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Thermal switch and thermal rectification enabled by near-field radiative heat transfer between three slabs

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ABSTRACT

In this paper, the near-field radiative heat flux of the system consisting of two SiO_2 plate sources and one 50 nm thick VO_2 film, a kind of insulator–metal transition material, placed between them is studied. The two sources are maintained at 400 and 300 K, respectively, and separated by a distance of 150 nm. By this configuration, the temperature of the film can be regulated by the control of the separation distance between the film and the sources via a piezoelectric motor. It is found that the net radiative heat flux of this system can be varied in a range of 7.5×10^3–3.2×10^4 W/m^2 for different position of the VO_2 film due to its phase transition. Hence, the functions of thermal switch and thermal rectification are able to be realized by this system. Particularly, the direction of the larger heat flux in the proposed thermal rectification can be reversed by changing the position of the VO_2 film. The effects of some parameters are investigated to improve the performance of the thermal rectification.

1. Introduction

As the counterpart of an electric rectifier and an electric switch in electronics, a thermal rectifier is a device that allows heat to flow preferentially in one direction [1,2], and a thermal switch is a device that allows the heat flux in the "on" mode being obviously larger than that in the "off" mode [3,4]. Such devices may have enormous applications in thermal management and control for energy systems and microelectronic devices. The previous thermal rectifications were mainly limited to heat conduction and convection [1,5,6]. Recently, photonic thermal rectification based on near-field radiative transfer [7–13] has attracted attention due to the advantage of obtaining large rectification factors over a broad temperature range. The reported photonic thermal rectifiers are all made of two terminal parts and realized by one or two of the following mechanisms: (1) an asymmetric geometric arrangement [9], (2) dissimilar materials with different temperature-dependent thermal properties [7,8,10–13].

Recently, Ben-Abdallah and Biehs [4] designed a photonic thermal transistor, and the functions of thermal switch, thermal modulation and thermal amplification were realized simultaneously. The thermal transistor is composed of three basic elements, thermal source, thermal drain, and gate, and the heat flux can be controlled by the gate made of an insulator–metal transition (IMT) material, whose optical property is able to be changed through a small variation of its temperature around the critical temperature T_c. In literature [4], the temperature of the gate was controlled by a certain amount of heat added to or removed from it. However, there may be two weaknesses of that way to regulate the temperature of the gate. One probably comes from the fact that two different elements are needed to add heat to or remove heat from the gate, which makes the system more complicated. The other is that there exists a region where a certain amount of heat added to the gate corresponds to three different temperatures of the gate (as shown in Fig. 3 of literature [4]), which makes it difficult to control the heat flux.

In this paper, we propose a new way to control the temperature of the gate by changing the distance between the gate and the thermal source, which can be carried out, for example, with the piezoelectric motors from Attocube as used in the experiment conducted by Rousseau et al. [14], where the displacements of a silica microsphere were carried out with the piezoelectric stages by steps of 7 nm. With this improvement, a three-part system is realized simply to switch or rectify the heat flux carried by photons.

2. Configuration and calculation of the heat flux

2.1. Configuration

The structure of the proposed near-field system is schematically plotted in Fig. 1. Medium 1 and medium 3 both made of

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amorphous silicon dioxide (SiO_2) are assumed to be semi-infinite and maintained at 400 and 300 K, respectively, by some thermostats. A thin layer (medium 2) made of vanadium dioxide (VO_2) having thickness δ is placed between them at distances d_{12} from medium 1 and d_{23} from medium 3. VO_2 is one of the IMT material that undergoes a phase transition from a high-temperature metallic phase to a low-temperature insulating phase around its critical temperature ($T_c \approx 340$ K) [15,16]. The thickness of the film is 50 nm, and distances d_{12} and d_{23} are related by $d_{12} + d_{23} = 100$ nm to introduce the near-field effect and to get large heat flux. The temperature T_2 of the film is determined by thermal equilibrium with media 1 and 3, and undoubtedly T_2 is a function of d_{12} or d_{23}, which enables the control of heat flux by regulating d_{12} or d_{23} with the piezoelectric motors.

2.2. Calculation of heat flux

The dielectric function of insulating VO_2 in the bulk shape is related to the crystal orientation in the infrared wave region, while that of insulating VO_2 in the film shape or VO_2 in metallic phase does not exhibit anisotropy [15–17]. Here we consider the case where the optical axis of VO_2 film is orthogonal to its interfaces, and its dielectric functions are obtained from [15,16], while the dielectric functions of SiO_2 are taken from Ref. [18]. Fig. 2 shows the real (ε') and imaginary (ε'') parts of the dielectric functions of VO_2 and SiO_2. It can be seen from Fig. 2 that SiO_2 has two strong phonon modes at the frequencies 8.5×10^{13} and 2.0×10^{14} rad/s, and the phonon mode at lower frequency overlaps with that of insulating VO_2.

