Near-field Radiative Thermal Modulation by Tunneling Through Graphene Sheet

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Abstract

In this paper, we have theoretically demonstrated a graphene-mediated near-field radiative thermal modulator based on doped silicon-graphene-doped silicon three-slab configuration. The near-field photon tunneling between the doped silicon emitter and receiver is modulated by changing chemical potential of graphene sheet and the separation distance between the sheet and the emitter. The near-field three-body theory built on fluctuational electrodynamics is used to calculate total radiative heat flux, which could be modulated in a range of 10-70 kW/m² with different setup for graphene chemical potential and its position. The underlying mechanism is illustrated as varied coupling behavior of surface plasmon polaritons between doped silicon and graphene sheet. Several dimensionless factors such as normalized heat flux, sensitivity factor and switching factor are also introduced for comprehensive analysis of the performance of modulation effect. The results obtained here will trigger a new way for near-field active thermal management between bulk materials utilizing suspended 2-D materials.

Keywords: near field radiation; thermal modulation; three-slab configuration; graphene sheet; surface plasmon polaritons

Received: 3 February 2020; Accepted: 4 March 2020

Article type: Research article

1. Introduction

For classic thermal radiation, the radiative heat flux between two bodies is governed by propagation waves which obey the Stefan-Boltzmann law. If the distance is smaller than the characteristic wavelength of thermal radiation predicted by Wien's displacement law, the interference of evanescent waves and photon tunneling would contribute to dramatic increase in radiative heat transfer, which is known as near-field thermal radiation.^[1,2] Moreover, in near-field regime, heat flux will show a further enhancement due to the excitation of additional resonance modes, such as surface plasmon polaritons (SPPs),^[3-5] surface phonon polaritons^[6-8] and magnetic polaritons.^[9,10]

Recently, considering practical application scenarios, how to regulate near-field heat flux has become one of hot research topics.^[11] A variety of near-field radiative thermal transistor,^[12,13] rectifier,^[14-19] switch^[20,21] and thermostat^[22] have been theoreti-

cally designed and studied to actively control heat flux utilizing different mechanisms. Adding another body between two fixed bodies will achieve a notable change in primary radiative heat flux, which already becomes a novel way to adjust near-field photon transport.^[23-25] Ben-Abdallah *et al.*^[12] designed a near-field thermal transistor based on such a three-parallel-slabs system and the Mott phase transition of intermediate vanadium dioxide (VO₂) slab, which can realize the functions of thermal switch, amplification and modulation simultaneously. A thermal rectification was also proposed by Gu *et al.*,^[21] which could mediate near-field thermal transfer via the control of the separation distance between the central VO₂ part and the emitter part. The key of these configurations is the use of insulator-metal transition material,^[26,27] which is capable of changing its own optical property through temperature variation, resulting in coupling or mismatch of surface resonant modes. Thus, the near-field heat flux will vary accordingly. However, the optical characteristic change of insulator-metal transition material is so strongly dependent on threshold temperature that the regulation speed, resolution, and

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flexibility are limited.

Graphene, a two-dimensional material, has attracted extensive attentions because of its unique and astonishing electronic and optical properties.^[28] One of the main features is tunable surface plasmon^[29,30] with variable chemical potentials induced by external voltage biases or doping. The feature makes graphene become a favorable alternative for radiative thermal management device.^[31-34] Yang *et al.*^[35] conceived of an electrically-controlled near-field thermal modulator made of two graphene-coated silicon carbide plates. He *et al.*^[22] designed a near-field thermostat consisted of graphene-coated dielectric emitter, receiver and intermediate layer without graphene. Similarly, changing chemical potentials of graphene by gate voltage, the temperature of intermediate body can be reset due to the coupling of graphene plasmon and dielectric phonon polaritons.

