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Citation: Appl. Phys. Lett. **100**, 233114 (2012); doi: 10.1063/1.4723713
View online: http://dx.doi.org/10.1063/1.4723713
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v100/i23
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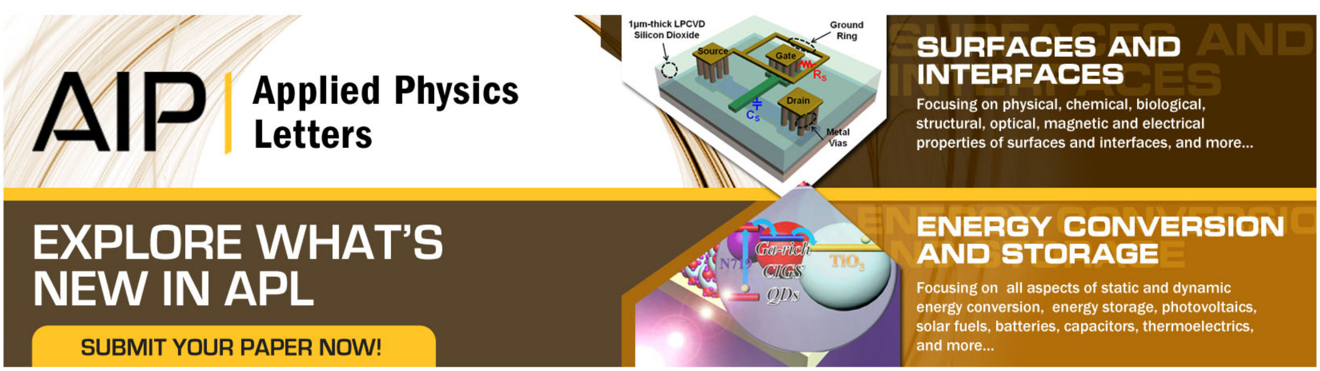

Nanoscale thermal radiation between two gold surfaces

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(Received 1 March 2012; accepted 15 May 2012; published online 6 June 2012)

In this letter, we measured the nanoscale thermal radiation between a microsphere and a substrate which were both coated with thick gold films. Although gold is highly reflective for thermal radiation, the radiative heat transfer between two gold surfaces was demonstrated to be significantly enhanced at nanoscale gaps beyond the blackbody radiation limit due to the tunneling of non-resonant evanescent waves. The measured heat transfer coefficient between two gold surfaces agreed well with theoretical prediction. At a gap $d = 30\,\text{nm} \pm 5\,\text{nm}$, the heat transfer coefficient between two gold surfaces was observed to be as large as $\sim 400\,\text{W/m}^2\cdot\text{K}$, much greater than the blackbody radiation limit ($\sim 5\,\text{W/m}^2\cdot\text{K}$). © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4723713]

When the gap size between two objects is smaller than the dominant thermal wavelength at the temperatures of the objects, photon tunneling can significantly enhance the radiative heat transfer beyond Planck's law of blackbody radiation. Cravalho *et al.*[1] theoretically investigated the enhancement of thermal radiation between two dielectrics at small separations. Polder and van Hove[2] established a theoretical approach to calculate the near-field radiation between metallic surfaces based on fluctuational electrodynamics theory developed by Rytov[3] that became the foundation for future investigations. This theoretical framework has been extensively used subsequently by many groups to study the near-field radiation between the surfaces of dielectrics,[4,5] semiconductors,[6] and thin films.[7]

