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PROBING NANOSCALE HEAT AND FORCE INTERACTIONS USING ATOMIC FORCE MICROSCOPES (AFM)

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ABSTRACT

Many devices and instruments such as magnetic hard disk drives and atomic force microscopes (AFM) rely on the stable operation of their small probing heads at nanoscale gaps. Due to the small scale of the probing heads, the force interactions (Casimir force and electrostatic force) between the small probes and the surrounding become more significant. The local heating caused by read/write electric currents in hard disk drives or probing laser beams in AFM on the probes inevitably leads to the heat transfer between them and the surrounding. The nanoscale heat and force interactions play a critical role in the performances of those instruments. In this paper, we use a bimaterial AFM cantilever to measure the nanoscale air heat conduction, radiation and force between a microsphere and a substrate. The resulting "heat transfer-distance" and "force-distance" curves clearly show the strong dependence of nanoscale interactions with gap distances.

Recently, there have been general interests in measuring force [1-3] and heat transfer [4-6] interactions between bodies at nanoscale gaps. When two objects are very close to each other, the so-called Casimir force effects occur because of the fluctuation of the zeropoint energy of the electromagnetic field [1]. Casimir force can be attractive and repulsive depending on the way that materials interact with light [3]. In the nanoscale, thermal radiation can be significantly enhanced beyond the Planck's blackbody radiation limit due to the photon tunneling [4, 7]. Many devices such as hard disk drives and atomic force microscopes (AFM) rely on the stable operation of their small probing heads at nanoscale gaps [8], thus the force and heat transfer effects between the probe and the substrate (or the sample) can become significant and influence the performance of the devices under certain circumstances.
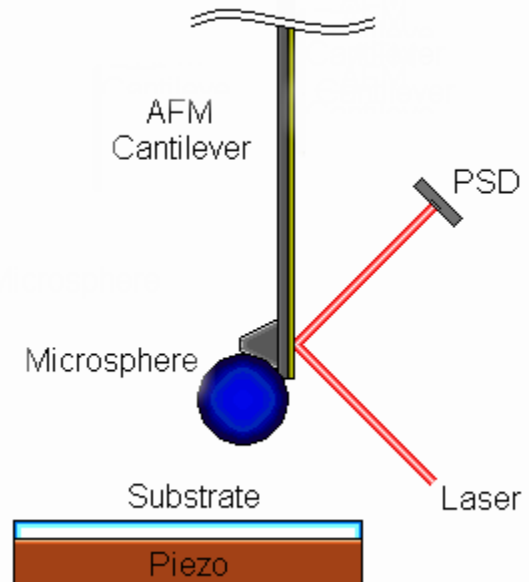
FIG. 1 Schematic diagram of experimental setup.

