Single-electron transistor probes two-dimensional electron system

In the last several years theoretical and experimental investigations have emphasized the important role of the edge of a two-dimensional electron system (2DES) in understanding the quantum Hall effect: Strips of metal-like and insulator-like behavior, so-called compressible and incompressible strips, are expected to develop with magnetic field within the depletion region at the edge of the 2DES. Theoretical works (see for instance K. Lier and R.R. Gerhardts, Phys. Rev. **B50**, 7757 (1994)) describe these strips at the edge as a consequence of quantizing the electronic levels of the 2DES by the magnetic field into Landau and spin levels. Increasing the electron concentration from the edge to the bulk, which happens over a typical distance of 1 μm, requires locally filling up more and more levels, but whenever a level is filled, due to the energy quantization it is energetically favourable to keep the electron concentration constant for a certain width. An incompressible strip is formed. The widths and the positions of these strips depend on the imprinted potential profile at the edge and on the quantization energy, i.e. the magnetic field. In the experiments here, a single-electron transistor (SET), made of metal, is used as a local electrometer to investigate the bulk and the predicted edge strips of the 2DES.

Figure 3 a shows a sketch of the SET which is deposited on top of the $Al_{0.33}Ga_{0.67}As$-GaAs heterostructure with the 2DES, 86 nm below the surface. The SET consists of a small aluminum island – 0.1 μm in width and 1 μm in length – which is coupled by aluminum oxide tunneling barriers to the aluminum source and drain electrodes. Due to the small size of the electronic island and small area of the tunnel junctions (about 0.1 μm by 0.1 μm), the total capacitance C of the island is small. Adding an electron to the island requires the Coulomb charging energy $e^2/2C$ (about 0.1 meV here), which acts like an energy barrier and blocks electrical transport through the island at the temperature $T < 100$ mK used in our experiments. Alloyed ohmic contacts to the 2DES allow to use the 2DES as a gate electrode for the SET island. With changing V_{2DES}, the electrostatic potential of the island is shifted and the energy for adding an electron is lowered. The island is charged by another additional electron whenever the voltage is increased by $\Delta V_{2DES} = e/C_{2DES}$ where C_{2DES} is the 2DES-island capacitance. As shown in Fig. 3 b, a sequence of conductance peaks is observed with the period ΔV_{2DES} – the so-called Coulomb blockade oscillations (CBO).

Applying a magnetic field B perpendicular to the 2DES, the Coulomb blockade oscillations shift on the axis of the externally applied voltage V_{2DES}, as shown in Fig. 3 c. These shifts reflect the variation of the chemical potential of the 2DES at constant electron concentration with changing magnetic field (Y.Y. Wei, J. Weis, K. v. Klitzing and K. Eberl, Appl. Phys. Lett. **71**, 2514 (1997)). This becomes clear when taking into account the intrinsic contact voltage $V_{contact}$ in series with the external applied voltage V_{2DES} which contributes to the electrostatic potential difference between the 2DES and SET island. This contact voltage is given by the difference in the chemical potentials (workfunctions) of the aluminum and the 2DES in the heterostructure. The magnetic field affects the electronic structure of the 2DES whereas in comparison the effect on the aluminum is negligible. Therefore, changes in the contact voltage follow mainly the variations of the chemical potential of the 2DES. In the low magnetic field regime, the depopulation of Landau levels with increasing magnetic field is nicely observed. This is different at high magnetic fields in the regime of well developed quantum Hall plateaus where the Fermi level is located in the mobility gap, i.e. between two Landau levels: The 2DES no longer works as a gate electrode for the SET. The 2DES below the SET island is electrically decoupled from the edge where the voltage V_{2DES} is applied. Instead relaxation processes and charge fluctuations versus time become visible (in Fig. 3 c around B = 3 T).

