The Helium Field Effect Transistor (I): Storing Surface State Electrons on Helium Films

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Abstract We present investigations of surface state electrons on liquid helium film in confine geometry, using a suitable substrate structure microfabricated on a silicon wafer, similar to a Field Effect Transistor (FET). The sample has a source and drain region, separated by a gate structure, which consists of two gold electrodes with a narrow gap (channel) through which the transport of the surface state electrons takes place. The sample is illuminated to provide a sufficient number of free carriers in the silicon substrate, such that a well-defined potential distribution is achieved. The eventual goal of these experiments is to study the electron transport through a narrow channel in the various states of the phase diagram of the 2D electron system. In the present work we focus on storing the electrons in the source area of the FET, and investigate the spatial distribution of these electrons. It is shown that under the influence of a potential gradient in the silicon substrate the electrons accumulate in front of the potential barrier of the gate. The electron distribution, governed by Coulomb repulsion and by the substrate potential, is determined experimentally. The result is found to be in good agreement with a parallel-plate capacitor model of the system, developed with the aid of a finite element calculation of the surface potential profile of the device.

Keywords Helium field effect transistor · Surface electron · Helium film · Electron storage

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1 Introduction

Electrons on the surface of liquid helium have been studied quite extensively as an example of a particularly well-defined and clean Coulomb system [1, 2]. In most of the investigations the properties of the quasi-infinite 2-dimensional system of electrons on *bulk* helium have been considered and many prominent effects characteristic of charged systems, like magnetotransport phenomena and Wigner crystallization, have been observed [3, 4]. More recently also electrons in *confined* geometry, e.g. in channels filled with liquid helium due to capillarity, have revealed intriguing effects in the charge transport of these systems [5, 6]. Lately, due to their high mobility and long coherence time, 2D electrons on helium have been discussed as a system for testing concepts of quantum computing [7, 8]. In contrast to the well-known 2D electrons at semiconductor interfaces, electrons on liquid helium in nearly all the measurements carried out so far were not in the high density range of the degenerate Fermi gas, but in the classical fluid or crystal regime, since the charge density is limited to values $n < n_c = 2 \times 10^9 \text{ cm}^{-2}$ on bulk ^4He (and even lower on ^3He) because of an electrohydrodynamic instability [9]. For surfaces in confined geometry the limit in the electron density is somewhat increased due to the stabilizing action of surface tension, but considerably higher densities on the order of 10^{11} cm^{-2} , which are required to reach the degenerate Fermi regime, are only accessible on thin helium *films*. Electrons on helium film thus lend themselves not only for tracing out the regime of the classical Coulomb fluid and its transition to the Wigner crystal, but also the quantum melting of the Wigner crystal towards the degenerate Fermi gas [10].

A benchmark experiment for revealing the nature of electron transport is given by studying the flow of electrons through a one-dimensional channel, the width of which can be controlled independently. For degenerate electron gases in semiconductor heterojunctions, these studies led to the discovery of conductance quantization in quantum point contacts [11–13]. This line of investigation is also of particular interest for electrons on liquid ^4He film in which the various regimes of the 2D phase diagram may be addressed. A crucial information for obtaining a quantitative understanding of the transport is the knowledge of the density and the spatial distribution of the electrons on the surface. In this experiment we use a source-gate-drain configuration similar to a Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) supported by a silicon substrate [14]. In the present paper we focus on the spatial distribution of the electrons, as they are stored in the source area of the He FET, under the influence of a potential gradient in the silicon substrate.

2 Experimental Set-up and Method

The sample used in this work was a rectangular piece of a 0.3 mm thick silicon wafer $22 \times 18 \text{ mm}$ in size (see Fig. 1). The Si was covered by a 500 nm thick oxide layer, and several gold electrodes on top, prepared by photolithography, provided the structures for the FET. The source (S) and drain (D) areas were separated by a split gate (G) with a 10 μm wide and 100 μm long channel, and a guard electrode surrounded the S–G–D structure to confine the surface state electrons (SSE) to the FET area. The Si

Fig. 1 (Color online)

Photograph of the He FET. The size of the sample is 22×18 mm. It is covered by an insulating oxide layer with a thickness of 500 nm. The evaporated gold electrodes are 100 nm thick. The *right hand side* shows a scanning electron microscope image of the gate channel, which is 100 μm long and 10 μm wide

substrate had ohmic contacts at the S and D edge of the wafer. The voltages applied to the various contacts were typically in the range of a few volt.

