Stability of Charged ^{4}He Films

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We have investigated the stability of electrons above saturated films of superfluid ^{4}He on both insulating and conducting substrates. Electron densities of up to 10^{11} cm^{-2} have been observed to be stable, nearly 2 orders of magnitude more than on bulk ^{4}He. Charging the films to such high densities leads to a drastic reduction in film thickness.

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Electrons on liquid helium have proven to be a quite suitable candidate for studying two-dimensional (2D) behavior: They form a particularly clean system characterized by simple forces, their interaction with the substrate is small, and their density—at least below a limit of $n_c = 2.4\times 10^9$ cm^{-2}—can readily be varied.[1] A number of intriguing phenomena have been observed in this system, the most spectacular probably being the transition to a 2D electron solid.[2] In the experiments performed to date these electrons behave like a *classical* Coulomb system, because for $n < 2.4\times 10^9$ cm^{-2} the Fermi energy is much smaller than the Coulomb energy.

It would be most interesting to move towards higher electron densities, where first quantum corrections in the phase transition to the Wigner solid are expected to appear, and at still larger n, when the Fermi energy dominates, melting of the Wigner lattice into a degenerate Fermi gas should occur.[3] Unfortunately, on bulk liquid helium this regime is not accessible, because an electrohydrodynamic instability of the charged surface develops at the critical density n_c.[4-6] In order to circumvent this restriction it has been suggested to use a thin helium film as a substrate rather than bulk liquid, because a film is additionally stabilized by van der Waals forces,[1] as is seen from the dispersion relation for ripplons coupled to the 2D electron layer[7,8]:

$$\omega^2 = \frac{\rho_s}{\rho}\left[\left(\frac{3\alpha}{\rho d^4} + g\right)k + \frac{\sigma}{\rho}k^3 - \frac{4\pi n^2 e^2}{\rho}k^2 F(k,\epsilon)\right]\tanh(kd). \qquad (1)$$

The various terms originate from the van der Waals coupling α, the acceleration due to gravity g, the surface tension σ, and the charge density ne. (Here ω and k are the angular frequency and wave vector of the ripplon, ρ is the helium density, ρ_s/ρ is the superfluid fraction, d is the film thickness, and it is assumed that the film is charged to saturation so that the electric field above the film vanishes.) The function F takes into account the effect of image charges in the solid substrate; for dielectric materials it is approximately equal to the dielectric constant ϵ, whereas for metals $F = \coth(kd)$. According to Eq. (1) charging a film reduces the ripplon frequency just as it does for bulk liquid ($d = \infty$), but the critical charge density where ω becomes imaginary is increased for a film. For a thickness of 300 Å—a typical value for a saturated film at a height $H = 1$ cm above the bath level—it is expected that an electron density $n_c = 3\times 10^{10}$ cm^{-2} can be reached, about 10 times more than on bulk helium. In fact, densities of that order of magnitude have been observed on such substrates as glass, copper,[9] and solid neon.[10] However, quantitative investigations of the stability of charged films, in particular as a function of the film thickness d, have not yet been reported.

In our experiment[11] we have determined the two relevant quantities entering the problem, the electron density and the film thickness, by capacitor measurements and ellipsometry,[12] as sketched in Fig. 1. A small glow discharge served as the source for the electrons. The bottom capacitor plate of the sample cell was covered with the respective material forming the substrate for the helium film. The top plate had a central part which was vibrated vertically so that a pickup signal proportional to the electric field E_u above the electron layer was induced.[13] From E_u and the knowledge of the applied voltage U the difference between the lower and the upper field, $E_l - E_u$, and hence the electron density $n = (E_l - E_u)/4\pi e$, could be calculated. A decision whether at a certain density all the electrons were located above the film, or whether some amount had penetrated the helium, was obtained by reducing U to zero or a somewhat negative bias. The electrons on the film, which are only weakly bound, then leave the film surface, whereas those charges which have punched the film are localized on the

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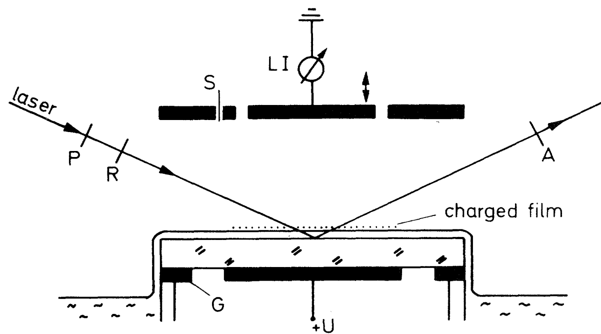

FIG. 1. Schematic of the experimental setup: S, electron source; G, guard ring; LI, lock-in amplifier. Ellipsometer components: P, polarizer; R, retardation plate; A, analyzer. The spacing between the capacitor plates is 1 cm.

solid substrate and cannot be removed by small negative fields.

