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Mobile electrons on a helium film supported by capillary action

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Abstract. A thick film of liquid ^{4}He is suspended by the effect of capillary action on an array of small discs. A two-dimensional electron system (2DES) has been realized on this film. Using standard low-frequency impedance measurements it could be established that the electrons remain mobile when passing from the regime of a bulk liquid to a suspended film. Using these techniques allows the investigation of a new class of low-dimensional electron systems.

Free electrons can be trapped at the surface of liquid ^{4}He to form a two-dimensional electron system (2DES). There is however an upper limit, n_c, to the density of the 2DES that the bulk surface can support. This limit is determined by an instability [1], where the electronic pressure leads to a softening of surface waves at wave numbers around the inverse capillary length. In the case of a helium film an additional term appears in the dispersion relation for surface waves as a result of van der Waals forces [2] and effectively decreases the capillary length. The instability shifts to much higher electronic pressures and therefore helium films can support 2DESs of much higher densities.

The 2DES on helium has so far been investigated in a density and temperature region where the Fermi energy is smaller than the thermal energy. It has already become an important system to investigate 2D phenomena [3], in particular Wigner crystallization [4]. Helium films would enable to the study of much higher densities [5], possibly reaching the degenerate region, and allow application of in-plane potentials [6]. A major disadvantage of using films is, however, that the electrons become immobile [7, 8] as a result of localization which may be induced by the roughness of the substrate on the length scale of the film thickness.

A way to partially circumvent this problem is to use a film supported by capillary action. The substrate is now made up of some elevated periodic structure, which provides points of suspension for a thick film, which is not determined by van der Waals forces [7–9]. This thick film is stable because the periodicity of the structure is smaller than the capillary length, and again this acts so as to shift the instability to higher densities. The thickness of the film is controlled by the distance from the top of the substrate to the (lower) bulk helium surface and by the height and the spacing of the elevations on the substrate. At a certain critical distance the suspended film will sag sufficiently to touch the substrate and pinning of electrons is expected [7, 8].

A few experiments which exploit this principle have already been performed [9–11]. These were all carried out at fixed helium level below the substrate, such that variation in the suspension of the thick film with helium level was not studied. When the distance between elevations is very small, as in [11], it is not even practically possible to reach the regime below the critical distance. The substrates used so far have either a poorly defined structure [9] or a one-dimensional periodicity [10, 11]. In [10] no information about the conductance of the system was obtained.

To study the effects of film suspension, a special substrate was prepared with a periodic array of discs on a scale at least an order of magnitude larger than before. This made it possible to follow the conductance of the 2DES from bulk helium down to well below the critical distance. In this paper we shall show experimentally that the 2DES retains its conductance on suspended films, indicating that the electrons are mobile on these films. Furthermore, the conductance drops only slowly when the bulk level passes below the critical distance, and successive runs show an enhanced conductance at the same liquid level.

The sample cell is a cylindrical, parallel plate capacitor situated inside a leak-tight pot immersed in a pumped helium bath. The capacitor consists of a top plate, a vertical guard ring, a substrate, and a bottom plate as shown in figure 1(a). The substrate is an epoxy printed circuit board of 1.5 mm thickness, which has a triangular array of $b = 30$ μm high, $D = 250$ μm diameter copper discs etched on it (see figure 1(c)). The separation, a, between the discs is about 400 μm. The substrate is sandwiched between the guard ring and the bottom plate, which contains an outer annular electrode and an inner circular electrode separated by a ring electrode to reduce stray capacitance. This is the so-called Corbino geometry. Electrons can be deposited onto the helium by pulsed heating of a tungsten filament, which is placed in a small hole in the top plate. Once the electrons enter the sample space, they are pushed towards the helium surface by a vertical electric field supplied by a negative voltage and the top plate (typically -10 V) and form a 2DES. The temperature and density are such that the Fermi energy is three orders of magnitude smaller than the thermal energy and the system is therefore non-degenerate. The 2DES is laterally confined by a negative voltage on the guard ring (typically -15 V). The helium surface will charge up to a point where the electron potential is equal to the top plate voltage and the areal density of the 2DES will saturate. In this case the electron density can be easily calculated from the top plate voltage. The densities used here are well below the critical density $n_c = 2.2 \times 10^{13}$ m^{-2} of the electrohydrodynamic instability mentioned above.

