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Pulsed transport of electrons on liquid helium confined in narrow channels

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Abstract. We have used a Source-Gate-Drain configuration with electrons on liquid helium (the Helium Field Effect Transistor “He-FET”) to study the transport of “classical” electrons through narrow channels. The channels, formed by the split gate of the device, were between ten and a hundred μm long and several μm wide, and could be blocked completely by a negative bias voltage applied to the gate. In contrast to previous experiments, where the electron densities in source and drain were nearly the same and the system therefore was close to equilibrium, in the present measurement the drain was empty. The transport of the electrons through the channel was initiated by opening the gate with a short positive pulse with a duration down to nanoseconds, and the amount of electrons which passed during this time was registered. In this way, we could determine for the first time the transport properties of such a system on a nanosecond time scale and far off equilibrium. Measurements with varying gate voltage provide clear evidence for the formation of lanes of electrons in the channels.

1. Introduction

The transport of electrons through narrow constrictions has been a topic of considerable interest for decades. Most systems which have been investigated so far were either metals, where point contacts down to the size of a single atom have been realized [1], or semiconductors, e.g. MOSFETs with split gate geometry, where the effective contact size can be tuned electrically by applying a proper gate voltage [2-4]. For Surface State Electrons (SSE) on liquid helium, which form a two-dimensional Coulomb system of exceptional purity, only a small number of investigations in confined geometry exists so far. The first experiment with a Source-Gate-Drain configuration like in a Field Effect Transistor was reported by Klier et al. [5] and switching of the source-drain current I_{sd} by varying the gate voltage was demonstrated. Since then, investigations with similar set-ups have revealed interesting phenomena like the transport of strongly correlated electron systems through narrow channels [6,7,8].

Usually, experiments with SSE on liquid helium are carried out with nearly the same electron density in source and drain, the system is therefore close to equilibrium. Transport properties are derived from the response to an ac driving field, obtained by capacitive coupling to the electrodes and recorded by lock-in technique at a typical frequency in the kHz range. The behavior of the system is therefore studied on a scale of microseconds and above [8]. In contrast, we report here on pulsed dc measurements, where a temporal resolution for the electron transport down to some ten nanoseconds has been reached. Moreover, in our transport studies the system is far off equilibrium, because the electron density in the



source at the channel entrance is adjusted to some finite value, whereas the drain is completely empty because all arriving electrons are removed immediately. It also should be mentioned that in our measurements here, like in nearly all other experiments with SSE on helium, the electron density was in the range of 10^{10} cm^{-2} or below, where the SSE behave like a classical system [9].

2. Experimental

The principle of our experimental set-up has been described previously [5,10]. A tiny heated filament above the source area supplies the electrons and is operated in a pulsed mode with a pulse duration of 25 ms and a repetition rate of 4 Hz to minimize the thermal load. The electrons which have passed through the gate channel to the drain are collected by a pick-up electrode. Whereas in the first experiments with a Helium FET the electrode structures consisted of gold films evaporated on glass, the substrate used in the present work was a piece of a silicon wafer, covered with 500 nm oxide, which formed the source-channel-drain area. The split-gate electrodes and also a guard electrode surrounding the whole device consisted of 100 nm gold films evaporated onto the wafer (see figure 1a). A voltage on the order of a few volts was applied to the Si substrate between the source and the drain side. Together with the voltages applied to the split gate and the guard this provided the potential landscape for the electrons on the device (figures 1b, 1c). The sample was positioned at an adjustable height in the gas space above the liquid level of a ^4He cryostat and was therefore covered with a superfluid He film whose thickness could be controlled between 20 and 60 nm. The temperature in all the measurements was 1.3K.

