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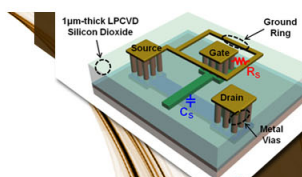
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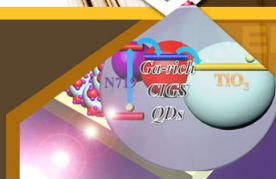
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Near-field thermal radiation between two closely spaced glass plates exceeding Planck's blackbody radiation law

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This work reports experimental studies on radiative heat flux between two parallel glass surfaces. Small polystyrene particles are used as spacers to maintain a micron-sized gap between two optical flats. By carefully choosing the number of particles and performing the measurement in a high-vacuum environment, the experiment is designed to ensure that the radiative heat flux is the dominant mode of heat transfer. The experimental results clearly demonstrate that the radiative heat flux across micron-sized gaps can exceed the far-field upper limit given by Planck's law of blackbody radiation. The measured radiative heat flux shows reasonable agreement with theoretical predictions. © 2008 American Institute of Physics. [DOI: 10.1063/1.2905286]

At a finite temperature, electrons and ions in any matter are under constant thermal agitation, acting as the random current source for thermal emission. The thermally excited electromagnetic waves have two forms: the propagating modes that can leave the surface of the emitter and radiate freely into the space and the nonpropagating modes (evanescent modes) that do not radiate.^{1,2} The contribution from the propagating modes to the radiative heat flux is well known and its maximum is governed by Planck's law of blackbody radiation.³ The nonpropagating modes do not propagate and thus do not carry energy in the direction normal to the surface, unless a second surface is brought close to the first to enable photon tunneling. The contribution from the nonpropagating modes to radiative heat flux is the near-field radiative flux.

Theoretical study of the radiative flux between closely spaced parallel surfaces has been carried out by various researchers.¹⁻⁸ Most of the theoretical studies are based on the fluctuating electrodynamics approach pioneered by Rytov *et al.*⁶ and Polder and van Hove.⁵ These theoretical studies show that, when the distance between two parallel surfaces is small compared to the dominant thermal radiation wavelength, the near-field radiative heat flux can exceed the far-field upper limit imposed by Planck's law of blackbody radiation. Experiments have followed to measure the near-field radiative heat flux. Domoto *et al.* measured radiative heat transfer between two metallic surfaces at cryogenic temperatures, reporting a value only $\frac{1}{29}$ of the upper limit for gaps between 50 μm and 1 mm.⁹ Hargreaves extended the measurements to gaps as small as 1 μm between two chromium surfaces, which gave a radiative heat transfer rate at 50% of the blackbody upper limit.¹⁰ Xu *et al.* conducted measurement of radiation heat transfer between two metallic surfaces for reduced gap sizes between 50 and 200 nm, but the explanation of their experimental data is hindered by the sensitivity of the experimental technique.¹¹ More recently, Kittel *et al.* measured near-field radiative transfer between a scanning thermal microscope tip and a flat substrate.¹²

The previous experiments were done with conducting surfaces, which made gap control possible based on measur-

ing the electrical capacitance or tunneling current. Around room temperature (300 K), the peak wavelength of thermal radiation is approximately 10 μm (Wien's displacement law),¹³ where metals are not good candidates for the purpose of exceeding the Planck blackbody radiation law and extremely small gaps are required to obtain high radiative flux.¹⁴ In this work, we report measurements on near-field radiative heat transfer between two glass surfaces, which supports surface phonon polaritons in the infrared region of the electromagnetic spectrum.¹ The resonant wavelength of surface phonon polaritons in glass is well aligned with the peak wavelength of thermal radiation in the temperature range of interest, leading to higher radiative heat transfer even with moderate gap sizes. Our experimental data demonstrate breakdown of Planck's blackbody radiation law in the near field.

To guide the experimental design, we analyze the near-field radiative heat transfer between the two parallel flat glass surfaces using Green's dyadic¹⁵ and the fluctuation-dissipation theorem.⁶ The frequency-dependent optical constant of glass (fused quartz) is taken from Ref. 16. The Lorentzian model¹⁷ is used to interpolate the data points between 26.67 and 100 μm because no data are available in this range. The gap dependent heat transfer coefficient is defined as $h_r = q_r'' / (T_h - T_c)$ and plotted in Fig. 1(a), where q_r'' is the radiative heat flux and T_h and T_c are the temperatures of the hot surface and the cold surface ($T_h = 50^\circ\text{C}$ and T_c

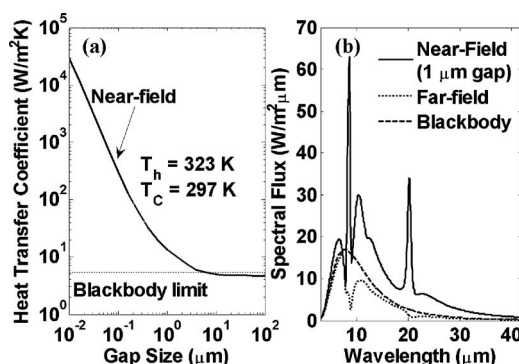


FIG. 1. (a) Gap-size dependent heat transfer coefficient. (b) Calculated spectral radiative heat flux between two glass surfaces.

