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Surface Science 361/362 (1996) 835–838

surface science

Many-electron magnetoconductivity in 2D electrons on liquid helium

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Received 21 June 1995; accepted for publication 8 August 1995

Abstract

The magnetoconductivity of $\sigma(B)$ of nondegenerate two-dimensional electrons on superfluid helium was measured and calculated below 1 K in fields B up to 8 tesla. The results show that the internal electric fields from electron–electron interactions strongly influence $\sigma(B)$ in the 2D electron fluid. This internal field strength is in good agreement with Monte Carlo simulations. The magnetoconductivity increases at the transition to the 2D solid phase.

Keywords: Computer simulations; Electrical transport measurements; Liquid–gas interfaces; Liquid helium; Surface electrical transport; Two-dimensional electrons

1. Introduction

Experimentally the simplest possible conductor is a sheet of nondegenerate two-dimensional (2D) electrons, density n, on the surface of superfluid helium. They can have higher mobilities μ than any solid state conductor and are a prime example of a strongly interacting system. The ratio of the Coulomb energy to the kinetic energy, the plasma parameter, $\Gamma = e^2(\pi n)^{1/2}/4\pi\epsilon_0 kT \gg 1$, there is short-range order in the electron system and, for $\Gamma > 127$, a 2D electron crystal forms. A fundamental question is the extent to which these interactions influence the conductivity. It is now known that fluctuating internal electric fields, magnitude E_f, control the diffusion of cyclotron orbits and hence the magnetoresistivity $\rho(B)$ [1] and magnetoconductivity $\sigma(B)$ [2]. We present new measurements of $\sigma(B)$ below 1 K in the electron fluid (see Ref. [3] for some previous work), and obtain values of E_f, in good agreement with Monte Carlo simulations. The transition to the 2D solid is also observed.

2. Experimental

The magnetoconductivity was measured using a 4 mm diameter Corbino disk (see Fig. 1) made using optical lithography and the precision device fabrication techniques of the Southampton

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PII S0039-6028(96)00545-6

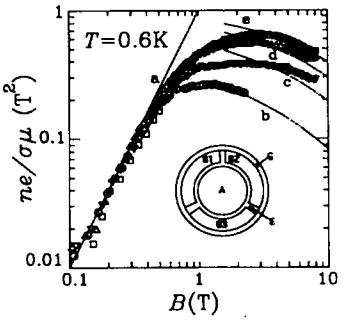

Fig. 1. $ne/\mu\sigma$ versus B for $n = 0.51$ (b), 1.21 (c), 1.60 (d) and 2.07 (e) $\times 10^{12}\,m^{-2}$ at 4 kHz. The solid lines show the many-electron theory.

University Microelectronics Centre [2]. A central electrode A was surrounded by a ring E which separated the annular receiving electrode B into three segments B1, B2 and B3, all enclosed by a guard electrode G. Electrons were produced by glow discharge and held on the helium surface (typically 50 μm above the electrodes) by DC potentials. The gaps in the electrode pattern were only 10 μm so the electron sheet was very homogeneous. An AC voltage V_0 (typically 1–10 mV) at a frequency f ($=\omega/2\pi$) between 2 and 70 kHz was applied to electrode A and $\sigma(B)$ was obtained from the phase of the AC current to electrode B. The electron density was found from the $-$ve DC bias voltage on electrode E needed to "cut-off" this current.

3. Results and discussion

3.1. The Drude region

In low fields, $B < 0.5$ T, the data for $\sigma(B)$ follow the simple Drude-like result, even for classically strong fields with $\mu B \leq 500$,

$$\sigma(B) = \frac{\sigma(0)}{1+(\mu B)^2} \quad \text{and} \quad \frac{ne}{\mu\sigma(B)} \approx B^2 \text{ for } \mu B \gg 1 \tag{1}$$

where $\sigma(0) = ne\mu$. The mobility μ was obtained from the B^2 dependence of $\sigma^{-1}(B)$ [4] in good agreement with measurements at $B = 0$ by Mehrotra et al. [5]. The mobility is density dependent because the vertical electric pressing field, and the electron-ripplon coupling, increases with density. Fig. 1 shows measurements of $ne/\mu\sigma(B)$ versus B for several densities, using the experimental μ values. In the Drude region, the data all lie on the line, $ne/\mu\sigma(B) = B^2$ (line a).

