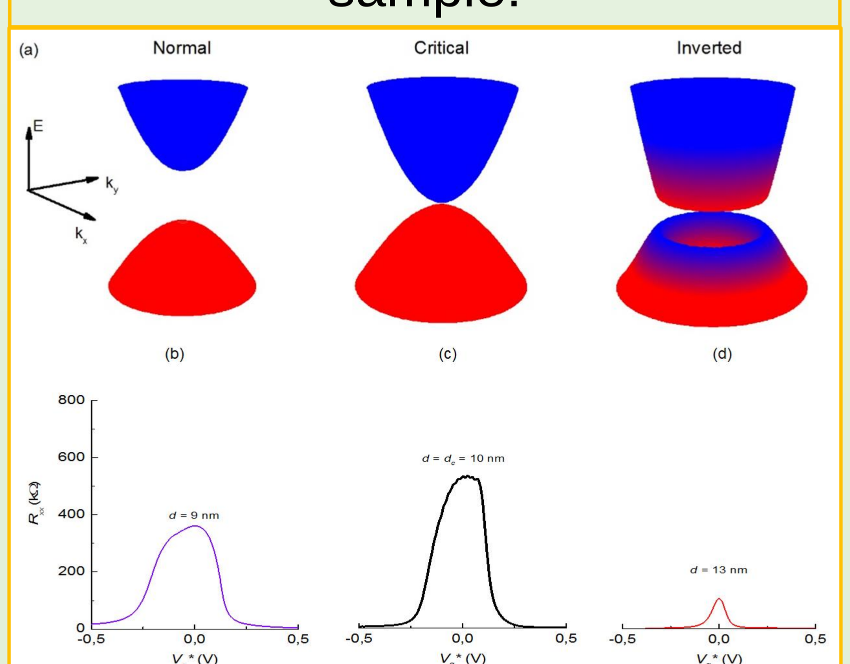


Figure 2: (a) Band structures of the InAs/GaSb DQWs calculated using the 8-band k.p method for three typical configurations: (left) d = 9 nm, (middle) d = 10 nm, and (right) d = 13 nm. (b-d) 4terminal resistance as function of gate voltage, measured at T = 500 mK, in samples A-C, respectively. The gate voltage is normalized so that the gate voltage at the CNP is zero (Vg* = Vg −Vg(CNP).