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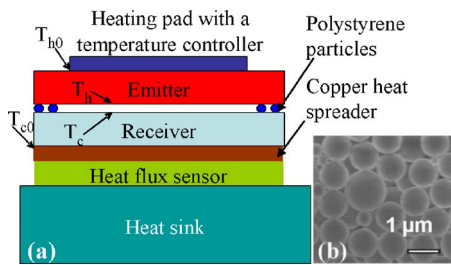


FIG. 2. (Color online) (a) A schematic drawing of the experiment setup. (b) A scanning electron microscope image of polystyrene particles.

$=24\text{ }^{\circ}\text{C}$), respectively. As the gap decreases below $5\text{ }\mu\text{m}$, the heat transfer coefficient starts to exceed the blackbody limit. As the gap shrinks even more, the coefficient continues to grow, owing to enhanced tunneling of the surface waves. Around $1\text{ }\mu\text{m}$, the coefficient is more than 50% higher than the blackbody limit, which is readily measurable without the need to shrink the gap further. Figure 1(b) shows the wavelength dependent radiative heat flux between the two surfaces, assuming the hot side and cold side temperatures to be 50 and $24\text{ }^{\circ}\text{C}$, respectively, and a gap of $1\text{ }\mu\text{m}$. The figure clearly reveals two dominant peaks at 8.7 and $20.2\text{ }\mu\text{m}$, which are the resonance wavelengths of surface phonon polaritons in glass,¹ indicating the radiative heat transfer across a $1\text{ }\mu\text{m}$ gap is primarily due to the contribution from the surface phonon polaritons.

Figure 2(a) shows the schematic drawing of the experimental setup. Two identical precision glass optical flats ($\lambda/20$ accuracy) are used as an emitter (hot side) and a receiver (cold side). The diameter of the glass optical flats is 0.5 in. (1.27 cm) and the thickness is 0.25 in. (0.635 cm). The surface flatness of the optical flats is better than $0.05\text{ }\mu\text{m}$. To maintain a gap between the emitter and the receiver, polystyrene microspheres [Fig. 2(b)] are placed between the two surfaces as spacers. We decide to set the gap to be $1\text{ }\mu\text{m}$ and, thus, choose the nominal diameter of the spheres to be $d=1\text{ }\mu\text{m}$. Polystyrene is selected because its thermal conductivity is low, with a reported value at 0.18 W/mK .¹⁸ Assuming a cross-section area of $\pi d^2/4$ for heat conduction and a radiative heat transfer coefficient of $5\text{ W/m}^2\text{ K}$, the heat conducted through a polystyrene sphere is $\frac{1}{4500}$ of the far-field radiative heat flux. Note that in a real measurement situation, the heat conduction leakage is an even smaller fraction of the radiative flux because a contact area of $\pi d^2/4$ between the sphere and the glass surface is overestimated. The spherical particles are diluted in deionized water as liquid suspension. Small droplets of the liquid suspension are dispensed with a pipette over the surface of the cold side to obtain a uniform spatial distribution of the particles. A total of about 80 particles are deposited between the two optical flats, thus, limiting the conduction heat flux to be less than 2% of the radiative heat flux. After the water in the droplets evaporates, the emitter is placed on top of the receiver with the particles serving as spacers to separate the two objects. We carefully conduct all the operations in a laminar flow workstation to eliminate dust particles in the air.

As illustrated in Fig. 2(a), a heating pad is attached on the top surface of the emitter. The temperature of the heating pad T_{h0} is monitored with a platinum resistance temperature detector, which feeds the signal to a temperature controller.

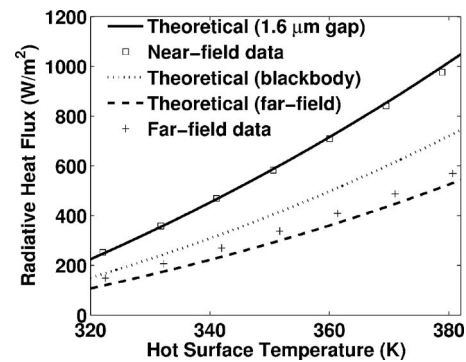


FIG. 3. Measured radiative heat flux between the two optical flats.