In operation, the sample was cooled to a temperature of 1.3 K, with the sample surface slightly above the bulk liquid helium level. The FET structure was therefore covered with a thin superfluid He film with a thickness d_{He} depending on the height of the surface above the bulk liquid. In the experiments reported here this height was 2.5 mm, corresponding to a He film thickness $d_{\text{He}} \approx 50$ nm [15].

In order to charge the source S, we used a small filament mounted several mm above the source area, which was heated with short (25 ms) current pulses. Thermionic emission then gave rise to about 10^7 electrons per pulse. They were pulled towards the source and trapped in the image potential well on the film surface, where they redistributed according to the potentials applied to the FET electrodes. Electrons reaching the drain area were collected by a pick-up electrode and registered with a sensitive electrometer.

3 Results and Discussion

3.1 Potential Distribution of the Uncharged FET Structure

Since the Si used here as a substrate was undoped, its resistance diverges rapidly at low temperature, which leads to an ill-defined potential distribution in the presence of surface state electrons. In order to increase the conductivity we illuminated the sample continuously during each experimental run using an external light source, thus generating a sufficient number of electrons and holes in the Si that the resistance between the S and D contact dropped to ≈ 1 M Ω . The electrostatic potential measured under these conditions at four positions between S and D by additional contacts at the back of the Si wafer is shown in Fig. 2. In the whole voltage range up to 10 V the profile is nearly linear and so the electric field is approximately uniform within the Si wafer. This is important for analyzing the SSE distribution in the source, as will be shown further below.

Fig. 2 (Color online) Potential distribution in the Si substrate for different source-drain voltages, as shown in the legend. The data were taken at 1.3 K and with illumination. S (D) denotes the position of the source (drain) electrode

In addition to these pointwise measurements we used a computer simulation to determine the potential energy landscape in the FET structure, including the gate and guard electrodes. We define the electrostatic potential energy on the uncharged helium surface as $\Phi_{\text{sur}}(x, y) = -eV(x, y)$, where e is the magnitude of the electron charge ($-e$ is the electron charge) and $V(x, y)$ is the voltage on the helium surface with respect to ground, at the location x, y . Since we have two separated Coulomb systems here, on the one hand the surface state electrons, on the other hand the charge carriers in the substrate, we also define the electrostatic potential energy within the substrate, Φ_{sub} . The channel is oriented along the x direction ($x = 0$ to $x = 0.1$ mm) and is located around $y = 0$ (from $y = -5$ μm to $y = 5$ μm). As the channel lies approximately midway between the source and drain, the value of Φ_{sub} at the center of the channel can be estimated as $\Phi_{\text{sub}}^0 = -eV_0$ where $V_0 \approx (V_d - V_s)/2$. We define the potential on the helium surface at the center of the channel as Φ_{sur}^0 .

Figure 3a shows a schematic representation of Φ_{sur} across the sample surface. The voltages applied to source and drain are chosen here as $V_s = +1$ V and $V_d = +2$ V, and the guard voltage is $V_{\text{guard}} = -1.5$ V. By applying a negative voltage to the two gate electrodes (with respect to the voltage of the Si substrate at the gate position) a potential barrier is generated between source and drain. In Fig. 3b, which is a schematic plot of $\Phi_{\text{sur}}(x)$ along the center of the sample ($y = 0$), the potential barrier shows up as a sharp spike at the location of the gate channel reaching from $x = 0$ to 0.1 mm. We define the height of the potential barrier as $\Phi_{\text{bar}} = \Phi_{\text{sur}}^0 - \Phi_{\text{sub}}^0 = -ke(V_g - V_0)$, where k is a constant of proportionality. Figure 3c, which shows results of the simulation, gives a blow-up of the potential in the central part of the gate channel for $V_g = -10$ V, $V_0 = 1.5$ V. Figure 3d shows a profil of the potential across the channel for various gate voltages, for $V_0 = 0$ V. Here, because $V_0 = 0$ V, the potential at the center of the channel gives the barrier height directly. As expected, the potential at the center of the channel is distinctly smaller than the potential of the gate itself. The constant k depends on the thickness d_{He} of the helium film as is obvious from Fig. 3e, in which we plot the barrier height for different gate voltages and d_{He} , for $V_0 = 0$ V. For $d_{\text{He}} = 50$ nm—the situation of our measurements—the simulations yield a value of $k = 0.024$.

