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First *dc* Measurements of Electrons on Liquid Helium: the Helium-FET

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We present the first dc–measurements on a 2–dimensional (2D) electron system floating above a liquid ^{4}*He-film which covers a structured metal surface. With our arrangement of a source–, gate–, and drain–electrode a 2–dimensional charge transport is realized in analogy to a field-effect-transistor. The electrons which are moving along the x–direction due to different dc potentials are directly measured. This dc current, of the order of pA, is strongly dependent on the applied split–gate voltage. So the electrons were laterally confined to a narrow channel between the two gate electrodes. The effective width of the channel is reduced by the gate potential, so that a quasi–1D configuration can be realized. The measured electron current through the split–gate is analyzed and discussed on grounds of reduced dimensionality and 1D electron transport behaviour.*

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1. INTRODUCTION

2–dimensional electron systems (2DES) on liquid helium surfaces [1] form an important field for studying condensed matter phenomena, as in tests of electron transport theories. 2–dimensional electron systems also exist in semiconductors and heterostructures. Here the probes are generally in direct contact with the electrons which allows a measurement of the dependence of the electron *dc* current as a function of the applied voltages; e.g. to acquire *I*-*V* characteristics. With a central electrode, the gate, this flux can be well controlled. However, direct contact to the 2DES on liquid helium cannot be achieved [2], so the only measuring techniques which have been applied so far are either via capacitive coupling to this system using the *ac* techniques [3] or via microwave resonance in a cavity [4]. On the other hand, the

2DES on liquid helium has many advantages. The system is extremely pure and essentially free from scattering by lattice atoms and impurities, as the electrons are floating about 100Å above a liquid helium surface and so form an ideal 2–dimensional system. On bulk liquid helium the only scattering mechanisms are due to helium atoms in the vapour for $T \gtrsim 1$K, whereas below 1K scattering from quantised capillary waves on the helium surface, known as ripplons, becomes important. Another advantage is that one can continuously adjust the electron density from very low values, where the system behaves like a classical gas, via a Coulomb crystal, up to a degenerate Fermi-gas.

We report here first measurements [5] of a direct *dc* transport of the 2DES on liquid helium *films* using a certain arrangement of metal electrodes. With such a structured surface we can, as in MOSFETs, sensitively control the *dc* current which is flowing through a small channel between a split–gate electrode. This results in the realization of a Helium–FET. As we can force the electrons to go only through the channel a reduction of dimension (from 2D to quasi–1D) is possible when the width of the channel is roughly of the average electron distance or by applying the right field configuration to the split–gate.

We have also measured the relaxation times of the *dc* current. This gives some information of the density and mobility of the electrons as functions of the applied voltages.

2. EXPERIMENTAL PROCEDURE

To measure directly the electrons above the liquid ^{4}He surface, we have used an electrode arrangement comprising a source, gate and drain electrode as in MOSFETs; see Fig. 1a. The electrons are generated via a continuously powered tungsten filament above electrode E1. To prevent a direct path of the electrons to the pick-up electrode E4 a collimator is used. Electrode E2 acts as a split–gate, separating source (E1) and drain (E3). These three electrodes build up the He–FET. The potential applied to the pick-up electrode (E4) has to be high enough to collect all the electrons above the drain. So the *dc* current is measured via E4 with a sensitive electrometer; see Fig. 1b. The guard ring prevents an electron flux outside the structure to E4.

The electrodes are made of gold evaporated onto a glass substrate. The surface of the electrodes should be as smooth as possible to allow both a high mobility of the electrons above the He–film and little loss of electrons on rough spots. However, the pick-up electrode is rough to allow the electrons to tunnel through the isolating helium film. These horizontal electrodes are