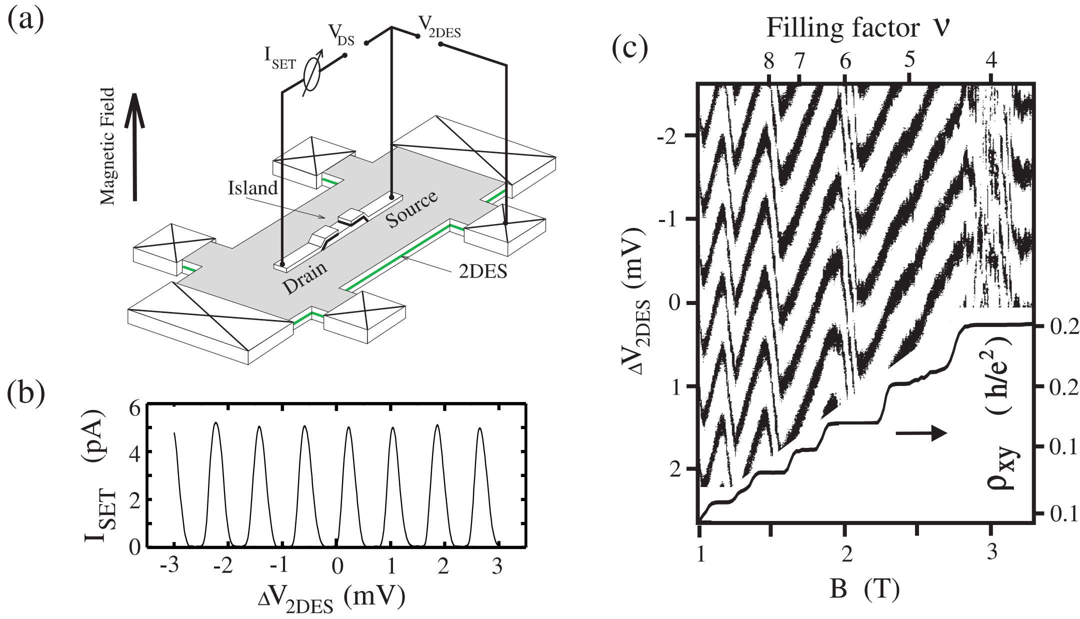

Figure 3: *(a) A single-electron transistor consisting of a metal island, which is coupled to drain and source electrodes via tunneling barriers, is deposited on top of a Hall bar which has been etched into a GaAs/AlGaAs heterostructure containing a two-dimensional electron system (electron concentration* n_s*=2.9×*10^{11} *cm*$^{-2}$*, electron mobility* μ_e*=4×*10^5*cm*^{2}*/Vs at T=4K). Alloyed ohmic contacts give electrical connection to the 2DES. (b) The Coulomb blockade oscillations measured at T=100mK by using the 2DES as the gate electrode for the SET island (*V_{DS}*=80μV). (c) The Coulomb blockade oscillations shown in greyscale as a function of magnetic field. The shifts reflect the variations of the chemical potential of the 2DES. For comparison, the quantum Hall curve is shown in the inset.*

The 2DES in the bulk has lost its good conductivity and the screening properties of a metallic layer. This interpretation is verified by changing the voltage applied to the metal electrode on the backside of the heterostructure. Coulomb blockade oscillations as a function of *backgate voltage* are not observable whenever the 2DES, which lies between the backgate and the SET, shows metal-like behavior in the bulk. But Coulomb blockade oscillations as a function of the backgate voltage become visible within the quantum Hall regime which demonstrates that under this condition the 2DES behaves like an insulator and can not screen the voltage variations of the backgate for the SET island.

By electrostatically depleting the 2DES below a metal gate electrode as shown in Fig. 4 a, the edge of the 2DES is redefined at a distance of about 0.9 μm from the SET island. Instead of measuring the CBO, a feedback circuit is used which keeps the SET current constant by controlling $\mathrm{V}_{\mathrm{2DES}}$. The fluctuations of the feedback signal are plotted in Fig. 4 b. In the quantum Hall regime (for instance around B = 9 T and zero sidegate voltage), the SET is decoupled from the edge, i.e. the 2DES does not work as an effective gate electrode and therefore the feedback signal fluctuates due to charge fluctuations in the 2DES below the SET island. With a more negative depletion voltage, the edge is shifted further towards the SET island. The feedback signal becomes stable (for instance for $\mathrm{V}_{\mathrm{sidegate}} < -1$ V at B = 9 T), since the metal-like region at the boundary of the 2DES has been moved below the SET by the sidegate voltage.

