Stabilization of a charged liquid-helium surface

A. P. Volodin and V. S. Édel'man
Institute of Physical Problems, Academy of Sciences of the USSR

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A method is proposed for raising the critical density of electrons suspended above a liquid-helium surface. The idea is to use a fine-structure dielectric substrate wetted with superfluid helium. Experimentally, an electron charge density $\sim 8\times 10^9$ cm^{-2} has been achieved. This charge density is ~ 3.5 times the critical density of electrons suspended above a free helium surface.

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Experimental study of the electrons suspended above liquid helium (or above some other cryogenic dielectric) is limited by the circumstance that the charged liquid surface loses its stability at a very modest critical electron density $n_{cr} \approx 2\times 10^9$ cm^{-2} and at a "compressional" electric field $E_{\perp cr} \approx 2$ kV/cm (Ref. 1). In the hydrodynamic

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approximation, at the maximum electron density n, corresponding to complete screening of the field above the charged surface, the stability condition is[2]

$$\left(\frac{3\alpha}{\rho h^4}+g\right)q+\frac{\sigma}{\rho}q^3-\frac{4\pi e^2 n^2}{\rho}q^2\frac{1+\epsilon-(1-\epsilon)\exp(-2qh)}{1+\epsilon+(1-\epsilon)\exp(-2qh)}>0, \qquad (1)$$

where α is the van der Waals constant (a measure of the force exerted by the substrate on the helium), h is the thickness of the helium layer above the dielectric substrate with dielectric function ϵ, q is the wave number for oscillations of the helium surface, and ρ and σ are, respectively, the density and surface tension of liquid helium. According to (1), the critical density can be raised by one or two orders of magnitude if the electrons are suspended above a van der Waals film[1-3] In this arrangement, however, the electrons are acted upon by not only the external compressional field but also the image force from the substrate, which creates an effective electrostatic field

$$E_{\text{eff}}\approx\frac{(\epsilon-1)e}{4(\epsilon+1)h^2}, \qquad (2)$$

which is $E_{\text{eff}}\approx 10$ kV/cm at the typical values $h\approx 10^{-6}$ cm. It is difficult to control the film thickness, and for real surfaces there may be significant local variations in the thickness. It is therefore difficult to obtain unambiguous, reproducible results in a study of electrons above liquid films.

A high critical charge density can be achieved, and the effect of the substrate can be avoided at the same time, by (for example) using a substrate surface of the "diffraction-grating" type as in Fig. 1. In the equilibrium state of the uncharged liquid surface, the protuberances are covered by a van der Waals film with a typical thickness $\sim 10^{-6}$ cm. The surface sags slightly in the regions between these protuberances. The radius of curvature in such a region is $R\approx\sigma/\rho gL$, and the magnitude of the sag is $\sim d^2/8R$. With $d\approx 10^{-4}$ cm, and $L\approx 0.1$ cm, the sag is $\sim 10^{-7}$ cm: i.e., the surface of the liquid on the substrate can quite accurately be assumed flat. The effect of the substrate image force on the electrons in the region of a "deep" layer, at external fields $\gtrsim 1$ kV/cm, can be seen from (2) to be negligibly weak even at $h'\gtrsim 10^{-5}$ cm.

With increasing charge density on the surface, the stability of the surface may be disrupted in two ways. First, there may be an instability with respect to long-wave oscillations with $qd\gg 1$. In this case the stability condition is the same as for a homo-

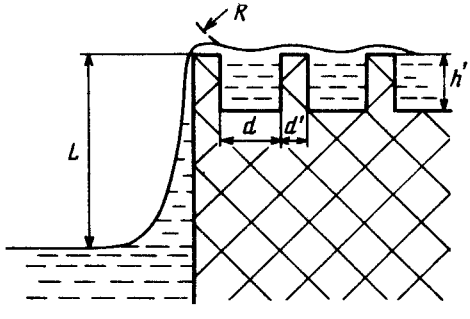

FIG. 1.

geneous film (1), except that the corresponding constant α, which determines the van der Waals interaction, must be reduced by a factor $\sim d'/(d + d')$. Under otherwise equal conditions, in particular, at the same values of L, this circumstance leads to a change in n_{cr} proportional to $[d'/(d + d')]^{-1/6}$. Upon an instability in this case, charge will be lost only in those regions which lie above protuberances, and the protuberances themselves become charged. By raising the external field above the critical value one can recharge the liquid surface to $\sim n_{cr}$ in the region of the protuberances; this approach evidently corresponds to doubling the charge density in the regions between protuberances. This procedure can be repeated.

