Carrier transport in quasi-one-dimensional electron systems over liquid helium under strong localization conditions

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(Submitted May 26, 1997)
Fiz. Nizk. Temp. **23**, 1172–1177 (November 1997)

The conductivity of carriers in a quasi-one-dimensional electron system over liquid helium is measured in the temperature interval 0.5−1.9 K in confining electric fields up to 4 kV/cm at a frequency of 1.1 MHz. Quasi-one-dimensional channels were created by using an optical diffraction grating covered with a thin helium layer. The carrier conductivity decreases exponentially with temperature T, and the activation energy is of the order of a few degrees, thus pointing towards localization of electrons in a quasi-one-dimensional electron system. As the thickness of the helium layer covering the grating is increased, a departure from a mono exponential dependence is observed at $T<0.8$ K, which indicates that quantum effects begin to play an active role in electron mobility at these temperatures. An analysis of the obtained results leads to the assumption that under localization conditions, quasi-one-dimensional electron systems may contain two branches of the optical mode of plasma oscillations, viz., a high-frequency branch associated with electron oscillations in potential wells, and a low-frequency branch associated with the oscillations of the electron-dimple complex with a large effective mass.
[S1063-777X(97)00311-3]

The behavior of charge carriers in quasi-one-dimensional (Q1D) and one-dimensional (1D) electron systems over liquid helium is very interesting because of the possibility of realization of conducting channels with small transverse dimensions, containing one to ten electrons.[1] Surface electrons (SE) over liquid helium form an extremely pure and homogeneous low-dimensional electron system, and it can be expected that Q1D and 1D electron systems employing SE will also be homogeneous and perfect. Quasi-one-dimensional conducting channels over liquid helium were created experimentally by using the surface undulations of liquid helium flowing under the action of capillary forces into the grooves of the profiled substrate.[2,3] Under the action of a confining electric field, electrons are displaced towards the bottom of the groove and can move freely only in one direction. A distinguishing feature of such channels is that the depth of the liquid in the grooves of the profiled substrate reach values $\sim 10^{-4}$ cm and the roughnesses of the substrate have no effect on the behavior of the electron. Transfer measurements in such quasi-one-dimensional systems have shown that the mobility of electrons in Q1D channels may become close to the electron mobility in bulk helium.[4–6] However, experimental results obtained by increasing the separation H between the bulk helium surface and the upper plane of the substrate, i.e. by decreasing the radius of curvature of the liquid in the substrate grooves, indicate that the mobility of charge carriers decreases, and its temperature dependence begins to differ strongly from the analogous dependence for SE over bulk helium. The obtained results were attributed to the localization of carriers in potential wells emerging in conducting channels under the influence of electrons localized over a thin helium film in the immediate vicinity of the grooves filled with the liquid.[2,4]

In this research, we have measured the conductivity of electrons over liquid helium in quasi-one-dimensional channels under strong localization conditions. Measurements were made in the temperature range 0.5-1.9 K in the electron density of states between 10^8 and 10^9 cm^{-2} at a frequency of 1.1 MHz. The experimental cell used for measurements is shown in Fig. 1a. A high-quality glass optical grating 1 of size 24.4×19.6 mm and thickness $d=0.8$ mm (Fig. 1b) was used to obtain quasi-one-dimensional liquid channels. The glass used to form the optical grating had a dielectric constant $\varepsilon \simeq 4$, and the number of grooves in one centimeter of the grating was 1670. The grating was mounted over electrodes A, B, and C which were held at zero potential. The size of the electrodes A, B, and C was 15.6×9.2, 2×9.2, and 15.6×9.2 mm, respectively. A negative voltage confining the electrons to the surface of the liquid helium wetting the substrate was applied to electrodes *2* and *3*. In order to produce an electron spot with a sharper electron density profile at the edge, a negative potential was applied to the shielding electrode *4*. Two opposite cuts of width ~1.2 mm were made on the electrodes 2 and 3 to ensure a free leakage of helium to the drift space of the experimental cell and to reduce the possible temperature gradient between the liquid helium film at the grating surface and bulk helium. The generator voltage was supplied to the electrode A, while the signal passing through the cell was recorded at the electrode C. For such a voltage supply, the drift electric field is

