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Localization and Ordering of Carriers in a Quasi-One-Dimensional Electron System on Liquid Helium

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Abstract Charge transport in a quasi-one-dimensional (Q1D) electron system on liquid helium surface is studied in a temperature range 0.1–1.3 K at linear electron densities 6×10^3–10^5 cm^{-1} in confining electric fields up to 1000 V/cm. It is shown that the electron conductivity increases with decreasing temperature T and starts to decrease passing through a maximum at $T \approx 0.8$ K. The plasma frequency ω_p of the electrons in Q1D channels has been estimated; the value of ω_p is much larger than that for free electrons. We attribute this effect to localization of carriers and the formation of polarons (microdimples on the liquid helium surface). The mobility of polarons is smaller than that for free electrons. The decrease in the conductivity at $T < 0.8$ K may be connected with spatial ordering of the polarons in Q1D channels.

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1 Introduction

The electrons localized on the liquid helium (surface electrons, SE) form an extremely pure and homogeneous low-dimensional charge system which is very convenient model for investigation of properties of systems with restricted geometry [1]. Some years ago a method for realization of one-dimensional (1D) and quasi-one-dimensional (Q1D) electron systems on liquid helium surface was proposed [2] and a number of experiments were carried out in such systems. Electron transport and localization of carriers were studied [3, 4]. It was shown that the electron mobility in

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narrow homogeneous conducting channels was rather high at low temperatures, the value of the mobility agrees with theoretical calculations [5]. An anomalous electron transport was observed in wide channels [6, 7]. It was assumed that the effect might be caused either by the charge ordering in a quasi-one-dimensional system [6] or by both the charge ordering and the formation of polarons [7].

In ref. [6], a rectangular potential well was used for confining electrons. In this study the confinement potential for electrons was parabolic. The charge ordering in a parabolic well was considered theoretically in ref. [8]. Thus we can compare our results with theoretical calculations. We studied the anomalous electron transport in the temperature region 0.1–1.3 K at linear electron density in the conducting channels 6×10^3–10^5 cm^{-1}. The holding electric fields were up to 1000 V/cm. The experiments were carried out at frequencies 20 and 100 kHz.

2 Experimental

The experimental cell is shown in Fig. 1a. Fifty optical fibers 0.24 mm in diameter were placed above identical driving and measuring electrodes A and C, of a size 8×15 mm^2. The electrode B placed between electrodes A and C was used to decrease the mutual influence of electrodes A and C. All the electrodes were held at zero potential and negative potential $V_\perp$ was applied to electrodes 2. A negative potential V_g ($|V_g| > |V_\perp|$) was applied to the guard electrode 3. Under these conditions an electron layer with rather sharp boundaries could be formed on the liquid helium surface.

The electrodes A, B, and C were placed at a height H above the liquid helium level. The optical fibers were covered by liquid helium, and channels of bulk liquid helium were thus formed between them. The curvature radius r of the channels was dependent on the height H. On applying a confining electric field $E_\perp$, the electrons localize at the bottom of the liquid channels. The electric field $E_\perp$ forms a parabolic potential well (Fig. 1b). The electrons oscillate in the direction perpendicular to the conducting channels at a frequency $\omega_0 = (eE_\perp/mr)^{1/2}$ (e and m are the charge and mass of an electron, respectively).

An ac voltage 10–30 mV from a generator was applied to the electrode A. The signal transmitted through the experimental cell was taken from the electrode C and

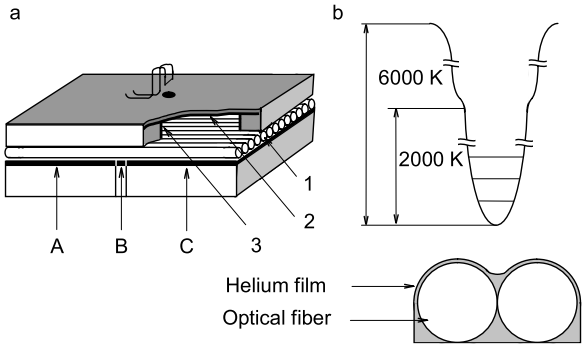

Fig. 1 **a** Experimental cell. *A*, *B*, *C*—electrodes, *1*—optical fibers, *2*—upper electrode, *3*—guard electrode; **b** Potential energy of an electron in a liquid channel, $E_\perp = 1000$ V/cm

