Competition between the Superfluidity and the Slippage of $^4$He Films Adsorbed on Porous Gold

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Abstract. We have carried out QCM measurements for $^4$He films adsorbed on porous gold in the crossover region between the superfluidity and the slippage. In relative low areal densities, the resonance frequency increases gradually below $T_S$ due to the slippage of solid film, while the superfluid onset is observed in high areal densities. In the crossover region, we observed a peculiar behavior: The increase in the resonance frequency below $T_S$ is suddenly suppressed at a certain temperature $T_D$. From these observations, it is concluded that the superfluidity and the slippage of $^4$He competes with each other.

1. Introduction

We have carried out QCM experiments for $^4$He films adsorbed on Grafoil, and have measured the sliding friction and the superfluidity. Up to 10 atoms/nm$^2$, the sliding friction acting on the substrate is considerably small, and shows no temperature dependence. As the areal density increases above 12 atoms/nm$^2$, the friction becomes large. Between 14 and 20 atoms/nm$^2$, it decreases slightly below $T_S$ from the value at high temperatures. It was found that $T_S$ shifts to a lower temperature rapidly around the second layer promotion of 20.4 atoms/nm$^2$. Above 22 atoms/nm$^2$, the decrease below $T_S$ in the friction acting on the substrate is enhanced significantly. This decrease can be explained by the slippage between the first and second atomic layers [1,2]. On the other hand, above 32 atoms/nm$^2$, which corresponds to a four-atom thick film, decoupling due to superfluidity is observed at $T_C$, which is in good agreement with torsional oscillator measurements. For the thinner films, we observed no signature of superfluidity.

Recently, we have observed a peculiar behavior in the crossover region between the superfluidity and the slippage for $^4$He films adsorbed on Grafoil. In this region, the slippage below $T_S$ stops abruptly at a certain temperature $T_D$. It is of great interest to examine whether the competition between the superfluidity and the slippage occurs for $^4$He films adsorbed on other substrates. Thus motivated, we carried out QCM measurements for $^4$He films adsorbed on porous gold.

2. Experimental Procedure

In QCM measurements, the change in the resonance frequency is related to the coupled mass of film with the oscillating crystal. When the film moves in concert with the oscillating crystal,
the resonance frequency decreases from that of no films as \( \Delta f/f_R = -\sigma/M \), where \( f_R \) is the resonance frequency, \( \sigma \) is the areal mass density of the film and \( M \) is the areal mass density of the crystal. When the film is decoupled with the the oscillating crystal due to the superfluidity or the slippage, the coupled mass decreases and the resonance frequency increases.

In the present experiments, the sensitivity was enhanced by replacing conventional gold flat electrodes with porous gold ones [3]. To prepare porous gold electrodes, a 70 at.% Ag-Au alloy film was sputtered onto the original gold electrodes of a 4 MHz AT-cut quartz crystal. Then, the silver was selectively leached out from the Ag-Au alloy film by nitric acid. Its effective surface area was 20 times larger than that of the gold flat electrodes. The \( Q \)-value of the crystal with porous gold electrodes was about 3.5 \( \times 10^4 \), and the sensitivity was about 0.7 Hz/atoms/nm\(^2\). After setting the QCM in the sample cell, we heated it to about 130 °C under vacuum for 2 days. To easily control \(^4\)He coverage on the porous gold electrodes, 1 mm-thick porous gold flakes were put on the top of the sample cell. The total surface area of the sample cell was 6.9 m\(^2\).

The resonance frequency and the \( Q \)-value of the quartz crystal were measured using the transmission circuit. The crystal was placed in series with a coaxial line connecting a 50Ω cw signal generator and an RF lock-in amplifier. For precise measurements, the frequency of the signal generator was controlled in order to keep the in-phase output zero, and was locked to the resonance frequency.

3. Results and discussion
We have carried out QCM measurements for various \(^4\)He areal densities down to 0.08 K. Figure 1 shows the temperature dependence of the resonance frequency. The sets of data were taken during cooling, and the oscillation amplitude of the crystal is about 0.9 nm. Its temperature dependence shows a similar behavior to that of \(^4\)He films adsorbed on Grafoil, although the corresponding areal density is different. Up to 10 atoms/nm\(^2\), the frequency has no strong temperature dependence and decreases parallel to that of no film with increasing the areal density. As the \(^4\)He areal density increases above 13 atoms/nm\(^2\), it is clearly observed that the frequency increases gradually below a certain temperatures \( T_S \). This demonstrates that \(^4\)He films adsorbed on porous gold undergo slipping from the oscillating substrate at low temperatures.

In high areal densities the frequency decreases largely from 4 K down to around 1.5 K because of the desorption of \(^4\)He at high temperatures. At 23 atoms/nm\(^2\), after the temperature
dependence becomes small, it increases rapidly below $T_S$ with a dissipation peak. This increase corresponds to the superfluid onset, and shows the Kosterlitz-Thouless (KT) signature. The areal density dependence of $T_C$ is in good agreement with torsional oscillator measurements [4].

Figure 2 shows the crossover region between the superfluidity and the slippage where the areal density is between 20 and 23 atoms/nm$^2$. As mentioned above, at 23 atoms/nm$^2$, the superfluid onset is observed at $T_C$. Slightly below this density, the resonance frequency shows a peculiar behavior. At 20 atoms/nm$^2$, the increase below $T_S$ starts to drop at $T_D$ down to the value above $T_S$. As the areal density increases, $T_D$ shifts to a higher temperature and the drop at $T_D$ becomes sharp. The change in resonance frequency for several oscillation amplitudes at 20 atoms/nm$^2$ is shown in Fig. 3. At 1.67 nm, the frequency increases gradually below $T_S$. As the amplitude decreases, the increases below $T_S$ drops suddenly at $T_D$. After the drop, the
frequency increases slightly with decreasing temperatures. At the lowest amplitude, the increase below $T_S$ disappears and the superfluid onset is observed at $T_C$.

From these observations, we can conclude that the superfluidity of the film suppresses the slippage below $T_S$. In addition, it should be noted that the drop at $T_D$ has a strong amplitude dependence: When the amplitude becomes large, $T_D$ shifts to lower temperature. The mechanism of the suppression is an open question.

4. Summary
We have carried out QCM measurements for $^4$He films adsorbed on porous gold in the crossover region between the superfluidity and the slippage. It was found that the increase due to slippage below $T_S$ is suddenly suppressed at $T_D$, and that $T_D$ depends strongly on oscillation amplitude. From these observations, we conclude that the slippage for $^4$He films adsorbed on porous gold competes with the superfluidity.

References
[1] Hosomi N and Suzuki M 2008 Phys. Rev. B 77 024501
[2] Hosomi N, Tanabe A, Suzuki M and Hieda M 2007 Phys. Rev. B 75 064513
[3] Hieda M, Garcia R, Dixon M, Daniel T, Allara D and Chan M H W 2004 Appl. Phys. Lett. 84 628
[4] Csathy G A and Chan M H W 2000 J. Low Temp. Phys. 121 451