In Fig. 1, the heat flux across any planes parallel to the surfaces of the three bodies can be obtained by calculating the Poynting vector. Considering the three-body configuration, the theory developed by Messina and Antezza [19] recently is used to investigate the net radiative heat flux. This theory is valid for arbitrary bodies of a three-body system, i.e., for any set of temperatures and geometrical properties, and describes each bodies by means of their scattering operators. The net heat flux emitted by body 1 reads [20]:

$$\Phi_1 = \int_0^\infty \frac{d\omega}{2\pi}\hbar\omega \int_0^\infty \frac{d^2k}{(2\pi)^2} \times \sum_{j=s,p}\left[n_{12}(\omega)\Gamma_j^{1/2}(\omega,k,d_{12},d_{23}) + n_{13}(\omega)\Gamma_j^{1/3}(\omega,k,d_{12},d_{23})\right] \quad (1)$$

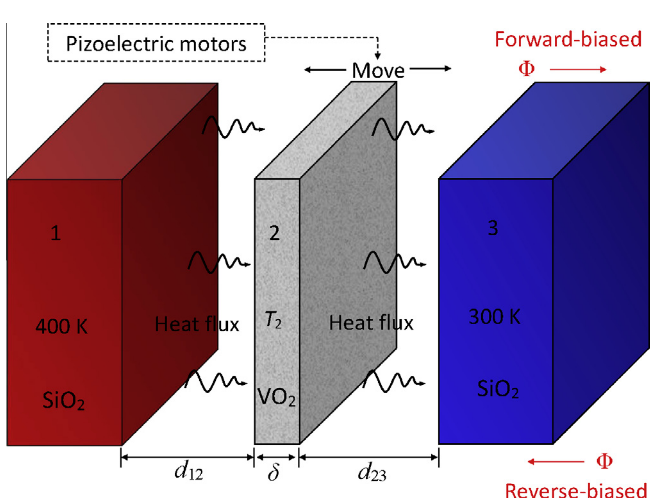

Fig. 1. Schematic of the system in the three-slab configuration.

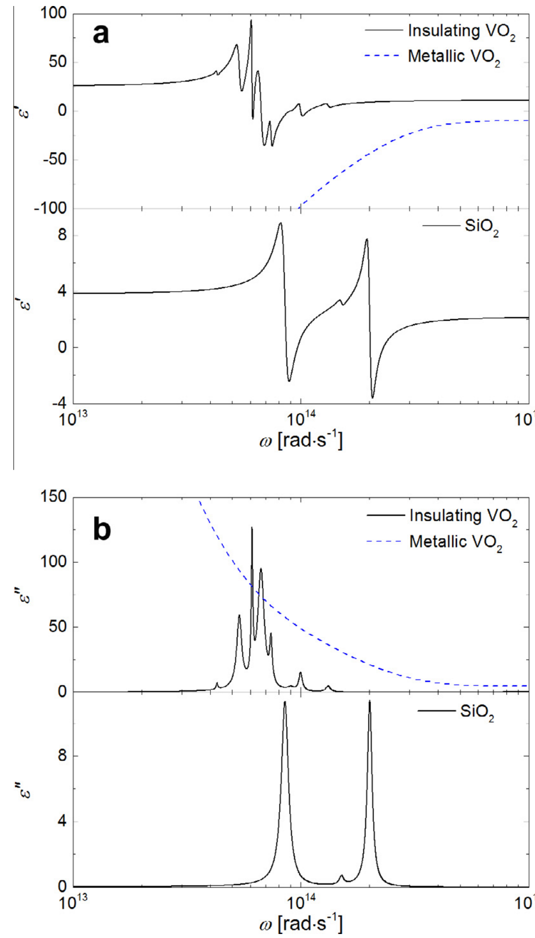

Fig. 2. Dielectric functions of VO_2 and SiO_2: (a) real parts, (b) imaginary parts.

where, $\Gamma_j^{1/2}$ and $\Gamma_j^{2/3}$ denote the transmission probabilities of photons, defined by mode (ω, $\mathbf{k}$) for polarization state $j = s, p$, from body 1 to body 2 and from body 1 to body 3, respectively; $\mathbf{k} = (k_x, k_y)$ is the wave vector parallel to the surfaces of multilayer system. $n_{ij}(\omega) = n_i(\omega, T_i) - n_j(\omega, T_j)$ denotes the difference of Bose-distribution functions with $n_{i/j} = 1/[\exp(\hbar\omega/k_B T_{i/j}) - 1]$. $2\pi\hbar$ is the Planck's constant and k_B is the Boltzmann's constant.

Similarly, the heat fluxes received by body 2 and body 3 are given by:

$$\Phi_2 = \int_0^\infty \frac{d\omega}{2\pi}\hbar\omega \int_0^\infty \frac{d^2k}{(2\pi)^2} \times \sum_{j=s,p}\left[n_{12}(\omega)\Gamma_j^{1/2}(\omega,k,d_{12},d_{23}) + n_{32}(\omega)\Gamma_j^{3/2}(\omega,k,d_{12},d_{23})\right] \quad (2)$$

$$\Phi_3 = \int_0^\infty \frac{d\omega}{2\pi}\hbar\omega \int_0^\infty \frac{d^2k}{(2\pi)^2} \times \sum_{j=s,p}\left[n_{13}(\omega)\Gamma_j^{1/3}(\omega,k,d_{12},d_{23}) + n_{23}(\omega)\Gamma_j^{2/3}(\omega,k,d_{12},d_{23})\right] \quad (3)$$

It is easy to derive the relation $\Phi_2 = \Phi_1 - \Phi_3$ from Eqs. (1)–(3). At steady state, the heat flux Φ_1 emitted by body 1 equals the heat flux Φ_3 received by body 3, and hence the net heat flux Φ_2 received by medium 2 vanishes.

All the transmission probabilities Γ_j are defined in terms of optical reflection coefficients $\rho_j^{(i)}(i = 1,2,3 \text{ and } j = s,p)$ and