measured by a lock-in-amplifier. The driving electric field was directed along the liquid channels. We measured the 0° and 90° components of the signal. This allowed us to determine the real G_r and imaginary G_i parts of the conductance of the cell with electrons [4] and thus to find the conductivity σ and a parameter a in the Q1D channels. The parameter a is expressed as

$$a = \frac{m\omega_p^2 - e\omega\chi_2\lambda}{n_s}. \tag{1}$$

Here χ_2 is imaginary part of the resistance for one electron, n_s is the average density of the mobile electrons, ω_p is the frequency of the plasma waves propagating in the system of parallel conducting channels, λ is the parameter depending on the cell geometry [4]. The parameter a is a formal value, which depends on ω_p and χ_2. For free electrons the second term in (1) is much smaller than the first one, as a result $a = m\omega_p^2/n_s$. In this case a depends only on the cell geometry [4].

3 Results and Discussion

The conductivity σ plotted as a function of temperature T for different average electron densities n_s is shown in Fig. 2a. Curve 1 corresponds to the electron density $n_s = 3.7 \times 10^6$ cm^{-2} (saturated case, the linear electron density is $n_l = 9 \times 10^4$ cm^{-1}), curve 2 and 3 correspond to unsaturated case ($n_s = 5 \times 10^5$ and 2.5×10^5 cm^{-2}, corresponding linear electron densities $n_l = 1.25 \times 10^4$ and 6×10^3 cm^{-1}, respectively). It is seen that the conductivity increases with decreasing temperature, passes through a maximum at $T_{\max} \sim 0.7$–0.8 K and then starts to decrease. The temperature $T_{\max}$ is practically independent of the electron density n_s. At temperature $T \simeq 0.2$ K, the conductivity σ reaches the value approximately equal to those in the gas scattering region.

Figure 2b shows temperature dependencies of a. We see that a increases with the holding electric field $V_\perp$. The magnitude of a is dependent on n_s, but practically independent of temperature in the whole temperature interval. It is seen from Figs. 2a and 2b that a is larger for the conducting channels with lower value of σ.

It is found that the experimental a-value is about two orders of magnitude higher than the theoretical one [4]. The difference can be explained by localization of the

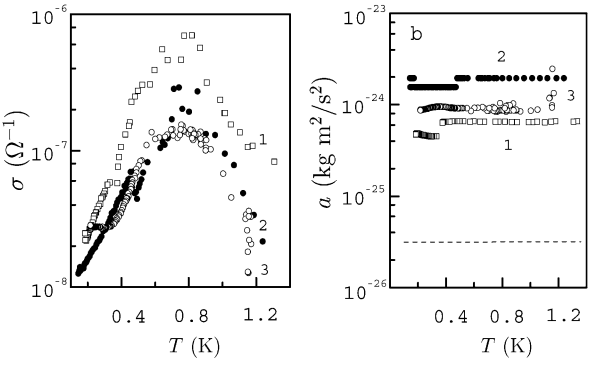

Fig. 2 **a** Temperature dependence of the conductivity of Q1D channels, and **b** the value of a for (*1*) $V_\perp = 10$ V (saturated case), (*2*) $V_\perp = 80$ V, (*3*) $V_\perp = 40$ V. *Dashed line* is the theory [4]

electrons in the conducting channels. During charging the liquid helium surface, some electrons localize on the thin helium film. They are practically immobile and formed a random potential in which free electrons move. This leads to carrier localization.

The authors in ref. [6], who observed anomalous resistivity in a conducting channel on the liquid helium surface, attributed this behavior to spatial ordering of the electrons in the conducting channel.

