Measuring the chemical potential of a two-dimensional hole gas across the metal-insulator transition

An application using Oxford Instruments Superconductivity's HelioxTL, top loading single shot ^{3}He refrigerator

The possibility that the zero temperature ground state of a 2D system might be metallic has been raised by experiments carried out six years ago by S. Kravchenko and co-workers in silicon two dimensional electron systems. These have revealed a metal-insulator transition in two-dimensions (2D) and clearly show a metallic like behaviour above a certain critical density. Since then, this phenomenon has been observed in many different material systems such as holes in GaAs and in SiGe, challenging the scaling theory of localisation, which predicts only an insulating phase in 2D.

To date, the vast majority of experimental findings have been obtained through transport measurements. However, it was expected that the existence of a true zero temperature phase transition would reveal itself in other properties of the system such as the magnetisation and electronic compressibility, $\partial n/\partial \mu$, where μ is the chemical potential and n is the carrier density.

For example, a transition to a Mott insulator would result in a vanishing compressibility at the transition, in contrast with a crossover to an Anderson insulator where the compressibility is expected to remain nearly unaffected. It was therefore clear that determining the chemical potential as a function of the carrier density and hence the compressibility across the transition would help to unravel the microscopic origin of this phase transition.

Recent experiments carried out by Drs Ilani, Yacoby, Mahalu and Shtrikman at the Weizmann Institute of Science, Israel, have measured the dependence of the compressibility of a 2D hole gas (2DHG) as a function of its density as it crosses through the metal-insulator transition. The experiments required a very low base temperature, 220 mK, to be held for up to five days in a relatively large sample space. This was achieved successfully using Oxford Instruments Superconductivity's HelioxTL 38 mm ^{3}He insert - although even this was being stretched to its limit, the hold time being four times its design specification. The measurements were performed using several single electron transistors (SETs) situated directly above the 2DHG. The transistors act as extremely sensitive voltage probes that measure locally the chemical potential of the 2DHG. Monitoring different transistors across

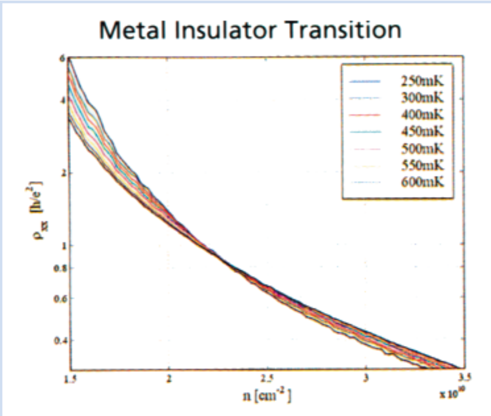

Fig. 1: Density dependence of the resistivity: Traces from top to bottom on the right correspond to T=600, 550, 500, 450, 400, 300 and 250 mK . The low-T crossing point is at nc = 2.1cm -2

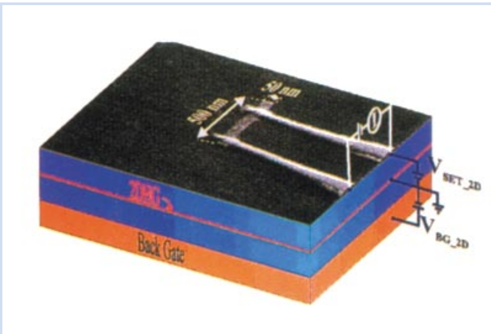

Fig. 2: A SEM micrograph of the SET on a schematic device structure, together with the measurement circuit.

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the same sample also allows determination of the spatial variations in the compressibility. Simultaneous transport measurements were conducted to ensure a precise determination of the critical density within the same sample.

In the metallic phase the measurements clearly show that the compressibility is negative. This result agrees quantitatively with previous macroscopic measurements and the predictions of the mean field Hartree Fock theory. However, at the transition into the insulating phase the compressibility becomes positive and its magnitude decreases with increasing penetration into the insulating phase. Furthermore, measurements done with different transistors on the same sample show that, although the behaviour in the metallic phase is homogeneous in space, the behaviour in the insulating phase differs from point to point across the sample, suggesting that the insulating phase is spatially inhomogeneous.

These measurements, showing a clear difference between metallic- and insulator-like behaviour, therefore support the existence of a metal-insulator transition in the two-dimensional system.

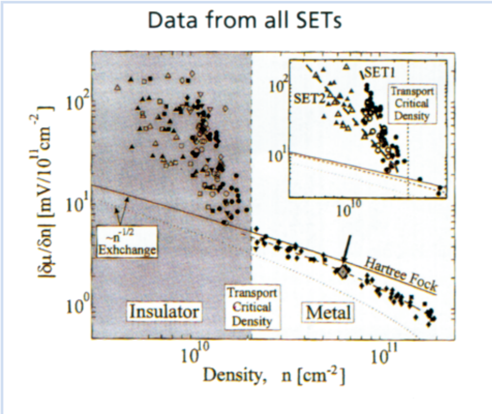

Fig. 3: The absolute value of the inverse compressibility, ∂μ/∂n, collected from five SETs on three different Hall bars from two different wafers. In the metallic regime the compressibility is negative and all the SETs show the same dependence, suggesting a homogeneous phase. In the insulating regime, the compressibility is positive and vanishes. Hence the inverse compressibility diverges.

Inset: Results from two SETs on the same device demonstrating the spatial dependence of ∂μ/∂n on the insulating side.

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