With the feedback control, the temperature of the heating pad can be set to a value with variations within $1\text{ }^{\circ}\text{C}$. The side surfaces of the optical flats are wrapped with aluminum foil to minimize radiative heat exchange with the environment. A $1\times 1\text{ in.}^2$ heat flux meter is positioned between the receiver and the heat sink. A copper heat spreader ($1\times 1\text{ in.}^2$) is sandwiched between the receiver and the heat flux meter to homogenize temperature over the surface. Thermal grease is applied to the interfaces for good thermal contact. To ensure that the heat flux meter measures only the radiative flux, the entire setup is placed in a vacuum chamber pumped down to $8.5\times 10^{-3}\text{ Pa}$. The vacuum level limits heat conduction through the rarefied air¹⁹ in the small gap to be less than 0.05% of the radiation flux.

To test the experimental system, we measured the far-field radiation. The emitter was clamped to a sample holder for the far-field measurement and the gap between the two surfaces was set to be 2 mm . We then proceeded to the near-field measurement using the particles as the spacers. The temperature of the bottom surface of the receiver T_{c0} was recorded by a K -type thermocouple inserted in between the copper spreader and the flux meter. For each measurement, we made sure that the reading from the heat flux meter stabilized before the data were taken. Note that even at the steady state, the temperatures inside the optical flats is not uniform due to a nonzero one-dimensional (1D) heat flux along the cylinder axis direction of the optical flats. From the temperature reading T_{h0} on the heating pad and the heat flux data, we can derive the temperature T_h on the lower surface of the emitter by solving a 1D heat conduction problem. The lower surface temperature is given by $T_h=T_{h0}-q_r''d_{\text{glass}}/k_{\text{glass}}$, where q_r'' is the measured flux and d_{glass} and k_{glass} are the thickness and thermal conductivity of the optical flat, respectively. Similarly, the temperature T_c on the upper surface of the receiver is given by $T_c=T_0+q_r''d_{\text{glass}}/k_{\text{glass}}$. The temperatures T_h and T_c are the effective temperatures for thermal emission because the electromagnetic penetration depth in glass is much less than 1 mm and thermal radiation is essentially a surface phenomenon in the wavelengths of interest.

The measured heat flux data are presented in Fig. 3, which has been adjusted by taking into account a heat spreading factor of $16/\pi$ between the circular optical flat and the square flux meter. The variation of the temperature T_{c0} on the bottom surface of the receiver is less than $0.5\text{ }^{\circ}\text{C}$ during the experiment and the average value is $23.7\text{ }^{\circ}\text{C}$. The far-field upper limit of the radiative heat flux is given by $q_b''=\sigma(T_h^4-T_c^4)$, where σ is the Stefan-Boltzmann constant. Note

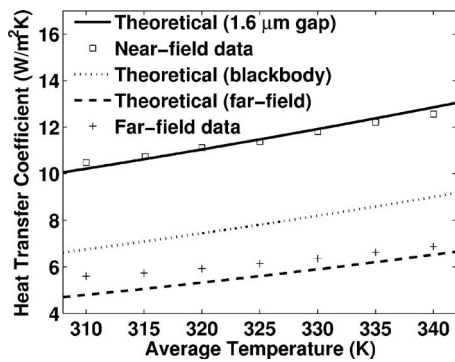


FIG. 4. Temperature dependent heat transfer coefficient. The temperature is the average of the hot surface and cold surface temperatures.

that T_h and T_c are derived based on the 1D heat conduction model. As the temperature of the hot surface increases, both the near-field and far-field radiative fluxes increase. While the far-field heat flux stays below the upper limit, the near-field heat flux clearly exceeds the blackbody upper limit by more than 35% in the entire temperature range. Also shown in Fig. 3 is the calculated far-field radiative heat flux. The far-field curve agrees reasonably well with the experimental data.

Figure 4 compares theoretical predictions and experimental data for the temperature dependent heat transfer coefficient. The measured data agree well with the theoretical prediction for a 1.6 μm gap. This larger-than-expected gap is most likely because the polystyrene particles have a deviation in diameters, as shown in Fig. 2(b). The gap is determined by the larger particles. Another factor that affects the fitting of experimental data is the accuracy of the optical data we used for the theoretical calculation. Nevertheless, the data clearly show that the radiative heat transfer exceeds the blackbody radiation flux. The heat transfer coefficient increases as the temperature of the hot side rises. An increase of 19% is found for the temperature range. In the same temperature range, the thermal conductivity of polymer typically decreases and that of glass²⁰ increase at much lower rate, excluding the possibility that the origin of the measured heat flux is conductive in nature.

In summary, we conducted experimental study on the near-field thermal radiation between two closely spaced glass surfaces. The measured radiative heat flux exceeds the blackbody radiation for more than 35% in the entire temperature range, and agrees reasonably well with the calculation results. From theoretical considerations, we attribute the primary contribution to the heat transfer to surface phonon polaritons at the interface between glass and vacuum.

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