In this paper, a two-parameter near-field radiative thermal modulator made of three-slab system is introduced. The system basically has semi-infinite doped silicon slab emitter and receiver. In the middle of them, a monolayer of graphene is placed in parallel to make near-field radiative photons tunnel through. It is similar to other graphene-based modulator, and opto-electronic control technology is adopted to tune the chemical potentials of graphene, which possesses a superiority of fast operating speed and high resolution. Moreover, the distance between emitter and graphene sheet is also tunable to guarantee regulative magnitude at a larger scale and achieve a

better modulating performance. Based on such a two-parameter mediated three-slab configuration, the total radiative heat flux can be varied in a range of 10-70 kW/m² for the coupling of graphene plasmon and doped silicon plasmon polaritons. Although theoretically calculated results provide us more flexibility for heat flux modulation with three-body configuration, we also need to notice that it will be more challenging to implement experimental measurement than that with two-body system. A possible way we can think about to achieve it is by dividing it into two separate two-body systems. Through fixing the middle layer position, we can approach the other two bodies to it within a small gap distance by using the existing methods like custom-built nano-positioning method^[36] and piezoelectric motor technology.^[37] Thermal modulation and switching effects, which are indispensable features of modulator, are quantitatively studied with the independent or simultaneous change of two parameters in detail.

2. Physical model and theoretical calculation

2.1 Physical model

The configuration we study consists of three separate parallel slabs labeled with subscripts 1-3, which is schematically shown in Fig. 1. The slabs 1 and 3 located on both sides of the configuration are set as doped Si and they are supposed as semi-infinite. A classic Drude model is used to characterize the dielectric function of doped Si:^[5]

Fig. 1 (a) Schematic illustration of proposed near-field radiative thermal modulator made of Si-graphene-Si three-slab configuration. The three separated slabs are labeled 1-3 and the temperatures of Si emitter and receiver are set as $T_1 = 400$ K and $T_3 = 300$ K. The slabs on two sides of the configuration are semi-infinite. The intermediate slab is graphene sheet with thickness t_g and temperature T_2 . (b) Side view of the configuration. The heat flux emitted by slab 1 and obtained by slab 3 are Φ_1 and Φ_3 , respectively. The separation distance between slab 1 and graphene slab is d_{12} , while the distance between graphene and slab 2 is d_{23} and $d_{12} + d_{23} = 100$ nm. The position of graphene slab can be moved, while the chemical potentials of it can also be changed.

$$\varepsilon_{\text{Si}}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}, \quad (1)$$

where $\varepsilon_{\infty} = 11.7$, $\omega_p = 1.08 \times 10^{15}$ rad/s is the plasma

frequency and the scattering rate γ is taken as 9.34×10^{13} rad/s, which are corresponding to a doping concentration on the order of 10^{20} cm⁻³ at room temperature. The reason to

choose this doping concentration is to maintain Si SPPs within the frequency domain that Graphene SPPs can match. The slab 1 is hot emitter and slab 3 is cold receiver, which are kept unchanged at $T_1 = 400$ and $T_3 = 300$ K, respectively. The thin slab 2 is a monolayer graphene with thickness $t_g = 0.3$ nm, which is placed between slab 1 and slab 3 at a distance of d_{12} away from slab 1 and d_{23} from slab 3. It should be noted that the d_{12} and d_{23} are not independent and constrained by $d_{12} + d_{23} = 100$ nm. The graphene layer can be moved via the piezoelectric motor, inducing the changes in d_{12} and d_{23} , and the corresponding heat flux will get modulated. In our present work, the graphene sheet is modeled as a medium with dielectric function determined by the Drude model.^[38]

$$\varepsilon_g(\omega) = 1 + \frac{i\sigma_g}{\omega\varepsilon_0 t_g}, \quad (2a)$$

$$\sigma_g = \sigma_d + \sigma_i, \quad (2b)$$

$$\sigma_d = \frac{i}{\omega + i/\tau} \frac{2e^2 k_B T_2}{\pi \hbar^2} \ln \left[2 \cosh \left(\frac{\mu}{2k_B T_2} \right) \right] \quad (2c)$$

