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Optimization of a near-field thermophotovoltaic system operating at low temperature and large vacuum gap

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ABSTRACT

The present work successfully achieves a strong enhancement in performance of a near-field thermophotovoltaic (TPV) system operating at low temperature and large-vacuum-gap width by introducing a hyperbolic-metamaterial (HMM) emitter, multilayered graphene, and an Au-backside reflector. Design variables for the HMM emitter and the multilayered-graphene-covered TPV cell are optimized for maximizing the power output of the near-field TPV system with the genetic algorithm. The near-field TPV system with the optimized configuration results in 24.2 times of enhancement in power output compared with that of the system with a bulk emitter and a bare TPV cell. Through the analysis of the radiative heat transfer together with surface-plasmon-polariton (SPP) dispersion curves, it is found that coupling of SPPs generated from both the HMM emitter and the multilayered-graphene-covered TPV cell plays a key role in a substantial increase in the heat transfer even at a 200-nm vacuum gap. Further, the backside reflector at the bottom of the TPV cell significantly increases not only the conversion efficiency, but also the power output by generating additional polariton modes which can be readily coupled with the existing SPPs of the HMM emitter and the multilayered-graphene-covered TPV cell.

1. Introduction

Near-field thermophotovoltaic (TPV) system is a promising technique for a power generation, in which an emitter is placed at a sub-micron distance from a TPV cell to significantly increase the radiative heat transfer in the near-field regime [1–23]. The TPV cell is an infrared-sensitive photovoltaic cell, which can directly convert absorbed infrared radiation into electricity and has potential to outperform other solid-state electricity-generation techniques, such as thermoelectric and thermionic converters [1,2]. In addition, the fact that a TPV system has no moving parts and is independent of pressure and gravitational force makes it attractive for space, industrial, residential and microelectronic applications [2,3].

In a TPV system, an emitter is first heated by an external thermal source and then re-emits the thermal energy in the form of infrared radiation. Because there is no restriction on material selection of the emitter, there has been a myriad of studies which show various kinds of near-field interaction between the emitter and the TPV cells [8–23], resulting in enhanced performance of the near-field TPV system. For example, a monolayer of graphene [8], metallo-dielectric multilayer structures [15,17], gratings [18,19], a nanowire array [13], a thin film [11] and a fictitious Drude emitter [14] have been employed as an emitter to increase the power output or the conversion efficiency of the TPV system by tuning the spectral emission. These nanostructures also can be applied on the top of the TPV cell: a monolayer of graphene [9,12], multilayered graphene [20], a nanowire array [21], and a thin film [23]. Further, on the backside of the TPV cell, a reflector, which can also be used as an electrode, is placed to reflect back the unabsorbed photons to the emitter, yielding an increment in the conversion efficiency [10,17]. Recently, several works introduced a thin TPV cell and a backside reflector such that thin-film waveguide mode as well as surface mode supported by the thin TPV cell can significantly enhance the performance of the TPV system [11,16,22,23].

Despite above plentiful theoretical works, experimental validation of the near-field TPV system is rather limited [24]. One of the main challenges in this demonstration is maintaining a nanogap between planar surfaces with a large area. Although two groups have reported drastically enhanced near-field radiation between two planar surfaces separated by 50 nm [25,26], heat transfer area in those works is considerably small. For the near-field TPV application, other groups demonstrated the near-field enhancement of the radiative heat transfer between two planar surfaces with a large area separated by 150–200 nm [27,28]. They increased the total radiative heat transfer rate by increasing the heat transfer area at the expense of a small vacuum gap between surfaces. Further, almost all of the experimental works maintained the temperature

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difference between the emitter and the receiver less than 200 K [25,27–33]. One group measured near-field radiation at the temperature difference larger than 200 K; however, as the vacuum gap distance became smaller, the temperature difference could not be maintained due to the increased heat transfer [26]. Thus, the restriction in the maximum temperature difference of 200 K as well as the minimum vacuum gap width of 200 nm can be considered as the current technical limit for a practical near-field TPV system. Because of the significantly reduced radiation at low temperature, few works have reported the enhanced performance of the near-field TPV system with the low-temperature emitter (∼ 500 K) [9,11,12,20,23].

In order to enhance the performance of the low-temperature near-field TPV system, a monolayer of graphene was introduced to the cell side, but its effect diminishes when the vacuum gap width is larger than 50 nm [9,12]. Our previous publication [20] introduced multilayered graphene on the TPV cell side, which allows significant enhancement at the vacuum gap of 50 nm. However, the effect also diminished when the vacuum gap is 200 nm. This is because the coupled surface plasmon polaritons (SPPs) generated in the multilayered graphene have a negligible effect on the heat transfer at the vacuum gap width of 200 nm. Nevertheless, a high-temperature near-field TPV system with a hyperbolic metamaterial (HMM) emitter is known to have higher performance than that with a bulk emitter at a large vacuum gap due to a coupling of SPPs in the HMM emitter [15]. Thus, to meet the demand at the experimentally achievable vacuum gap (i.e., about 200 nm), we propose a near-field TPV system with a HMM emitter and multilayered graphene on the TPV cell side to get an enhanced heat transfer through a coupling of coupled SPPs from the HMM emitter and coupled SPPs from the multilayered graphene. The structure is optimized with the genetic algorithm to maximize the power output through a strong coupling of SPPs generated in both HMM emitter and multilayered graphene. Further, by introducing a backside reflector, additional polariton modes can be supported in the TPV cell of finite thickness. Detailed discussion on the coupling of these polaritons from the HMM emitter, the multilayered graphene, and the TPV cell with the backside reflector will be provided with the performance analysis on the near-field TPV system.