We developed a sensitive technique to measure near–field radiative heat transfer between a microsphere and a substrate using a bi-material AFM cantilever [4, 9], which can resolve power measurements as low as 0.1 nW and energy measurements down to 0.15 pJ [10, 11]. In Fig. 1, a glass (silica) microsphere 50 μm or 100 μm in diameter is attached to the tip of a bi-material (Si$_3$N$_4$/Au) AFM cantilever with UV adhesive. A laser beam (650 nm wavelength, 3 mW output power) is focused on the tip of the cantilever and reflected onto a position sensitive detector (PSD). A part of the laser power is absorbed by the gold film on the cantilever and thus create a temperature rise on the cantilever tip and the sphere. The substrate and the base of the cantilever are passively maintained at the ambient temperature. The substrate is rigidly fixed to a piezoelectric motion controller which is able to reduce the gap between the sphere and the substrate below ~ 10 nm. In order to measure heat transfer signals only, the cantilever with the microsphere can be oriented perpendicularly to the substrate to reduce the bending caused by Casimir and electrostatic forces during the experiment. In this case, the forces are mainly exerted in the longitudinal direction of the cantilever and have a less effect on its transverse direction (bending direction) because the longitudinal stiffness of the cantilever is much higher than its transverse stiffness. When the system is put in the ambient, the heat conduction through the air gap between the sphere and the substrate dominates the bending of the cantilever. Figure 2 shows that the deflection signal of the cantilever is plotted as a function of the gap size between a 100 μm-diameter silica sphere and a thick gold film (1 μm in thickness) coated on a glass microscope slide. The temperature difference between the sphere and the ambient is estimated to be around 16 K [4]. The deflection signals caused by force and radiation were observed in Ref. 4 to be much smaller compared to that by air heat conduction. At larger gaps where the gap is much larger than the mean free path of air molecules (~ 60 nm) under one atmospheric pressure, the thermal conductivity of air is a constant around 0.024 W/m.K at room temperature. When the gap between the sphere and the substrate is comparable with the mean free path of air molecules, molecular rarefaction effects become important. Hence, the thermal conductivity of air decreases with reduced gap sizes [8, 12].
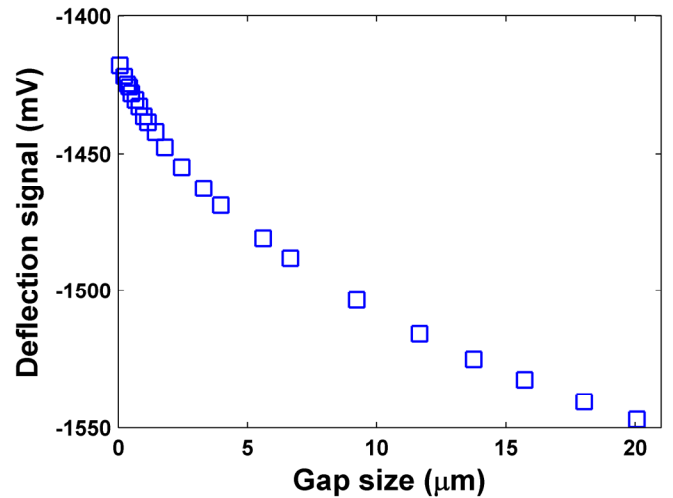
FIG. 2 Deflection signals caused by air heat conduction versus the gap sizes.

When the system is pumped down to pressures less than 1×10^{-3} Pa, the heat conduction across the air gap between the sphere and the substrate can be neglected, and thermal radiation is dominant in heat transfer. In particular, at nanoscale gaps, the near-field thermal radiation can be significantly enhanced due to the photon tunneling and resonant surface waves. We have demonstrated that the near-field radiation between the polar dielectric materials (SiO$_2$, SiC, BN, *etc.*), which support surface waves (surface phonon polaritons), can exceed Planck's blackbody radiation law by several orders of magnitude at nanoscale gaps [4]. For metallic materials, Chaputis *et al.* [13] calculated the near-field radiation between two parallel metallic surfaces. They showed that near–field radiative heat flux saturates when the gap size is smaller than the metal skin depth, and *s*-polarized field dominates the heat transfer between metallic surfaces rather than the *p*-polarized dominance in dielectrics. Here, we coated a ~ 50 μm diameter silica sphere with a 100 nm thick gold film and studied its nanoscale radiation and force interactions with a gold substrate (a 1 μm thick gold film on a glass slide). The force interaction (Casimir and electrostatic forces) between the sphere and the substrate may become apparent in the case that the AFM cantilever is not perfectly perpendicular to the substrate during the experiment. Once the gap between the sphere and the substrate is small enough, the near-field radiation and forces cause the cantilever to bend. The total signal including both the

contributions from force and heat radiation is shown in Fig. 3.