$$\sigma_i = \frac{e^2}{4\hbar} \left[G \left(\frac{\hbar\omega}{2} \right) + i \frac{4\hbar\omega}{\pi} \int_0^\infty \frac{G(\xi) - G(\hbar\omega/2)}{(\hbar\omega)^2 - 4\xi^2} d\xi \right] \quad (2d)$$

where ε_0 is the permittivity in vacuum and σ_g indicates the conductivity of graphene, which is a sum of an intraband term σ_d and an interband term. Note that σ_d stands for deviation from the intraband electron-photon scattering, while σ_i is related to the interband electron drift. $G(\xi)$ is defined as $\sinh \left(\frac{\xi}{k_B T_2} \right) / \left[\cosh \left(\frac{\mu}{k_B T_2} \right) + \cosh \left(\frac{\xi}{k_B T_2} \right) \right]$, relaxation time τ is chosen as 10^{-13} s at room temperature,^[37] e is the magnitude of electron charge, $\hbar$ is the reduced Planck's constant, k_B is the Boltzmann constant and μ is chemical potential, which can be tuned by applying voltage bias and thereby change the dielectric property as well as radiative heat flux. Although it is not shown here, we have plotted σ_g with different chemical potentials at both 300 K and 400 K, and the consistent values within infrared region indicate the insensitivity to temperature of σ_g , which could also be verified by the equation applied in Ref. [39-41] to calculate σ_g in infrared region. For sake of improving the computational efficiency, we assume that σ_g is independent of T_2 for all the calculations. Another way to calculate the radiative heat transfer contribution of graphene is to construct the Fresnel reflection coefficient at the interface between vacuum and graphene layer directly, which has been proved to be equivalent to our method.^[42]

2.2 Theoretical calculation

Based on fluctuational electrodynamics associated with the stochastic thermal sources,^[43] the general analytic expression of radiative heat flux of arbitrary three-body system with three distinct temperatures was theoretically put forward.^[23,44] By means of computing the time-averaged Poynting vector, the

total heat flux gained by receiver in our configuration is given by the following Landauer-like formula:^[12]

$$\Phi_3 = \int_0^\infty \frac{d\omega}{8\pi^3} \sum_{i=\{s,p\}} \int d^2\mathbf{k} \left[\Theta_{12}(\omega) \phi_i^{12}(\omega, \mathbf{k}; \mu, d_{12}, T_2) + \Theta_{23}(\omega) \phi_i^{23}(\omega, \mathbf{k}; \mu, d_{23}, T_2) \right] \quad (3)$$

Here $\phi_i^{jk}(\omega, \mathbf{k})$ signifies the transmission factor from slab j to slab k ($j, k \in \{1, 2, 3\}$), which indicates the tunneling probability of a photon with momentum $\mathbf{k}$ at frequency ω for all polarization states $i \in \{s, p\}$. It should be noted that, in the infrared region that we are interested in, the transmission factor $\phi_i^{jk}(\omega, \mathbf{k})$ is nearly independent of T_2 due to the insensitivity of the conductivity σ_g of intermediate graphene to T_2 as previously discussed. $\mathbf{k} = (k_x, k_y)$ is the wave vector parallel to the slab planes and $\Theta_{jk}(\omega) = \hbar\omega \left(1 / \left[\exp(\hbar\omega/k_B T_j) - 1 \right] - 1 / \left[\exp(\hbar\omega/k_B T_k) - 1 \right] \right)$ is the difference of mean energy of two Planck oscillators at frequency ω . According to near-field three-body theory, projecting general scattering operators into a special case, ϕ_i^{21} and ϕ_i^{32} can be described as^[45]

$$\phi_i^{12}(\omega, \mathbf{k}) = \begin{cases} \frac{|\tau_{2,i}|^2 (1 - |\rho_{1,i}|^2) (1 - |\rho_{3,i}|^2)}{|1 - \rho_{12,i} \rho_{3,i} e^{2jk_z d_{23}}|^2 |1 - \rho_{1,i} \rho_{2,i} e^{2jk_z d_{12}}|^2}, & k < k_0 \\ \frac{4|\tau_{2,i}|^2 \text{Im}(\rho_{1,i}) \text{Im}(\rho_{3,i}) e^{-4\text{Im}(k_z) d_{12}}}{|1 - \rho_{12,i} \rho_{3,i} e^{2jk_z d_{23}}|^2 |1 - \rho_{1,i} \rho_{2,i} e^{2jk_z d_{12}}|^2}, & k > k_0 \end{cases}, \quad (4)$$