A number of experiments were also reported to measure the near-field thermal radiation between two parallel plates or between a small tip and a flat substrate. Domoto *et al.*[8] and Kuteladze *et al.*[9] investigated the radiative transfer between two parallel metallic surfaces at cryogenic temperatures. Hargreaves[10] carried out the experiments between two metallic films of chromium at room temperature and showed the enhanced heat transfer around 1 μm. Xu *et al.*[11] measured the radiative transfer between a deformed indium surface and a small gold surface but did not conclusively confirm near-field effects. Hu *et al.*[12] measured the radiative heat transfer between two glass plates and observed the radiative heat transfer exceeding the predictions of the Planck law by 35% when the two plates were separated by $\sim 1\,\mu$m. Very recently, Ottens *et al.*[13] measured the radiative heat transfer between two macroscopic planar sapphire surfaces with a separation down to several micrometers around room temperature. Kittel *et al.*[14] measured the radiative heat transfer between a scanning probe microscope (STM) tip and a flat substrate. The saturation of heat flux was observed at extremely small distances ($\sim$10 nm). They attributed this phenomenon to spatial dispersion effects and the contribution of the infrared magnetic dipole component.

We have developed over the last few years a technique to measure the near-field radiation between a microsphere and a substrate at nanoscale gaps, using a bi-material atomic force microscope (AFM) cantilever.[15,16] The nanoscale thermal radiation between polar dielectrics, for example, glass-glass (SiO_2-SiO_2) was experimentally demonstrated to exceed the blackbody radiation limit by three orders of magnitude, which is attributed to the resonant surface waves excited on the surfaces of polar dielectrics as theory predicted.[4] A similar experimental technique was also adopted by Rousseau *et al.*[17] to demonstrate the near-field enhancement, although subtle but important differences exist between the two groups. As we heated only the sphere, the view factor associated to far-field thermal radiation did not change when approaching the substrate, which is different from Rousseau *et al.*'s experiment that heated up the substrate. In our experiment, only the near-field contribution is changing when decreasing the sphere-plate distance. In addition, the deflection of the cantilever was measured by Rousseau *et al.* using a fiber interferometric technique rather than a position sensing detector. Gu *et al.*[18] have recently improved the optical lever technique[15,16] to measure the near-field radiation between a sphere and a plate, and position the sphere away from the edge of the substrate so that the substrate can truly be modeled as an infinite plane.

Although Polder and van Hove theoretically demonstrated the near-field enhancement of thermal radiation between metallic surfaces in the 1970s, there is no experimental work reported on the radiative heat transfer between two metallic surfaces at nanoscale gaps. Physically, the mechanism for enhancing the radiative heat transfer between metallic surfaces in the near-field is different from that for dielectric systems. In Fig. 1(a), we calculated the spectral heat flux between two semi-infinite gold or glass (SiO_2) plates at a 100 nm gap, where the optical constants of gold used in the calculation were from the experimental data summarized by Ordal *et al.*[19] The observed peaks for the case of SiO_2-SiO_2 correspond to the resonances of surface phonon polaritons. Thus, the contribution from surface waves dominates the radiative heat transfer of SiO_2-SiO_2 in the

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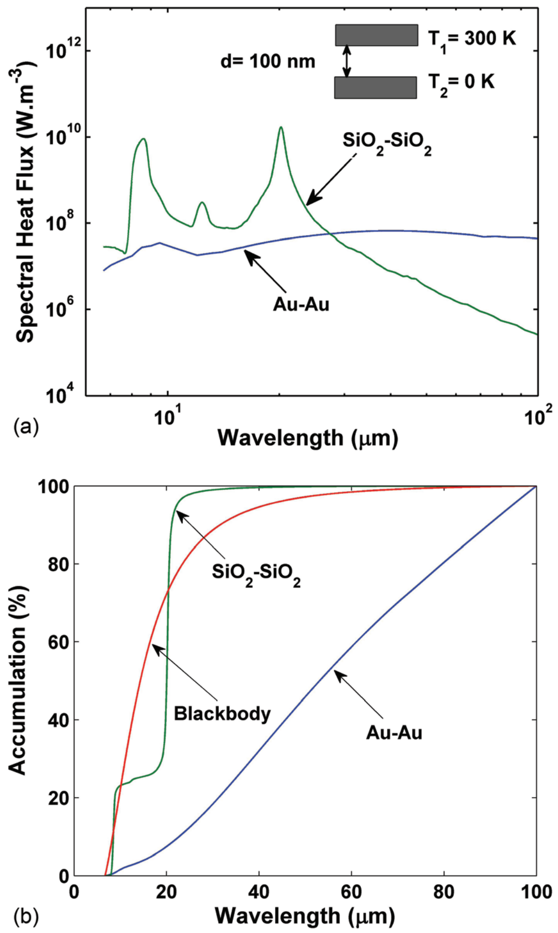

