Electron tunneling measurements in atomic scale gap filled with liquid $^4$He below 4.2K

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Abstract. We report the tunneling spectroscopy investigation in an atomic scale gap filled with liquid $^4$He using mechanically controllable break junction (MCBJ) technique. In order to assure the filling of liquid $^4$He into the gap, we construct a cryostat with an inner chamber for the tunneling spectroscopy inside the vacuum jacket of the liquid $^4$He bath. MCBJ apparatus is installed in the inner chamber with a flexible bellows. After filling inner chamber with liquid $^4$He below 4.2 K, Au electrical electrodes were stretched by the mechanical force generated by a piezo device. We observed the increase of the tunnel conductance through liquid $^4$He compared to that in the vacuum environment.

1. Introduction

Recently, it has become possible to investigate the electrical property of nano-scale devices using atomic scale electrodes fabricated by STM $^1$ and mechanical controllable break junction (MCBJ) techniques $^2$. In MCBJ technique, one can prepare two atomic-sized metallic electrodes and control the gap of the two electrodes precisely by piezo-electronic force. These electrodes can be used for the measurements of the conductance in a single molecule bridging the atomic scale gap between the two electrodes. In fact, electrical properties have been studied in a variety of organic molecules, e.g., fullerene $^3$, to develop single molecular devices with high performances.

Generally, single molecular devices with the bridge structure are fabricated by depositing a dilute solution of the molecule dissolved in solvent such as toluene and evaporating the solvent $^4$. In this method, however, a lot of trials are necessary to obtain the device working properly because of the poor probability of molecule placed on the atomic scale gap.

A different method is also employed for the conductance measurements in a single molecule, where two atomic electrodes are fabricated in a solution of molecule dissolved in solvent $^5$. By using this technique, the probability of bridging the molecule between the electrodes increases. However, this method has been only used near room temperature, where the solvent is in liquid state. Hence, the thermal fluctuation for the electrodes is increased enormously, degrading the signal for conductance measurements.

We focus on molecules such as $\text{O}_2$, $\text{H}_2$ and $\text{He}$ which condense at low temperatures to assure bridging the molecule between the electrodes and investigate the conductance precisely. In this
presentation, we report the tunnel current measurements in atomic scale gap filled with liquid $^4$He as a function of gap size. Our results indicate that the tunnel current in liquid $^4$He shows clear deviation from an exponential decay and increases compared with that in the vacuum environment.

2. Experimental Setup

In order to fabricate atomic scale gap in low-temperature liquids, we construct a new cryostat shown in Fig. 1. The cryostat has an inner chamber for the tunneling spectroscopy experiments in liquid $^4$He inside the vacuum jacket of the liquid $^4$He bath. The inner chamber is filled with liquid $^4$He condensing at the 1 K plate. MCBJ apparatus is installed in the inner chamber with a flexible bellows. After filling the inner chamber with liquid $^4$He below 4.2 K, atomic-sized electrodes are prepared by the following procedure with the MCBJ technique. A commercial Au wire with a diameter of 0.2 mm is used as the electrodes. The notched Au wire was rigidly fixed on the top of a phosphor-bronze bending beam and mounted in a three-point bending configuration inside the inner chamber. When a metallic wire is broken gently by piezoelectric force, a thin neck is formed between the edges of wire. By further stretching the contact, the neck is thinned down and finally two atomic scale electrodes are fabricated.

Our experiments are performed below 4.2 K, suppressing the thermal fluctuation and allowing the distance of electrodes retain for sufficient time in the measurements. Moreover, a high vacuum (~$10^{-3}$ Pa) environment before filling the inner chamber with liquid $^4$He achieved by the cryopumping effect prevents the contamination of the atomic-sized electrodes due to outgassing.

