Electron Mobility on Thin He Films

M. A. Paalanen and Y. Iye[a]
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 3 July 1985)

We have investigated the electron mobility on the surface of H_2 crystals coated with a thin He film. The mobility is found to be smaller than on the bare H_2 or on the bulk He surfaces. The extra electron scattering is due to the He gas atoms, the ripplons, and the density fluctuations in the uppermost He monolayer. The scattering from the density fluctuations is a direct measure of K_2, the two-dimensional compressibility of the He monolayer.

PACS numbers: 67.70. + n, 05.30.Fk, 73.25. + i

The two-dimensional electron gas on the liquid He surface is stable up to a density of $n_c \simeq 2\times 10^9/\mathrm{cm}^2$, where a hydrodynamic instability takes place. In the low-density regime $n < n_c$ the electrons behave like a classical Coulomb gas, the Fermi energy E_F is less than the Coulomb energy E_C, and the Wigner crystallization is observed at the density predicted by a classical theory.[1] At higher electron densities quantum corrections are expected to appear in the phase transition to the Wigner solid and at still higher n, when the Fermi energy E_F dominates, the Wigner lattice should melt into a degenerate Fermi gas.[2]

Recently two techniques to enter the high-density regime have been tested. In order to suppress the hydrodynamic instability Kajita and Sasaki[3] studied electrons on solid neon and Etz *et al.*,[4] following the suggestion of Ikezi and Platzman,[5] studied electrons on thin He films. In both cases high electron densities close to $10^{11}/\mathrm{cm}^2$ were reported, but the electron mobility was found to be fairly low. For low mobilities, $\hbar/\tau \gtrsim E_\mathrm{F}$, the Fermi level is considerably smeared and the simple picture of quantum melting is seriously disturbed. In addition, the low electron mobility on thin He films might be partly due to the polaronic enhancement of the electron mass[6,7] which would make $E_\mathrm{F} < E_\mathrm{C}$ and prohibit the observation of the quantum melting. In order to understand the different electron scattering mechanisms, we have studied the electron mobility in the low-density regime $n < 4\times 10^8/\mathrm{cm}^2$ on a bare H_2 surface[8,9] and on H_2 coated with a thin He film.

The experimental setup is shown schematically in the inset of Fig. 1. A 0.5-mm-thick sapphire substrate was placed on the bottom plate of a parallel capacitor. The H_2 crystal, typically 0.1–1 mm thick, was grown on the substrate above the triple-point temperature of 13.8 K.[8,9] The crystal was cooled down to 4.2 K over a period of 5 h. Helium gas was introduced into the cell and, consequently, a He film was formed on the H_2 surface. The charging of the surface was performed at a temperature of about 13 K by use of a tungsten filament, which was turned on briefly while the appropriate dc biases were applied to the electrodes.

The principle of the mobility measurement was essentially the same as the one used by Sommer and Tanner.[10] The bottom capacitance plate consisted of two electrodes separated by a thin metal strip kept at the ac ground to minimize the crosstalk. The complex admittance between the two electrodes was measured by a capacitance bridge operated at a frequency of 21 kHz. One can calculate the conductance of the electron sheet from the real and imaginary parts of the admittance[11] and the electron mobility from the conductance, if the electron density n is known. One can also determine the electron mobility directly from the magnetoconductance without knowing n or the geometrical shape of the electrodes. In a perpendicular magnetic field, B, the classical conductivity is

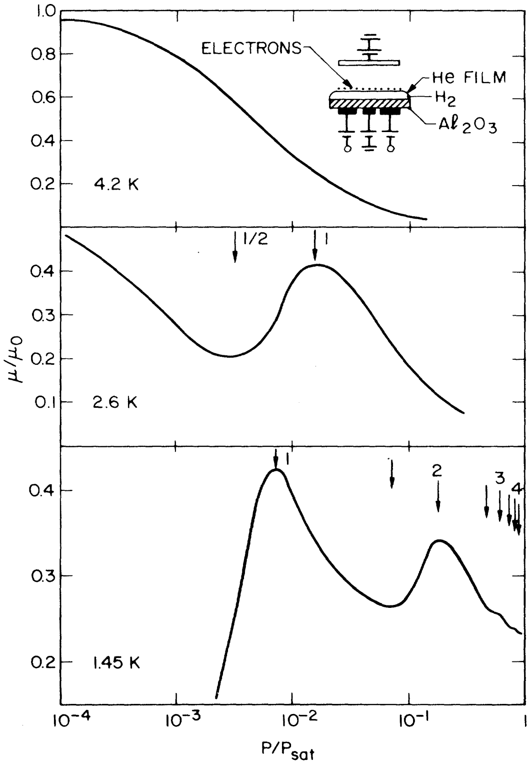

FIG. 1. Normalized electron mobility for unsaturated He films as a function of He pressure. The results at different temperatures, from bottom to top, are from the 19th, 25th, and 26th H_2 crystals with $\mu_0 = 4.0$, 2.3, and 1.7 $\mathrm{m}^2/\mathrm{V}\cdot\mathrm{s}$, respectively.

