Quasi-one-dimensional electron transport over the surface of a liquid-helium film

Sviatoslav Sokolov[a, b], Nelson Studart [a,1],

[a] *Departamento de Física, Universidade Federal de São Carlos, 13565-905 São Carlos, São Paulo, Brazil*

[b] *B. I. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, 61103 Kharkov, Ukraine*

Abstract

Quasi-one-dimensional mobility of surface electrons over a liquid-helium suspended film is studied for a conducting channel. The electron mobility is calculated taking into account the electron scattering by helium atoms in the vapor phase, ripplons, and surface defects of the film substrate both in one-electron regime and in the so called complete-control limit where the influence of inter-electron collisions on the electron distribution function is taken into account. It is shown that the mobility for low temperatures is dominated by the surface-defect scattering and its temperature dependence is essentially different from that of the electron-ripplon scattering.

Key words: Helium film; low-dimensional electron transport; electron-ripplon interaction; surface-defect scattering;

The interest for studying quasi-one-dimensional electron systems (Q1DES) over the liquid helium [1] has grown significantly in the last years because these Q1DES have been created over a suspended helium film deposited on a structured substrate. [2] In such a condition the properties of the Q1DES differ significantly of those over bulk helium in two ways. Firstly, the confinement potential across the charged channel is determined not only from the holding electric field in the direction normal to curved helium surface but also due to strong polarization effects in the solid substrate which are quite important in the case of a thin film. [3] Furthermore the electrostatic confinement due to the specific arrangement of the electrodes plays the crucial role in restricting the electron motion across the channel which leads to the formation of the Q1DES. Secondly, the roughness of the film-substrate interface influences strongly the transport properties of electrons along the channel, in addition to the scattering processes by helium atoms in the vapor phase and by quantized oscillations of the free helium surface (ripplons). [4]

The aim of the present work is to study, from a theoretical point of view, the electron mobility in the Q1DES over a helium film. We limit ourselves to the non-degenerate regime and consider only the contribution of the lowest subband for the motion across the charge channel. This can be justified for $\hbar\omega_0 \gg T$ where ω_0 is the frequency of the confinement potential which is supposed to have the parabolic form.

The electron mobility along the channel is given as [5]

$$\mu = \frac{2e}{\sqrt{\pi}m}\left(\frac{\hbar\omega_o}{T}\right)^{3/2}\int_0^\infty \frac{\sqrt{x}\exp(-\hbar\omega_0/T)}{[\nu_g(x)+\nu_r(x)+\nu_d(x)]} \qquad (1)$$

where $x = \hbar k_x^2/(2m\omega_0)$, e and m are the electron charge and mass, respectively, and k_x is 1D electron wave number. The collision frequencies $\nu_g(x)$, $\nu_r(x)$, and $\nu_d(x)$ describe the electron scattering by vapor atoms, ripplons, and defects of the solid-helium boundary, respectively. The frequency $\nu_g(x)$ is proportional to the volume concentration of the helium atoms in

[1] Corresponding author. E-mail: studart@df.ufscar.br

the vapor which decreases exponentially with the temperature. For this reason one can disregard $\nu_g(x)$ for $T < 1$ K.

For the ideal helium-solid interface, the mobility is determined, for temperature below 1 K, by the electron-ripplon scattering and can be written, for a thin helium film with thickness $d \lesssim 10^{-6}$ cm, as

$$\mu_r \simeq \frac{8\mu_\perp}{\sqrt{\pi}}(\frac{\hbar\omega_0 x_c}{T})^{1/2}\frac{\exp(-4x_c)}{[1-\text{erf}(2\sqrt{x_c})]} \qquad (2)$$

where $x_c = \hbar\rho g'/(8\alpha m\omega_0)$ and $\mu_\perp = \alpha\hbar/[em(E^*_\perp)^2]$. Here α and ρ are helium surface-tension coefficient and density, respectively, g' is the effective acceleration of gravity modified by van der Waals forces, and $E^*_\perp$ is the effective holding filed which includes the contribution of the polarization forces in the substrate.

To calculate the contribution of the roughness of the solid-helium interface to the electron mobility, we use the Gaussian two-parameter model for surface defects where the correlation function for the profile $\xi_s(\mathbf{r})$ of the solid-helium interface is $\langle\xi_s(\mathbf{r})\xi_s(\mathbf{r}')\rangle = \xi_0^2\exp[|\mathbf{r}-\mathbf{r}'|^2/a^2]$ where ξ_0 and a play the role of the characteristic height and width, of the defects. [6] In order to obtain the scattering potential we apply the method of summing the electron interactions with the induced dipole moments of the atoms as it was done to calculate the interaction potential for the electron-ripplon scattering. [7] The approach is reliable for media whose dielectric constants are essentially near the unity (case of solid neon or hydrogen) in such a way that one can neglect screening effects in the electrostatic electron field. For values of ξ_0 and a satisfying the condition $\xi_0 \ll a$ and $\xi_0 \ll d$ in the range of smooth enough interface roughness the frequency $\nu_d(x)$ is near two orders of magnitude larger than $\nu_r(x)$ for $x = T/\hbar\omega_0$ giving the dominat contribution to the integral of Eq. (1). In such a condition the defect-limited mobility is given by

$$\mu_d \simeq \frac{e}{m\nu_d^{(0)}}(\frac{T}{\hbar\omega_0})^{1/2} \qquad (3)$$

where the frequency $\nu_d^{(0)}$ is given by a cumbersome expression depending on ξ_0, a, d, and the matrix element of the electron-defect interaction potential averaged over the wave function for the electron motion in the direction normal to the liquid.

The results given by Eqs. (1)-(3) have been obtained by solving the Boltzmann equation in the single-electron approximation. Moreover the same qualitative behavior is obtained in the complete-control approximation where the electron collisions are predominant in the electron distribution function leading to its dependence on the drift velocity for the electron system. [8] Correspondingly the absolute values of electron mobilities are smaller than those in the single-electron approximation.

One concludes that the temperature dependence of the electron mobility along the charged channel over the helium film changes drastically when one goes from an ideal substrate, where the ripplon-limited mobility is proportional to $T^{-1/2}$, as given by Eq. (2), to a rough substrate with the defect-limited mobility, given by Eq. (3), where $\mu_d \sim T^{1/2}$. Such a difference in the temperature dependence of the electron mobility may be very favorable to check experimentally both the role of surface defects in the electron transport and the reliability of the models used to describe the electron-defect interaction.

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