FIG. 1. (a) Spectral radiative heat flux for two gold or glass plates at a 100 nm gap. (b) Percentage of heat flux accumulation. The curve for blackbody radiation is calculated from Planck's law at T = 300 K.

near-field.[4] From Wien's displacement law, the peak intensity of blackbody radiation is around the wavelength of 10 μm at 300 K. However, in the near-field, the photons with wavelengths as long as 100 μm can also largely contribute to the radiative heat transfer between two gold plates. To quantify the contribution of photons at a certain wavelength to the total heat flux, we calculated the percentage of heat flux accumulation η as a function of wavelength in Fig. 1(b), where η is defined as $\eta(\lambda) = \int_{\lambda_1}^{\lambda} Q(\lambda')d\lambda'/Total\ Heat\ Flux$ with $Q(\lambda')$ representing the spectral heat flux for Au-Au and SiO_2-SiO_2 in Fig. 1(a), and λ is photon wavelength. The curve of blackbody radiation calculated from Planck's law at T = 300 K indicates that in the far-field, the heat radiation emitted from a blackbody is mainly in the wavelength range of 10–30 μm. Two jumps in the near-field radiation of SiO_2-SiO_2 correspond to the resonances of surface phonon polaritons. For the case of Au-Au, non-resonant evanescent waves (photon tunneling effects) with long wavelengths dominate the near-field radiation because gold has higher refractive indexes in the long wavelength range. We report, in this letter, experimental results on the near-field radiative heat transfer between two gold surfaces separated by nanoscale gaps.

Our experimental details were described in previous publications[15,16] and are briefly summarized here. A 50 μm diameter glass microsphere is coated with a nominally 100 nm thick gold film by sputtering technique. The coverage of the gold on the sphere is approximately half of the sphere. The gold coated sphere is then attached to the tip of a bi-material (SiN_x/Au) AFM cantilever in the way that the area predominated with 100 nm thick coating is facing to the substrate during experiments. The skin depth of gold in the wavelength range contributing to near-field radiation is less than 20 nm, thinner than the coated gold films. Thus, the near-field radiative heat transfer reported can be attributed to two gold surfaces. A laser beam is used to measure the deflection of the cantilever and heat up the microsphere. The substrate and the support base of the cantilever are passively maintained at ambient temperature. The substrate is coated with a 1 μm thick gold film and rigidly fixed to a piezoelectric moving stage. Although the initial bending of the cantilever is determined by the heat conduction along the cantilever and the far-field radiation between the heated system and the surrounding, our experiment measures the subsequent bending which is only sensitive to near-field effects. The surface roughness of the gold substrate is measured using an AFM to be ~3 nm. The surface roughness of the glass sphere without coating is measured to be ~20 nm. The surface roughness of the gold coated sphere is estimated to be ~30 nm by scanning electron microscopy (SEM) imaging.

In order to measure heat transfer signals only, the cantilever with the microsphere is oriented perpendicularly to the substrate to reduce the bending caused by Casimir and electrostatic forces during the experiment. 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 (<1 K) between the sphere and the ambient, and therefore the near-field radiation between them. When the gap between the sphere and the substrate is changed by the piezo-system, the observed deflection signal is only caused by the forces. In Fig. 2, a power law function is used to fit the deflection-distance curve from the force measurements. The deflection signals resulting from near-field radiation can be obtained by subtracting the deflection signal calculated by the power law function from the total deflection signal at the same gap. The measured cantilever deflection signal for near-field radiation is linearly proportional to the heat transfer between the