$\sigma_{xx}(B)=\sigma_0/[1+(\mu B)^2]$, where $\sigma_0=ne\mu=ne^2\tau/m_{\rm el}$ is the zero-field conductivity.

The electron mobility is shown in Fig. 1 as a function of He pressure at three different temperatures. The increase in the He pressure affects the mobility in two obvious ways: The electrons are scattered from both the He atoms in the gas phase and from the excitations of the unsaturated He film formed on the H_2 surface. The electron scattering from gas atoms dominates at 4.2 K. However, at lower temperatures the value of the saturated vapor pressure drops drastically and the electron interaction with the He film dominates in the data at 2.6 and 1.45 K. At these temperatures we also notice oscillations in the mobility as a function of the pressure. These oscillations become larger toward lower temperatures, and at our lowest temperature of 1.45 K we can resolve up to four mobility maxima. We suggest that these oscillations reflect the atomic layer structure of the film, and that mobility maxima (minima) occur whenever the uppermost monolayer is completely (half) filled.

The thickness of an unsaturated film can be calculated from the gas pressure by use of the van der Waals (vdW) equation $d^3=\alpha/T\ln(p/p_{\rm sat})$, where α is the van der Waals constant. In Fig. 2 we have plotted the maxima and minima data of Fig. 1 in a form suggested by the vdW formula. The data can be fitted fairly well by a straight line through the origin, giving a value of 20 ± 7 K (layer)^3 for α. A theoretical estimate of the binding potential of the closest monolayers gives a smaller value of $\alpha\simeq13$ K (layer)^3.[12] However, the vdW equation is only valid in $d\to\infty$ limit and for thin films the binding energy of the uppermost monolayer and its distance from the substrate are affected by the quantum mechanical zero-point motion. The error bars of α are estimated from a $\pm\frac{1}{2}$ monolayer uncertainty in d.

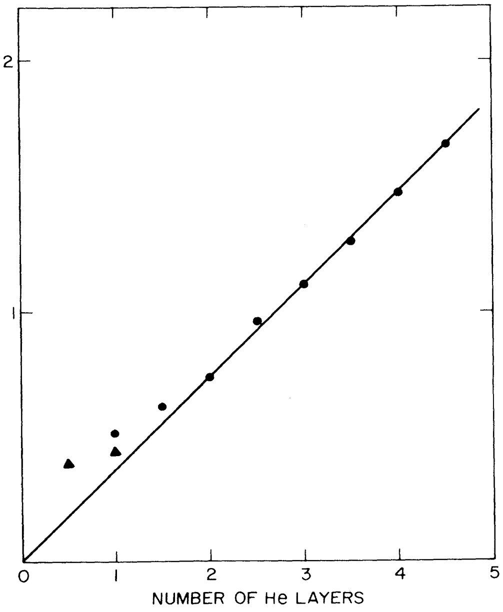

FIG. 2. The van der Waals film thickness $d=[\alpha/T\ln(p/p_{\rm sat})]^{1/3}$ plotted against the number of monolayers for the mobility maxima and minima at 2.6 K (triangles) and 1.45 K (circles). The straight line corresponds to $\alpha=20$ K (layer) (Ref. 3).

In the following we will explain the mobility oscillations observed for electrons on the thin He films ($d<2$ monolayers), which do not exhibit superfluidity.[13] Consequently, the surface waves (ripplons) are damped because of the high viscosity of the normal fluid, but there still exist two-dimensional phonons in the uppermost monolayer. The thermal wavelength, $2\pi/q$, of the electrons is of the order of 1000 Å and therefore the electrons are coupled to the long-wavelength density fluctuations. We simply estimate the electron scattering potential by $V_q=eE_\perp|\Delta n_2|_q/n_3$, where $E_\perp$ is the perpendicular holding field (image plus external field), $|\Delta n_2|_q$ the Fourier transform of the two-dimensional (2D) density fluctuations in the uppermost He monolayer, and n_3 is the three-dimensional density of liquid He. From Fermi's "golden rule" we get

