Single-electron transistors on tips for the use in scanning probe microscopy at low temperatures

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Single-electron transistors have been proven as local electrometers at low temperatures with sensitivity to a fraction of the elementary charge. A metal SET consists of a submicron metal grain – also denoted as 'island', connected by tunnel barriers – usually thin oxide layers – to source and drain metal electrodes. Due to the small size, the total electrostatic capacitance C_Σ of the island is small, leading to an energy $e^2/2C_\Sigma$ required for charging the island by an additional electron which exceeds the thermal energy at low temperatures. Electron transport via the island is blocked by Coulomb repulsion. Electrodes capacitively coupling to the island act as gates controlling the electrostatic potential and therefore also the electron number on the island. Under small source-drain voltages $V_{DS} < e/C_\Sigma$, a strong periodic modulation of the current through the SET is found as a function of gate voltage, – the SET conductance is switched between Coulomb blockade and single-electron tunneling ('Coulomb blockade oscillations'). These oscillations are shifted in gate voltage by adding an electron charge close to the island which makes the SET suitable as a highly sensitive electrometer.

Metal SETs have been evaporated on top of (AlGa)As/GaAs heterostructures to measure successfully the local chemical potential variations or local electrical compressibility of a two-dimensional electron system (2DES) under quantum Hall conditions. However, such an arrangement collects information only locally from a single site and might change the band structure and electronic properties of the 2DES underneath the SET due to mechanical strain. The first scanning SET was introduced by Yoo *et al.* [1] in 1997. A sharp glass fiber tip was evaporated with aluminum from different sides so that shadowing by the fiber's geometry led naturally to the electrode arrangement of an SET. The tunnel barriers were defined by a controlled oxidation process between evaporation steps. The typical grain size at the tip end was about 100 nm. We have now developed a new concept to define an array of tips, each with an SET on its end. This tip array sensor allows to probe several positions in designable distances at the same time.

Our tip array sensor was processed from an (AlGa)As/GaAs heterostructure grown in the MBE Service Group of the Institute. On a GaAs wafer, a 500 nm thick sacrificial $Al_{0.7}Ga_{0.3}As$ layer was deposited, topped by an (AlGa)As/GaAs layer sequence with a GaAs quantum well in the middle containing a 2DES for the integration of amplifying electronics in the future. The top layers were laterally structured to form tips which were then separated from the substrate by etching the underlying sacrificial layer. Cleaving the wafer, a free standing tip array was obtained at the edge of a piece of wafer.

The aluminum SETs with their crucial tunnel barriers had to be prepared as the last steps in the overall processing of the tip array sensor. As lithographic processing on sharped tips is hardly possible, we defined with the tip array preparation shallow grooves cutting the surface along each tip length. Using the natural shading by these grooves during metal evaporation under an angle we obtained two adjacent metal electrodes separated by a small gap on each tip. By this, source and drain electrode were naturally formed on the tip surface, and in extension connected to bond pads. Similar grooves were used to separate the lead electrodes of adjacent SETs. A controlled oxidation process under ultrahigh vacuum condition formed a thin oxide layer on the aluminum. A second evaporation step from the front onto the tips lead to the formation of an aluminum island on each tip end.

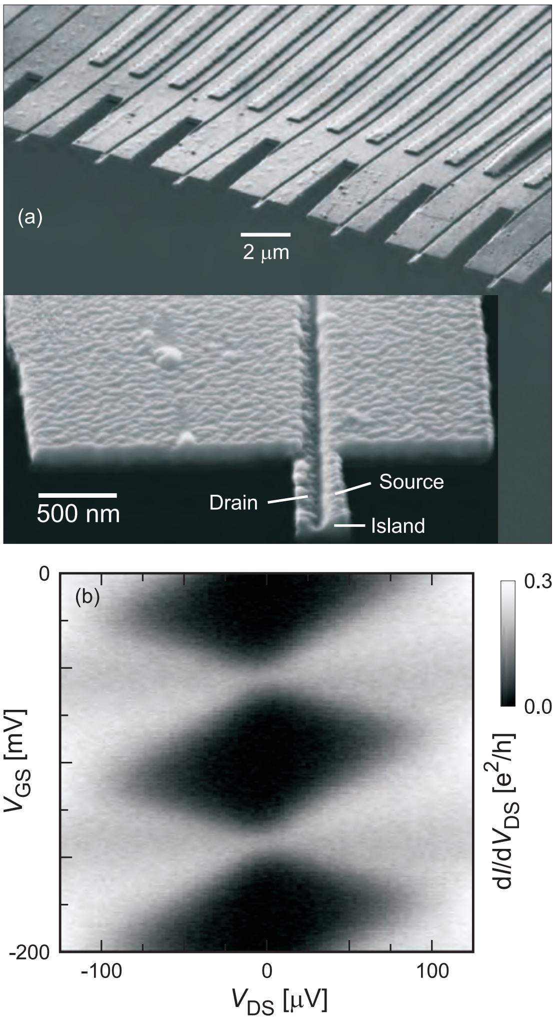

Figure 103: (a) SEM image of a tip array sensor with separately contacted single-electron transistors on each tip. Inset: SEM image of a single tip. (b) Typical electrical characteristics measured on a single SET. Differential conductance in grayscale as a function of source-drain voltage V_{DS} and gate voltage V_{GS} applied to a nearby metal electrode.