Ordering in a quasi-one-dimensional electron system with a parabolic confining potential (used in our work) was considered in ref. [8]. The melting of such a system at a finite temperature was investigated by Monte Carlo simulations using the modified Lindemann criterion. The authors constructed the phase diagram "liquid-ordering state" for a Q1D electron system. The results obtained were presented in terms of the reduced melting temperature $T'_m = T_m/T_0$ and the dimensionless linear density of particles $\tilde{n}_l = lr_0/a_0$, where l is the number of electron chains in a Q1D system in the ordering state, a_0 is the average distance between the particles in the chain. The value T_0 is expressed as $T_0 = (m\omega_0^2 e^4/2\varepsilon^2)^{1/3}k^{-1}$, where ε is the dielectric constant of the substrate on which conducting channels are formed, k is the Boltzman constant. Proceeding from the consideration of ref. [8], we determined the melting temperature T_m for curves 1–3 in Fig. 2a. The linear electron density was estimated from the theoretical value [5] for the mobility in a Q1D system at high temperature ($\sim$1.3 K). The calculation shows that T_m in curves 1–3 of Fig. 2a is not higher than $\sim$0.2 K and much lower than the temperature $T_{\max}$. The $T_{\max}$ is approximately the same for curves 1–3. Apparently, it means that the anomalous electron transport observed in our experiments is not connected with spatial ordering of free electrons in a Q1D electron system.

It is likely that the anomalous electron transport observed in this work is connected with localization of the electrons caused by a random potential along the channel. Such a potential can be generated by electrons localized on the thin helium film near the edges of the channels. Comparison of experimental and theoretical values of a supports the suggestion about carrier localization in the Q1D channels.

As it was noted for unlocalized electrons, the value a is expressed as $a \approx m\omega_q^2/n_s$. The plasma frequency ω_q for a system of parallel ideal conducting channels was calculated in [4]. For our cell, a is $\sim 2 \times 10^{-26}$ kg m^2 s^{-2}. It is about two order of magnitude lower than the experimental values of a. To illustrate how a-value changes when the carrier localization takes place, we consider a two-dimensional system of electrons localized in parabolic potential wells. The conductivity σ of such a system is

$$\sigma = \frac{i\omega n_s e^2}{m(\Omega_0^2 - \omega^2 + 2i\omega\lambda_0)}, \tag{2}$$

where Ω_0 is the eigenfrequency of an electron in the potential well, $\lambda_0 = 1/2\tau$ is the attenuation coefficient (τ is the relaxation time). Based to the result of ref. [4], we can write the real χ_1 and imaginary χ_2 parts of the resistance of the electron layer as

$$\chi_1 = \frac{m}{e\tau}, \tag{3}$$

$$\chi_2 = -\frac{m(\Omega_0^2 - \omega^2)}{e\omega}. \tag{4}$$

Using (1) and (4), we obtain

$$a = \frac{m(\omega_q^2 + \Omega_0^2\lambda) - m\omega^2\lambda}{n_s}. \tag{5}$$

It is seen that (5) has an additional term so-called "optical" mode reflecting the fact of particle localization.

Equation (5) makes it possible to estimate Ω_0: $\Omega_0 = 1.6 \times 10^8$, 0.65×10^8, 1.5×10^8 s^{-1} for curves 1–3 in Fig. 2, respectively. Note that the experimental value of a is practically independent of temperature at $T = 0.2$–1.1 K.

Knowing Ω_0, we can estimate the localization length of the particles. It is $\sim 10^{-4}$ cm for curves 1–3. This kind of localization can lead to the formation of electron polarons with the effective mass much larger than that of a free electron. T_0 depends on the particle mass. According to the phase diagram, the relation $T_m/T_0 \leq 15 \times 10^{-3}$ holds for a Q1D system [8] consisting of a several linear chains. Assuming that the $T_{\max}$ is the temperature at which the ordering begins in the system of polarons, we can estimate the effective mass of the polaron m_p: $m_p \sim 100m$. This value seems to be reasonable. The polaron ordering can change the character of carrier transport in a Q1D electron system. Additional experiments are needed to explain the nature of the anomalous carrier transport in a Q1D electron system.

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