$$\phi_i^{23}(\omega, \mathbf{k}) = \begin{cases} \frac{(1 - |\rho_{12,i}|^2) (1 - |\rho_{3,i}|^2)}{|1 - \rho_{12,i} \rho_{3,i} e^{2jk_z d_{23}}|^2}, & k < k_0 \\ \frac{4\text{Im}(\rho_{12,i}) \text{Im}(\rho_{3,i}) e^{-2\text{Im}(k_z) d_{23}}}{|1 - \rho_{12,i} \rho_{3,i} e^{2jk_z d_{23}}|^2}, & k > k_0 \end{cases}, \quad (5)$$

for propagating ($k < k_0$) and evanescent ($k > k_0$) modes where index j is recorded as imaginary number, k is 2-norm of $\mathbf{k}$ in reciprocal space, $k_0 = \omega/c$ and $k_z = \sqrt{k_0^2 - k^2}$ are the wave vector and its tangential component along z direction in vacuum separately. The Fresnel reflection and transmission coefficients $\rho_{\alpha,i}$, $\tau_{\alpha,i}$ ($\alpha \in \{1, 2, 3\}$) for given three slabs dominate the quantity of transmission factor essentially, whose detail form can be found in Ref. [45] and obtained by the transfer-matrix method. Meanwhile, the reflection coefficient corresponding to an ensemble consisting of slab 1 and intermediate slab is given by

$$\rho_{12,i} = \rho_{2,i} + (\tau_{2,i})^2 \frac{\rho_{1,i} e^{2jk_z d_{12}}}{1 - \rho_{1,i} \rho_{2,i} e^{2jk_z d_{12}}}. \quad (6)$$

It is easy to notice that $\rho_{12,i}$ is influenced by the separation distance d_{12} and chemical potential μ of graphene sheet. Symmetrically, the heat flux that emitter launches can be written as

$$\Phi_1 = \int_0^\infty \frac{d\omega}{8\pi^3} \sum_{i=\{s,p\}} \int d^2\mathbf{k} [\Theta_{32}(\omega)\phi_i^{32}(\omega, \mathbf{k}; \mu, d_{23}, T_2) + \Theta_{21}(\omega)\phi_i^{21}(\omega, \mathbf{k}; \mu, d_{12}, T_2)] \quad (7)$$

and the transmission factors are updated by exchanging superscripts 1 and 3 trivially.

The operating mode of our modulator is elaborated as follows. Obviously, the heat flux of intermediate slab Φ_2 is equal to the difference of Φ_1 and Φ_3 , i.e. $\Phi_2 = \Phi_1 - \Phi_3$. If there is no variation of interior parameters and external perturbation, the system would tend to the steady state $\Phi_2 = 0$ in case of $T_1 > T_3$. In other words, at the steady state, the amount of cooling at hot emitter is exactly equivalent to the heat flux absorbed by cold receiver (i.e. $\Phi_1 = \Phi_3$), which is a quasi-static equilibrium. By taking measures of changing chemical potential μ or separation distance d_{12} of the intermediate graphene, the total heat flux of system corresponding to the equilibrium state can be modulated. In Fig. 2, the calculated results of varied Φ_1 and Φ_3 with increasing temperature T_2 for dissimilar control parameters are shown. The intersection of two branch lines is a pair of physical quantities (T_2^*, Φ^*) , which implies the equilibrium state. The equilibrium point (T_2^*, Φ^*) would change with the variation of chemical potential μ and distance d_{12} . These preliminary results illustrate that total heat flux of such configuration could be well modulated due to the existence of graphene sheet with different μ and d_{12} . In next section, we will display and discuss the detailed regulating results of μ and d_{12} control along with the corresponding mechanism.

