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Temperature dependence of electrical conductance in 1D electron system formed on liquid helium surface

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Abstract

The electrical conductance of one-dimensional (1D) electrons confined in the channels created on the surface of liquid helium was measured as a function of temperature down to 50 mK. A peak around 0.2 K, which was the evidence for 1D character originating in the intersubband transitions, was observed for the first time. The result of the temperature dependence is in agreement with an existing theory for 1D electron system. Below 0.2 K, the electrons occupy the ground state and behave as nearly ideal 1D system.

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Keywords: 1D electrons; Conductivity; Surface electrons; Superfluid helium

The quasi-one-dimensional (Q1D) electron system has been created by confining electrons in the linear channels formed on the curved helium surface [1–4]. This system has an advantage that the impurities and defects are free in comparison with the solid state one. Sokolov et al. [7] calculated the mobility for this system as a function of temperature. According to their theory, the characteristic point for this system is that there exists a maximum in the mobility around 0.2 K. However, this behavior has not been observed yet.

The real experiments are different from the ideal theory. The systems created so far are still narrow 2D because the width of the channel is larger than the inter-electron distance. The electrons near the edge of the channel contribute to the conductance. In addition, since the temperature is high, the system is not in the ground state and it is not strictly a pure 1D.

In this paper, we show the experimental results measured down to 50 mK. We observed a peak at 0.2 K in the conductance for the first time, which originates in the intersubband transitions. This is the clear evidence for the 1D electron system in the ground state.

To create channels, we used a glass optical-diffraction-grating which has 2000 parallel linear grooves on the surface. The cross-section view of the groove shows a very shallow V-shape. The distance between the adjacent grooves is 5 μm, the width of the groove is 3.8 μm, and the depth is 0.2 μm at the center. The superfluid helium comes up to the surface of the grating under the action of the capillary force and fills the grooves. The helium surface sags 0.05 μm at the center of the groove by a balance of the surface tension and the gravity. The electrons were fed from a tungsten filament and the conductance was measured by so-called Sommer–Tanner method.

Different from the 2D case, the 1D electrons' motion perpendicular to the channel is quantized and the discrete subbands are formed, because they are subjected to the parabolic confinement potential. According to the theoretical calculation [7], both the intersubband transitions and the increase of the population of electrons in higher subbands become important below 0.2 K. As a result, the conductance shows a maximum near 0.2 K. If the maximum is found, it is a strong evidence for the 1D character.

The 2D conductance is known to be a monotonic increasing function as the temperature is lowered [6]. However, our obtained result is quite different from that of 2D electrons as

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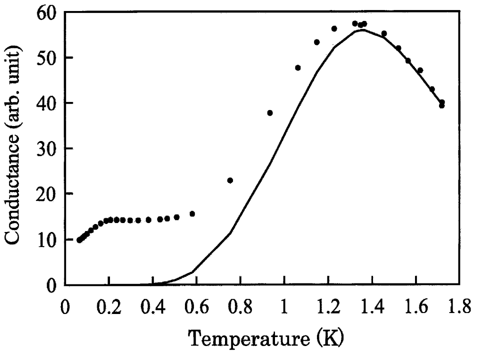

Fig. 1. Measured conductance as a function of temperature. The vertical electric field is $E_{\perp} = 1000$ V/cm. Dots are experimental values and the solid line is a contribution from the electrons near the edge of the grooves, $1/(R_L + R_G)$.

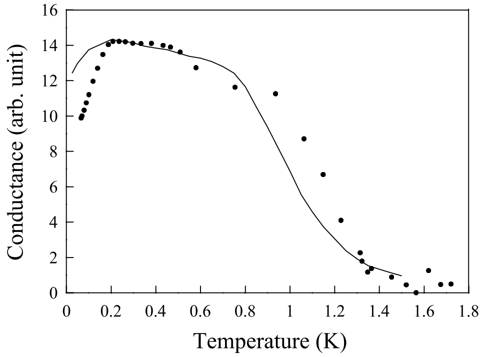

Fig. 2. Conductance of electrons in the center of the grooves as a function of temperature. Dots are obtained by subtracting $1/(R_L + R_G)$ (solid line) from the experimental data (dots) in Fig. 1. The solid line is a calculation [7].

shown in Fig. 1. To explain this complicated behavior, we consider the contribution of electrons existing near the edge of the grooves [8]. In our experimental condition, the average electron separation is calculated to be roughly 0.2 μm, assuming that in depositing the electrons the plateaus and grooves are uniformly covered with electrons at the saturated density. However, it is shown from the calculation that the electron density at the center of the groove is roughly $\frac{1}{3}$ of that on the plateau, because the distance between the electron and the image charge is larger at the center than on the plateau. Hence, the inter-electron distance in the groove is roughly 0.6 μm.

The width of the groove is larger than the inter-electron distance and so a few electrons distribute over the width of the groove. In this sense, the system is not pure 1D but Q1D. But the electrons in the center of the groove are expected to behave as nearly pure 1D electrons, because the helium thickness is large and hence the image force acting from the glass grating is small. In contrast, the electrons near the edge of the groove are captured by the random image force caused from the surface roughness of the grating because the helium thickness near the edge is small. For this reason, the electrons near the edge localize due to the potential irregularities at low temperatures.

Since the film thickness on the plateau is 30 nm, the electrons are immobile there. Based on the experimental facts [5], we can express the measured conductance as a sum of the conductance of the pure 1D electrons, $1/R_{1D}$, in the center of the groove and that of the 2D electrons near the edge of the groove, $1/(R_L + R_G)$. Here, R_L is the resistance caused by the localization due to the potential irregularities and R_G is the resistance caused by the collision with the helium gas. The effect of electron–ripplon scattering is very small compared with the localization effect and it is neglected. These resistances are expressed as $R_L = R_{L0}T\exp(4.2/T)$ [5] and $R_G = R_{G0}\exp(-8.5/T)$ [6], where the numerical values are determined from the data in each experiment, R_{L0} and R_{G0} are adjustable parameters and T(K) is the absolute temperature. The conductance of the pure 1D electrons, $1/R_{1D}$, is obtained by subtracting $1/(R_L + R_G)$ from the measured conductance.

In Fig. 2, the conductance of the 1D electrons in the center of the grooves is plotted with dots as a function of temperature. The theoretical conductance calculated from the Sokolov et al.'s mobility data [7] is also depicted by a solid line. A factor is adjusted to agree with the experimental data at $T = 0.2$ K. It appears that the experimental data essentially agree with the theoretical temperature dependence. Above 0.8 K, the conductance is governed with the scattering by helium gas atoms. Below 0.8 K, the electron–ripplon scattering is dominant. The most striking feature is the existence of a maximum at 0.2 K in agreement with the theory. This is the direct evidence for the 1D character which is observed for the first time.

Below 0.2 K, the electrons are in the ground state and therefore it is nearly ideal 1D electron system.

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