Two examples for electron densities determined by this method are shown in Fig. 2. Here the substrate was a 10-μm-thick polymer foil (Hostaphan) covered with a saturated helium film at 1.6 K. As the film was slowly charged by increase of the applied voltage with the electron source switched on, the electron density followed the dashed line (I). Then the source was turned off and the voltage reduced to probe the mobile part of the electrons (II). In Fig. 2(a), where the film was charged with 0.9×10^{11} e/cm^2, n dropped sharply after an initial delay, with a density of 0.25×10^{11} cm^{-2} remaining at $U=0$.[14] This latter value could be further reduced continuously by the application of a negative voltage, until at $U=-250$ V all the charges had disappeared. This indicates that in Fig. 2(a) the stability limit had not been exceeded. Conversely, in Fig. 2(b), where n had been increased to 1.4×10^{11} cm^{-2}, only a fraction of 0.95×10^{11} cm^{-2} could be removed, whereas the rest of 0.45×10^{11} cm^{-2} was localized and could be eliminated only by neutralization of the foil with positive ions from the glow discharge. Thus we conclude that on Hostaphan covered with a saturated helium film, densities up to 0.95×10^{11} cm^{-2} are stable; values of the same order of magnitude were found also for other insulators like Kapton and glass; an influence of temperature was not observed in the investigated range $1.3\leq T\leq1.9$ K.

At first glance our results are at variance with the stability limit derived from Eq. (1): Not only did the instability threshold appear to be independent of the thickness d_0 of the saturated helium films in the investigated range, 200 Å $< d_0 <$ 600 Å, but

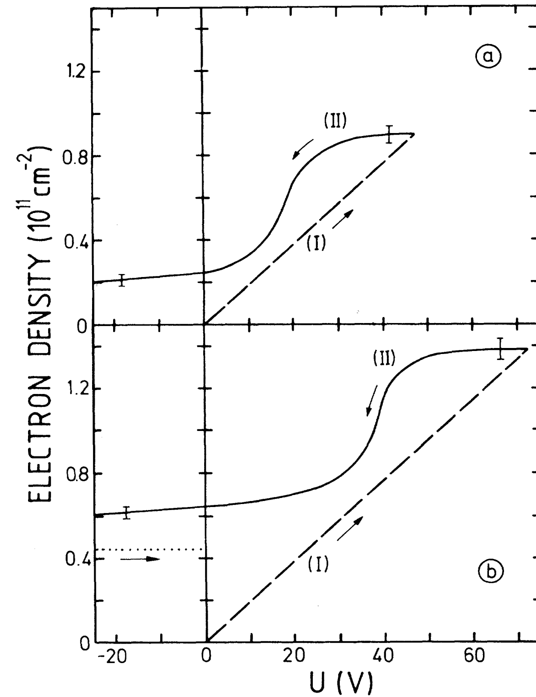

FIG. 2. Electron density n vs the voltage U applied to the bottom capacitor plate. The substrate for the saturated He film ($H=1$ cm) was a 10-μm-thick Hostaphan foil ($\epsilon=3.4$). (I), charging, electron source on; (II), discharging, electron source off. The dotted line in (b) indicates the amount of charge localized on the solid substrate.

also the experimental absolute value of the maximum charge density was distinctly larger than anticipated for these films. This apparent discrepancy is resolved when the electronic pressure p_{el} exerted on the film is taken into account. Since p_{el} adds to the gravitational and van der Waals terms in the chemical potential, the equilibrium thickness of a charged film will be reduced to[11,15]

$$d=d_0(1+2\pi n^2e^2/\rho gH)^{-1/3}. \qquad (2)$$

Here $d_0=(\alpha/\rho gH)^{1/3}$ is the thickness of the film before charging. The value of d given by Eq. (2) is an average, around which the local film thickness is expected to vary because of the formation of a dimple underneath each electron.[15-18] As a result of the reduction of d, the instability threshold, calculated from Eq. (1), is raised, the film thus stabilizes itself, and a higher charge density can be obtained.

The change in film thickness on charging was confirmed experimentally by an ellipsometric determination of d, as plotted in Fig. 3 for two values of d_0. The agreement between the data and the solid lines representing Eq. (2) apears to be quite satis-

study.

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