In order to quantitatively measure the force interaction between the gold sphere and the gold substrate, a very weak laser power is used to minimize the temperature difference between the sphere and the ambient (< 1 K) and therefore the near-field radiation between them. When the gap between the sphere and the substrate is changed by the piezosystem, the observed deflection signal is only caused by the forces. In Fig. 3, a power law function is also used to fit the deflection-distance curve from the force measurement. Thus, the deflection signal resulted from the near-field radiation can be obtained by subtracting the deflection signal calculated by the power law function from the total deflection signal at different gaps (Fig. 3). The measured cantilever deflection signal for near-field radiation is linearly proportional to the heat transfer between the sphere and the substrate [4, 9], and can be converted to a heat transfer-distance curve. Based on our previously developed calibration technique, the cantilever has a thermal conductance 3.09 μW/K and a tip temperature of 33.5 K higher than the ambient temperature at the given laser power [14]. Finally, the conductance of the near-field radiation between the gold sphere and the gold substrate is plotted as a function of the gap distances in Fig. 4, where we can see that the near-field radiation between two metallic surfaces is strongly enhanced at nanoscale gaps due to photon tunneling.
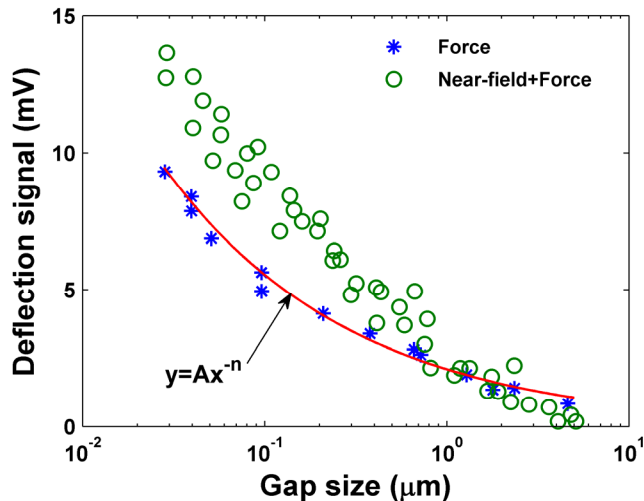
is normalized to the deflection signal at the gap size ~ 5 μm.

There is no rigorous theoretical calculation for the near-field radiation between a microsphere and a plate because of computational difficulties [4]. For the sphere-plate geometry, the near-field radiation is estimated by the so-called proximity force theorem which approximates curved surfaces by differential flat areas and using the known solutions for near-field radiation between parallel surfaces to obtain the sphere-plate near-field radiative conductance [15],

$$G_{near-field}^{sphere-plate}(d) \cong 2\pi R \int_{s=d}^{\infty} h_{near-field}^{plate-plate}(s)ds ,$$

where G is the near-field conductance, h is the heat transfer coefficient and R is the radius of the sphere. The heat transfer coefficients between two parallel gold surfaces can be calculated by solving Maxwell's equations based on the dyadic Green's function and fluctuation-dissipation theorem [13]. In Fig. 4, the calculated near-field radiative conductance from proximity theorem is compared with the experimental results. Overall, the proximity theory gives a correct order of magnitude in the experimental range and is in reasonable agreement with experimental results. At nanoscale gaps, theory also predicts that near-field radiation increases with increasing temperatures of bodies [7]. If the technique presented in this paper is applied for a range of heating power, this trend may be confirmed at a fixed gap.

FIG. 3 Reduced deflection signals by force and near-field radiation versus the gap sizes. The data
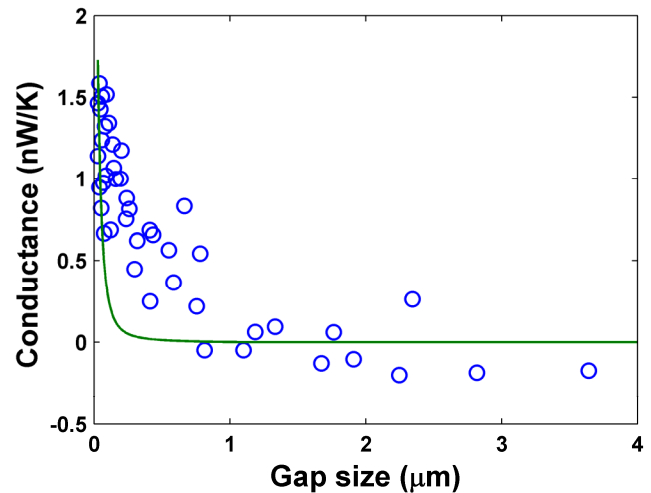

FIG. 4 Measured near-field radiative conductance between a gold sphere and a gold substrate, and comparison with the theoretical prediction from the proximity force theorem. Each of conductance

data presented here is the averaged value of ~ 100 measurements with the standard deviation ~ 0.4 nW.K^{-1}. The experimental error on distance measurements is the resolution of the piezo system (~ 5 nm).

In summary, we measured the force and heat transfer interactions between a microsphere and a substrate using an AFM based technique. Both force and heat transfer signals are strongly dependent on the gap sizes between the sphere and the substrate. The measured near-field radiative conductance between a gold sphere and a gold substrate agrees well with theory.

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