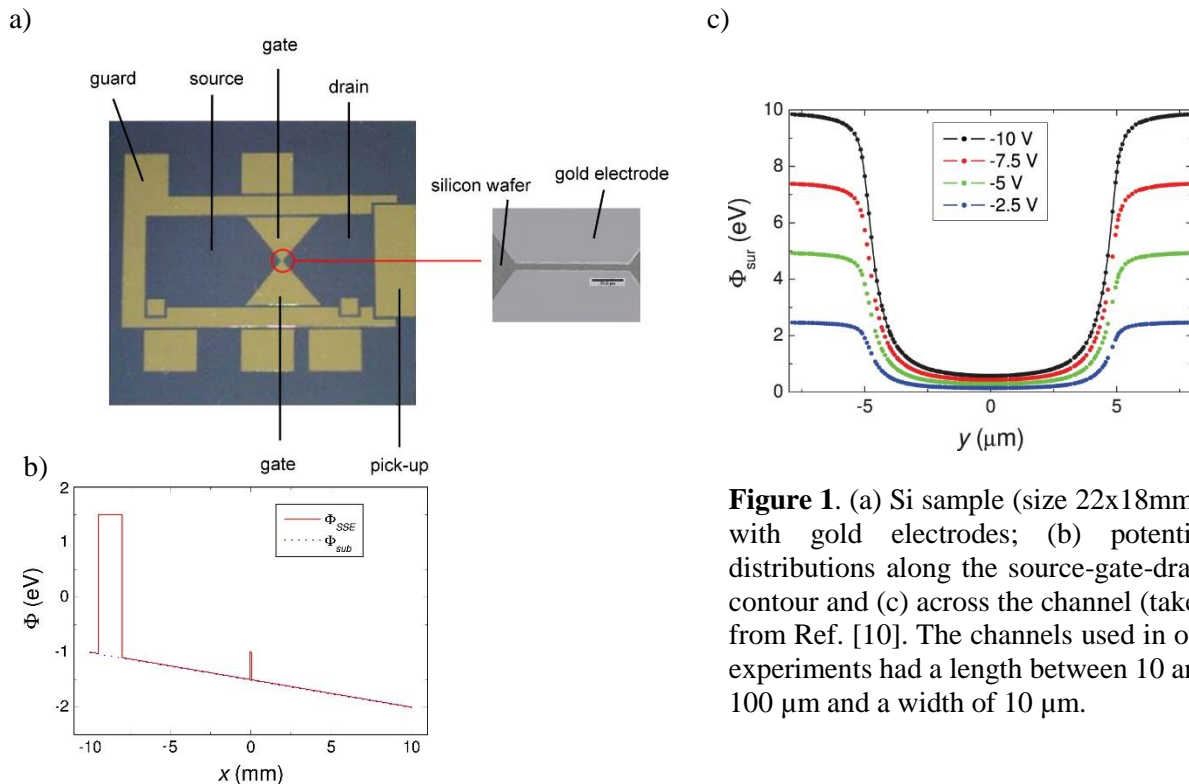


Figure 1. (a) Si sample (size $22 \times 18 \text{ mm}^2$) with gold electrodes; (b) potential distributions along the source-gate-drain contour and (c) across the channel (taken from Ref. [10]). The channels used in our experiments had a length between 10 and $100 \mu\text{m}$ and a width of $10 \mu\text{m}$.

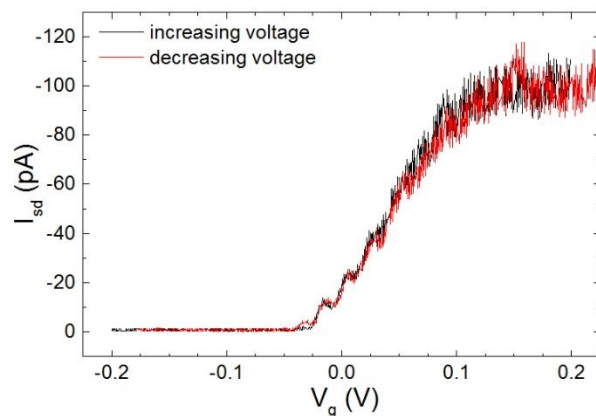
3. Results

3.1 I-V characteristics

We first describe steady state measurements of the variation of the source-drain current I_{sd} with the gate voltage V_g , as shown in figure 2. Starting at a value of V_g sufficiently negative to block the source-drain current, the gate voltage is slowly increased and the potential barrier of the gate therefore lowered. Above a certain threshold value, -0.03V in this case, the gate starts to open and a gradual increase of I_{sd} is observed. Two prominent features show up in addition: i) the current I_{sd} displays a periodic modulation

(not to be mistaken as noise) which is caused by the pulse-like supply of electrons from the filament to the source and is hence an artifact of the measurement. The amplitude of this modulation increases as the gate is opened more and more, because at large I_{sd} the depletion of charge between the recharging pulses is more pronounced; ii) at small values of I_{sd} steps are observed as the gate is opening. At first sight this feature is reminiscent of the steps in I - V characteristics of split-gate quantum point contacts made from semiconductor heterostructures, which are a quantum phenomenon [2-4]. However, in the present case we are dealing with a classical electron system, and therefore the steps have to result from a classical effect. We relate our observation to the well-known phenomenon of particle lane formation in channels [11]: As the gate voltage is increased and the effective channel width is getting larger, the number of electron lanes which fit into the channel increases as well, and each additional lane will give rise to a step in I_{sd} . A similar feature has been observed in ac measurements of SSE transport close to equilibrium by Rees et al. [8]. It results from the strong correlations between the electrons close to Wigner crystallization and is also found in the transport of other classical systems in confined geometry [11].

