Imaging of a Suspended Helium Film with 2-D Electrons by Interferometry

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A helium film suspended between elevations on a substrate forms an excellent surface for a two-dimensional electron gas. With the structure on the substrate a quasi one-dimensional electron system can be created. Experiments probing the electrical transport properties of this system have raised questions about the suspended helium film itself. We report measurements of the suspended film using interferometry. The profile is mapped out as a function of the bulk helium level beneath the substrate. By measuring the electron signal simultaneously the relation between the signal and the film profile can be obtained.

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1. INTRODUCTION

In the past few decades electrons floating above the surface of liquid helium have proven to be an ideal model system for two-dimensional electron systems (2DES).¹ So far most of the work was focused on quasi-infinite systems on bulk helium, or, when high electron densities were necessary that could not be obtained on bulk helium due to an electro-hydrodynamical instability, on thin helium films.

To reduce the size and go to one- and zero-dimensional electron systems, as have been realized in semiconductors,² is not possible with the bulk liquid surface, because the distance between confining electrodes and the electron sheet is too large. The confinement length is of the same order as the bulk helium height, which is typically 1 mm. In principle smaller sizes can be

realized using thin helium films, since there the thickness of the film is about 30 nm. It is however not easy to have mobile electrons on a film due to surface roughness of the substrate. A solution to this problem is to make use of suspended helium films.^{3,4} Due to the capillary force the region between elevations on a substrate will fill with liquid if the distance is smaller than the capillary length. In this way a surface with arbitrary dimensions and shape can be formed, which can also contain higher electron densities than the bulk liquid.

Quasi one-dimensional multi channel systems have been created using both dielectric optical gratings^{5,6} and a microfabricated metallic structure.⁷ A single channel of electrons was made using a bent foil⁸ and a metallic structure from printed circuit board.⁹ In the latter case the ribs on which the film was suspended were also used as measuring electrodes. The measurements raised some questions which could be related to the profile of the suspended film itself. Therefore it would be of interest to have independent information about the profile of this film.

We present measurements of the suspended helium film using interferometry to map out its profile as a function of the bulk helium level beneath the substrate, which is the usual parameter for the thickness of the film in the transport measurements. By measuring the electron signal simultaneously the relation between the signal and the film profile can be obtained.

2. EXPERIMENT

Two Ni ribs on a 0.5 mm thick glass plate connected at both ends are used to suspend the helium film. The separation between the ribs is 300 μm . They have a height of 25 μm and total length of 12 mm. Each rib consists of three segments, which serve as measuring electrodes, analogous to a Sommer-Tanner arrangement¹⁰ (see Fig. 1d). The electrodes are at DC ground. An AC excitation voltage of 150 mV and 10 kHz is applied to electrode 1 and the current induced on electrode 3 is measured. Below the structure at an electrical distance d_s/ϵ_s ($\epsilon_s \equiv$ permittivity of glass) of ~ 0.1 mm a bottom electrode and guard-ring are mounted, both at a DC voltage. The bottom electrode potential determines the holding field and electron density n in the channel. The helium surface is charged with electrons by pulse heating of a filament. At 2 mm above the structure is a top-plate, which provides the confining field together with the guard-ring and bottom electrode. It consists of a 200 Å Ag-layer on a glass plate. The top-plate also serves as one of the mirrors for the interferometer. Next to the cell is a cylindrical capacitor to determine the bulk helium level below the substrate H .

The experimental setup for the interferometry measurement is shown in

Fig. 1. a) Setup for interferometry; b) Experimental cell with top plate (1), glass plate with Ni Sommer-Tanner structure (2), bottom electrode and guard ring (3) and cylindrical capacitor (4); c) Typical picture as taken from the videotape with thick film in the channel; d) Sommer-Tanner structure, the dashed square indicates the part of the structure taken on the video.

Fig. 1a. Light from a HeNe laser is coupled into an optical fiber, that goes into the cryostat. The end of the fiber is positioned in the focal point of a biconvex lens, so that a parallel beam goes to the cell. The first mirror for the interferometer is formed by the substrate, which has a reflective coating on it. The top-plate (second mirror, $R \approx 0.9$) is slightly tilted with respect to the substrate which causes straight line fringes. A helium film on the substrate will result in a shift of the fringe due to change in the optical path length. A shift of one complete fringe is equal to a helium film thickness of $12.5 \mu\text{m}$. The reflected beam is focused on a CCD-camera on top of the cryostat, which is connected to a video recorder. The resolution of the interferometer is $4 \mu\text{m}$ for the lateral direction and $0.6 \mu\text{m}$ for the film thickness.