Initially, these results seem to confirm a single-particle approach to magnetoconductivity. In fact they come about through electron–electron interactions. First, the many-electron correlation time is less than the relaxation time τ from scattering by ^{4}He vapour atoms and ripplons [6]. This changes the averaging over the Boltzmann distribution and, for the energy-dependent ripplon interaction, decreases the mobility, compared to independent electrons, in satisfactory agreement with experiment. The agreement of the experimental μ values in zero and classically strong ($\mu_B \gg 1$) fields implies that the relaxation rate is independent of magnetic field, $\tau^{-1}(0) = \tau^{-1}(B)$ even where Landau level quantisation (energy spacing $\hbar\omega_c$, $\omega_c = eB/m$ is the cyclotron frequency) might be expected to change the density of states and the scattering rate for quasi-elastic scattering. But the fluctuating internal electric field E_f produces an energy uncertainty, $eE_f\lambda\!\!\!^{-}_T$ over an electronic thermal wavelength $\lambda\!\!\!^{-}_T$ and, for $kT \gg eE\lambda\!\!\!^{-}_T > \hbar\omega_c$, smears out the Landau levels. This also holds for $eE_fR_c > \hbar\omega_c$ ($R_c = \sqrt{2mkT}/eB$ is the classical cyclotron orbit radius), which corresponds to $B < B_0$, an onset field for deviations from the Drude model (typically 0.2 to 1 T). The Drude model is followed because of the internal electric fields, and the many-electron theory gives $ne/\mu\sigma = B^2$ for $\mu B \gg 1$, independent of n, in this region.

3.2. Many-electron magnetoconductivity

A distinctive feature in Fig. 1 is that the conductivity saturates above the Drude region. Moreover, the plots of $ne/\mu\sigma(B)$ are then density and temperature dependent. The energy uncertainty $eE_fR_c < \hbar\omega_c$ and the scattering rate $\tau^{-1}(B)$ are enhanced by a density of states factor $\approx \hbar\omega_c/eE_fR_c = B^2/B_0^2$. Hence we find [7],

$$\frac{ne}{\mu\sigma(B)} = K\pi B_0^2 \quad \text{and} \quad B_0^2 = \left[\frac{2m^3kT}{e^2\hbar^2}\right]^{1/2} E_f \tag{2}$$

where K is a dimensionless factor, depending on the scattering mechanism. For short range scattering, such as ^{4}He atoms, $K \equiv K_g(\hbar\omega_c/kT)$ reflects the change in the cyclotron orbit radius, and hence the diffusion length, from R_c for $\hbar\omega_c/kT \ll 1$, $K_g = 1$, to the magnetic length, $l = (\hbar/eB)^{1/2}$ for $\hbar\omega_c/kT \gg 1$, $K_g = 4(\hbar\omega_c/kT)^{-1/2}/\pi$. For ripplons $K \equiv K_r$ depends on $\hbar\omega_c/kT$ in the same way but the interaction strength also changes with field as the dominant scattering ripplon wavelength is proportional to the cyclotron orbit radius. This extra factor is numerically close to unity in these experiments. Thus, for $\hbar\omega_c/kT = 1.34B/T \gg 1$, $ne/\mu\sigma(B)$ decreases with field as seen in Fig. 1 above 2 T. An important conclusion is that, above the Drude region, $\sigma^{-1}(B)$ is proportional to the internal electric field E_f.

3.3. The internal electric field

For a classical electron fluid with thermal fluctuations, the mean-square internal electric field has a nearly Gaussian distribution and can be written as:

$$E_f^2 = \langle E_f^2 \rangle = \frac{n^{3/2}kT}{4\pi\epsilon_0} F(\Gamma) = E_0^2 F(\Gamma), \qquad (3)$$

where E_0 sets the scale for the internal field strength. The dimensionless function $F(\Gamma)$ is plotted in Fig. 2, from Monte Carlo computer simulations [8], for $10 < \Gamma < 200$. The variation of F is surprisingly small, given that the structure changes dramatically from a crystal to a liquid with short-range correlations. In the harmonic crystal, Γ can be calculated analytically as 8.91 (dashed line).

The magnetoconductivity was calculated using the many-electron theory for $\hbar\omega_c > kT$, using the internal fields from Fig. 2, as shown in Fig. 1 for several densities at 0.6 K. As B increases, the data cross over from the many-electron low field theory (equivalent to the Drude model, line a) to a density dependent behaviour, Eq. (2) (lines b, c d and e).