Fig. 103(a) shows an scanning electron microscope image of our tip array sensor, consisting of six separately contacted SETs on tips. The figure inset gives a closer look to one tip. The island size at the end of the tip is about 280 nm by 150 nm. In Fig. 103(b), the typical electrical characteristics of one of the SETs are shown, measured in a ^{3}He-^{4}He-dilution refrigerator at about 20 mK in a magnetic field of 1 T to suppress the superconductivity in the aluminum electrodes. As can be seen, the differential conductance measured as a function of source-drain voltage and a gate voltage shows regular Coulomb-blockade regions and a charging energy $e^2/2C_\Sigma$ of about 45 μeV.

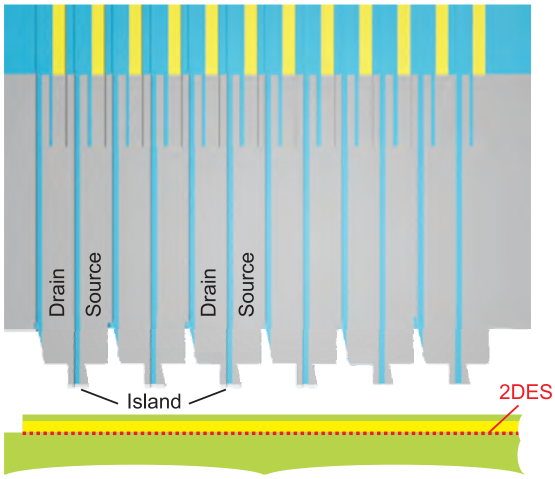

Figure 104: Sketch of a fixed arrangement of our tip array sensor and a quantum Hall sample. Two SETs at 8 μm distance were used to probe locally and simultaneously the electrostatic potential variations in the 2DES under magnetic field changes.

To prove the suitability of the SET tips as local electrometers without the complexity of a scanning probe microscope integrated in a ^{3}He-^{4}He-dilution refrigerator, a more simple approach was chosen where the tip array was mechanically adjusted 1 μm to 2 μm above the surface of a Hall bar mesa containing a 2DES and then fixed. A scheme of the setup is shown in Fig. 104. Potential measurement was done simultaneously with two tips, one located close to the Hall bar edge (about 2 μm), one located over the bulk of the Hall bar (about 10 μm from the edge). While a small, constant source-drain voltage was applied to both SETs, a separate electrical feedback loop for each SET held the current through the respective SET stable by adding a variable offset voltage common to source and drain. By this means changes in the electrostatic potential underneath the SET were transferred into changes of the offset voltage which then acted as measurement signal.

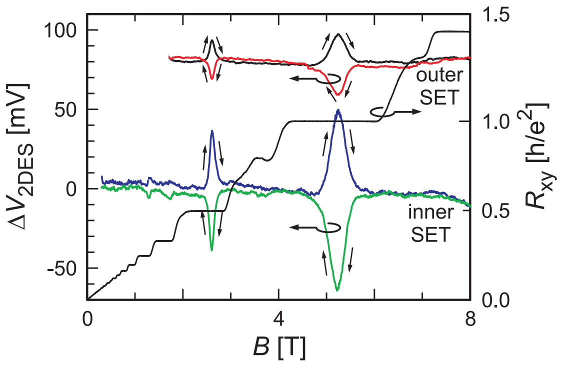

Figure 105: Hysteretic behavior of the local electrostatic potential under the inner and outer SET with sweeping the magnetic field up and down (data of outer SET plotted with offset). As reference, the Hall resistance curve is given showing that the hysteresis appear within Hall plateau regions.

Sweeping up and down the magnetic field applied perpendicularly to the 2DES, huge hysteretic curves are observed in the electrostatic potential probed by the two SETs (Fig. 105). The hysteretical behavior around integer values of the Landau level filling factor of the 2DES where the quantum Hall plateaus appear has also be seen by us and other groups in the past, using different setups and measurement techniques [2] and references in there). The effect has been attributed to the induction of eddy currents circulating in the quantum Hall sample, accompanied by a drop in the electrochemical potential between edge and bulk of the 2DES. Here over 55 mV difference between edge and bulk are observed. Furthermore, here the hysteretic curves show no significant dependence on the sweep rate of the magnetic field between 1 mT/s and 500 mT/s. It means, in conventional magnetoresistance measurements done on quantum Hall samples, a strong non-equilibrium situation between edge and bulk of the 2DES is present even if the magnetic field is swept at lowest speed. Pausing the field sweep somewhere on the hysteretic curve lead to a sudden relaxation of only part of the electrochemical potential difference, followed by no further significant change over hours. On the other hand it is very easy to move from the upper side of the curve to the lower one (and vice versa) by reversing the field sweep direction since for this only small field changes of few ten mT are necessary. Any kind of time stable voltage difference between edge and bulk could be tuned inside the hysteresis range by a sequence of slight steps in the magnetic field. A sequence of magnetic field steps forth and then back lead again to hysteretic behavior independent how long the waiting time was between steps. We have interpreted the behavior in terms of a compressible and incompressible landscape formed by the magnetic field inside the 2DES [3].

In the future our tip array sensor will be integrated in a scanning probe microscope operating in a ^{3}He-^{4}He-dilution refrigerator.

[1] *Yoo, M.J., T.A. Fulton, H.F. Hess, R.L. Willett, L.N. Dunkleberger, R.J. Chichester, L.N. Pfeiffer and K.W. West.* Science **276**, 579–582 (1997).

[2] *Hüls, J.* Ph.D. Thesis, Universität Hamburg (2001).

[3] *Weber, J.* Ph.D. Thesis, Technische Universität Ilmenau (2009).