3. RESULTS

A typical picture as recorded on the video is shown in Fig. 1c. The Ni structure reflects diffuse due to its roughness. Therefore the structure can be recognized on the picture as the area without interference fringes. The area

Fig. 2. a) Helium film profile in channel at $t = 0$ ($\bullet$), 8 ($\diamond$) and 18 ($\square$) minutes; b) Electron signal ($\diamond$ amplitude, $\square$ phase) and helium level decrease ($\bullet$ from level meter, $\circ$ from curve fit) as a function of time.

of the substrate that is on the picture is indicated in Fig 1d. Since the line of tilt of the top plate is not exactly parallel to the structure, the fringes are not normal to the structure but form with it an angle of $\approx 60^\circ$. The fringes shift also with respect to this angle, therefore the interference pattern of the suspended film appears to be asymmetric. The thickness of the thin van der Waals film outside the channel changes very little as a function of H , so the fringes outside the channel can be used as a reference.

Fig. 2 shows the results of a measurement where H was lowered by pumping out the vapour in the cell. The surface was charged just before the start of the measurement. The film profile across the channel is plotted at $t = 0, 8$ and 18 minutes. The radius of curvature of the film depends on H according to $R_c = \alpha/\rho g H$ (α and ρ are the surface tension and density of the liquid, g is the acceleration due to gravity), which follows from equilibrium of the chemical potential between the bulk liquid and the film. The lines in the graph are curve fits using above formula with H as fitting parameter. The data agree well with the curve fits except for the last one ($t = 18 \text{ min}$) where the film appears to be thinner in the center of the channel than the curve fit predicts. This is not caused by the electron pressure, since comparison with the profile of the film without electrons did not show a difference. It could be that the film profile starts to deviate from the theoretical prediction, which is only valid for $R_c \gg w$. More measurements are needed, however, to draw more definite conclusions. The change in H from the start of the measurement, ΔH , as calculated from the curve fit is compared with the measured ΔH from the level meter in Fig. 2b. Both ways of determining ΔH show the same trend, but the absolute values of ΔH from the level

Fig. 3. a) Helium film profile in channel at $t = 0$ ($\circ$) and 59 ($\square$) minutes; b) Amplitude ($\square$) and phase ($\diamond$) as a function of time (decreasing bulk helium level).

meter are larger. This could be due to the experimental error in the level meter, which gives an accuracy for the film thickness in the channel of $3 \mu\text{m}$.

The electron signal is also plotted in Fig. 2. The amplitude decreases when the film thickness is reduced and the phase increases. From the transmission line model¹¹ this can be understood by a decrease in the conductivity. Loss of electrons can be ruled out, since recondensing in helium gives full recovery of the signal. Due to the reducing film thickness the electron sheet approaches the bottom electrode, which leads to a stronger holding field. This could cause a lower mobility and thus also lower conductivity.

Fig. 3 shows again a measurement of the film profile and the electron signal during pump-out taken from a different run, now starting at a bulk helium level where the film touches the bottom. As seen in Fig. 3a, a strip of about $150 \mu\text{m}$ width is covered only with a thin film and this region increases during the measurement. The phase shift goes in the opposite direction as in Fig. 2, whereas the amplitude after a short increase decreases again. The surface was charged just before the start of the measurement, and the increase in amplitude is probably due to electrons coming to the surface from other places in the cell. The decreasing phase shift together with decreasing amplitude is an indication for a decreasing capacitive coupling between electrodes and electron sheet. This can be understood from the film profile if we assume that electrons in the thin film region are pinned at surface roughnesses and therefore do not contribute to the capacitive coupling. The increasing thin film region leaves a decreasing width of the conducting electron sheet and therefore a smaller capacitive coupling.

Combining the two measurements shown here, it is obvious that with decreasing helium bulk level and film thickness there is a crossover in the signal reduction. It goes from a reduction due to a change in conductivity towards a reduction due to a decrease in capacitive coupling. This crossover is actually observed in other measurements not shown here. It occurs always with a thin film region in the channel, and is dependent on the applied bottom plate potential and electron density.

4. CONCLUSIONS

We have shown that it is possible to measure the suspended helium film profile and the transport properties of a 2DES floating above it simultaneously. The relation between the helium film profile and a change in conductivity or capacitive coupling was obtained. This method can be an important tool for understanding the transport properties of electrons on a suspended film and for studying the influence of the electrons on the suspended film itself. Further experiments are in progress.

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