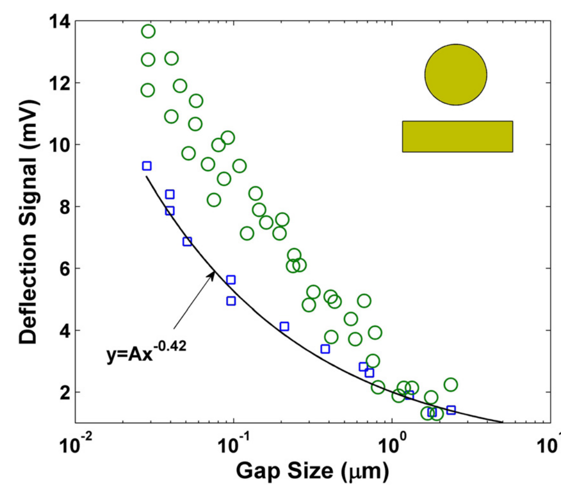

FIG. 2. Reduced deflection signals by both force and near-field radiation ("green circles"), and only by force ("blue squares") versus the gap sizes.

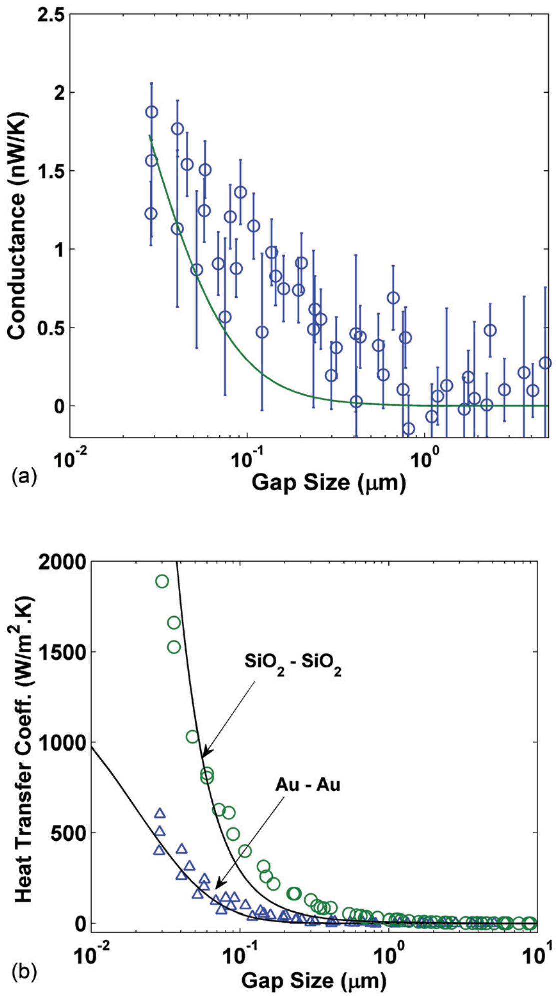

FIG. 3. (a) Measured near-field radiative conductance between a gold sphere and a gold substrate and comparison with the theoretical prediction from the proximity theorem. The uncertainty of gap sizes is 5 nm. (b) Equivalent sphere-plate near-field heat transfer coefficients normalized to the area $2\pi Rd/1.46$ versus gap distances. The data of SiO_2-SiO_2 are from Ref. 15 for the 50 μm diameter sphere. The black lines are the near-field heat transfer coefficients obtained after subtracting the far-field portion.

sphere and the substrate[15] and can be converted to a thermal radiation-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 ambient temperature at the given laser power.[20] Finally, the conductance of the near-field radiation between the gold sphere and the gold substrate is plotted as a function of gap distances in Fig. 3(a), where we can see that the near-field radiation between two metallic surfaces is strongly enhanced at nanoscale gaps. Kittel *et al.*[14] measured the near-field radiative heat transfer between a gold coated STM tip and a gold substrate. The thermal conductance for a 30 nm gap was estimated to be 5 nW/K, given that the measured heat current was ~1000 nW under a temperature difference of 200 K. This value is larger than our measured conductance (1.5 nW/K) at a ~30 nm gap, though the sphere (50 μm in diameter) used in this work has a much larger surface area than the STM tip which is approximated to have a circular effective area with the radius of 60 nm. The large heat flux observed by Kittel *et al.* may be attributed to the large absorption cross section of the sub-wavelength STM tip.