Figure 2. Source-drain current I_{sd} , collected at the pick-up electrode, as the gate voltage V_g is varied from closed to open conditions. The black line represents the opening curve, the red line the closing curve. A slight hysteresis between opening and closing voltages of 0.024V is compensated for clarity by shifting the red curve by this amount to negative values. The gate channel had in this case point contact geometry with a width of 10 μm .

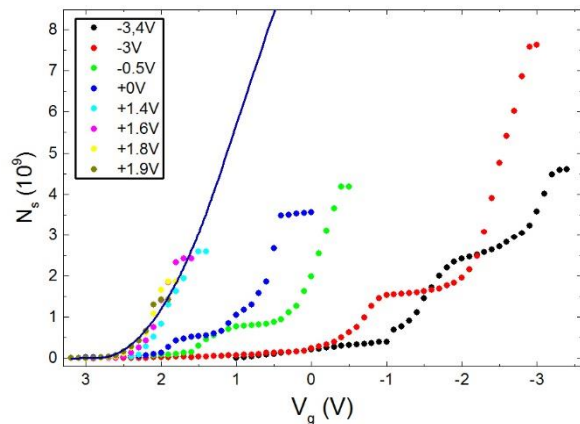


3.2 Gated Transport Measurements

We now turn from the quasi-continuous measurements of the source-drain current to experiments where first electrons are added to the source for some time, with the gate being closed, and then the filament is switched off. Starting from an empty source, the chemical potential of the electron ensemble in the source increases as the density of the electrons grows, until it becomes high enough that the electrons “spill” over the gate and a pick-up current is observed. At this point the filament is switched off, and a state with a well-defined number of source electrons N_s is thus prepared. N_s can be determined by opening the gate completely and integrating over the current pulse that arrives at the drain. It was found previously that N_s grows nearly quadratically as the gate barrier is increased, due to the particular charge density profile in the source which has its maximum right at the channel entrance [10].

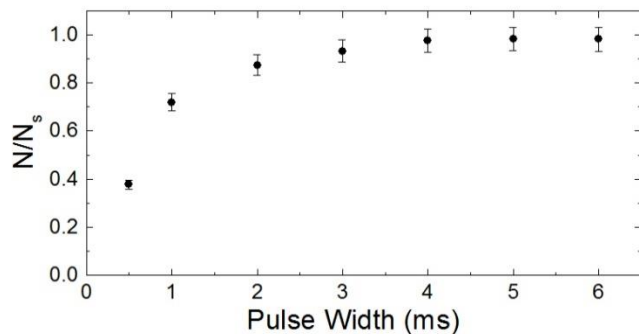
Such a measurement also allows one to determine the maximum number of electrons that can reversibly be stored in the source: It is known that above a critical charge density, which depends on the roughness of the substrate, SSE on the film surface locally break through the film and are then localized on the SiO_2 surface of the substrate [9]. This part of the source electrons is then immobile and does not contribute to the charge that moves to the drain when the gate is opened. However, the immobile electrons still add to the Coulomb energy when the source is charged anew. This implies that the characteristic curve which relates the number of stored (mobile) electrons N_s to the gate voltage is shifted step by step to more negative V_g values, as more and more localized electrons are present. An example is shown in figure 3. For this particular sample, the maximum charge that could safely be stored as mobile electrons was $N_s \sim 2 \times 10^9$, corresponding to an electron density of about 10^{10} cm^{-2} at the channel entrance. In a normal experimental run the electron density was kept well below this critical value to avoid complications due to trapped surface charge.

Figure 3. Number of mobile source electrons, N_s , determined as described in [10], for a sequence of runs where the source was successively charged at higher and higher potential barriers (the gate voltage where the charging of the source took place is indicated in the inset). The blue curve shows the result for the ideal case, when all the electrons collected in the source are mobile. The gradual shift of the data towards more negative gate voltage is due to an increasing number of immobile source electrons.



