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Enhanced energy transfer by near-field coupling of a nanostructured metamaterial with a graphene-covered plate

Jui-Yung Chang, Yue Yang, Liping Wang*

School for Engineering of Matter, Transport & Energy Arizona State University, Tempe, AZ 85287, USA

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ABSTRACT

Coupled surface plasmon/phonon polaritons and hyperbolic modes are known to enhance radiative transfer across nanometer vacuum gaps but usually require identical materials. It becomes crucial to achieve strong near-field energy transfer between dissimilar materials for applications like near-field thermophotovoltaic and thermal rectification. In this work, we theoretically demonstrate enhanced near-field radiative transfer between a nanostructured metamaterial emitter and a graphene-covered planar receiver. Strong near-field coupling with two orders of magnitude enhancement in the spectral heat flux is achieved at the gap distance of 20 nm. By carefully selecting the graphene chemical potential and doping levels of silicon nanohole emitter and silicon plate receiver, the total near-field radiative heat flux can reach about 500 times higher than the far-field blackbody limit between 400 K and 300 K. The physical mechanism is elucidated by the near-field surface plasmon coupling with fluctuational electrodynamics and dispersion relations. The effects of graphene chemical potential, emitter and receiver doping levels, and vacuum gap distance on the near-field coupling and radiative energy transfer are analyzed in detail.

1. Introduction

Near-field radiation has attracted much attention in the fields of energy harvesting [1–4] and heat management [5–10] since it can exceed the far-field blackbody limit through coupling of evanescent waves [11–14]. In particular, the near-field enhancement could be orders of magnitude with the excitation of surface plasmon/phonon polaritons (SPP/SPhP) across the nanometer vacuum gaps [15–20]; however, it usually requires identical or similar materials for the emitter and receiver to achieve the best coupling effect and thereby maximum heat flux enhancement. Recent studies on hyperbolic metamaterials (HMMs) [21–25], which exhibit large photonic local density of states, show the promise in enhancing the near-field radiative transfer by means other than resonant coupling, while the strong enhancement also requires matching hyperbolic behaviors for the emitter and receiver materials. It is still a challenge to greatly enhance the performance of near-field thermophotovoltaic (TPV) by either resonance coupling of SPP/SPhP or strong hyperbolic modes because of inherent mismatch in the dissimilar optical properties of the emitter and cell. TPV emitters are usually made of plasmonic metals or polar materials, while the cells are semiconductors with bandgap in the near infrared [26]. Therefore, it becomes crucial to find an efficient way to enhance near-field radiative transfer between dissimilar materials.

Graphene, which supports surface plasmon [27,28] with excellent tunability from near infrared to terahertz frequencies [29–31], has been recently studied and shown with capability to effectively modulate near-field radiative flux. By properly tuning the properties of graphene, near-

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* Corresponding author.
E-mail address: liping.wang@asu.edu (L. Wang).

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field radiation between dielectrics can be significantly enhanced by covering graphene [32,33]. Lim et al. [34] theoretically showed enhanced or suppressed near-field radiative heat flux between two graphene-coated doped silicon plates, which varies with the silicon doping level and graphene chemical potential. Liu and Zhang [35] found more than one order of magnitude enhancement in near-field radiative flux between two corrugated silica gratings with graphene coating. By covering graphene on doped silicon nanowires, which exhibit strong hyperbolic behaviors, Liu et al. [36] theoretically demonstrated near-unity photon tunneling probability in a broad frequency range and k space by the coupling between graphene plasmon and hyperbolic modes. In terms of near-field radiative transfer between dissimilar materials, Ilic et al. [37] applied graphene on an emitter and showed that the near-field TPV system performance can be optimized by matching the graphene plasmon with the cell bandgap. Messina and Ben-Abdallah theoretically demonstrated improved near-field TPV efficiency between a hexagonal boron nitride (hBN) emitter and graphene-coated InSb cell by effective near-field coupling of hBN phonon modes with graphene plasmon [38].

In this study, we theoretically investigate the near-field radiative transfer between a nanostructured metamaterial emitter made of doped silicon nanohole (D-SiNH) arrays and a doped silicon plate covered by monolayer graphene, as depicted in Fig. 1. The emitter and receiver, which are separated by a vacuum gap with distance d, are respectively maintained at $T_1 = 400$ K and $T_2 = 300$ K with doping levels N_1 and N_2. The SiNH emitter is described as a uniaxial homogeneous medium by effective medium theory (EMT) and graphene modifies the reflection coefficients at the vacuum-receiver interface as a surface current. Fluctuational electrodynamics incorporated with uniaxial wave propagation is employed to calculate the near-field radiative heat flux. The enhancement in spectral near-field radiative transfer will be illustrated, while the underlying mechanism will be elucidated as surface plasmon coupling between dissimilar materials with fluctuational electrodynamics and dispersion relation. The effects of graphene chemical potential, silicon doping levels, and vacuum gaps on the near-field energy transfer will be studied in detail as well.

