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Anomalies of Conductivity of Quasi-One-Dimensional Surface Electron System over Liquid Helium in the Presence of Non-Uniform Potential

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Abstract We present the results of experimental study of the conductivity of surface electron quasi-one-dimensional system over liquid helium. The measurements are carried out in conducting channels in the presence of inhomogeneous potential. The electron conductivity is measured in temperature range of 0.5–1.9 K covering both electron-ripplon and electron-gas a scattering. The possible qualitative explanation of the effects observed is proposed.

Keywords Surface electrons · Superfluid helium · Low-dimensional system

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1 Introduction

The problem of electron transport in the systems of reduced dimensionality over liquid helium still attracts noticeable attention. Last years this interest was strongly enhanced after proposing [1] and realization [2] of the quasi-one-dimensional (Q1D) electron nanosystems using the specific properties of superfluid helium. As a result, the system of conducting channels is realized where electrons are located near the bottom of the channels which walls are distorted by the capillary forces. The characteristic scale of electron localization across the channel $\sqrt{\hbar/m\omega_0}$ is about 10^{-6} cm being essentially smaller than the typical value of curvature radius of the liquid in the channel, $R = \alpha/(\rho g h) \simeq 10^{-3}$–$10^{-4}$ cm (here α is surface tension coefficient, ρ is liquid density, g being gravity acceleration, and h the height of the substrate over bulk helium, m being electron mass). Note that the estimation of the effective

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width of conducting channel [3] according to the expression $a = 2\sqrt{eRn_l/E_\perp}$ valid for $a < R$, gives the value $a \lesssim R$ (e is electron charge, $E_\perp$ is pressing electric field normal to liquid surface, $E_\perp = V_\perp/d$, $d \lesssim 1$ mm is the effective distance between the upper electrode and lower one covered by dielectric substrate and liquid helium with corresponding dielectric constants, n_l is linear electron density). This gives grounds to use the oscillatory approximation to describe the electron motion across the channel with effective frequency $\omega_0 = \sqrt{eE_\perp/(mR)}$. The energy gap between oscillatory subbands $\hbar\omega_0 \lesssim 0.3$ K. This means that not only ground but also excited subbands do contribute into electron transport in temperature range investigated.

The electron conductivity in Q1D systems over liquid helium was studied intensively both experimentally and theoretically (see, for example [4, 5]). The main attention was paid to the "clean" conducting channels allowing to study the influence of electron-ripplon and electron-gas scatterings. Among the effects registered one should note the observation of the weak localization of the charge carriers on the gas atoms in classical Q1D electron system [6]. At the same time the Q1D electron system over helium is demonstrated to be the attractive tool to investigate the influence of non-uniform potential along the conducting channel on the transport in the system [7]. It was shown that non-uniform potential changes significantly the dependence of electron mobility along the channel as a function of $E_\perp$. Note that pressing electric field influences strongly the scale of electron localization across and along the channel and intensity of electron interaction with both scatterers and roughness of the substrate and channel walls. The aim of present work is the detailed experimental study of the influence of non-uniform potential, acting in the conducting channel, on electron mobility. The experiments are performed in wide range of pressing electric field $E_\perp = 0$–1600 V/cm at temperatures 0.5–1.9 K.

2 Experiment

The construction of measuring cell, the substrate, and measurement method are similar to those described in [7]. In Fig. 1, we depict the main part of experimental cell. The cell contains two rectangular measuring electrodes (1) 5×9 mm^2 located in the same plane and divided by the grounded strip (2) 0.2×9 mm^2. The tungsten wire in the gap of upper pressing electrode was the source of electrons (not shown). The surface density of electrons (4) changed from 10^4 to 10^6 cm^{-2}. The distance between upper (6) and measuring electrodes was $\lesssim$1 mm. The substrate (5) was formed by 45 nylon threads 0.24 mm in diameter. The helium (3) filled the intervals between the

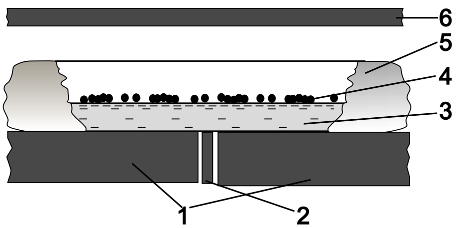

Fig. 1 Fragment of the experimental cell. (1) Rectangular measuring electrodes. (2) The grounded strip. (3) The helium. (4) Surface electrons. (5) The substrate. (6) Upper electrode

threads forming the channels of near semispherical form. The conductivity was measured by Sommer-Tanner method with driving electric field potential up to 30 mV and signal frequency up to 20 kHz. The exciting potential was applied to one of measuring electrodes whereas the measuring current came out from other electrode. We registered both 0° degree and 90° degree components of measuring signal (U_0 and U_{90}, respectively) using the lock-in-amplifier. These components characterize the real and imaginary parts of the inverse electron conductivity. The procedure of the calculation is similar to that used in [8].