Critical sample does not depend on parallel magnetic field

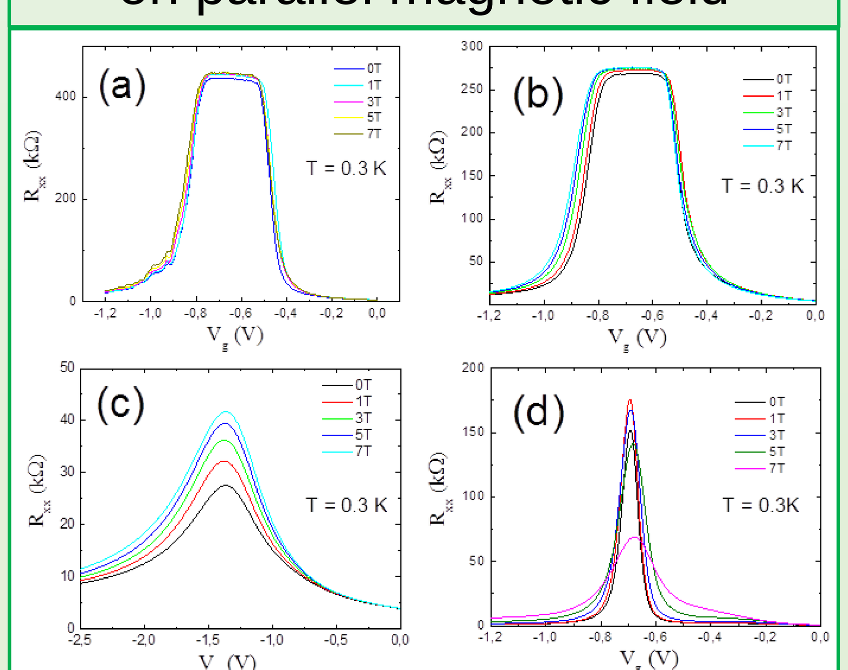


Figure 3: Longitudinal resistance versus gate voltages in the presence of different parallel magnetic fields for the critical (a) and two inverted samples (b) and (c). While the critical sample (10/5 nm) has almost no parallel magnetic field dependence, samples (11/5) nm and (13/5 nm) show a strong parallel magnetic field dependence, characteristic of inverted band configurations.

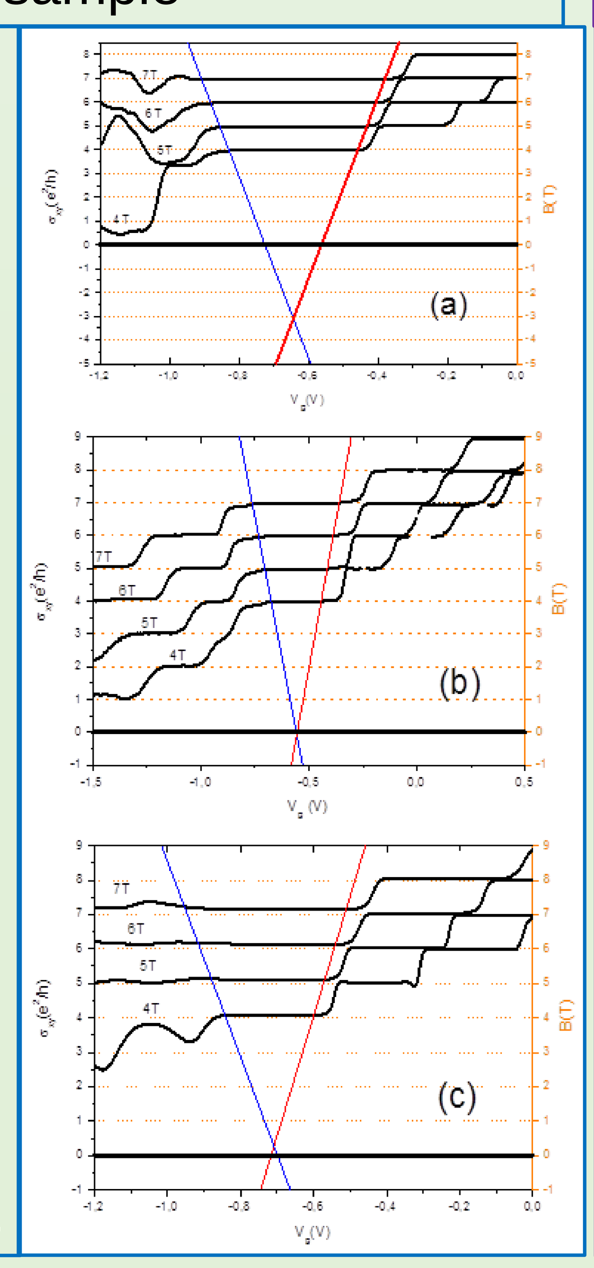
Büttner method confirms critical sample

Figure 4: Hall conductivity(σ_{xy}) at 300 mK at different perpendicular magnetic fields. The blue and red lines, defined by the bondauries of the plateau in the CNR:

in sample cross at B_c < 0T revealing a normal insulator regime for sample (9/5 nm) (a);

in sample (10/5 nm) cross at B_c ~ 0T revealing a zero gap sample (b);

in sample (12/5 nm) cross at B_c > 0T , indicating an inverted regime (c).