2. Theoretical methods

2.1. Effective dielectric functions of doped silicon nanohole emitter

With the assumption that the feature size like hole array period P is much smaller than the characteristic thermal wavelength, the D-SiNH emitter can be considered as a homogeneous uniaxial medium with effective dielectric functions described by the Maxwell–Garnett effective medium theory [19,39,40]:

$$\varepsilon_{\parallel,\mathrm{eff}} = \frac{\varepsilon_{\mathrm{Si}}(1+\varepsilon_{\mathrm{Si}})+f\varepsilon_{\mathrm{Si}}(1-\varepsilon_{\mathrm{Si}})}{(1+\varepsilon_{\mathrm{Si}})-f(1-\varepsilon_{\mathrm{Si}})} \quad (1)$$

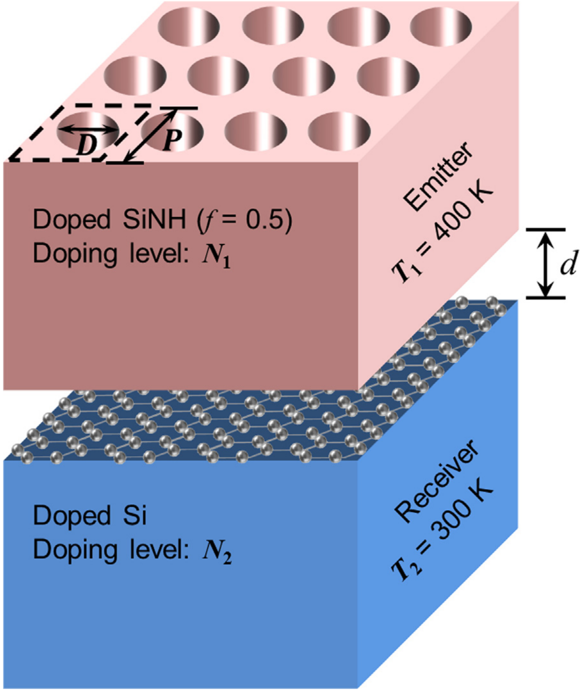

Fig. 1. Schematic of the simulated structure separated by vacuum gap d where both the doped SiNH emitter and graphene covered D-Si receiver are assumed to be semi-infinite.

and

$$\varepsilon_{\perp,\mathrm{eff}} = \varepsilon_{\mathrm{Si}} + f(1-\varepsilon_{\mathrm{Si}}) \quad (2)$$

Here, the subscripts "$\parallel$" and "$\perp$" respectively denote directions parallel and vertical to the SiNH-vacuum interface, and $f = \pi D^2/4P^2$ is the volumetric filling ratio. $\varepsilon_{\mathrm{Si}}$ is the dielectric function of doped silicon which can be obtained by a Drude model [41]:

$$\varepsilon_{\mathrm{Si}}(\omega, N, T) = \varepsilon_\infty - \frac{\omega_{\mathrm{p}}^2}{\omega^2 + i\Gamma\omega} \quad (3)$$

where $\varepsilon_\infty = 11.7$ is the high-frequency constant, Γ is the temperature-dependent scattering rate, and $\omega_{\mathrm{p}} = \sqrt{N_{\mathrm{c}}e^2/m^*\varepsilon_0}$ is the plasma frequency with carrier concentration N_{c}, electron charge e, carrier effective mass m^*, and the permittivity of free space ε_0. Here, the effect of doping level is accounted by carrier concentration which is the product of doping level and degree of ionization.

As shown in Fig. 2(a), the D-SiNH emitter with p-type doping level $N_1 = 10^{20}\ \mathrm{cm}^{-3}$ and $f = 0.5$ exhibits uniaxial metallic behavior at frequencies $\omega < 2.3 \times 10^{14}$ rad/s where both $\varepsilon_{\perp,\mathrm{eff}}$ and $\varepsilon_{\parallel,\mathrm{eff}}$ are negative. Furthermore, the material property will change with different doping level N_1, and the region of uniaxial metallic behavior will shift towards higher frequency with increasing doping level (not shown here). Though filling ratio f can also tune material property of the D-SiNH emitter besides N_1, it is fixed at $f = 0.5$ in the present study for simplicity.