Fig. 3 (Color online) (a) Schematic of the potential energy landscape $\Phi_{\text{sur}}(x, y)$ on the He film covering the FET structure. Here $V_g = 0$ V, $V_{\text{guard}} = -1.5$ V, $V_s = 1$ V and $V_d = 2$ V. (b) Schematic profile of the potential energy along the center of the sample between the source and drain, for the same bias conditions. The narrow spike at $x = 0$ corresponds to the position of the 1D channel. (c) Potential energy landscape for the gate channel obtained from the simulation for $V_g = -10$ V, $V_0 = 1.5$ V and $d_{\text{He}} = 300$ nm. (d) Potential profile across the channel obtained from the simulation for various values of V_g , as shown in the legend. Here $V_0 = 0$ V and $d_{\text{He}} = 300$ nm. (e) The dependence of barrier height on V_g according to the simulation, at various helium film thicknesses, as shown in the legend. Here $V_0 = 0$ V. The slope of the line gives the coupling constant k , which for $d_{\text{He}} = 50$ nm is $k = 0.024$.

3.2 Charging the Source

We now consider the charging procedure of the source and assume for that purpose that the gate is negatively biased so that it provides a potential barrier, as schematically depicted in Fig. 4. As the filament is activated, the electrons supplied by the

Fig. 4 (Color online) Schematic potential profile along the x -axis of the sample for (a) charging the source and (b) electron ‘spill-over’ when the chemical potential of the electron system is equal to the barrier potential

Fig. 5 (Color online) Procedure for filling the source and determining the number of stored electrons. Here $V_{\text{guard}} = -1.5$ V, $V_s = 1$ V and $V_d = 2$ V. The pick-up current I_p shows the spilling over of electrons when the source is full. At the beginning, the source is empty. Then the following steps are taken: First, the gate is closed by switching V_g from 0 to -2 V. Then the filament is pulsed periodically at a rate of 4 pulses/s, and charging of the source begins. I_p remains zero because of the closed gate. After a filling time of about 10 s an onset of I_p is observed, indicating that the source is filled to its maximum capacity and electrons begin to spill over the barrier (peak nr. 1). The filament is then switched off, and I_p drops back to zero. After a certain waiting time—in this case 8 seconds—the gate is opened and the charges stored in the source area pass the channel and are collected by the pick-up electrode. This gives rise to peak nr. 2 in the pick-up current, which integrated in time represents the number of stored electrons N_s . In the example shown here N_s is 1.5×10^8 .

First charging pulse will move under the influence of the substrate potential towards the entrance of the gate channel, where they are blocked by the gate barrier. As more and more charges are added, the electron pool increases in size and the chemical potential of the electrons rises due to their Coulomb interaction, until eventually it is high enough that electrons start spilling over the barrier, pass through the channel and reach the drain (Fig. 4b). An example for this process is shown in Fig. 5, where the pick-up current I_p is plotted as a function of time.

Fig. 6 (Color online) (a) Pick-up current as a function of time for different gate voltages, as shown in the legend, and $V_{\text{guard}} = -7$ V, $V_s = 10$ V, $V_d = 12$ V. (b) Number of stored electrons, N_s , as a function of gate voltage. The *dashed curve* is a fit to the model described in Sect. 3.4

3.3 Storage Capacity of the Source

We have carried out the procedure described above for different values of V_g , filling in each case the source until spill-over of the electrons took place, and then determined the number of stored electrons N_s . The result is shown in Fig. 6 for $V_{\text{guard}} = -7$ V, $V_s = 10$ V, $V_d = 12$ V and $V_0 = 11$ V. As V_g and hence the potential barrier in the channel is increased, the number of stored electrons also increases, as expected. However, somewhat unexpectedly—at least at first glance—the relation between V_g and N_s is distinctly nonlinear.