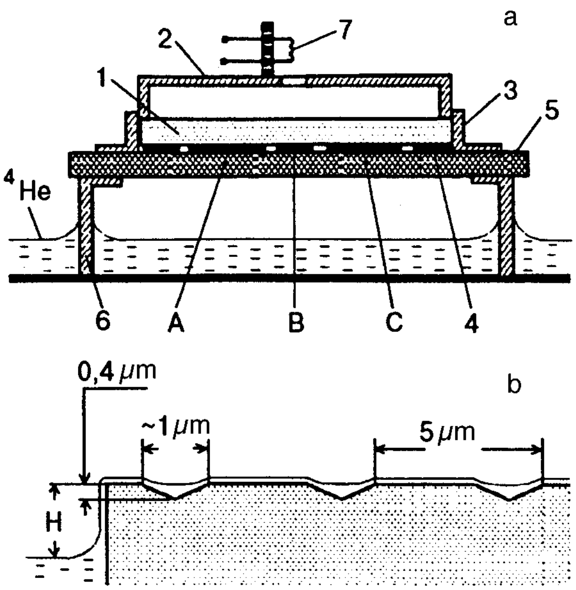

FIG. 1. (a) Schematic diagram of the measuring cell: optical grating *1*, confining electrodes (*2*, *3*), shielding electrode (*4*), foliated textolite glass (*5*), copper supports (*6*), incandescent filament (*7*), and measuring electrodes (A,B,C), (b) Optical grating profile.

directed along the liquid grooves. The electrode B was earthed.

The signal passing through the experimental cell was amplified by a wide-band preamplifier[1)] and detected by a phase-sensitive detector. In the experiments, we measured the phase shift $\Delta\varphi$ and the signal amplitude variation ΔU produced during charging of the measuring cell by electrons. Using the measured values of $\Delta\varphi$ and ΔU, we determined the real G_r and imaginary G_i components of the conductance of the cell. According to the computations made in Refs. 7, the values of G_r and G_i are defined by the real and imaginary components ρ_r and ρ_i of the electron layer resistance, as well as the frequency of plasma oscillations ω_p in the two-dimensional electron system.

Estimates reveal that, under the conditions of such measurements, we can disregard terms containing ρ_i in the expressions for G_r and G_i. In this case, the expressions for G_r and G_i assume the form

$$G_r=-n_s e^2\sum_{q_n}\Lambda_{q_n}\frac{n_s e^2\omega^2\rho_r}{m^2\tilde{\omega}_p^4+(n_s e^2\omega\rho_r)^2};\tag{1}$$

$$G_i=-n_s e^2\sum_{q_n}\Lambda_{q_n}\frac{m\omega^2\omega_p}{m^2\tilde{\omega}_p^4+(n_s e^2\omega\rho_r)^2}+g_0.\tag{2}$$

Here, e and m are the electron charge and mass, n_s is the average density of electrons in the conducting channels, ω the cyclic frequency, $\tilde{\omega}_p$ the plasma frequency in conducting channels, q_n the wave vector of plasma oscillations, and q_0 the conductance of the cell in the absence of electrons. Since the plasma wave in a quasi-one-dimensional system can propagate only in one direction, summation in Eqs. (1) and (2) is carried out over wave vectors of oscillations directed along the conducting channels. The quantities q_n are determined by the length L_x of the grooves. For a rectangular geometry and quasi-one-dimensional channels, the coefficient Λ_{q_n} was taken from Ref. 6.