$$\frac{1}{\tau}=\frac{m_{\rm el}(eE_\perp)^2}{\hbar^3 n_3^2}A\langle|\Delta n_2|_q^2\rangle\,, \tag{1}$$

where A is the area. We can further write the density fluctuations in the long-wavelength limit in the following more transparent forms:

$$A\langle|\Delta n_2|_q^2\rangle=k_{\rm B}Tn_2^2K_2=k_{\rm B}T(\partial n_2/\partial\phi)_T\,,$$

where K_2 is the two-dimensional compressibility and $\phi=k_{\rm B}T\ln(p/p_{\rm sat})$ is the chemical potential.[14] We conclude that the scattering rate is proportional to the 2D compressibility of the monolayer and consequently to the isothermal derivative of the coverage n_2 with respect to the logarithmic pressure $\ln(p/p_{\rm sat})$. The oscillatory structure in Fig. 1 should be compared to the derivative of the isothermal steplike coverage-versus-$\ln(p/p_{\rm sat})$ curves.[15]

When the He monolayer is dilute, we can neglect the interactions between the atoms, use the ideal-gas formulas, and write $K_2=(n_2k_{\rm B}T)^{-1}$. Similarly in the dilute limit we estimate n_2 from N_G, the He density in the gas phase; $n_2=\lambda_{\rm th}N_Ge^{E_B/k_{\rm B}T}$. Here $\lambda_{\rm th}=h/(2\pi m_{\rm He}k_{\rm B}T)^{1/2}$ and E_B is the binding energy of the He monolayer. By combining these with (1) we get a simple formula for electron scattering from the dilute He layer:

$$\frac{1}{\tau}=\frac{m_{\rm el}}{\hbar^3}\frac{(eE_\perp)^2}{n_3^2}\lambda_{\rm th}N_Ge^{E_B/k_{\rm B}T}\,. \tag{2}$$

In order to test Eq. (2) we have measured the increase of the scattering rate when the gas was introduced into the empty cell. In Fig. 3 we have plotted the increase of the scattering rate normalized by $N_G/\sqrt{T}$ at different temperatures. We have subtracted from the measured rate a small contribution from the gas-atom scattering, which is T independent and equals $(0.4\times10^{-8}\ \mathrm{cm^3/s})N_G$.[16] The activated behavior observed in Fig. 3 is in agreement with Eq. (2) and reflects the increase in the first monolayer coverage. The binding energy E_B deduced from Fig. 3 is 18 K and should also be compared with the measured binding energy of 12 ± 3 K for the ^{3}He atoms[12] and with the theoretical estimates of 13.8 and 15.5 K for ^{3}He and ^{4}He on the H_2 surface.[17] In order to estimate the numerical value of τ^{-1} we have used the following interpolation formula for the holding field, which is dominated by the image charge field of the H_2 substrate:

$$eE_\perp=\Lambda/(d+d_0)^2\ , \tag{3}$$

where $\Lambda=5.8\times10^{-30}$ J m and $d_0=7.1$ Å.[18–20] The quantity d_0 results from the average extension $\langle z\rangle_H=17$ Å of the electron wave function above the H_2 surface.[18] If we substitute $E_B=18$ K and $eE_\perp=\Lambda/d_0^2$ into Eq. (2) we get the solid line in Fig. 3, which agrees surprisingly well with the data.

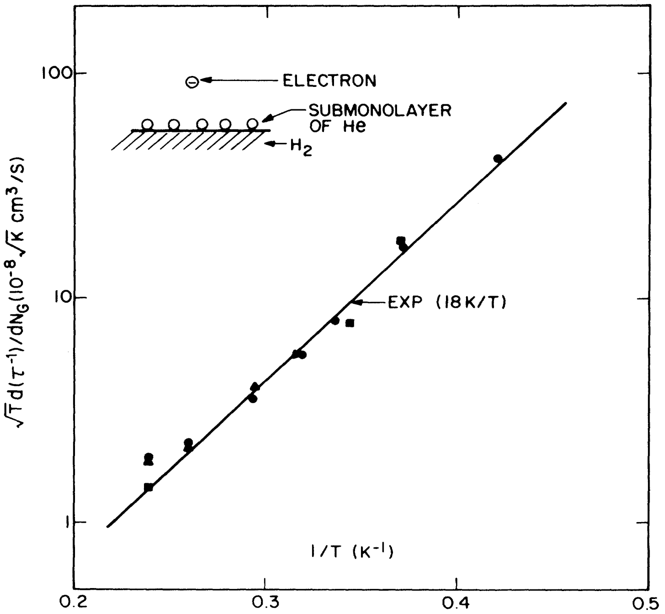

FIG. 3. Electron scattering rate on a submonolayer He film as a function of $1/T$. The vertical axis represents the extra scattering due to the film normalized by the He gas density. The solid line is the theory [Eq. (2)] with $E_B=18$ K.