In order to make sure that this nonlinear behavior is not an experimental artefact, we have repeated the measurement of the number of stored electrons using a slightly modified method as a consistency check (see Fig. 7). As in the procedure shown in Fig. 5, the source was filled at a certain V_g until electron spill-over was observed. Then, however, the gate was not opened completely in one large, but rather in several small steps, and the charge reaching the pick-up after each step was registered. From the current peaks, the total number of electrons stored in the source for each value of V_g can be determined, with a result similar to Fig. 6. (The values of V_{guard} , V_s and V_d were identical to those in Fig. 6.)

3.4 Model for the Electron Distribution in the Source

The nonlinear storage capacity for surface state electrons, as it is presented in Figs. 6 and 7, can be explained by an inhomogeneous electron density $n(x)$ in the source area. This inhomogeneity, which results from the potential gradient in the Si substrate, is schematically sketched in Fig. 8. Qualitatively, on the basis of Fig. 4, one expects the highest electron density at the entrance of the gate channel. More quantitatively, we consider the system of surface state electrons and the Si substrate as two plates of a parallel capacitor, whose charge density will vary because the potential difference between the two plates depends on the x -coordinate. Whereas the chemical potential of the surface state electron system is constant throughout the charged area,¹ the

¹In the absence of a transport current the charges arrange in such a way that this condition is fulfilled

Fig. 7 (Color online) (a) Pick-up current as a function of time for a stepwise reduction of the gate voltage. (b) Number of stored electrons, N_s , as a function of gate voltage. The dashed curve is a fit to the model described in Sect. 3.4

Fig. 8 (Color online) Schematic distribution of the surface state electrons in the source region when a potential gradient between the S and D contacts exists

potential of the Si substrate varies along the x -direction according to Fig. 2. From this model we expect a linear drop of $n(x)$, from a maximum density $n(0)$ at the channel entrance to $n = 0$ at a certain value of x (here called $x_{\min}$) which depends on the total charge, the potential gradient between source and drain and the height of the potential barrier Φ_{bar} . On the basis of the capacitor model, $n(x)$ is given by

$$n(x) = \frac{\epsilon_0 \epsilon_1 \epsilon_2 V(x)}{(\epsilon_1 d_{\text{He}} + \epsilon_2 d_{\text{S}})e} = \frac{\epsilon_0 \epsilon_1 \epsilon_2 c(x - x_{\min})}{(\epsilon_1 d_{\text{He}} + \epsilon_2 d_{\text{S}})e}. \quad (1)$$

Here ϵ_0 , ϵ_1 , ϵ_2 , d_{S} , d_{He} and c are the vacuum permittivity, relative silicon oxide permittivity (3.9), relative helium permittivity (1.055), silicon oxide thickness (500 nm), helium film thickness (50 nm) and the electric field ($2 \text{ V}/2.2 \text{ cm} = 0.91 \text{ V cm}^{-1}$) within the substrate, respectively. $V(x)$ is the voltage which corresponds to the depth of the potential well in which the electrons are stored. $V(x)$ is zero for $x = x_{\min}$ and reaches a maximum of $-\Phi_{\text{bar}}/e$ at the channel entrance, for the case in which the source is charged until electrons spill over the barrier (i.e. the electrostatic energy of the electrons due to Coulomb repulsion is equal to Φ_{bar} , as in Fig. 4b). The total number of stored electrons is calculated by integrating over the electron distribution in the source:

$$N_s = \int_{x_{\min}}^0 n(x) W(x) dx, \quad (2)$$

where $W(x)$ is the width of the source at the position x . For $-2 \text{ mm} \leq x_{\min} \leq 0 \text{ mm}$, the source area is triangular and $W(x) = bx$ where b is a constant. For our sample geometry $b = 6.5 \text{ mm} / -2 \text{ mm} = -3.25$. For $x < -2 \text{ mm}$, the source is rectangular with width 6.5 mm . For $-2 \text{ mm} \leq x_{\min} \leq 0 \text{ mm}$, using (1) we obtain

$$N_s = \frac{\epsilon_0 \epsilon_1 \epsilon_2 c b}{(\epsilon_1 d_{\text{He}} + \epsilon_2 d_s) e} \int_{x_{\min}}^0 x(x - x_{\min}) dx, \quad (3)$$

and finally

$$N_s = \frac{\epsilon_0 \epsilon_1 \epsilon_2 b c}{6(\epsilon_1 d_{\text{He}} + \epsilon_2 d_s) e} x_{\min}^3. \quad (4)$$