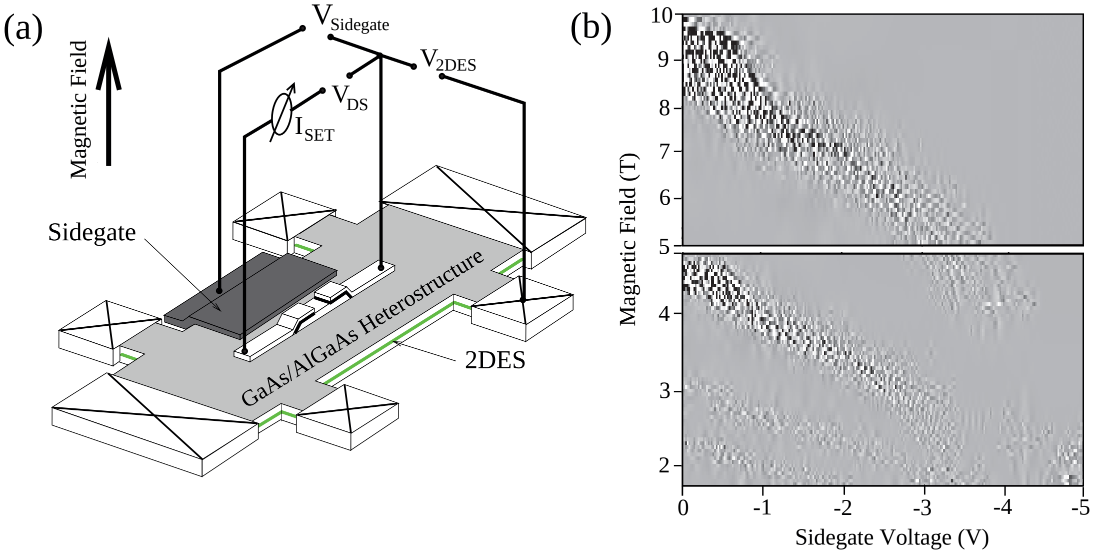

Figure 4: *(a) The second experimental setup: A sidegate electrode is deposited close to the SET island. It is used to redefine an edge of the 2DES close to the SET island (2DES electron concentration* n_s*=2.1×*10^{11} *cm*$^{-2}$*, electron mobility* μ_e*=1.3×*10^6 *cm*^{2}*/Vs). (b) Greyscale plot of the 'fluctuations' observed in the SET current as a function of sidegate voltage and of magnetic field. With more negative sidegate voltage, the edge is shifted closer to the SET.*

In conclusion, fluctuations in the feedback signal in Fig. 4 b can be identified as incompressible (insulating) regions at the position of the SET. At low magnetic fields, several strips of different screening properties become visible as expected from the compressible–incompressible strip model. Since the sidegate voltage moves the electrically defined edge, the $\mathrm{V}_{\mathrm{sidegate}}$ axis in Fig. 4 b can be directly used as a measure of the distance of the SET from the edge. Simple model calculations show that the relation is almost linear. The 2DES is depleted below the gate at $\mathrm{V}_{\mathrm{sidegate}} = -0.25$ V, i.e. the edge is at the boundary of the sidegate and reachs the SET at about $\mathrm{V}_{\mathrm{sidegate}} = -4.5$ V. To confirm that we have strips which are – at least on a length scale of several tens of microns – isolated from each other by an incompressible strip, the electrochemical potentials of the different metal-like strips are separately modulated and the capacitive coupling to the SET island is detected as a function of the edge position. By this technique, the strips are resolved individually and even the chirality of the strips is demonstrated (not shown).

In summary, the chemical potential of the 2DES is directly measured by a SET. Charge fluctuations become visible in the quantum Hall regime where the bulk of the 2DES is decoupled from the edge of the 2DES. By using a sidegate at a distance of about 0.9 μm distance from the SET island, fingerprints of strips with different screening properties are clearly detected.

(J. Weis, Y.Y. Wei, K. v. Klitzing and K. Eberl)