Peculiar dependence of the critical sample from perp Magnetic field

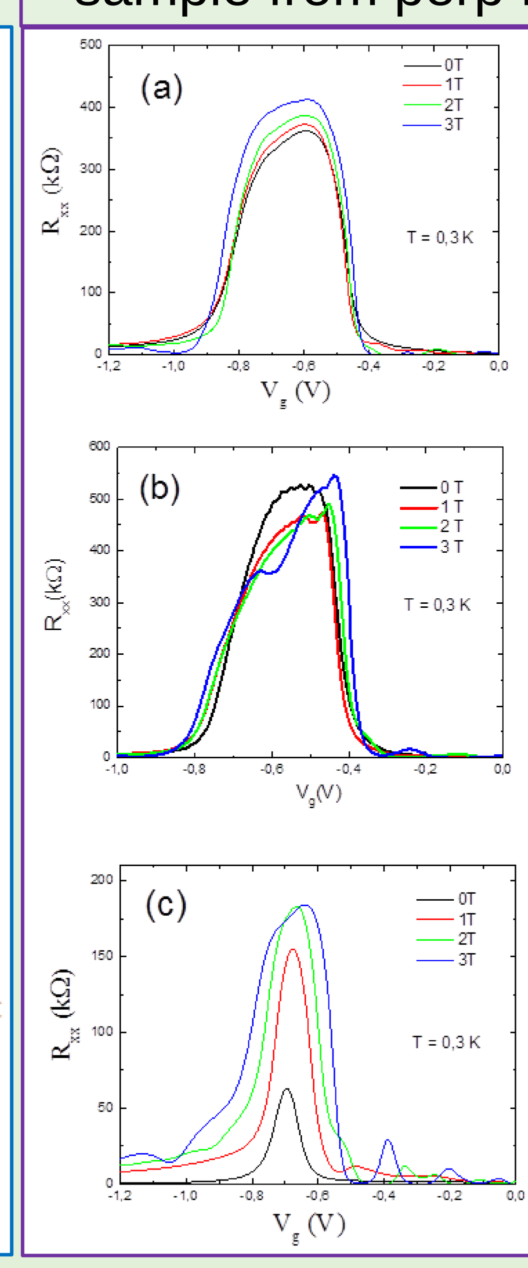
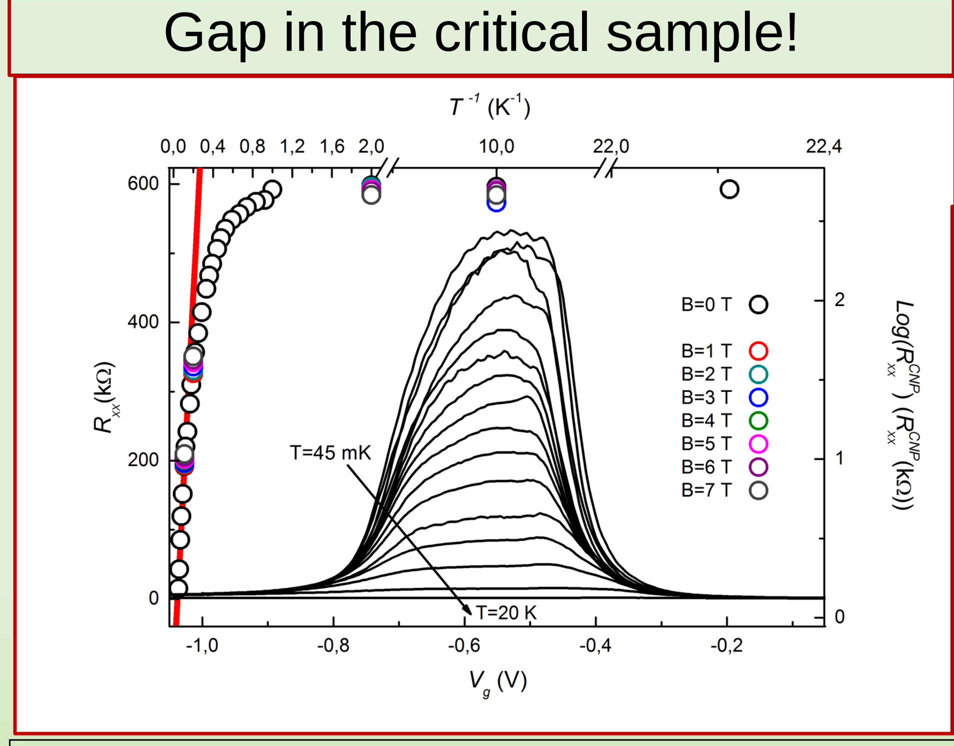