Helium is condensed into the pot via two capillary fill lines. This also allows a subsequent adjustment of the amount of helium in the pot by either pumping or condensing. The height of the helium in the pot can be monitored by a capacitor made up of two long concentric cylinders. The height of the helium is referenced to the position of the top of the substrate.

A measurement of the response of the 2DES is performed by applying an alternating voltage (typically 150 mV$_{RMS}$, 10 kHz) to the inner electrode of the bottom plate and detecting the current induced on the outer, using a lock-in amplifier. The inner and outer electrodes couple capacitively to the 2DES, such that a configuration can be represented by a series C–R–C circuit [12] as shown in figure 1(b). The resistance R represents the finite conductance of the 2DES, which is proportional to the mobility and the density of the electrons, and depends on the size and geometry of the system. If the mobility of the electrons is high (>10 m^2 V^{-1} s^{-1} for the parameters used), resulting in a high conductance of the 2DES, the response will be purely capacitive. A decreasing conductance will give rise to an in-phase component of the detected current. As the conductance decreases further, the capacitive out-of-phase current decreases to zero, whereas the resistive in-phase current goes through a maximum and then vanishes (for mobilities less than 10^{-3} m^2 V^{-1} s^{-1} for

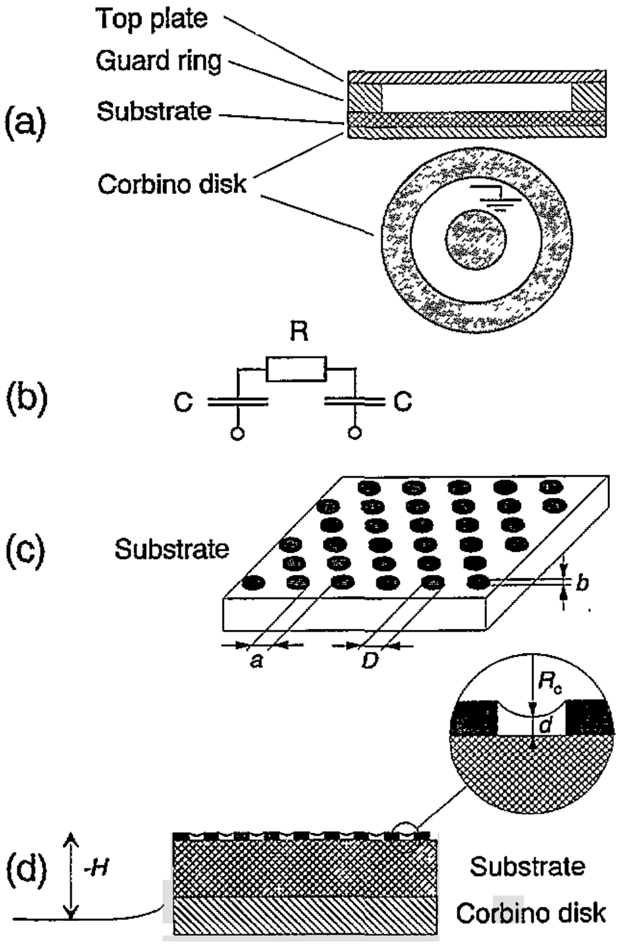

Figure 1. (a) A schematic diagram of the experimental cell. (b) The equivalent circuit of the 2DES ignoring capacitances to the top plate. (c) The structured substrate. (d) The suspended helium film with a lowered bulk liquid level.

the parameters used). It has to be emphasized that the array of discs on the substrate cannot itself give rise to a measurable signal, since the interdisc capacitance is simply too small. Therefore, any signal above the stray signal is caused by the 2DES.