Fig. 2 The lines represent the heat flux emitted by slab 1 (Φ_1) and heat received by slab 3 (Φ_3) with dissimilar cases of chemical potential μ and separation distance d_{12} . The crossover points of Φ_1 and Φ_3 is pointed out, which infers the equilibrium point (T_2^*, Φ^*) of such three-slab system.

3. Results and discussion

Now let us introduce the major modulation effects of heat flow from this three-slab configuration. The total radiative flux $\Phi(\mu, d_{12})$ of this modulator for equilibrium state is obtained after integration with respect to frequency ω from 0.1 to

5×10^{14} rad/s. Please note that Φ here represents either Φ_1 or Φ_3 because based on the above analysis, Φ_1 is equal to Φ_3 at equilibrium state. The frequency range of integration is selected to cover the spectrum of both doped Si and graphene SPPs, and the spectral heat flux out of the range is negligible compared to the part within integration range. For the sake of quantifying the thermal modulation effect of μ and d_{12} with regard to total heat flux $\Phi(\mu, d_{12})$, a dimensionless number (normalized radiative heat flux) is defined as $\Omega = \Phi(\mu, d_{12})/\Phi_0$, where $\Phi_0 = 26.5 \text{ kW/m}^2$ is the benchmark total radiative heat flux with $\mu = 0 \text{ eV}$ and $d_{12} = 50 \text{ nm}$. Independent regulatory role is taken into consideration from the start, i.e. only one of μ and d_{12} changes. Instead of total heat flux, the normalized radiative heat flux Ω as a function of μ and d_{12} is presented in Fig. 3(a) and 3(b), respectively. Additionally, the variation of equilibrium temperature T_2^* with μ or d_{12} is reported together. When d_{12} is fixed at 50 nm, the normalized heat flux Ω monotonically increases from minimum ($\Omega_{\min} = 1$) to the maximum ($\Omega_{\max} = 2.4$) around $\mu = 0.5 \text{ eV}$, and then decreases slowly with increasing μ . In addition, a similar trend for heat flux change could be observed for the case of $d_{12} = 70 \text{ nm}$, where the maximum heat flux exists at $\mu = 0.5 \text{ eV}$ as well due to strong coupling between Si

Fig. 3 Normalized radiative heat flux Ω of such a three-slab configuration as a function of (a) chemical potential μ when $d_{12} = 50$ or 70 nm and (b) separation distance d_{12} when $\mu = 0.1$ or 0.5 eV. The corresponding equilibrium temperature T_2 is also plotted by dash-dotted line.

and graphene SPPs. On the other hand, we could also observe that the heat flux for $\mu = 0.5$ eV is always higher than that for $\mu = 0.1$ eV, while both of them achieve the maximum value at $d_{12} = 55$ nm. It shows that the coupling role of photons and Si/Graphene SPPs is absent for $\mu = 0.1$ eV, resulting in that the modulation effect is not significant at this time. The detailed analysis will be performed hereafter. The dash-dotted lines show us the modulation of T_2^* with μ and d_{12} , which is different for distinct cases of fixed μ or d_{12} . Interestingly, as shown in Fig. 3(a), a minimum value of equilibrium temperature T_2^* is obtained at around $\mu = 0.2$ eV when d_{12} keeps unchanged.

To understand the nature of modulation functions with μ or d_{12} , the spectral heat fluxes $\Phi(\omega)$ with a series of μ and d_{12} are plotted in Fig. 4(a) and 4(b) individually. In both Fig. 4(a) and 4(b), all the spectra exhibit a quasi-monochrome peak with varying degrees of amplitude, which is at frequency $\omega = 2.76 \times 10^{14}$ rad/s. This spectral flux peak was well investigated and understood as the SPPs coupling between two metal or doped semiconductor (doped Silicon for one) plates^[46]. However, for low chemical potential ($\mu = 0.1$ eV), a lower secondary peak is observed at around 1.2×10^{14} rad/s, which is