Fig.5: R_{xx} versus gate voltages at 0.3K from 0 to 3 T perpendicular magnetic field for the normal insulating sample 9/5 nm (a), the critical sample 10/5 nm (b); and an inverted sample 13/5 (c). Notice the decrease in CNP peak at low magnetic fields up to 2 T for the critical sample whereas in the other two there is always a systematic increase.

Excitonic insulator state

Gap in the critical sample!



$R_{xx} \cong \exp(\Delta/(2k_BT))$

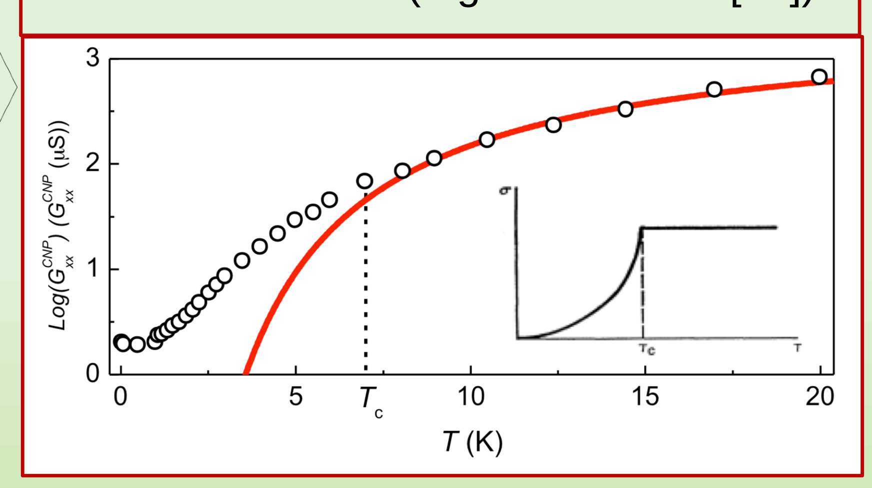
Δ=2.08±0.1 meV

Figure 6: Longitudinal resistance Rxx of the critical sample EB4338 as a function of gate voltage Vg for increasing temperatures at B = 0 T, measured in sample B. Colour open circles: maximum of Rxx in the CNR as a function of 1/T, showing activated behavior. The red continuous line is a fit to R_CNP xx ∝ exp(Δ/2kBT), obtained for the data at T > 7 K, which provides the estimation of the energy gap Δ

Our measurements reveal a peculiar behavior in the critical sample

From the binding energy Eb ~ 2.13 meV, according to the theoretical argument of Ref. [3], we obtain a critical temperature Tc ~ 0.45Eb/k_B ~ 7K. This value is in extremely good agreement with the temperature at which we observe a clear change from an activated behavior (continuous red line in Figure 4) to a weak T dependence in our experimental data.

Figure 7: Open circles: Longitudinal conductivity Gxx at the CNP measured at B = 0 T as a function of temperature. Continuous red line: fit to the data with GCNP xx ∝exp(−Δ/2kBT). In the inset we include the behavior expected for an excitonic insulator (Fig. 2 from Ref. [10]).



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This work was supported by the following projects: MINECO and FEDER MAT2013-46308-C2-1-R and Junta de Castilla y Le´on SA226U13 and SA045U16, the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division. W.Y., Y.J., D.S., and Z.J. acknowledge the support from the U.S. Department of Energy (Grant No. DE-FG02-07ER46451). Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
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