If the liquid helium level is above the substrate, the substrate has little or no effect on the 2DES. As the helium level is dropped a distance H below the substrate, the helium film will be suspended between the discs as shown in figure 1(d). Electrons directly above the copper discs will sit on a thin helium film arising from van der Waals forces (see below). They most probably tunnel through the film at some rough structure of the copper surface [5] and charge up the discs. The electrons between the discs sit on a thick suspended helium film and their mobility should differ little from that on bulk helium [7, 11]. The radius of curvature, R_c, of the suspended film between the discs depends on H, $R_c = 2\alpha/(\rho g H)$, where α and ρ are the surface tension and the density of liquid helium and g is the acceleration due to gravity. The thickness, d, of the suspended helium film halfway between two discs depends on R_c and is therefore controlled by H. At a certain critical distance, $H_c \approx 16b\alpha/(a^2\rho g)$ (valid for $b \ll R_c$), surface tension will not be able to suspend the helium any longer. The film thickness d is then determined by van der Waals forces, $d = (\beta/(\rho g H))^{1/3}$ [13] (β is the van der Waals parameter), and will be of the order of a few tens of nanometres. This is much smaller than the surface roughness of the epoxy substrate. An interdisc separation of $a = 400$ μm gives $H_c = 0.8$ mm.

Charging the surface is usually done with the liquid helium level above the substrate. The helium level is then slowly lowered by pumping on the capillaries. Figure 2 shows the measured in- and out-of-phase current for several runs as the level, H, is lowered. Starting with the substrate submerged ($H > 0$), the out-of-phase current, I_{90}, increases as a function of H, whereas the in-phase current, I_0, remains zero. This is because the 2DES increases the capacitive coupling between the inner Corbino disc and the outer Corbino ring as it approaches the bottom electrodes.

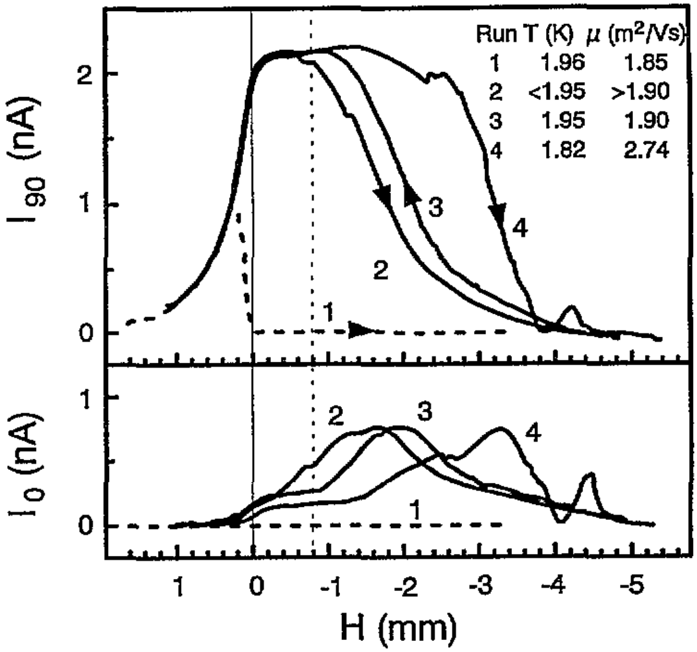

Figure 2. The measured in- and out-of-phase current as a function of distance of the bulk helium level to the top of the substrate for different runs (see inset), areal density $n = 6 \times 10^{11}$ m^2. Mobilities μ correspond to bulk liquid helium and were taken from [12]. The vertical dashed line indicates the value of H_c.

For purposes of reference, a plain piece of epoxy material with all the copper removed was used for run 1. It can be clearly seen that I_{90} quickly vanishes as H goes to zero, whereas I_0 remains zero for all H. Once $H < 0$, both in- and out-of-phase components of the detected current are zero. Therefore, the conductance of the 2DES on a thin film supported by the epoxy substrate is too small to be measured, as expected. The width of the transition from bulk to film behaviour is about 0.2 mm. The reduction in I_{90} occurs gradually as the substrate is gradually uncovered by the bulk liquid due to misalignment. *This is also the reason why I_0 remains zero. The high-conductance region of the 2DES still* on the bulk short-circuits the low-conductance region on the film.

For runs 2, 3, and 4, the substrate with the triangular lattice of copper discs was used. For $H < 0$ a helium film is suspended by the array of discs and the separation between the 2DES and the Corbino electrodes is now determined by the thickness of the substrate

(1.5 mm). Therefore I_{90} saturates initially in all three runs. The in-phase signal slightly increases above the value for $H > 0$, and reaches a plateau. The conductance of the 2DES has decreased due to either a geometry effect or a decreasing conductivity. Because of the complicated geometry of the 2DES no attempt was made to convert the raw data to conductivities.

