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Near-field radiative thermal control with graphene covered on different materials

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ABSTRACT

Based on the structure of double-layer parallel plates, this paper demonstrates that thermal radiation in near field is greatly enhanced due to near-field effects, exceeding Planck's blackbody radiation law. To study the effect of graphene on thermal radiation in near field, the authors add graphene layer into the structure and analyze the ability of graphene to control near-field thermal radiation with different materials. The result indicates that the graphene layer effectively suppresses the near-field thermal radiation between metal plates or polar-dielectric plates, having good ability of thermal insulation. But for doped-silicon plates, depending on the specific models, graphene has different control abilities, suppressing or enhancing, and the control abilities mainly depend on the material graphene is attached to. The authors also summarize some common rules about the different abilities of graphene to control the near-field thermal radiation. In consideration of the thickness of 0.34 nm of monolayer graphene, this paper points out that graphene plays a very important role in controlling the near-field thermal radiation.

1. Introduction

The classical theory of thermal radiation deals with problems of far-field radiative heat transfer at macroscopic scale and it is often not applicable once the separation between bodies reaches or even becomes smaller than the dominant wavelength of thermal radiation at micro/nanoscale [1–6]. In this condition, radiative heat transfer between bodies is much larger than the prediction of Plank's law. When the separation decreases below microns, nonpropagating electromagnetic surface modes across the gap between bodies grow stronger, and the heat transfer, i.e., near-field radiative heat transfer, between the gap becomes distance-dependent, larger than that given by the Stefan–Boltzmann law [1–3,7]. For the past years, many groups have studied thermal radiation in near field theoretically or experimentally [2,3,8–12], and systematic theory has been formed. Especially over the recent years, with the development of detection methods and scientific instruments, many experiments have successfully demonstrated the enhancement of thermal radiation in near field [10,12–14].

With the rapid development of microfabrication, the size of precision devices is getting smaller and smaller, and the structure is getting tighter and tighter. Thus, the separation between different structures is decreasing rapidly, resulting in the great enhancement of radiative heat transfer between structures. Sometimes, designers may need to enhance the heat transfer to accelerate the cooling of the devices. Other times, however, designers may need to suppress the heat transfer to protect the devices nearby from the thermal influence. Graphene, made from graphite, which is very cheap, has unique properties of optics, electromagnetics and mechanics. It is

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considered as a novel material having a very broad prospect. By now, the research about graphene mostly focuses on the enhancement of heat transfer [15–20]. Volokitin and Persson studied the near-field radiative heat transfer between graphene and an amorphous SiO_2 substrate, reporting a significant contribution of the non-suspended graphene to the heat transfer [15]. Svetovoy et al. calculated the near-field radiative heat transfer between two dielectrics covered with graphene, and the result showed that the heat transfer can be larger than that between best known materials and becomes especially efficient below the room temperature [16]. Ilic et al. conducted a detailed theoretical study of several implementations of thermal emitters using plasmonic materials and graphene, reporting a particularly beneficial effect on near-field energy transfer by bringing the graphene surface close to the emitter [19]. Liu et al. covered graphene on top of a Ag grating, improving both the magnitude and coherence of the transmitted infrared radiation, which may help improve the performance and robustness of optical devices [20]. These investigation efforts above-mentioned were devoted to study the enhancing effect of graphene using different materials or based on different structures, paid little attention to the analyses of the ability to suppress the energy transfer, which also plays an important role in thermal control. In this paper, on the basic of the parallel-plate configuration, the authors study both the enhancing effect and the suppressing effect of graphene on near-field thermal radiation with different materials (e.g., metals, doped silicon and polar dielectrics) and models. Attaching the monolayer graphene to the doped-silicon plate, the heat transfer of the model consisting of metal plate and doped-silicon plate can be increased by up to 28.8%, while it can be decreased by up to 0.6% if graphene is attached to the metal plate. For the model consisting of silica plates, the heat transfer can be decreased by about 20.9% after adding graphene into the model. In addition, some other models of different materials are also studied, and by comparing the different effects of graphene, the authors summarize some common rules about the different abilities of graphene to control the near-field thermal radiation.

2. Model of near-field thermal radiation

2.1. Models of structure

The structural models studied in this paper are depicted in Fig. 1. Fig. 1(a) depicts the structural model of double-layer parallel plates, i.e., plate A and plate B. Between the plates is the vacuum gap. In Fig. 1(b), graphene clings to the upper surface of plate A. Two models in Fig. 1 have the same gap size (d). In near field, the gap size is commonly below 1 μm, thus the surfaces of the plates can be considered as infinite compared with the gap size, and there is no need to take account of the thickness of the plates. The model above is the half-infinite parallel-plate model in near field [5].