The estimates obtained from an analysis of the experimental data show that for the values of H used in this work, the total resistance of all channels was quite large, and hence the condition $m\tilde{\omega}_p^2\ll n_s e^2\omega\rho_r$ is satisfied. Moreover, experiments reveal that, during charging of the cell by electrons, the signal amplitude varies by just a few percent, while the phase shift turned out to be of the order of a few degrees. This means that we can disregard the contribution from electrons to G_i, and we can write $G_i\approx g_0$. In this case, the quantity tan $\Delta\varphi$, which is defined by the ratio of the quantities G_r and G_i, can be presented in the form

$$\tan\ \Delta\varphi\approx\Delta\varphi=-\frac{1}{g_0}\sum_{q_n}\Lambda_{q_n}\sigma,\tag{3}$$

where the quantity $\sigma=1/\rho_r$ corresponds to the conductivity of the channels over an area of 1 cm^2.

The electron density at the surface of liquid helium wetting the substrate was determined from the condition of complete charge saturation. Note that the signal from SE appears, as a rule, starting from a certain value $V_\perp$, thus pointing towards a slight initial charging of the substrate. The electron density in each experiment was determined by plotting the dependence of $\Delta\varphi$ on $V_\perp$. While recording this dependence, the liquid surface was charged each time at a new value of $V_\perp$ at which the quantity $\Delta\varphi$ was measured. The dependence of $\Delta\varphi$ on $V_\perp$ was practically linear. Upon a decrease in voltage, the curve $\Delta\varphi(V_\perp)$ was displaced, i.e., a slight hysteresis was observed. Unfortunately, a spread of about 30% was observed in the value of $\Delta\varphi$ in different experiments for the same values of H, $V_\perp$, and T. Such a spread is probably caused by the presence of a small number of impurities of solidified gases on the substrate, which could vary from experiment to experiment, by uncontrollable charging of the substrate, as well as by an uncertainty in determining the value of H. However, the results showed a very good reproducibility in the course of a single experiment. The total number of electrons over 1 cm^2 of the liquid surface was determined from the condition

$$n_0=\frac{V_\perp-V_\perp^k}{eC},$$

where $C=\varepsilon/4\pi d$.

Figure 2 shows typical temperature dependences of $\Delta\varphi$ and σ for values of H equal to 1.8 (curve *1*) and 0.8 mm (curve *2*). It can be seen that the smaller the value of H, the larger the value of σ, the dependence of σ on T being the steeper, the larger the value of H. An analysis of the experimental data shows that curve *1* can be described by the dependence

$$\sigma=\frac{\alpha}{T}\exp(-E/T),\tag{4}$$

where the coefficients α and E do not depend on temperature. For curve *1*, these quantities have the following values: $\alpha=(4\pm0.1)\cdot10^4\Omega^{-1}\cdot$K, $E=(6\pm0.2)$K. It can be seen that

