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Influence of substrate charge on electron transport in narrow conducting channels

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Abstract
Electron transport in inhomogeneous quasi-one-dimensional conducting channels on the liquid helium surface is studied in the temperature range 0.6–1.5 K. Inhomogeneities are created by charging the substrate on which the conducting channels are formed. It has been established that the electron conductivity practically does not depend on temperature at some substrate charge. The results obtained are explained by localization of carriers and creation of electron polarons.

1. Introduction

Investigations of electron transport in systems with restricted geometry are of great interest [1]. It was proved to be possible to realize a quasi-one-dimensional (Q1D) charge system using surface electrons on liquid helium (SE) [2]. It has been observed that the character of the transport in conducting Q1D channels is essentially different in channels of different width and quality of the substrate surface on which the conducting channels are formed. For a clean homogeneous substrate and narrow conducting channels, the electron mobility is determined by the interaction of carriers with helium atoms in vapor and ripplons [3, 4] and is described well by theory [5]. As the width of the conducting channel increases, an anomalous charge transport is observed [6, 7]; the mobility first increases with decreasing temperature T, and then at $T < 0.8$ K starts to decrease. The quality of the substrate influences the character of the electron transport. As has been suggested, this effect is connected with the appearance of potential wells due to inhomogeneities on the surface of the substrates. For the creation of potential wells it is convenient to use electron charge deposited on the surface of a substrate. In this case it is possible to change in a controlled way the density of the potential wells. Preliminary data on the investigation of electron mobility in Q1D channels with a charged surface have been obtained in [7]; in this work the results of detailed investigations of the influence of the charge of the electron substrate on the carrier conductance in Q1D channels over liquid helium are presented.

2. Experimental details

We used the standard ^{3}He evaporating refrigerator [10]. At the first stage ^{4}He evaporation was applied to achieve a temperature of 1.4 K. Next, adsorbing pumping ^{3}He allowed a temperature as low as 0.45 K to be obtained. The experimental cell consisting of the top and bottom metal plates with a profiled dielectric substrate in between is depicted in figure 1. The bottom plate of the cell represents a coplanar system of measuring electrodes consisting of two equal parts by size 6×13.5 mm^2 and with a gap between them of $a \simeq 10$ μm. The small value of the gap practically excludes a non-uniformity of electric field in the plane of the substrate which is proportional to $\exp(-b/a)$, where b is the distance from the lower plate to the electron channels.

The structure of the substrate and the technique of measurement of conductivity were similar to the description in [4]. A signal of frequency 20 kHz from a generator was applied to one of the electrodes, the signal passing through the experimental cell was taken off from the other electrode. The substrate represents 50 light guides of diameter 240 μm and length 12 mm located on a glass plate of size $12 \times 13.5 \times 0.2$ mm^3. Liquid helium covers the substrate realizing 'deep' liquid channels with some surface curvature between the light guides. The tops of the light guides are covered with the liquid film of thickness about 300 Å. The shift of amplitude of the 0^0 and 90^0 components of an electrical signal, passing through the cell with electrons, was measured; this allowed us to determine the real G_r and imaginary G_i parts of the conductance of the cell.

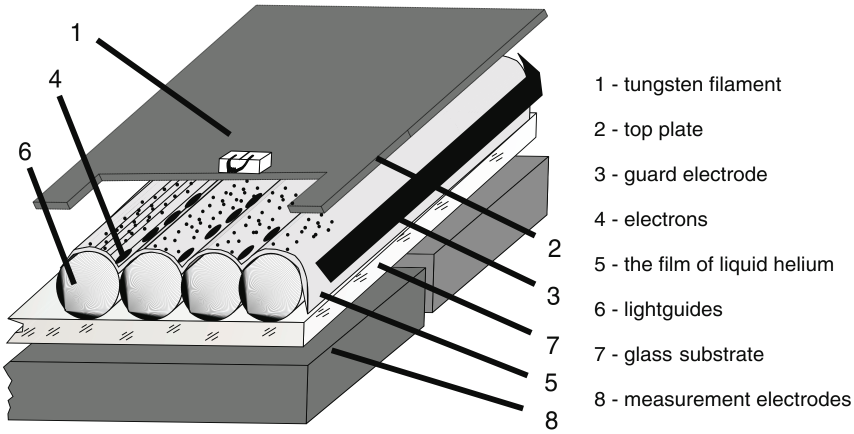

Figure 1. Schematic of the experimental cell.

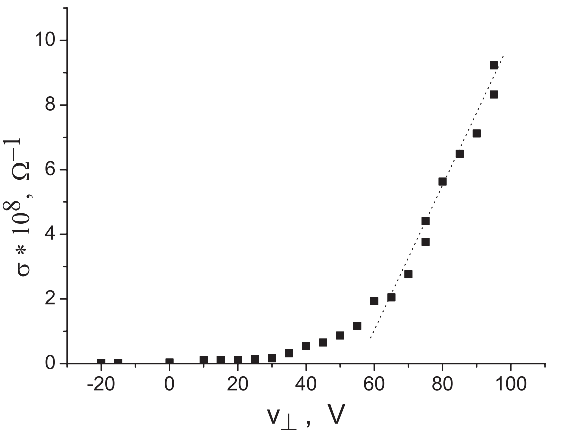

Figure 2. A typical dependence of the conductivity of the channels σ on a pressing potential $V_\perp$.