Conversely, the measured $\sigma^{-1}(B)$, at $B = 2$ T, was used to obtain experimental values of the internal electric field E_f as plotted in Fig. 3 versus E_0 from Eq. (3). The points come from over 40 combinations of density and temperature between 0.6 and 0.9 K. Within the errors the measured field $E_f = \nu E_0$ with $\nu = 3.11 \pm 0.10$ is in close agreement with $\nu = \sqrt{F} = 3.07 \pm 0.03$ from the Monte Carlo calculations for $20 < \Gamma < 70$.

3.4. The 2D electron solid

At lower temperatures, the 2D electron system forms a classical solid below $T_m = 0.225 \times 10^{-6} n^{1/2}$ K. The zero-field mobility decreases at the transition [5] but little is known about the magnetotransport. Hysteresis in the highly nonlinear magnetoconductivity has been interpreted as shear-induced melting [9] or the decoupling of

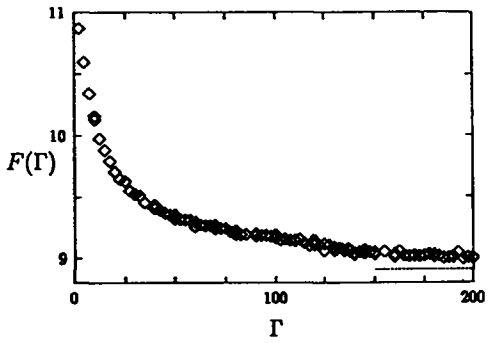

Fig. 2. The many-electron field scaling function $F(\Gamma)$ from Monte Carlo calculations.

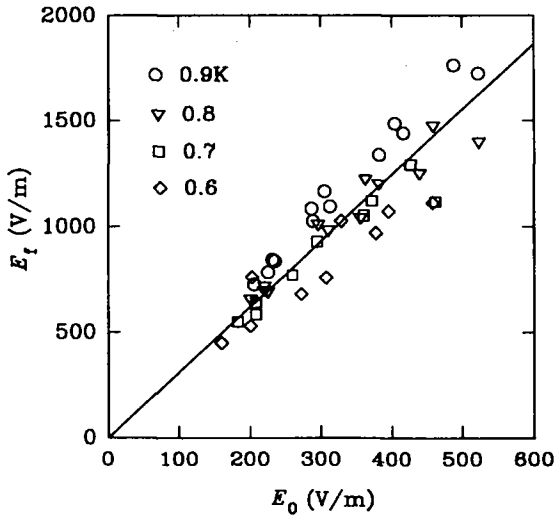

Fig. 3. The internal field E_f, measured for a range of electron densities at 0.6, 0.7, 0.8 and 0.9 K, versus the reference field E_0.

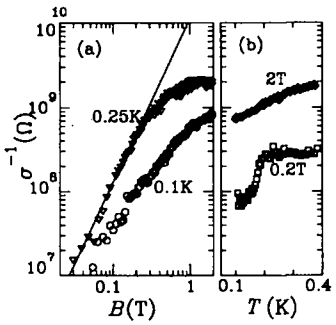

Fig. 4. (a) $1/\sigma$ versus B at 0.25 and 0.1 K for $n = 0.8 \times 10^{12}\,\mathrm{m}^{-2}$, (b) $1/\sigma$ versus T at 0.2 and 2 T for $n = 0.9 \times 10^{12}\,\mathrm{m}^{-2}$.

the crystal from commensurate "dimples" in the helium surface [10]. Fig. 4a shows $\sigma^{-1}(B)$ in the fluid at 0.25 K (good agreement with Eqs. (1) and (2)) and in the solid at 0.1 K for $n = 0.80 \times 10^{12}\,\mathrm{m}^{-2}$ ($T_m = 0.19$ K), assuming that the phase shifts are due to magnetoconductivity (i.e. neglecting Lorentz force coupling to shear modes in the crystal). The many-electron $\sigma(B)$ is not expected to change substantially at the transition from a highly correlated fluid to a crystal for comparatively high fields where $2\pi^{1/2}\hbar n\Gamma/m\omega_c \ll 1$ [7,11]. This is seen in Fig. 4b where the change in $\sigma^{-1}(B,T)$ in low fields corresponds to a change in mobility [5], though the B^2 Drude region is no longer clear experimentally at 0.1 K. However, at higher fields the transition (at the same T_m) is much less pronounced. The many-electron theory must now be extended to include the region where the electron motion in the field created by the other electrons is quantised, and the field E_f is non-uniform over the electron wavelength.

Acknowledgements

This work was supported by the EPSRC, UK, and EU Contract CHRXCT 930374.

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