The liquid surface in the regions between protuberances may lose charge only if there is a loss of stability with respect to short-wave oscillations with $q \gtrsim \pi/d$. From (1) with $h' \gtrsim d$ we find for this case

$$n_{cr} = \frac{1}{2e}\sqrt{\sigma/\pi d}\,. \tag{3}$$

At the present state of the art, $d \approx d' \approx 10^{-4}$–$10^{-5}$ cm, the critical density is thus raised by a factor $\sim 10^2$ with respect to n_{cr} for bulk helium.

The increase in the critical electron density in the case of a dielectric substrate with a fine-cell structure was tested experimentally in the apparatus shown schematically in Fig. 2. The substrate, 1, made of a porous glass filter sintered from grains ~ 30–40 μm in size, was a square plate 3.5 mm thick. The substrate was placed in a measuring capacitor. The lower electrode of this capacitor, 2, lay directly below the substrate. The upper electrode, 3, consisted of two coplanar plates separated by a gap of 0.05 cm, which were connected to an oscillator circuit with a resonant frequency

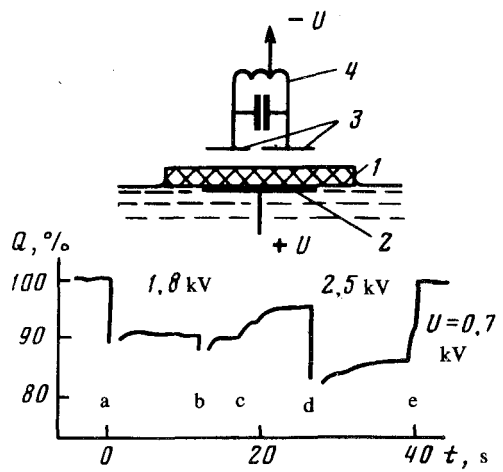

FIG. 2. Top: the experimental arrangement. Bottom: time evolution of the circuit Q. The electron emitter is turned on at a. The voltage U at this point is 1.8 kV. At time b the emitter is turned on again. In the interval c–d, the voltage U is gradually raised to 2.5 kV. At time d, the emitter is turned on, and at time e the voltage U is removed. The line segment at the right shows the calibration signal in the case in which the charge was deposited on a free surface of liquid helium at $U = 0.7$ kV, just slightly lower than the voltage at which the instability was observed during the charging.

~ 5 MHz. In the course of the experiments we measured the changes in the quality factor of the circuit, Q, caused by the loss inserted in the circuit by the surface electrons. The superfluid helium surface, parallel to the capacitor plates, could be positioned in any cross section between the capacitor electrodes through the use of a thermomechanical effect. A voltage U was applied to the capacitor plates to produce the compressional field $E_\perp$.

The diagram in Fig. 2, showing the time evolution of the circuit Q, demonstrates the events that occurred during the experiment. At time a the helium surface above the porous substrate was charged at $U = 1.8$ kV. A repeated brief operation of an emitter (b) at a constant U caused no change in the Q, showing that there was a complete screening of the field between the upper capacitor plate and the liquid surface by the electrons. In the interval c–d the voltage was raised to $U = 2.5$ kV, and the emitter was not turned on. The slight increase in Q here was apparently caused by a decrease in the electron mobility due to $E_\perp$ (Ref. 4). When the emitter was turned on (d), there was a further increase in the density n without an instability of the charged liquid surface.

In some other experiments the charge density was determined, because the charge was deposited on a free helium surface above a porous substrate, and only after the deposition was the helium level lowered below the upper plane of the substrate. Comparison of the results of these experiments with those of the other experiments leads to an estimated density $n \gtrsim 5 \times 10^9$ cm^{-2} at $U = 2.5$ kV. This value is on the low side, since it ignores the decrease in the mobility as a result of increasing the compressional field. If we assume that the static field is screened above the electron layer, we find $n \approx 8 \times 10^9$ cm^{-2}, which is ~ 3.5 times the critical density for the free surface of liquid helium. This is not, we might note, the maximum value possible. We were not able to observe an instability, since a further increase in the voltage resulted in the ignition of a cold discharge.

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