Mobility of electrons on helium film capillary condensed on two dimensionally corrugated surface of dielectric substrate

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Abstract. Electrical conductivity of electrons on helium film covering a two dimensionally corrugated dielectric substrate was measured in a temperature interval between 0.4 and 1.64 K. As the temperature decreased from 1.5 K, the electrical conductivity decreases and approaches gradually to zero around 0.4 K. This temperature dependence is different from that measured in 2D electron system on bulk liquid helium. In order to understand the effect of the dielectric substrate, the dependences of electrical conductivity on magnetic field were measured by using a Corbino electrode and the mobility was evaluated in different temperatures. The results revealed that the mobility of electrons increases as the temperature decreases. Combining the data of electrical conductivity and the mobility, it is deduced that the decrease in conductivity as the temperature decreases is due to the decrease in number of mobile electrons.

1. Introduction

Electrons in the surface state of liquid helium form a pure and clean two dimensional electron system (2DES). To reduce the dimensionality of this 2DES, first idea was independently proposed by two groups$^{[1,2]}$. The idea uses a dielectric substrate on which parallel grooves are formed. When the level of superfluid helium is set below the surface of the substrate, the helium film goes up and flows into the grooves. Electrons are fed in the grooves to form multi-channel electron chains.

Experimental realization of quasi-one-dimensional (Q1D) electron system by Kovdrya and Nikolaenko$^{[3]}$ using an optical grating as the substrate opened a new research direction in this field. The developments in this area show a trend of more sophisticated experiments to bring micro fabrication techniques$^{[4]}$, to manipulate small number of electrons$^{[5]}$, etc.

In the Q1D electron system, electrical conductivity has been measured as a function of temperature$^{[6,7]}$. The electrical conductivity for the Q1D system decreases as the temperature is lowered showing different behaviour from the 2DES on bulk helium. This type of temperature dependence is commonly observed in such a system that the dielectric substrates are used to suspend the helium surface. A question still exists which parameter is responsible for the temperature dependence, the mobility or the density of electrons. The mobility has been measured once at a fixed temperature$^{[8]}$, but its temperature dependence has not been observed.

To clarify this problem, in this research, we measured the mobility of electrons on thick helium film suspended between elevations of a two dimensionally corrugated surface of a plastic film. In this system, thick helium film can be created between the elevations and a large mobility is expected. The
use of Corbino electrode allows us to obtain absolute and accurate values of the mobility of electrons on suspended film independently from density of electrons. From the mobility data, we deduced the temperature dependence of the electron density.

2. Experimental

Figure 1 (a) schematically illustrates a side-view of electrode arrangement. A 0.1 mm thick plastic film whose surface is two dimensionally corrugated is laid on a 1.3 mm thick glass substrate placed on the lower concentric Corbino electrode with a diameter of 25 mm. An AFM image of surface geometry of the plastic film is shown in Fig. 1 (b); note that the size in z direction is exaggerated for clarity. The surface height is modulated in sinusoidal form in both x and y direction. The spatial periodicity is 5 μm and the height from bottom to top is 0.45 μm. Liquid helium was condensed in a sample chamber and the helium level was set at a position by 0.5 mm lower than the surface of plastic film.

![Figure 1](image)

**Figure 1.** (a) Schematic drawing of the electrodes and measurement system. The lower Corbino electrode consists of three concentric parts, outer diameters of which are 9, 11, and 17 mm. (b) AFM image of two dimensionally corrugated surface of the plastic film. Spatial periodicity is 5 μm in both x and y-direction. Distance between bottom and top in z direction is 0.45 μm. The vertical scale is exaggerated. (c) Magnified cross-section image of the surface of plastic film (schematic). Liquid helium flows in the grooves of the plastic film and form a thick helium film. The image is not to the scale.

Superfluid helium wets the solid materials and capillary condenses on the plastic film. The helium is suspended from the tops by surface tension to form a curved surface. The sag of the surface Δs can be represented as $\Delta s = a^2 \rho g H / 8a$, where $a$ is the distance between the adjacent two tops, $g$ is the acceleration of gravity, $H$ is the height of plastic film measured from helium level, $\alpha$ and $\rho$ are the surface tension and mass density of helium, respectively. Using $a = 5 \mu m$, we get $\Delta s = 6 \times 10^{-9}$ m: the surface of helium is almost flat.

Electrons were supplied through a hole on the upper electrode by briefly turning on a small tungsten filament. Once electrons have been deposited on the helium surface, they did not escape while experiments were conducted. The lower electrodes were dc grounded and a negative voltage was applied to the upper electrode to press the electrons downward. A magnetic field perpendicular to the electron sheet could be applied.

An ac voltage 0.1 V with a frequency of 10 kHz was applied to the lower central electrode to drive the electrons in radial direction. When a magnetic field is applied perpendicular to the electrodes, Lorentz force acts on the electrons to drive in the direction along the circumference of the electrodes. The voltage induced on the outer electrode by motion of electrons is measured by a lock-in-amplifier. The narrow ring-shaped electrode between the central and outer electrode is grounded to reduce a direct...
capacitive coupling between them for a purpose of minimizing a cross-talk. The electrical conductivity of electrons is obtained from in-phase and 90 degree out-of-phase signal voltage by calculation based on Mehrotra’s analysis[9].