Run 2 corresponds to lowering of the helium level for the first time after cool-down. As I_{90} decreases from its saturated value below the critical height $H_c = 0.8$ mm, I_0 goes through a maximum corresponding to a steadily reducing conductivity. It has to be pointed out at this stage that there is very little noise on the signal. The fluctuations in the signal strength are therefore caused by changes in the properties of the 2DES, be it conductivity, size, or connectivity.

After having lowered the helium level to $H = -5$ mm, the cell was filled again in run 3. The temperature of runs 2 and 3 is almost the same. The signal recovers at slightly lower helium level than in run 2. I_{90} reaches saturation and remains constant until the helium is lifted from the substrate and the 2DES is supported by bulk helium again.

In run 4 helium was pumped out of the cell at a slightly lower temperature such that H changed more slowly with time. In this run I_{90} stays at saturation value for even longer than in the two previous runs, although the plateau shows a certain amount of structure. This behaviour can also be seen in I_0, which displays two plateau regions before it goes through a maximum. The signal begins to decrease at about $H = -3$ mm and falls to zero over a smaller interval of H than in runs 2 and 3. It is interesting that after the initial disappearance of I_0 and I_{90} at $H = -4$ mm, both components increase again to go through maxima. A behaviour like this was observed for electrons on thin helium films [14]. It results from two competing trapping mechanisms for electrons, one being trapping by the substrate potential, the other trapping by helium film curvature. At a certain film thickness both of these mechanisms have the same energy, which allows electrons to move without being scattered by a random potential. If this is the reason for the maxima in run 4, it would give a typical length scale of 1 μm for the surface roughness, which is reasonable.

The 2DES remains conducting at increasingly lower helium levels as the number of runs is increased. This behaviour could be related to the effect of electrons tunnelling through the helium film at a low helium level to charge up the substrate [5] and the copper discs. Run 2, being the first run after cool-down with the structured substrate, would not suffer from trapped charge on the substrate or discs, whereas for the successive runs it should have an increasing effect. The trapping of charge also results in a decreasing density of the 2DES, which leads to a decreasing electronic pressure on the film. This would cause the film thickness to increase at a given helium level, leading to a higher electron mobility.

It is also quite surprising that the 2DES remains conducting at all for helium levels below H_c, since the electrons should sit on a van der Waals film where they are immobile, as can be seen from run 1. The geometry of the array of discs leaves also no possibility for percolating paths to exist. Neither can misalignment be the cause of nonzero conductance, since in run 1 it is shown to be of the order of 0.2 mm. Furthermore, the saturated magnitude of I_{90} indicates that the whole of the 2DES is conducting and not only a small part of it. For all these reasons it seems likely that the 2DES is supported by a film which is thicker than a van der Waals film at helium levels below H_c.

An effect that could generate an increased film thickness between the discs is the thermomechanical or fountain effect [13]. Here a flow of helium is induced by a temperature difference, the superfluid helium flowing to the point of higher temperature. The temperature differences required to increase the thickness of the helium film thermomechanically are very small indeed (of the order of a few microkelvin). It could well be that enough power from the excitation signal on the central Corbino electrode is dissipated either in the copper discs or in the 2DES itself to cause such an effect. The presence of the array of discs is however essential for obtaining mobile electrons, as can be seen from run 1. This means either that the power is dissipated within the discs, or that the reduced length scale that the array imposes onto the system is of importance.

The 2DES supported by the suspended helium film forms a multiply connected sheet with a periodic array of holes mirroring the array discs. This is a so-called antidot structure which has recently attracted theoretical and experimental interest in semiconductor structures [15, 16]. In the presence of a magnetic field the antidot structure gives rise to strong effects when either the wavelength of magnetoplasmons or the magnetic length is equal to the disc diameter. The present geometry will give access to such new physical phenomena. An increase in density is not expected with the dimensions used here but comes into reach with a downscaling of only one or two orders of magnitude, which is still technologically easy.

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