Finally, we would like to estimate the intrinsic electron mobility limit for thicker He films. The following formula estimates the electron scattering from the gas atoms and ripplons on saturated He films ($p=p_{\mathrm{sat}}$) as a function of the film thickness[16,19,20]:

$$\left[\frac{1}{\tau}\right]_{\mathrm{gas}}+\left[\frac{1}{\tau}\right]_{\mathrm{ripplon}}=(6.80\times10^{-8}\ \text{Å}\ \mathrm{cm^3/s})N_G\langle z\rangle^{-1}+\frac{(eE_\perp)^2}{4\hbar\sigma}\left[1-\left[\frac{8m_{\mathrm{el}}T\sigma d^4}{3\alpha n_3\hbar^2}+1\right]^{-1/2}\right]. \tag{4}$$

In the scattering from the gas atoms, $\langle z\rangle^{-1}$ depends on the film thickness and we will use an interpolation formula

$$\langle z\rangle^{-1}=\langle z\rangle_{\mathrm{He}}^{-1}[1+2\langle z\rangle_{\mathrm{He}}^3/3\langle z\rangle_H(d+d_0')^2]\ ,$$

where $d_0'=72$ Å. This formula is accurate both in the $d\to\infty$ limit and at $d=0$. In Eq. (4) the ripplon spectrum has been estimated by $\omega^2=m_{\mathrm{He}}^{-1}(3k_B\alpha q/d^4+\sigma q^3/n_3)\times\tanh(qd)$, where σ is the surface tension. Equation (4) is not valid for very thin films, where a ρ_s/ρ correction should be added into the ripplon spectrum. In the limit of $\rho_s/\rho\to0$ we expect an increase in the ripplon damping, which is also left out from Eq. (4).

Equation (4) predicts a mobility minimum at $d\simeq30$ Å as shown by Fig. 4. The mobility increase for $d\le30$ Å is due to the stiffening of the film surface caused by the vdW term in the ripplon spectrum. The mobility increase for thicker films is explained by the rapid decrease of the electron holding field $E_\perp$. A similar mobility minimum has been observed by Kajita on Ne substrates,[3] and by us in the present work as shown by the inset of Fig. 4. The experimental minimum mobility value of $0.7\pm0.1\ \mathrm{m^2/V\cdot s}$ agrees with the theoretical value of $0.68\ \mathrm{m^2/V\cdot s}$ calculated from Eq. (4) at 1.45 K. However, the film thickness could not be determined accurately in this experiment.

Finally, we estimate at practical temperatures $T>0.05$ K an intrinsic mobility limit of the order of $30\ \mathrm{m^2/V\cdot s}$ for electrons on 100 Å or thinner He films on ideally smooth H_2 substrates (Fig. 4). A similar estimate for He film on a metal substrate yields $\mu<0.3\ \mathrm{m^2/V\cdot s}$. For comparison the Rayleigh-wave—limited electron mobility on a bare H_2 surface is about $10^3\ \mathrm{m^2/V\cdot s}$.[8] This value is well above the observed electron mobilities of $\mu\le10\ \mathrm{m^2/V\cdot s}$, which presumably are limited by surface defects and can be improved by more careful crystal growth.[8] Therefore, bare H_2 or Ne substrates seem better suited for studies of Wigner crystallization in the quantum limit.

In summary, we have grown high-quality H_2 crystals, measured the mobilities of surface electrons up to 6.5 $\mathrm{m^2/V\cdot s}$, and have used these crystals as substrates to study the electron mobility on thin He films. The He film is always found to suppress the mobility. A good quantitative mobility estimate has been achieved for different film thicknesses by taking into account the scattering from the He gas atoms, from the ripplons, and from the 2D phonons. We have not observed any additional mobility decrease due to the polaronic enhancement of the electron mass, in agreement with the theoretical estimate of the critical polaron coupling constant $\beta_c=0.35$.[6] We estimate that

$$\beta_H=m_{\mathrm{el}}d^4(eE_\perp)^2/12\pi k_B\alpha\hbar^2n_3\le0.27<\beta_c\ .$$