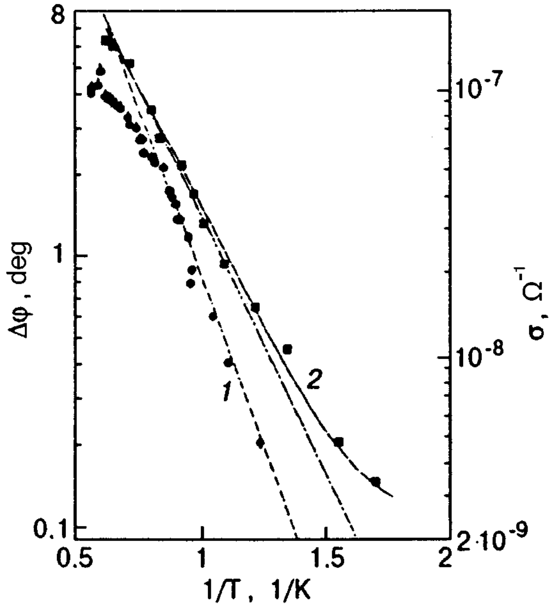

FIG. 2. Temperature dependences of the phase shift $\Delta\varphi$ of the signal transmitted through the experimental cell and electron conductivity σ in $Q1D$ channels for $n_s = 6.7\cdot 10^8$ cm^{-2}, $H = 1.8$ (●) and 0.8 mm (■). The dotted and dashed curves correspond to the dependence $\sigma = (\alpha/T)\exp(-E/T)\Omega^{-1}$ with $\alpha = (4\pm 0.1)\cdot 10^{-4}\Omega^{-1}\cdot$K, $E = (6\pm 0.2)$K; and $\alpha = (7.8\pm 0.9)\times 10^{-6}\Omega^{-1}\cdot$K, $E = (5.4\pm 0.2)$K; respectively, while the solid cuve describes the dependence $\sigma = (\alpha/T)\exp(-E/T) + (\beta/T)\exp(-E_1/T)\Omega^{-1}$, $E = (5.4\pm 0.2)$K, $E_1 - 0.05$ K. $\alpha = (7.8\pm 0.9)\cdot 10^{-6}\Omega^{-1}\cdot$K, $\beta = (4\pm 0.5)\times 10^{-10}\Omega^{-1}\cdot$K.

curve *2* displays a departure from the mono exponential dependence. An analysis of the data reveals that this curve can be described satisfactorily by the expression

$$\sigma = \frac{\alpha}{T}\exp(-E/T) + \frac{\beta}{T}\exp(-E_1/T) \tag{5}$$

with coefficients $\alpha = (7.8\pm 0.9)\cdot 10^{-6}\Omega^{-1}\cdot$K, $E = (5.4\pm 0.2)$K, $\beta = (4\pm 0.5)\cdot 10^{-10}\Omega^{-1}\cdot$K, and $E_1 \simeq 0.05$ K.

The experimental dependences of σ on T indicate that carriers are localized in $Q1D$ channels. In the case of classical thermally activated motion of localized carriers, the conductivity is described by the following expression:

$$\sigma = \frac{n_s e^2 \nu_0 a_0^2}{k_B T}\exp(-E/T), \tag{6}$$

where k_B is the Boltzmann constant, a_0 is the mean separation between potential wells in which the electrons are localized, ν_0 the electron vibrational frequency in potential wells, and E the height of the potential barrier.

The obtained results allow us to estimate the value of ν_0. For this purpose, we must know the values of n_s and a_0. During charging of the surface of helium covering the substrate, plane segments of the helium film are charged as well as the liquid channels. Our earlier calculations show[4] that, for a given value of H, the number density of electrons over a thin helium film is about double the value of electron density over the grooves with a thick helium layer. Knowing the total number of electrons over a unit area of helium surface and the relative areas of the thin helium film and liquid channels on the substrate, we can determine the value of n_s. Such calculations were made by using the condition of constant potential over the charged helium surface. Since the width of channels exceeds the mean separation between electrons insignificantly, this condition is not satisfied exactly, and the computation of n_s is approximate. The quantity a_0 defining the characteristic scale of variation of the potential relief in a liquid channel is determined by the mean separation between electrons localized over a thin helium film. Thus, knowing n_s and a_0 and using (6) with the corresponding activation energy E, we can determine the mean frequency ν_0 of electron oscillations in potential wells. For curves *1* and *2*, these frequencies are found to be $\sim 1.0\cdot 10^{11}$ s^{-1} and $\sim 5\cdot 10^{10}$ s^{-1}, respectively.

At temperatures T below 0.8 K, curve *2* exhibits a deviation from the monoexponential dependence. Two possible explanations can be given for this effect. The first one is associated with the assumption that two types of potential wells of different depths exist in Q1D channels. The number of carriers in deeper potential wells is larger than in shallower wells. At relatively high temperatures, carriers in deep potential wells play the main role in transport phenomena, while at low temperatures, when the mobility of such carriers becomes small, the main contribution to the conductivity comes from the electrons in shallower potential wells. Another possible reason behind the observed effect may be the emergence of quantum effects of electron tunneling from one potential well to another in the electron mobility at $T < 0.8$ K.

A characteristic feature of the system under consideration is that there is a certain spread in the values of potential well parameters in $Q1D$ channels. This spread is probably not significant since at relatively high temperatures the data are described quite well by a single activation energy exponential. However, even a slight variation of the potential well parameters or a nonuniformity in their distribution along a channel can considerably affect the behavior of carrier conductivity in $Q1D$ channels. In particular, displacement of energy levels in potential wells may lead to tunneling if energy levels in adjacent potential wells coincide as a result of fluctuations. It should be borne in mind that electrons localized in $Q1D$ channels will form dimples (ripplon polarons) at the surface of liquid helium. The picture is further complicated due to the fact that the potential well may contain several potential levels.