3 Results and Discussion

Measuring the mobility of electrons we aimed to check the role of different parameters of the measuring cell influencing the electron mobility. As was noted in [7], the non-uniform potential having effect on the electron transport, could arise both from inhomogeneities across the channel near its walls where the helium thickness is small and film effects are available, and from special structure of measuring electrode. In [7], the fragmenting electrodes were used with a pitch 0.5 mm between periodic depressions of $\sim 10^{-4}$ cm. To make more clear the role of electrode fragmentation, we used, in present experiment, the smooth copper measuring electrodes. In Fig. 2, we depict the typical experimental dependencies of electron conductivity vs pressing electric field to a different nylon substrate. The diameter of threads were 0.09 mm (signed by stars) and 0.24 mm (signed by points and triangles). The measurements were made at $T = 1.4$ K and $T = 0.6$ K, i.e. in the regions of electron-gas and electron-ripplon scattering. The characteristic feature of the dependencies is the anomaly (strong decrease) of the conductivity at some values of $E_\perp$. Qualitatively the dependencies are similar for both temperatures. One notes there is no hysteresis and the position of the anomaly does not depend on both scanning pressing electric field and temperature. One should also note that the position of the anomaly in conductivity changed, from experiment to experiment when the quality of the substrate could change, in narrow interval of 5–10%. We did not observe the dependence of anomaly position neither on driving electric field amplitude nor on the measuring signal

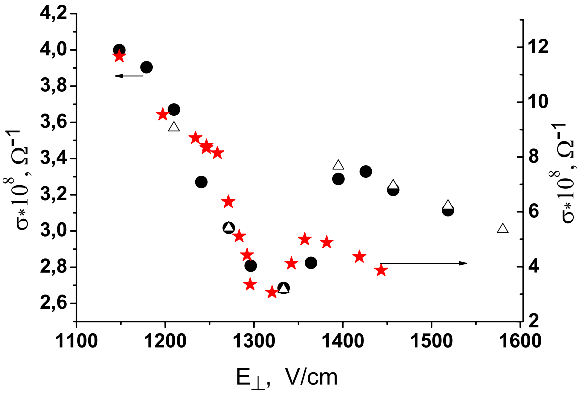

Fig. 2 (Color online) The conductivity of the channel as a function of pressing electric field. The *right axis* (*red stars*) is dependence for $T = 1.4$ K, the *left axis* is for data of $T = 0.6$ K. The *points* and *triangles* are for increasing and decreasing pressing field, respectively

frequency. But the dependence on the electron density and the substrate quality is available. In experiments [7] sometimes the additional anomaly of the conductivity was registered. On a contrary, we did not observe any additional anomalies in actual experiments. Taking into account the different structure of the measuring electrodes in [7] and present work, one can suppose that the second anomaly of [7] would be attributed to the fragmenting the electrodes. It means that the principal reason for anomaly observation is, probably, the non-uniform potential acting across the conducting channel.

Unfortunately one cannot conclude definitely on this potential nature. Analyzing the possible reasons for conductivity anomalies one should note that electrons emitted inside the experimental cell charge not only the grooves filled by bulk helium between the threads but also helium film covering the elevated parts of the substrate. If one increases the pressing field, the electron moves to the center of the groove forming the conducting channels. However a part of electrons is still located in the traps on the roughness covered by film where the imagine forces act as an effective pressing field $E^* \sim D^{-2}$ where D is film thickness. These localized electrons can form the peculiar charged strips. From one hand, these strips may screen the conducting channels from each other. From another hand they produce the additional potential and potential variation along the channel.

One guesses that the observed behavior of the conductivity, probably, is provoked by the influence of pressing electric field on potential along the conducting channel walls. If one increases the pressing field, electrons moves to the channel center localizing on inhomogeneities of channel walls. This results in narrowing the channel and possible formation of electron “lakes” [7]. These “lakes” are connected by narrower “bridges” which size decreases strongly under increasing the pressing potential. The characteristic size of the “bridge” can attain the order of electron de Broglie wavelength (∼300 Å). Under the further increase of $V_\perp$ one should wait for a break of conducting channel after which one has a conductivity inside the isolated electron “lakes”. Note that we observed the “shot effect” in the region of conductivity anomaly. One can suppose the increase of the pressing field can lead to re-localization of electron from one trap to other located more close to the center of conducting channel. As a result the potential acting across the channel increases.

It is interesting to note that qualitatively similar anomalies of the conductivity of surface electrons were observed in two-dimensional system over both very thin superfluid ^{4}He film and normal ^{3}He film covering solid hydrogen [9]. The anomalies were explained by re-localization effects of electrons between potential wells formed over roughness of the film bottom [10].

4 Conclusion

In present work, we observed the anomalies of the conductivity of quasi-one-dimensional electron system localized in conducting channels formed over liquid helium. The anomaly is manifested by local decrease with subsequent growth of electron conductivity at some value of pressing electric potential. There is no hysteresis in anomaly position. The value of pressing potential for which the anomaly is observed does not depend on temperature, signal amplitude and frequency. The qualitative explanation is proposed for the effects observed basing on assumption of the electron localizing on inhomogeneities of channel walls. As a result one observes the narrowing of the channel and possible formation of electron "lakes" connected by "bridges". Other possible explanation is re-localization of electrons between the traps located in the places of reduced thickness of helium. The experiments are planned to be continued.

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