We gratefully acknowledge helpful discussions with

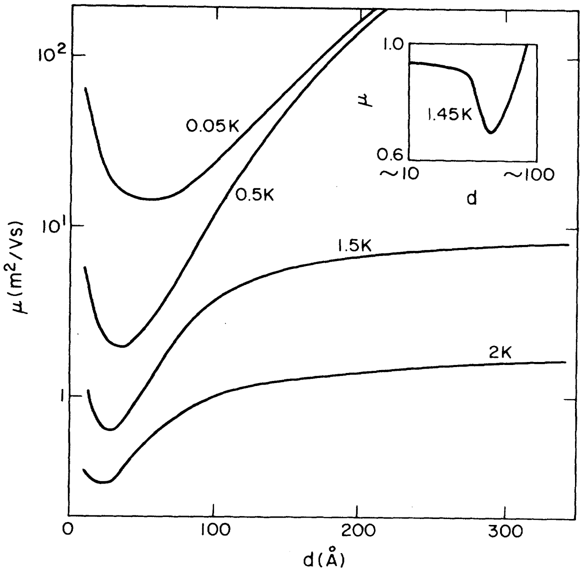

FIG. 4. Calculated electron mobility for saturated He films on the H_2 substrate. The minimum around 30 Å is due to ripplon scattering. The corresponding experimental result from the 19th crystal is shown in the inset.

R. N. Bhatt, C. C. Grimes, D. S. Fisher, D. A. Huse, L. Lévy, S. A. Jackson, D. D. Osheroff, and P. M. Platzmann and the technical assistance of H. W. Dail.

---

[a] Present address: IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. 10598.

[1] C. C. Grimes and G. Adams, Phys. Rev. Lett. **42**, 795 (1979).

[2] F. M. Peters and P. M. Platzman, Phys. Rev. Lett. **50**, 2021 (1983); F. M. Peters, Phys. Rev. B **30**, 159 (1984).

[3] K. Kajita and W. Sasaki, Surf. Sci. **113**, 419 (1982); K. Kajita, Surf. Sci. **142**, 86 (1984).

[4] E. Etz, W. Gombert, W. Idstein, and P. Leiderer, Phys. Rev. Lett. **53**, 2567 (1984).

[5] H. Ikezi and P. M. Platzman, Phys. Rev. B **23**, 1145 (1981).

[6] S. A. Jackson and P. M. Platzman, Phys. Rev. B **24**, 499 (1981), and **25**, 4886 (1982).

[7] Y. P. Monarkha and V. B. Shikin, Fiz. Nizk. Temp. **8**, 563 (1982) [Sov. J. Low Temp. Phys. **8**, 279 (1982)], and references therein.

[8] A. M. Troyanovskii, A. P. Volodin, and M. S. Khaikin, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 421 (1979) [JETP Lett. **29**, 382 (1979)]; A. M. Troyanovskii and M. S. Khaikin, Zh. Eksp. Teor. Fiz. **81**, 398 (1981) [Sov. Phys. JETP **54**, 214 (1981)].

[9] V. S. Edelman and M. I. Faley, J. Low Temp. Phys. **52**, 301 (1983).

[10] W. T. Sommer and D. J. Tanner, Phys. Rev. Lett. **27**, 1845 (1971).

[11] Y. Iye, J. Low Temp. Phys. **40**, 441 (1980).

[12] V. Lefevre-Seguin, thesis d'êtat, Paris, 1984 (unpublished), and private communcations.

[13] J. H. Scholtz, E. O. McLean, and I. Rudnick, Phys. Rev. Lett. **32**, 147 (1974).

[14] E. M. Lifshitz and L. P. Pitaevskii, *Statisical Physics* (Pergamon, New York, 1980), Pt. I, Chap. 12.

[15] See, for example, the Kr-on-graphite work of A. Thomy and X. Duval, J. Chim Phys. Phys. Chim. Biol. **66**, 1966 (1969).

[16] M. Saitoh, J. Phys. Soc. Jpn. **42**, 201 (1977).

[17] L. Pierre, H. Guignes, and C. Lhuillier, J. Chem. Phys. **82**, 496 (1985).

[18] M. W. Cole and M. H. Cohen, Phys. Rev. Lett. **23**, 1238 (1969).

[19] V. B. Shikin and Y. P. Monarkha, J. Low Temp. Phys. **16**, 193 (1974).

[20] K. Kajita, J. Phys. Soc. Jpn. **52**, 372 (1982).