2. Theoretical modeling

The proposed near-field TPV system with a HMM emitter and an InSb TPV cell with multilayered graphene is depicted in Fig. 1. The width of a vacuum gap separating the emitter and the cell is noted as d. The HMM emitter consists of alternating p-doped Si and SiO_2 layers which are stacked on the p-doped-Si substrate at the same doping concentration. The thickness of the p-doped Si layer, t_m, is set to be 10 nm. Throughout the paper, the number of periods of HMM emitter is fixed as five (i.e., five doped-Si layers and five SiO_2 layers on the doped-Si substrate) because the spectral heat flux does not change much with an increase in the number of periods of HMM emitter if it is higher than five [15]. For the multilayered graphene, each of graphene layers is separated by SiO_2 interfacial layer with the thickness of $t_{dr} = 5$ nm [20]. In Fig. 1, the InSb TPV cell is considered as a semi-infinite body; that is, the thicknesses of p-doped region and depletion region are L_p and L_{dp}, respectively, but n-doped region is set as semi-infinite. Temperatures of the emitter and the TPV cell are set to be 500 K and 300 K, respectively, and the dielectric function of SiO_2 both in the HMM emitter and the multilayered graphene is obtained from Ref. [34]. The frequency-dependent dielectric function of the p-doped Si is calculated with the assumption of complete ionization at 500 K [35]. Because the calculated electron mean free path in the heavily-doped Si is around 3 nm, the dielectric function of 10-nm-thick-doped-Si layer is assumed to be identical to that

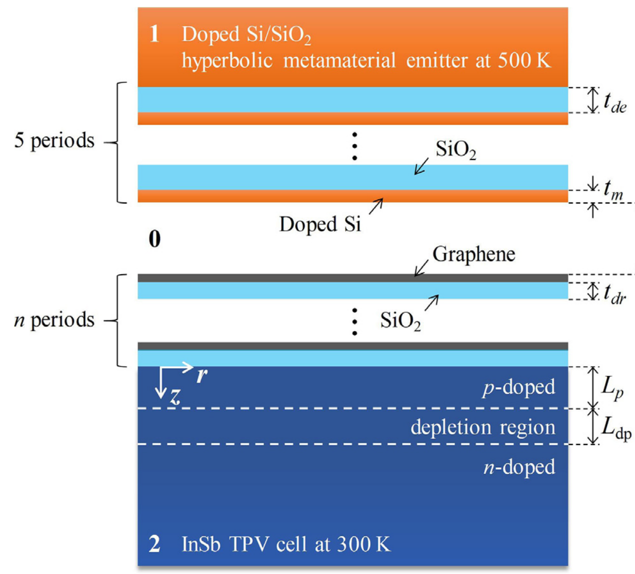

Fig. 1. Schematic of a near-field TPV system consisting of a hyperbolic-metamaterial emitter and a multilayered-graphene-covered InSb TPV cell.

of the bulk-doped-Si substrate for simplicity [35–37]. We presume homogeneous InSb TPV cell such that the dielectric function is not depending on its doping concentration [8,9,12,20]. Also, constant chemical potential (i.e., 1.0 eV) and the constant relaxation time (i.e. 10^{-12} s) are used for each layer of graphene [38].

2.1. Near-field thermal radiation and power generation in the near-field TPV system

Because the TPV cell can generate electric power from the radiation absorbed only inside the TPV cell (i.e., not from the radiation absorbed in the multilayered graphene), the dyadic Green's function for the multilayered structure which considers both forward and backward waves in each layer [6,39] is employed for calculating radiative heat flux emitted from the HMM, passing through the multilayered graphene, and absorbed in the TPV cell. Working with the multilayered formulation, a graphene layer is also considered as a very thin layer of the finite thickness of 0.5 nm with a dielectric function obtained from its surface conductivity and thickness [40]. The total net radiative heat flux q''_{net} is expressed as $q''_{net} = \int_0^\infty d\lambda \; q''_{\lambda,net} = \int_0^\infty d\lambda \; \int_0^\infty S_{\beta,\lambda}(\beta,\lambda) d\beta = \int_0^\infty d\lambda \; \int_0^\infty [S^p_{\beta,\lambda}(\beta,\lambda) + S^s_{\beta,\lambda}(\beta,\lambda)] d\beta$, where λ is vacuum wavelength, β is the parallel wavevector component, and the superscripts of p and s indicate the polarization states [6,39].

In calculating the photocurrent generated in the near-field TPV system, we employed the minority carrier transport model within the TPV cell in two ways: one is the semi-analytic method [12] and the other is the finite difference method [6]. Both methods produce the same results for the near-field TPV system with the semi-infinite TPV cell. In calculation with the finite difference method, the p-doped region and 30 µm of the n-doped region are discretized into 200 layers, respectively considering that 30 µm is much larger than hole diffusion length (∼ 970 nm) [6,12]. Because the semi-analytic method has much faster calculation speed than the finite difference method, the semi-analytic method is used for optimization with the genetic algorithm. In the latter part of the paper, a reflector will be introduced on the backside of the TPV cell. With the reflector, however, the semi-analytic method cannot be applied because the absorbed radiation within the finite-thickness TPV cell is not exponentially decayed in the z-direction [12]. Due to multiple reflections at each side of the finite-thickness