As stated above, $V(x)$ ranges from 0 at $x_{\min}$ to $-\Phi_{\text{bar}}/e$ at the channel entrance, with the voltage gradient c . Therefore, since $x_{\min} = k(V_g - V_0)/c$, we obtain

$$N_s = \frac{\epsilon_0 \epsilon_1 \epsilon_2 b k^3}{6(\epsilon_1 d_{\text{He}} + \epsilon_2 d_s) c^2 e} (V_g - V_0)^3. \quad (5)$$

For $x_{\min} < -2 \text{ mm}$, integration according to (2) yields

$$N_s = A(V_g - V_0)^2 + B(V_g - V_0) + C. \quad (6)$$

Here A , B , and C are constants that depend on b , c and k . For brevity, we do not write the full expressions for A , B and C here. Thus for a source which is filled up to electron ‘spill-over’, the total number of electrons is expected to vary with the gate voltage in a nonlinear way, as given by (5) and (6). We have fitted our data to this model, and the dashed lines in Figs. 6 and 7 show the result. The agreement can be considered as quite satisfactory. The only unknown parameter in these fits is the constant k , which, to avoid confusion with the value calculated using the simulation, we denote as k_{exp} . The value of k_{exp} obtained from these fits is $k_{\text{exp}} = 0.021$ for Fig. 6 and $k_{\text{exp}} = 0.018$ for Fig. 7. These values are in the same range as the value of k obtained from the simulation. Some deviation is to be expected, because of several experimental uncertainties, such as the exact thickness of the helium film and the role of immobile electrons, trapped at irregularities on the substrate, as found in earlier experiments [16]. Offsets in potential due to the difference in the work functions of gold and silicon may also play a role, although we find no evidence of this effect in our measurements. The fits give the value of the gate voltage at which $x_{\min} = -2 \text{ mm}$ as $V_g = 5.3 \text{ V}$. This value marks the boundary between fitting with (5) and (6).

From the results shown in Figs. 6 and 7 one can determine the electron density at the entrance of the gate channel, $n(0)$, using the model outlined above. The results, presented in Fig. 9, show that the maximum values of $n(0)$ reach $8 \times 10^9 \text{ cm}^{-2}$ and $1 \times 10^{10} \text{ cm}^{-2}$ for Figs. 6 and 7 respectively. Note that these densities are distinctly higher than the maximum average densities N_s/A_{source} (where A_{source} is the source area) for Figs. 6 and 7, which are on the order of $4.1 \times 10^9 \text{ cm}^{-2}$ and $4.3 \times 10^9 \text{ cm}^{-2}$.

4 Conclusions

In the experiments presented here we have shown that it is possible to store surface state electrons in the source area of a FET structure up to a density where electron

Fig. 9 (Color online) Electron density $n(0)$ in front of the gate channel as a function of the gate voltage, for the situation that the reservoir S is filled up to electron spill-over at the respective value of V_g . (a) For the data set of Fig. 6; (b) for the data set of Fig. 7. The dashed lines are linear fit to the data

spill-over across the potential barrier of the gate sets in. The storage capacity of the source is found to be a nonlinear function of the gate voltage. This can be ascribed to the inhomogeneous spatial distribution of the electron density, which—due to the potential distribution in the silicon substrate—has a maximum at the entrance of the gate channel and decreases linearly with distance from the gate. The electron density in front of the gate channel can be tuned by the potential gradient in the substrate and the gate voltage, which is important for further transport measurements in this system. The maximum densities investigated here have been kept below 10^{10} cm^{-2} , in order to avoid complications resulting from a breakthrough of charges through the helium film (For higher electron densities a pronounced thinning of the helium film takes place, due to the electrostatic pressure of the SSE [17], which increases the probability for electron breakthrough.) In the density range investigated here, the system of 2D electrons is either in the fluid or in the Wigner crystal phase [18, 19]. Investigations at higher densities, as they are relevant for the degenerate Fermi regime, will be the subject of a separate paper, as well as studies of the electron transport through the channel of the FET structure. However, the results presented here are essential for the interpretation of all the experiments carried out with surface state electrons in FET structures.

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