Fig. 4 Near-field spectral radiative heat fluxes $\Phi(\omega)$ between such three-slab configuration at (a) dissimilar graphene chemical potentials μ as $d_{12} = 50$ nm, and (b) dissimilar separation distances d_{12} as $\mu = 0.5$ eV. The lines and dots shown in figures correspond to the results obtained from different temperatures 300 K and 400 K.

from the excitation of graphene SPPs.^[47] As the chemical potential increases, the graphene SPPs modes blueshift towards higher frequency. Accordingly, the resonant interplay between Graphene and Si SPPs modes starts to take place, leading to resonant role peaks in the vicinity of $\mu = 0.5$ eV. Yet, as the modes move onward with rising μ , the coupling effect of Graphene and Si SPPs dissipates due to gradually inconsistent resonant frequencies. Meanwhile, for the influence of d_{12} on spectral heat flux, there exists a greatly enhanced one at around $d_{12} = 50$ nm, which is consistent with the results shown in Fig. 4(b). This is because that, as d_{12} changes, the resonance coupling between graphene sheet and emitter or receiver will be varied. The total heat flux is a consequence of both coupling effects and the temperature of graphene sheet. The present results indicate that the symmetric geometry with about $d_{12} = 50$ nm could excite strongest coupling effects between emitter, graphene sheet, and receiver. In addition, by fixing other parameters unchanged, we also present separately the corresponding results by taking conductivity of graphene sheet σ_g at 300 K and 400 K. The identical results confirm that the effect of temperature dependent graphene conductivity on the total heat flux is negligible at current case.

In order to describe how sensitive the change of modulation factor is to the increment of chemical potential μ or separation distance d_{12} , we introduce a quantity named sensitivity factor S , which is defined as $S_i = \partial\Omega/\partial\Delta_i$ ($i \in \{1, 2\}$). It is essentially the slope of modulation factor as a function of Δ_i , where Δ_i ($\Delta_1 = \Delta d_{12}/d^*$, $\Delta_2 = \Delta\mu/\mu^*$, $d^* = 100$ nm and $\mu^* = 1$ eV) is a new dimensionless number indicating the relative amplitude of variation. As shown in Fig. 5(a), at $\mu = 0.5$ eV when Δ_1 increases from 0.1 to 0.9, the sensitivity factor S_1 first increases to the maximum 5.7 at $\Delta_1 = 0.4$, then decreases rapidly to 0 at $\Delta_1 = 0.6$, where the total heat flux Φ reaches the maximum. As Δ_1 is beyond 0.6, S_1 becomes negative due to the continuous decrease of Φ with the increase of Δ_1 . And then it reaches the minimum value of -4.7 at around 0.8 eV. Soon afterwards, S_1 monotonically increases to -4 at 0.9. As for $\mu = 0.1$ eV, the general trend of S_1 is gentle, which means that the modulation effect of d_{12} on $\mu = 0.1$ eV is insensitive. In Fig. 5(b), S_2 shows us that the amplification of Φ with increasing Δ_2 is far more sensitive than the abatement of that when d_{12} is constant.

In order to possibly achieve larger thermal modulation effects, we now consider a combination of graphene chemical potential μ and separation distance d_{12} variation. By arranging different sets of μ and d_{12} within the domain of $(\mu, d_{12}) = [0, 1] \times [10, 90]$, the normalized radiative heat flux Ω of two-parameter thermal modulator and the equilibrium temperature T_2^* of intermediate graphene sheet are plotted in Fig. 6(a) and 6(b), respectively. The contour color represents the amplitude of Ω . The results show that largest radiative flux is obtained at $\mu = 0.55$ eV, $d_{12} = 55$ nm under which the coupling of Si/Graphene SPPs is strongest due to perfect

Fig. 5 Radiative heat sensitivity factor S_i as a function of (a) dimensionless separation distance Δ_1 when $\mu = 0.1$ or 0.5 eV and (b) dimensionless chemical potential Δ_2 when $d_{12} = 50$ or 70 nm. The dashed lines indicate $S_i = 0$.