3. Results and Discussion

Figure 2 shows the conductance histogram constructed from 600 conductance traces obtained during breaking process of Au wire in liquid $^4$He at 3.8K. The inset plots a typical conductance curve in the final breaking process of Au wire. The conductance plateau reflects the elastic elongation of the Au wire keeping the atomic scale contact. According to the Landauer formula, the conductance is given as $G = IV = NG_0 (G_0 = 2e^2/h)$, where $N$ is integer and $h$ is the Planck constant. Hence the plateau at $1G_0$ indicates the formation of a single atomic contact in Au. Moreover the histogram is similar to that observed in vacuum at $T \sim 4.2K$, giving an evidence that liquid $^4$He scarcely affect the conductance in the contact regime.

Figure 3 shows a typical conductance curve in the final breaking process of Au wire in vacuum at $T \sim 4.2K$. In the contact regime, we observe the conductance plateau as shown in the inset. As the wire is further stretched by increasing the piezo voltage, an exponential decay of conductance appears as shown in Fig. 3. In this regime, the gap between the electrodes opens. Generally the tunnel conductance between the two electrodes is given as

$$G = IV \sim \exp(-az\sqrt{\phi}), \quad a = 4\pi\sqrt{2m/h} \sim 2.56 \times 10^9$$

where $z$ is displacement of the electrodes and $\phi$ is work function. The tunnel conductance can
be fitted by eq. (1) as plotted by dashed line in Fig. 3, demonstrating that the piezo element works as a positioning actuator. From the exponential fit of the tunnel conductance for dozens of measurements, the average value of the slope is estimated to be \( \sim -10 \, [1/V] \). Moreover, the work function \( \phi \) in bulk Au is \( 5.1 \pm 0.1 \) eV. From these values, the displacement of the electrodes by the piezo voltage, \( V_{\text{piezo}} / z \), is \( \sim 0.1 \) V/Å. Thus, an electrode displacement of 0.1nm changes the tunnel conductance by about one order of magnitude. The conductance decreases by about two orders of magnitude from the contact regime to the tunnel regime as shown in Fig. 3, which comes from the shrink of the wire caused by the rupture of the contact.

In our results, the dip is observed at different positions for three curves, which can be understood as difference in shape of the electrodes. Before the dip, the slope of the exponential decay is almost the same with that in the vacuum for the three curves, which is consistent with the results in ref. 10. On the other hand, the slope after the dip is slightly smaller than that in the vacuum. Namely, the conductance decreases more slowly with the displacement for the three curves, where the slope is almost the same. These results suggest that there remains the effect of \( ^4\)He for the tunnel current even in the large gap region.

We discuss the possible origin for the increase of the tunnel current in the large gap region. As shown in eq. (1), the tunnel conductance is given as a parameter of the work function for electrodes in the vacuum environment. On the other hand, it is generally known that when the gap between the electrodes is filled with an insulator, the parameter of the work function is replaced by the difference between the Fermi level of the electrodes and the bottom of the conduction band above the Fermi level.

**Figure 2.** Conductance histogram constructed from 600 conductance traces obtained during breaking process of Au wire in liquid \(^4\)He at 3.8K. The histogram is similar to that in vacuum at 4.2K. The inset shows an example of the conductance trace at final stage of breaking process.

**Figure 3.** The breaking process of Au atomic scale contact in vacuum at 4.2K. In the contact regime (inset) the conductance plateau is observed, while in the tunnel regime an exponential decay is observed. Bias voltage between the two electrodes is 20mV.
of the insulator. Since liquid $^4$He is an insulator, the difference between the first excited level of $^4$He and the Fermi level of Au is taken as the parameter, which is smaller than that in the vacuum. Accordingly, the tunnel conductance increases in the large gap region filled with $^4$He. To investigate the conductance in the large gap region, we need further experiments, e.g., differential conductance measurements.

4. Conclusion

We measure the tunnel conductance in atomic scale gap between two atomic scale metallic electrodes filled with liquid $^4$He. For the experiment, we construct a new cryostat which has an inner chamber where MCBJ apparatus is installed inside the vacuum jacket of the liquid $^4$He bath. We observed the increase of the tunnel conductance through liquid $^4$He compared to that in the vacuum environment.

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