The electrons tend to move along the grooves which are running in 2 rectangle directions on the surface of plastic film. The electric field is formed in the radial direction but the grooves are not necessarily parallel to the electric field. Therefore, the measured conductivity is an average one over the all area of the plastic film.

The sample chamber is cooled by dilution refrigerator and the temperature is controlled during the experiment between 0.4 and 1.64 K.

3. Experimental results and discussion

Figure 2 shows a result of electrical conductivity of electrons when the magnetic field is not applied. As the temperature $T$ decreases from 1.64 K down to 1.5 K, the electrical conductivity $\sigma$ increases a little. This behaviour is the same as that for electrons on bulk liquid helium. The scattering in this temperature range is governed by collision with helium gas atoms: since the density of gas atoms diminishes as $T$ goes down, the conductivity $\sigma$ increases.

![Figure 2. Temperature dependence of electrical conductivity $\sigma$ of 2D electrons on suspended helium film, formed on a two dimensionally corrugated plastic film.](image)

![Figure 3. Temperature dependence of mobility $\mu$ and density of mobile electrons $n$. The lines are simply guide to the eye.](image)

Figure 2 clearly shows that the conductivity decreases monotonically as the temperature goes down below 1.5 K. Similar temperature dependences have been observed in such a system that the dielectric substrate is used underneath the liquid helium[6,7]. This behaviour is quite different from that for electrons on bulk liquid helium. The conductivity of electrons on bulk liquid helium contrarily increases as the temperature is lowered. The temperature dependence of electrons on bulk liquid helium in this temperature range has been explained in terms of the scattering by surface wave quanta ripplons.

The conductivity is determined by the mobility and the density of mobile electrons as $\sigma = en\mu$, where $e$ is the charge of electron, $n$ is the density of ‘mobile’ electrons, $\mu$ is the mobility of electrons. For electrons on bulk liquid helium, the $n$ does not change, and the $\mu$ increases monotonically as the temperature goes down. However, for electrons on liquid helium which covers the dielectric substrate, the $n$ may change due to a strong image force acting on the electrons from underneath dielectric. Actually, there are some experimental evidences which show strong electron localization on thin liquid helium film[10].

In order to clarify which is responsible for this temperature dependence, we determined $\mu$ from the results of dependence of $\sigma$ on magnetic field $B$ in a similar way in refs. [8] and [11]. In a single-
relaxation-time approximation, the conductivity tensor $\sigma_{xx}$ and resistivity tensor $\rho_{xx}$ of the 2D electrons in the presence of perpendicular magnetic field are expressed as,

$$\sigma_{xx} = \frac{en\mu}{1 + (\mu B)^2} \quad \text{and} \quad \rho_{xx} = \frac{1}{\sigma_{xx}} = \frac{\mu B^2}{ne} + \frac{1}{ne\mu}.$$  \tag{1}

We can obtain the mobility $\mu$ from a plot of $\rho_{xx}$ vs. $B^2$, since the ratio of the slope and the intercept on vertical axis is equal to $\mu^2$.

In Fig. 3, the data of $\mu$ obtained by above-mentioned method are shown as a function of temperature. As the temperature decreases from 1.35 K to 0.4 K, the value of $\mu$ increases from 1.2 to 5 m$^2$/Vs. Comparing these data with the one on bulk helium, the value of $\mu$ is in the same order in high temperature range but it is 3 orders lower than that on bulk helium in low temperature range.

The temperature dependence of $\mu$ in Fig. 3 is quite opposite to that of $\sigma$ in Fig. 2. From this fact we can deduce that the temperature dependence of $\sigma$ is caused by temperature dependence of $n$, since a relation $\sigma = en\mu$ holds. Once the value of $\mu$ is obtained in each temperature, we can estimate the value of $n$ with the data of $\sigma$ in Fig. 2. The estimated values of $n$ are plotted in Fig. 3 together. The temperature dependence of $n$ is similar to that of $\sigma$ in Fig. 2. This result strongly suggests that the decrease in conductivity as the temperature is lowered below 1.5 K is due to the decrease in the number of ‘mobile’ electrons.

A question arises why the number of mobile electrons decreases as the temperature decreases. A possible explanation is the following. Electrons have a strong affinity to solid dielectrics[10]. As one can see from Fig. 1 (c), the helium thickness is largest at the bottom and it becomes gradually thinner approaching to the top. The electrons are attracted to the plastic film by image force. The plastic film has a random surface roughness, and creates random potential for electrons. In high temperature region where the thermal activation energy is higher than the potential depth, the electrons can move freely. However, in low temperature region, the thermal energy is not high enough to activate the electrons. Therefore, the electrons are trapped in the random potential well and do not contribute to the electrical conductivity. In the middle temperature region, some of the electrons are trapped and some are mobile. As a result, the conductivity increases exponentially with temperature.

4. Summary

The mobility of electrons on liquid helium, whose surface was suspended by dielectric substrate, increased with decreasing temperature. This temperature dependence was opposite to that of conductivity. The result shows that the number of mobile electrons decreases as the temperature goes down.

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