matching of resonance frequency between doped Si and Graphene. And the maximum normalized heat flux $\Omega_{\max}(\mu, d_{12})$ is 2.64, which corresponds to the total heat flux of 70 kW/m^2 . The minimum value of Ω reached at $\mu = 0$ eV, $d_{12} = 10$ nm is equal to 0.38 due to the resonance frequency mismatch of Si/Graphene SPPs, which has only heat flux of 10 kW/m^2 . As a result, the total heat flux can be adjusted from 10 to 70 kW/m^2 . Obviously, the two-parameter modulator provides more flexibility to modulate the total heat flux. In contour plot of equilibrium temperature T_2^* , the contour curve is convex towards high temperature as mentioned before with d_{12} beyond 50 nm and μ around 0.2 eV. However, the contour curve is convex towards low temperature if d_{12} is below 50 nm.

Thermal switching of heat flow belongs to one of major functionalities of thermal modulator, which is also investigated in proposed thermal modulator. The maximum $\Phi_{\max} = \Omega_{\max} \Phi_0$ and minimum $\Phi_{\min} = \Omega_{\min} \Phi_0$ total radiative flux of modulator are respectively treated to be the “on” or “off” mode of thermal switch to allow or forbid the heat flow to pass. To quantitatively judge how effectively our modulator could switch the heat flow, a new dimensionless factor named switching factor is defined as $\Psi = 1 - \Omega_{\min}/\Omega_{\max}$ to characterize the performance. According to the results shown

in Fig. 6(a) and the definition of switching factor, the overall switching factor is $\Psi = 0.85$. Fig. 7 presents Ψ at different chemical potential μ from 0 to 1 eV or separation distance d_{12} from 10 to 90 nm. As can be observed, it will have a larger

Fig. 6 Normalized radiative heat flux Ω of three-slab configuration and (b) equilibrium temperatures T_2^* of intermediate graphene sheet as a function of different sets of graphene chemical potential μ and separation distance d_{12} .

Fig. 7 Radiative thermal switching factor Ψ of such three-slab configuration as a function of graphene chemical potential μ and separation distance d_{12} .

switching factor with graphene chemical potential fixed than that with fixed separation distance. This is because the heat flux modulation is more sensitive to separation distance change than graphene chemical potential, as illustrated in Fig. 3. The maximum switching factor at around $d_{12} = 50$ nm is consistent with previous results because it represents the strongest resonance coupling between these three slabs. In addition, we also notice that the switching factor barely changes with fixed $\mu > 0.3$ eV. This could be explained as that the resonance coupling is weak with $\mu < 0.3$ eV due to the mismatch of resonance frequency between graphene and Si SPPs, thus the heat flux modulation range is limited.

4. Conclusions

In present work, we have proposed a two-parameter mediated near-field radiative thermal modulator made of Si-graphene-Si configuration, to modulate the total heat flux by photon transport across the three-body system. The graphene sheet as intermediate slab is the main manipulation tool, which is applied to modulate the photon tunneling accurately and speedily with the regulatable chemical potential and separation distance between graphene and emitter. By using a slice of parameter combination, thermal modulation and switch are well realized by this modulator, which obtain a normalized radiative heat flux Ω in range of 0.38–2.64 and a switching factor $\Psi = 0.85$. The underlying mechanism of tunability is attributed to the coupling effect of graphene and Si surface modes, which gives rise to varied near-field radiative thermal flux with different chemical potentials and separation distances of graphene. By introducing novel 2-D material, near-field thermal transport between polar or hyperbolic materials can be well regulated in the future. This work will shed light on the understanding and design of 2-D material-based near-field thermal devices for active thermal management.

Acknowledgements

This research was supported by National Natural Science Foundation of China under grant number of 51806045 and Science, and Technology and Innovation Commission of Shenzhen Municipality under grant number of 201771343 and KQJSCX20170329111827540.

Supporting information

Not applicable

Conflict of interest

There are no conflicts to declare.

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