QCM studies of ^{4}He films adsorbed on grafoil

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Abstract

We applied the quartz-crystal microbalance (QCM) technique to a graphite substrate, and measured the slippage of nonsuperfluid ^{4}He films at MHz-frequency range, as well as the superfuidity. It was found that nonsuperfluid ^{4}He films undergo slipping at low temperatures, and that this slippage depends strongly on ^{4}He areal density.

Key words: QCM; slippage, nonsuperfluid helium film, graphite

Friction is a common force, but is poorly understood from a microscopic point of view.[1] Recently, experimental observations of an atomic-scale friction were reported using newly developed techniques. Regarding adsorbed films, Krim and her colleagues[2] found measured a partial slippage of noble-gas films adsorbed on a noble-metal substrate at 77 K using the quartz-crystal microbalance (QCM) technique.

On the other hand, physical properties of helium films adsorbed on graphite have been studied extensively both theoretically and experimentally, and the surface of graphite is atomically flat, at least, in the small region. So that these films is one of the ideal systems for a study on the interfacial friction between the substrate and film.

The superfluidity of ^{4}He films adsorbed on grafoil has been measured by means of the torsional oscillator.[3] However, the fraction of the films which remains locked to the substrate was rather large, possibly because of the low frequency of oscillation. This might be a drawback for a study on slippage. Thus motivated, we applied the QCM technique to grafoil.

The resonator used for QCM was an AT-cute quartz-crystal with the fundamental resonant frequency of 5.0 MHz. The crystal was commercially available. A piece of grafoil was pasted uniformly on Ag electrodes. Because of making use of grafoil, the effective surface area was 10∼20 times larger than that of the electrodes, and this is of great advantage for precise measurements. Although the Q-value of this crystal was lowered, it was better than 10^4.

A resonant frequency and amplitude were measured using the transmission circuit.[4] The crystal was placed in series with a coaxial line connecting a 50Ω cw signal generator and a phase-sensitive-detector (PSD). In PSD, the transmitted signal was multiplied by the in-phase and quadrature references using a double-balanced mixer (DBM). The two outputs of DBMs through the low-pass filters (LPF) were detected independently. Then, the frequency of the signal generator was controlled in order to keep the in-phase output zero. The quadrature output at this frequency is the resonant amplitude.

At the atomic-scale, the frictional force *does* exhibit a dependence on both the sliding speed and area. The interfacial friction F_f per unit area of the film is expressed as $F_f = -\sigma_2 V/\tau$, where σ_2 is the mass of the film per unit area and V is the sliding speed. Here, τ is called the slip time. If the film starts to slip relative to the lateral oscillation, the resonant frequency and amplitude are modulated. This change is characterized by the value of $\omega\tau$, where ω is the angular frequency of oscillation. At $\omega\tau \sim 1$, an rapid increase in the resonant frequency and a decrease in the amplitude are

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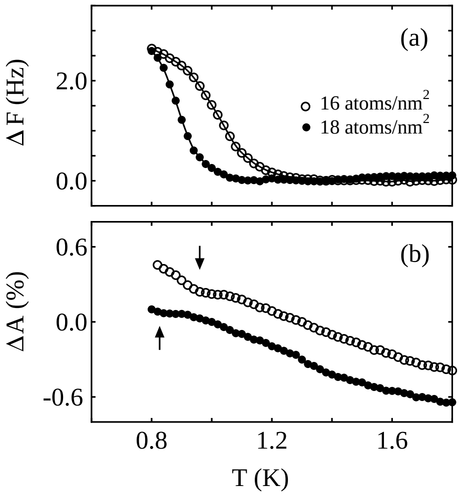

Fig. 1. Variation of (a) the resonant frequency and (b) the amplitude as a function of temperature. The amplitude shows a small dip as the resonant frequency increases. These areal densities correspond to nonsuperfluid ^{4}He films. For clarity, the sets of data are shifted vertically.

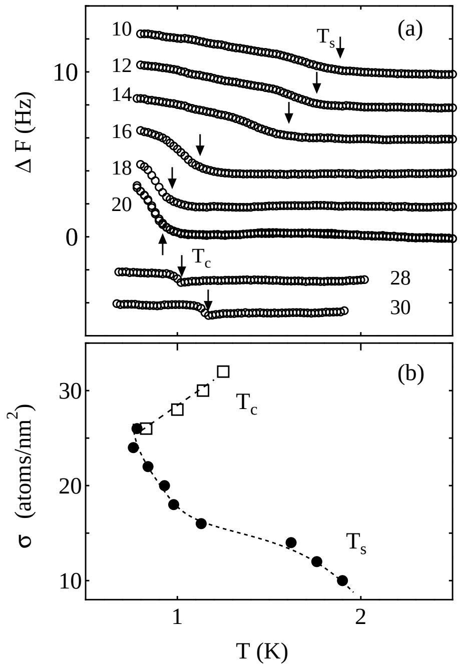

Fig. 2. (a) Variation of the resonant frequency for various ^{4}He areal density. Figures represent the areal density in the unit of atoms/nm^2. The arrows indicate the slip temperature T_s and the superfluid onset T_c. For clarity, the sets of data are shifted vertically. (b) T_s and T_c as a function of ^{4}He areal density.

observed.

We measured the change in the resonant frequency and amplitude down to 0.7 K. The amplitude of the lateral oscillation was estimated to be less than 1 nm. Figure 1 shows typical data for nonsuperfluid ^{4}He films. It was found that the resonant frequency increases as the temperature is lowered. Furthermore, a small dip in the amplitude was observed accompanied with this increase. This behavior demonstrates clearly that these films undergo slipping relative to the lateral oscillation. From the increase in the resonant frequency, it is estimated that 15∼30 % of ^{4}He adatoms contribute to this slippage at low temperatures. (Similar slippage was reported. Mohandas et al.[5] performed the torsional oscillator measurements for nonsuperfluid ^{4}He films adsorbed on grafoil, and found that a small amount of these films slip at low temperatures.) The slippage of nonsuperfluid helium films adsorbed on hectorite has been reported.[6] Thus, it is concluded that the slippage will be observed for various substrates and is a rather common feature of these films.

Figure 2 (a) shows the variation of the resonant frequency for various ^{4}He areal density. It was found that the temperature when the film starts to slip, T_s, decreases with increasing ^{4}He areal density. Above 26 atoms/nm^2 the superfluidity was observed above 0.7 K, and then above 28 atoms/nm^2 T_s was lowered below 0.7 K. Figure 2 (b) shows T_s as a function of ^{4}He areal density, together with the superfluid onset T_c. T_s changed stepwise around 15 atoms/nm^2, which suggests that the structure of film is closely related to the slippage of this system.

In summary, we applied the QCM technique to a graphite substrate, and measured the slippage of nonsuperfluid ^{4}He films at MHz-frequency range. It was found that these films undergo slipping at low temperatures, and that the slip temperature T_s depends strongly on ^{4}He areal density.

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