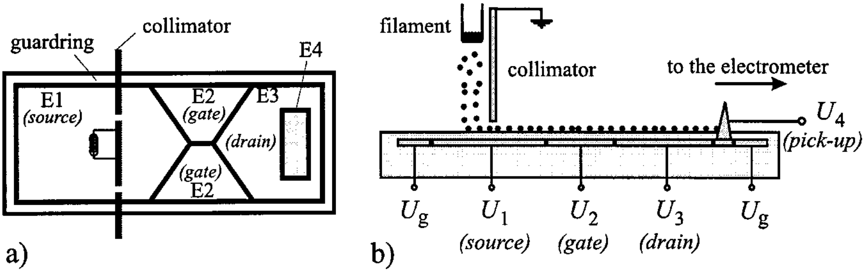

Fig. 1. a) Top view: the gate channel is 1mm long and 200μm wide. The evaporated gold electrodes are 200nm thick. The collimator and the guardring prevent lateral scattering of the electrons. b) Side view: different voltages at the electrodes cause the electron current along the x–direction until the electrons are picked up at electrode 4.

covered with a thin ^{4}He–film, whose thickness is determined by van der Waals forces. The measurements were done at 1.4K. The helium level outside the structure is measured with a cylindrical capacitor, with a resolution of the bulk level of about 60μm, and so the film thickness on the FET structure can be adjusted to an accuracy of a few nm.

Different voltages applied to the electrodes cause a field gradient along the plane E1 to E4, which drives the freely moving electrons in the xy–direction from source to drain via the gate electrode *and* through the channel. For a certain range of gate voltage there is only transport through the channel, as will be shown later. The dependence of the electron flux as a function of the applied voltages is investigated.

3. RESULTS

A typical *I-V* curve of the He–FET is shown in Fig. 2. The data show that one has to distinguish between two regimes of the charge transport. Due to impurities and roughness of the glass substrate electrons can break through the thin helium film and pin along the channel, but not on the Au electrodes. So when the channel is blocked due to substrate charge, the only path for the electrons is via the two gate parts. The current depends then on the potential gradient between electrodes source/gate and gate/drain and therefore there is only electron flow when $U_{source} < U_{gate} < U_{drain}$. However, when the channel is free of pinned electrons then the negative gate voltage only reduces the effective width with a consequent smooth decrease in current and so the current decreases smoothly. The inset of Fig. 2 shows

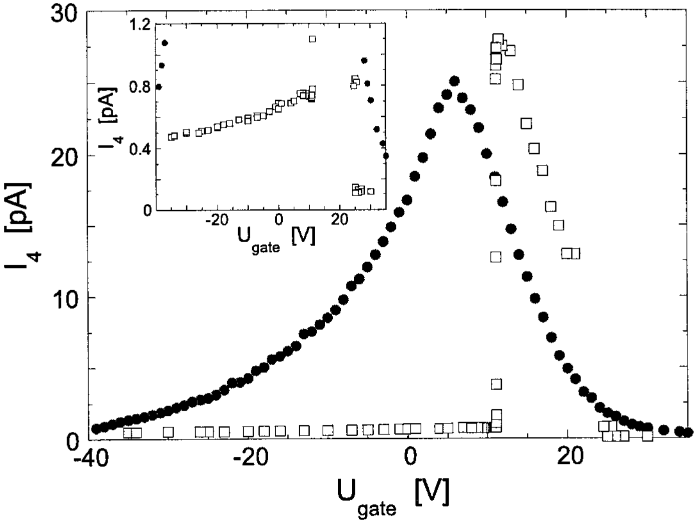

Fig. 2. *I-V* characteristics of the He–FET. Plotted is the current through the FET as a function of the gate voltage. The (□) are data for the blocked channel due to substrate charge, the (•) are data when the channel is free of pinned electrons. Here $U_{source}/U_{drain}/U_{guard} = +10/+30/-5$ V. Inset: even in case of the blocked channel there is still a very small current observable through the channel.

that even in the case of the blocked channel there is still a very small current observable through the channel; i.e. the substrate charge reduces drastically the electron flow, but not necessarily to zero.

In all our measurements we found good reproducibility of the shown *I-V* dependence. So the behaviour of the measured electron current was independent of whether the gate voltage was increasing or decreasing. This implies that the presence of substrate charge can reduce the magnitude of the gate current, but does not influence its relative change caused just by the gate voltage. Fig. 3 illustrates the role of U_{gate} in this context. We switched off the filament at various negative gate voltages, not before having established equilibrium. After switching on the current achieves the previous value.