2.2. Fluctuation–dissipation theorem and common models of complex dielectric function

The solution to problems of near-field thermal radiation is usually based on the random Maxwell's equations and fluctuation–dissipation theorem [21]. Details to calculate the radiative heat flux can be found in Refs. [3,8–11,22–24] and here are just the key processes. In calculation, material is assumed isotropic, homogeneous and no spatial dispersion. To calculate the heat flux between double-layer parallel plates, the Poynting vector is needed [9]

$$\langle \boldsymbol{S}(\boldsymbol{x},\omega)\rangle = \frac{1}{2}\langle \mathrm{Re}\left[\boldsymbol{E}(\boldsymbol{x},\boldsymbol{\omega}) \times \boldsymbol{H}^{*}(\boldsymbol{x},\omega)\right]\rangle \tag{1}$$

where

$$\boldsymbol{E}(\boldsymbol{x},\omega) = i\omega\mu_0 \int_V \overline{\overline{\mathbf{G}}}(\boldsymbol{x},x',\omega)\cdot j(x',\omega)dx' \tag{2}$$

and

$$\boldsymbol{H}(\boldsymbol{x},\omega) = \frac{1}{\mathrm{i}\omega\mu_0}\nabla\times\boldsymbol{E}(\boldsymbol{x},\omega) = \int_V \nabla\times\overline{\overline{\mathbf{G}}}(x,x',\omega) \cdot j(x',\omega)dx' \tag{3}$$

where $\langle\rangle$ represents time averaging, $\overline{\overline{\mathbf{G}}}(x,x',\omega)$ is the dyadic Green's function (DGF), and $\boldsymbol{E}(\boldsymbol{x},\omega)$ and $\boldsymbol{H}(\boldsymbol{x},\omega)$ are the electric and magnetic fields written by DGF. Here DGF helps to connect the current source $\boldsymbol{j}$ at location $\boldsymbol{x}'$ with the resultant electric field $\boldsymbol{E}$ at location $\boldsymbol{x}$ [9]. The superscript $*$ represents the complex conjugate and i is the imaginary unit. The heat flux from plate B to plate A in Fig. 1(a) is calculated by projecting the time-averaging Poynting vector, i.e., Eq. (1), into the z-direction [9]

$$q'_{\omega,2-1} = \frac{\Theta(\omega,T_2)}{\pi^2}\int_0^{\infty} Z_{21}(\beta)\beta d\beta \tag{4}$$

where $Z_{21}(\beta)$ is the exchange function, $\Theta(\omega,T)$ is the average energy of a Planck oscillator at angular frequency ω and temperature T. Hence the heat transfer between plate B and plate A is [9]

$$q = \int_0^{\infty}(q_{\omega,2-1} - q_{\omega,1-2})d\omega = \frac{1}{\pi^2}\int_0^{\infty} d\omega[\Theta(\omega,T_2) - \Theta(\omega,T_1)]\int_0^{\infty} Z_{21}(\beta)\beta d\beta \tag{5}$$

This is the equation to calculate the radiative heat flux of double-layer parallel-plate structure in near field. The key processes to calculate heat flux of multilayer structure is presented as follows.

The time-averaging z-direction Poynting vector $\boldsymbol{S}$, for materials of isotropic, homogeneous and no spatial dispersion, is expressed as [3,23]

$$\boldsymbol{S}(\boldsymbol{x}) = \int_0^{+\infty} S_{\omega}(\boldsymbol{x},\omega)d\omega \tag{6}$$

where

$$\boldsymbol{S}_{\omega}(\boldsymbol{x},\omega) = \mathrm{Re}\left\{\frac{2i\omega^2\mu_0\epsilon_0\epsilon'(\omega)\Theta(\omega,T_n)}{\pi}\int_V (G_{x\alpha}^{ee(\beta n)}G_{y\alpha}^{me(\beta n)^*} - G_{y\alpha}^{ee(\beta n)}G_{x\alpha}^{me(\beta n)^*})d\mathbf{V}\right\} \tag{7}$$

where ε_0 and μ_0 represent the dielectric constant (ε_0= 8.854×10^{-12} F/m) and magnetic permeability (μ_0=$4\pi\times$