Theoretical calculation of G_r and G_i, taking into account the cell geometry, are given in [4]. For the values of G_r and G_i the following expression has been obtained:

$$G_r = n_s e^2 \cdot \sum_{n,l=1}^{\infty} \frac{\Lambda_{n,l} e\omega^2 \chi_1 \lambda}{\left(m\omega_q^2 - e\omega^2\chi_2\lambda\right)^2 + (e\omega^2\chi_1\lambda)^2}, \qquad (1)$$

$$G_i = n_s e^2 \cdot \sum_{n,l=1}^{\infty} \frac{\Lambda_{n,l} \left(m\omega_q^2 - e\omega\chi_2\lambda\right)\omega}{\left(m\omega_q^2 - e\omega\chi_2\lambda\right)^2 + (e\omega^2\chi_1\lambda)^2} + g_0. \qquad (2)$$

Here the value g_0 characterizes conductance of the cell without electrons, the values χ_1 and χ_2 are real and imaginary components of resistivity of the channels on one electron, n_s is the average density of electrons in the cell, ω_q is the frequency of the plasma oscillations propagating in a system of parallel channels. The parameters $\Lambda_{n,l}$ and λ in expressions (1) and (2) are determined by the cell geometry. Estimations show that the main contribution to value G_r and G_i is given by the first term. Expressions (1) and (2) determine conductivity σ of the channels and the value a: $a = \frac{m\omega_q^2 - e\omega\chi_2\lambda}{n_s}$. The value a is determined by the frequency of plasma oscillations and the imaginary part of the resistivity of the channels. For free electrons $m\omega_q^2 \gg e\omega\chi_2\lambda$, and the value $a = \frac{m\omega_q^2}{n_s}$. Since ω_q^2 is proportional to n_s and inversely to m [4] the value a in this case depends only on the cell geometry.

3. Discussion

The results obtained are presented in figures 2 and 3. A typical dependence of the conductivity of the channels σ on a pressing potential $V_\perp$ is shown in figure 2.

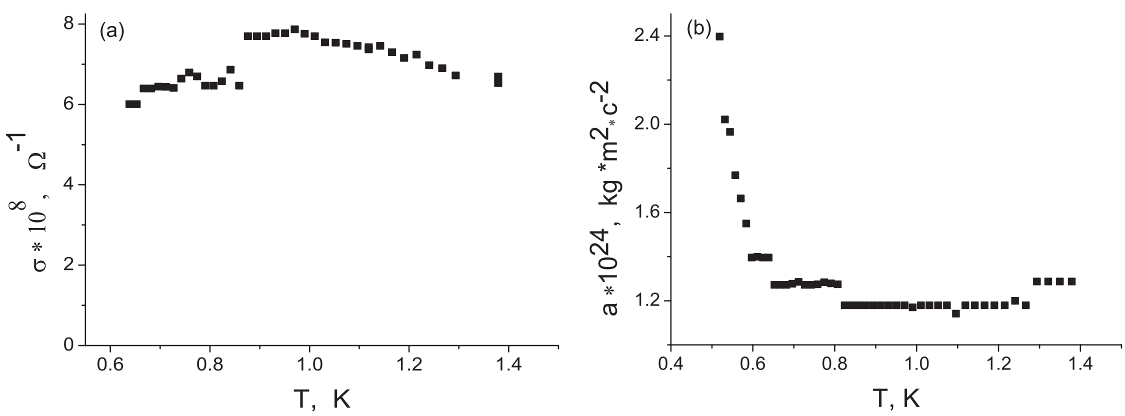

Figure 3. The conductivity of the channels σ (a) and the value a as a function of temperature (b).

Figure 2 describes the situation when we have a charge on the substrate and the appearance of the signal from SE demonstrates an increase from zero if the value of the holding potential of 30 V is achieved. It is seen that the signal appears not with zero but with some value $V_{\perp cr}$. The value $V_{\perp cr}$ with which the signal appears is determined by the density of electrons localized on the helium film and on the substrate surface. In figure 3(a) temperature dependence of the conductivity of the channels for an electron density $\sim 4 \times 10^{12}$ m^{-2} is presented. It is seen that σ at first slightly increases with decreasing temperature. At $T \approx 0.9$ K a step change of the value σ approximately 10% is observed. Unfortunately, the nature of such a decreasing σ is not clear at the moment, and additional experiments are needed for an explanation of this effect. The week temperature dependence of σ allows us to conclude that the helium atoms in vapor and ripplons practically do not influence the conductivity of the channels.