4. DISCUSSION

As shown in Fig. 3 the increasing negative gate voltage leads to a decrease of the measured electron current. This is due to a reduction of the

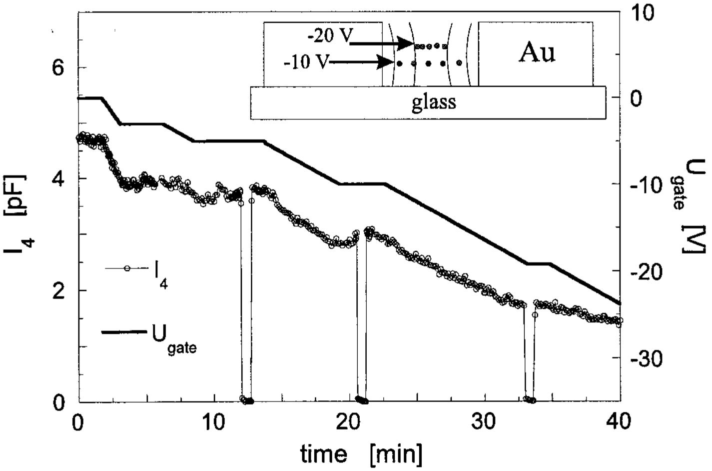

Fig. 3. Shown is the reduction of the electron current through the gate channel (left y-axis) by negatively increasing the gate potential (right y-axis) as function of time. Switching on/off the filament at constant U_{gate} shows equilibrium conditions of the electron current. The inset illustrates the reduction of the effective channel width (cross section) by increasing the constricting electric gate field.

effective channel width; see inset of Fig. 3. This behaviour can be explained by several effects. Firstly, the inhomogenity of the electrical field gradient across the channel, due to the applied potentials of the various electrodes, changes the electron density while varying U_{gate}. Subsequently, different scattering between the electrons can influence their mobility. Secondly, to ensure equilibrium the variation of U_{gate} has to be slow. During this process, however, electrons can break through the thin helium film onto the glass within the channel and so pinning effects due to the accumulated substrate charge also contribute to the measured current.

After switching off the filament the electron current decreases exponentially (and we measured $I(t) = I_{max}\ exp^{-t/\tau}$, where τ depends, e.g., on the thickness of the helium film). Via integration over time we can calculate the electron density over the whole substrate, which is between 10^7 and 10^8 cm^{-2} in the runs considered so far. We calculate mobilities, μ, between 10^{-1} and 1 cm^2/Vs using the relation $dI_{drain}/dU_{source/drain} \propto G = ne\mu$. These very low values, compared with the predictions and measurements of general mobilities of 2DES on bulk helium [6], are a consequence of pinning effects due to substrate roughness and are in line with previous mobility measurements of surface state electrons on helium films.

So by varying the lateral spread of the electron flux (see Fig. 2 and 3) it is possible to have an electron transport only through the gate channel. Although the geometrical width of the channel is so large that the electrons should behave as a 2–dimensional system, the effective width can be drastically reduced by increasing the gate voltage. In this way it should also be possible to create a 1–dimensional electron band – *quantum wire* – where the thermal wavelength of the electrons is larger than the channel width.

5. CONCLUSIONS

The possibility of adjusting the electron density quasi continuously from the classical range (low densities) to the quantum regime (high densities), makes the *dc* modus a powerful technique to investigate 2–dimensional and lower–dimensional electron systems in detail. In contrast to the conventional *ac* technique stray capacitances are not important, and very small currents can be measured. Possible experiments in analogy to the semiconductor systems, but here with quasi-free electrons, would be, e.g., to investigate the conductivity of quantum dots and anti-dot structures and the magneto-conductivity of a mesoscopic wire. The creation of a real one–dimensional electron channel should allow one to investigate electron interference effects (i.e. when the channel width is of the order of the mean free path of the electrons) and to study the Luttinger liquid behaviour in detail [7,8].

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