Analyzing the diffusion D of ^{3}He impurities in crystals of solid helium, Kagan[8] showed that as the temperature is lowered, the emerging quantum effects make the dependence of D on T weaker than the dependence corresponding to the classical activation motion of particles. The effects observed by us in this work are similar to a certain extent to those observed in Ref. 8, with the only stipulation that the spread of potential well parameters in the present case may further complicate the picture. Finally, we observe that the transition of a particle from one potential well to another may involve absorption or emission of ripplons. Unfortunately, a theory of this effect does not exist at present, and a quantitative comparison of the experimental and theoretical data is not possible.

It was mentioned above that the condition $m\tilde{\omega}_p^2 \ll n_s e^2 \omega \rho_r$ is satisfied in our experiments. This relation allows us to estimate the upper limit of the quantity $\tilde{\omega}_p$ which turns out to be below ~ 1 GHz in the present case. This value one or two order of magnitude lower than the characteristic oscillation frequency ν_0 of electrons in a potential well. Such an estimate does not contradict the data of Ref. 6 where it is shown that the maximum value of $\tilde{\omega}_p$ for the grating used by the authors does not exceed ~ 900 MHz. The fact that $\tilde{\omega}_p$ is much smaller than ν_0 indicates that the electrons localized in potential wells form dimples at the surface of liquid helium,[9] and the effective mass m^* of an electron-dimple complex is much larger than the free electron mass.

It was shown by Chaplik[10] that one-dimensional electron systems contain a longitudinal branch of plasma oscillations with an energy-momentum relation

$$\omega_\parallel \approx \frac{2e^2 k}{ma} \ln \frac{1}{ka},$$

where k is the wave vector of oscillations, and a is the mean separation between electrons. According to what has been stated above, two optical modes of plasma oscillations may exist on the helium surface in $Q1D$ channels under localization conditions. The high-frequency mode is associated with electron oscillations, and its energy-momentum relation has the form

$$\omega_p^2 = (2\pi\nu_0)^2 + \omega_\parallel^2. \quad (7)$$

The low-frequency mode is associated with the oscillations of electron-dimple complexes, and its energy-momentum relation has the form

$$\tilde{\omega}_p^2(k) = \omega_\alpha^2 + \frac{2e^2 k}{m^* a} \ln \frac{1}{ka}, \quad (8)$$

where ω_α is the oscillation frequency of electron-dimple complexes in potential wells. In view of a spread in the potential well parameters, the plasma oscillation spectra (7) and (8) obviously have a certain dispersion. However, since the experimental data on conductivity in $Q1D$ channels are described correctly by an exponential relation (at least at $T > 0.8$ K), the potential well parameters do not differ significantly from one another, and it can be expected that dispersion in the spectra will not be significant. It should be quite interesting to carry out experimental observation of such plasma oscillation modes.

Thus, we have shown in the present work that, in quasi-one-dimensional electron systems over liquid helium, the electron conductivity under localization conditions decreases exponentially with temperature, the activation energy being of the order of several degrees. At $T < 0.8$ K, the $\sigma(T)$ dependence corresponding to small values of H shows a departure from the exponential law. This is apparently due to the existence of two types of carriers with different activation energies, or to the tunneling of electrons to the neighboring potential wells. It is predicted from an analysis of the experimental data that, under localization conditions, the $Q1D$ channels may contain two optical modes of plasma oscillations. One of these is a high-frequency mode with limiting frequency of electron oscillations in potential wells, while the second is the low-frequency mode whose limiting frequency is determined by oscillations of massive electron-dimple complexes in potential wells.

The authors are grateful to V. N. Grigor'ev for his interest in this research and for fruitful discussions of the results.

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[1)]The authors are obliged to V. V. Dotsenko for his help in designing the measuring system.

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Translated by R. S. Wadhwa