In the temperature region 0.6–1.4 K the value a practically does not depend on temperature (figure 3(b)). As follows from [4], the theoretical value of a depends only on the cell geometry and must be independent of temperature. The experimentally found value of a is approximately two orders more than the theoretical value of a obtained for the ideally conducting channels, and equals $\sim 2.4 \times 10^{-26}$ kg m^2 s^{-2}. The plasma frequency, which has been calculated with using the results of [4], is $\sim 5.1 \times 10^8$ s^{-1}. The value ω_q, calculated from the experimental value of a, is $\omega_q = 2.3 \times 10^9$ s^{-1}. It has been assumed in [3, 7], that increase in the plasma frequency appears when localization of particles takes place in the channels. In this case, an additional so-called 'optical' mode; appears; the value ω_q thus can be presented as $\omega_q = \sqrt{\Omega_0^2 + \omega_p^2}$, where ω_p is the plasma frequency of ideal conducting channels [3, 8]. Estimations using of the experimentally found value for a give for Ω_0 the value $\Omega_0 = 2.3 \times 10^9$ s^{-1}. We can suppose, therefore, that electrons in quasi-one-dimensional channels in the presence of a charge on the substrate are localized. The characteristic value of the localization length of a particle is $l_{loc} \approx (\frac{\hbar}{m\Omega_0})^{1/2} = 2.2 \times 10^{-5}$ cm. This value practically coincides with the average distance between electrons in the channels $a_0 \approx n_s^{-1/2} = 2.4 \times 10^{-5}$ cm.

One can supposed that such localization of particles can lead to the formation of electron polarons: microscopic dimples on the liquid helium surface with an effective mass noticeably exceeding the mass of free electrons. The value n_s allows us to estimate the mobility of electron polarons in conducting channels, which is equal to $\mu \approx 0.125$ m^2 V^{-1} s^{-1}. This is much less than the theoretical value of the electron mobility in Q1D channels which is $\mu = 12$ m^2 V^{-1} s^{-1} at $T = 1.4$ K [5]. In the conducting Q1D channels above liquid helium, with sufficiently good homogeneity, a strong temperature dependence of the electron mobility is observed [4]. In this connection, the weak temperature dependence of σ, observed in the Q1D channels in the presence of a charge on the substrate, is interesting. One of the possible explanations for this effect is that due to the large number of potential wells formed by the immobile electrons, the carrier transport is realized by tunneling of particles from one potential well to another. The diffusion of particles in this case is determined by the expression $D \approx \nu_0 \cdot a_0^2 \cdot \exp[\int_a^b \sqrt{2m\Delta V}\, dx]$, where $\nu_0 = \frac{\Omega_0}{2\pi}$ is the frequency of oscillations of an electron in a potential well and ΔV is the height of the potential well. The value a_0 set the characteristic scale of variations of the potential relief, and is determined by the average distance between the electrons localized on a thin helium film and on the dielectric substrate. However, for an explanation of observable values of the mobility, it is required to assume that $\Delta V = 0.2$ K. This is too small a value for realization of the tunneling mechanism. A more probable explanation of the observed features of the carrier transport is scattering of electron polarons by variations of the potential, creating both localized immobile electrons and channel inhomogeneities.

The electron transport in quasi-one-dimensional channels on a liquid helium surface in the presence of inhomogeneities on a substrate was considered in [9]. It has been shown that the mobility of carriers limited by scattering of electrons by defects can be presented as

$$\mu_d \approx \frac{e}{m\nu_d}\left(\frac{kT}{\hbar\omega_0}\right)^{1/2}. \qquad (3)$$

Here ν_d is the frequency of collision of electrons with surface defects of the substrate, k is the Boltzmann constant, $\hbar$ is Planck's constant and ω_0 is the frequency of oscillation of an electron due to the movement of an electron across the channel. As defects, the roughness of the substrate on which the conductivity channels are formed were considered. It was also supposed that there was a layer of liquid helium in a sufficiently thin channel. In the calculation the condition $kT \ll \hbar\omega_0$ was used. It has been established that the value ν_d does not depend on temperature, and consequently the temperature dependence of μ is enough weak: $\mu \sim T^{1/2}$. In the conditions of our experiment $\hbar\omega_0 = 0.2$ K, so the requirement $kT \ll \hbar\omega_0$ does not arise. Beside, this scattering of the electrons on variations of the random potential probably has Coulomb character. Nevertheless, apparently, one can expect that weak temperature dependence of the mobility should take place in this case. Unfortunately, there is currently no theory of electron transport under the scattering electrons by the random potential caused by the charge of the substrate.

Thus, in the present work the electron transport in quasi-one-dimensional channels is investigated in the presence of a charge on the substrate on which the channels are formed. It is shown that the conductivity of the channels practically does not depend on temperature. It was assumed that localization of carriers in the non-uniform channels is accompanied by the formation of electron polarons. The effective mass of such a polaron essentially exceeds the free electron mass.

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