In the measurements of figure 3, the gate was opened completely for a long time (> 1 s) in order to collect all the mobile electrons present in the source on the pick-up electrode. In the experiments to be described now the gate was also opened completely, but then closed again after a time Δt ranging from nanoseconds to milliseconds. Figure 4 shows the collected number of electrons, N , for pulse widths in the millisecond range, normalized by the total number of electrons in the source. After an initial increase, the charge transported during the opening time of the gate saturates for $\Delta t > 4$ ms, which means that by then all mobile electrons have been removed from the source. This characteristic depletion time is caused by two contributions, namely the transport of the electrons within the source area towards the channel entrance, and the transport of the electrons through the channel. Since we are mainly interested in the latter mechanism, we now concentrate on short opening times $\Delta t < 10 \mu\text{s}$, where only a small fraction of the total charge N_s is removed from the source by each pulse and the redistribution of the electrons in the source area can therefore be neglected.

Figure 4. Normalized number of electrons moving from source to drain, as the gate is opened by positive pulses of various width. The channel in this sample was $100\mu\text{m}$ long.



One of our results – but this time for a sample with a short channel, resembling a point contact - are displayed in figure 5a, and in figure 5b on an expanded scale. In figure 5a the number of transported SSE increases linearly with the gate opening time Δt , which implies that on this time scale the charge per unit time transported through the channel (i.e. the current) is constant.

A closer look at the data on the expanded scale in figure 5b reveals that the straight line, representing the channel current, does not extrapolate through the origin, but rather suggests that a finite opening time Δt_{min} of the channel is required before the first electrons make it from the source to the drain. We identify this minimal time of about 45 ns with half the transit time of the electrons. Due to the shape of the potential barrier, those electrons which have not yet reached the middle of the channel will be pushed back into the source when the barrier is switched on again, while electrons which have travelled beyond the middle will be pushed forward and collected by the pick-up electrode. Based on this model, one can

derive a rough estimate for the electron mobility in the channel from the observed Δt_{\min} and the externally applied potential gradient

$$\mu = v/E = (l/2\Delta t_{\min})/E$$

where l is the channel length and v the velocity of the moving electrons. The resulting value for the mobility, $\mu \sim 2.4 \times 10^4 \text{ cm}^2/\text{Vs}$, is of the same order as the mobility of electrons on bulk ^4He in this temperature range. A more detailed analysis will be the subject of a separate paper.

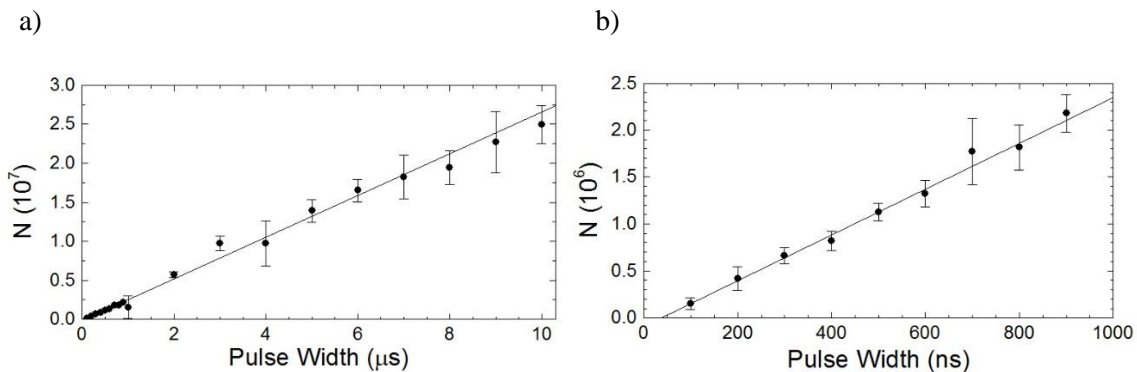


Figure 5. (a) Number of electrons moving from source to drain as the gate is opened for times short compared to the depletion time. The total number of electrons in the source was here $N_s \sim 10^9$. b) Same as in (a) for the regime of ns pulses. The shape of the gate channel was in this case like a point contact (geometrical width $10\mu\text{m}$), therefore the channel length was not well defined, but effectively was comparable to the width. The straight lines are just guides to the eye.

4. Conclusions

The results presented here show that Surface State Electrons in confined geometry are well suited for investigating the transport of correlated electrons in the classical Coulomb regime, which is not directly accessible with electrons in solid state systems. Experiments complementary to those in MOSFETs demonstrate phenomena like the formation of particle lanes and the manipulation of SSE ensembles on the micrometer and nanosecond scale. Of particular interest will be to achieve somewhat higher electron densities, where crossover effects towards the degenerate Fermi gas are expected [9].

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