For metals, Chapuis *et al.*[21] calculated the near-field radiation between two parallel metallic surfaces. They showed that near-field radiative heat flux dramatically increases when reducing gap distances, and *s*-polarized field dominates the heat transfer between metallic surfaces rather than *p*-polarized field for dielectrics. Although metals are highly reflective for infrared lights and used as thermal radiation shields, the thermal radiation (both propagating and evanescent waves) emitted from the hot surface is bounced between two gold surfaces at nanoscale gaps and eventually absorbed by the cold surface, which leads to the large enhancement in the near-field beyond the blackbody limit. For a sphere-plate geometry, the near-field radiation can be estimated by the so-called proximity theorem which approximates curved surfaces by differential flat areas and using the known solutions for the near-field radiation between parallel surfaces to obtain the thermal conductance for sphere-plate configurations,[22] $G^{sphere-plate}_{near-field}(d) \cong 2\pi R\int_{s=d}^{\infty} h^{plate-plate}_{near-field}(s)ds$, 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 using the formalism from Polder and van Hove.[2]

In Fig. 3(a), the calculated near-field radiative conductance from the proximity theorem is compared with experimental results. Overall, the proximity theory gives a correct magnitude in the gap range of the experiment and is in reasonable agreement with experimental results. The scattering of the data in Fig. 3(a) primarily results from the uncertainty during the experiment which is ~0.4 nW/K on average. Meanwhile, the large surface roughness of the sphere makes it difficult to precisely measure the gap sizes when the sphere is close to contact. The surface roughness also causes the extra scattering of experimental data at very small gaps. The calculated heat transfer coefficients for Au-Au can be well fitted with a power function of $A/d^{2.46}$ for the gap range considered in this work (30 nm–4 μm), where A is a constant and d is the gap size between the sphere and the substrate. The near-field conductance can be simplified as $G^{sphere-plate}_{near-field}(d) \cong (2\pi Rd/1.46)(A/d^{2.46})$ which indicates that the near-field conductance between a sphere and a plate can be equivalently approximated as the one between two plates with an effective area $2\pi Rd/1.46$. When normalized to this effective area, the heat transfer coefficient can be obtained for the near-field radiation between two gold surfaces. In Fig. 3(b), we plotted the near-field portion of the radiative heat transfer coefficients between two parallel plates (black lines) after subtracting the far-field contribution, where no error bars were added because the equivalent heat transfer coefficients are not directly measured data. The magnitude of the sphere-plate heat transfer coefficients agrees well with that between two parallel plates. Although the heat transfer between two gold surfaces at nanoscale gaps is largely enhanced due to the tunneling of non-resonant evanescent waves, it is still much smaller than that between two SiO_2 surfaces which results from the resonant surface waves existing on SiO_2 surfaces.[15] At a 30 nm gap, the heat transfer coefficient for SiO_2-SiO_2 is about 4 times greater than the one for Au-Au, as shown in Fig. 3(b). In the present work, we only experimentally demonstrated the near-field enhancement for gold surfaces, but the trend of near-field radiation varying with gap distances are quite similar for other metals such as silver and copper in terms of the theoretical work by Chapuis *et al.*[21] Thus, the physical explanation and the magnitude of the measured near-field radiation between two gold surfaces given in this letter can be referred when other metals are considered.

In summary, we used an AFM type technique to demonstrate that the near-field radiation between two gold surfaces is significantly enhanced due to the tunneling of non-resonant evanescent waves. The measured near-field radiative heat transfer coefficient agreed well with theory. Although metals are usually used as thermal radiation shields, we have demonstrated the near-field radiation between two gold surfaces is as large as 400 W/m^2·K at a ~30 nm gap, which is much greater than the blackbody radiation limit (~5 W/m^2·K).

This work is support by DOE BES (DE-FG02-02ER45977) (S.S. and G.C.) and AFOSR MURI via UIUC (A.M. and P.S.).

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