Thermal Switch with Multiple Discrete Levels

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Abstract

As the complexity of control technology increases, a binary switch is far from being able to meet people's needs for the number of control signals. However, few studies have considered how to achieve multiple discrete levels. To solve this problem, we design and demonstrate a 3-state thermal switch that employs a combination of layers with different metal-insulator transition temperatures of W-doped and undoped VO₂. These results overcome the limitation that the original binary radiative switch only provides two discrete thermal signals ("ON" and "OFF"). Moreover, we further demonstrate that the introduction of two-dimensional (2D) materials can effectively improve the resolution of discrete thermal signals, that is, makes the difference of radiative heat flux between two adjacent discrete thermal signals more obvious. Finally, the feasibility for performing a greater number of discrete thermal signals is discussed by setting the number of films and the W-doped concentration of each film. These results pave the way for the development of multi-state channel information processing and multiple thermal management at compact thermal circuits.

Keywords: Near-field radiative heat transfer; Thermal switch; Multiple discrete levels.

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1. Introduction

In electronics, an electrical switch is a vital circuit element that implements an electrical control based on an electric signal with distinct discrete levels. Non-electronic devices have been proposed during the last decades to perform such discrete signal without any electric power source. For example, purely optical,^[1] mechanical^[2] and even biological devices^[3] have been developed to support the discrete signal without an electric current. In 2007, the idea of thermal switch,^[4] in which the data processing is based on heat instead of electricity, has been introduced and has played a crucial role in controlling the heat flow, especially for microelectronics applications. As a thermal analog of electronic switch, it is needed to output a thermal signal at a distinct discrete level to convert into a binary digital code ("0" and "1"). Since the beginning of 2007, the possibility to realize the thermal signal with a distinct discrete level has been demonstrated, such as tailoring the heat

conduction through solid/solid,^[5] manipulating convection heat transfer mechanisms,^[6] and mechanical contact.^[7]

Furthermore, the application of thermal radiation from phase change materials (PCMs) is also a promising solution to realize the discrete thermal signal^[8] since the PCMs exhibit a large change to their dielectric constant upon a reversible phase change between the two states of the PCMs (from insulator to metal). Meanwhile, researches on nanoscale thermal radiation have shown that the radiant energy exchanges in near field can exceed that predicted by Planck's law by a few orders of magnitude.^[9-15] The surface plasmon or phonon polaritons (SPPs) effect can significantly enhance the near-field thermal radiation. These facts make it possible to improve significantly the discrete degree of thermal signal of the radiative thermal switch.^[16-21] These recent results, promising in the direction of information treatment with thermal photons and thermal management, greatly promote the development of binary thermal switches.

However, with the increased complexity of control technologies, a binary switch is far from being able to meet people's needs for the number of control signals. In order to achieve signal transmission with more than two states, additional switches are used generally, resulting in a continuous increase in the number of switches. Nevertheless, these added switches often occupy useful space, making the control system more complex. Unfortunately, the thermal switch with multiple discrete states has not been demonstrated

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so far, because the individual PCMs exhibit single abrupt transitions over a narrow temperature range, i.e., each material is either “ON” or “OFF” (“0” or “1”). This limits their application for supporting more thermal control signals. To solve this problem, in this paper, we firstly propose a way to realize multiple discrete thermal signals of thermal switch based on the tungsten-doped vanadium dioxide (W-VO₂). Doping tungsten into vanadium dioxide has been found to decrease the metal–insulator transition (MIT) temperature.^[22, 23] The combination of layers with different MIT temperatures, employing W-doped and undoped VO₂, will provide the possibility to achieve multilevel thermal states and makes discrete thermal signals of a thermal switch different from conventional ones (only outputting “0” and “1”).

In the present study, we will first quantitatively show the near-field 3-state thermal switching effect between two multilayer structures composed of W-doped and undoped VO₂. Receiver is maintained at a fixed temperature as an insulator while the emitter experiences an insulator–metal transition when its temperature varies. Furthermore, we will extend the study to the combination of metasurfaces. Such as graphene and graphene grating can further increase the difference of radiative heat flux between discrete thermal signals. Finally, by reasonably setting the number of film and the W-doped concentration of each film, a thermal switch with more discrete thermal signals is also investigated to adapt to the complex control environment that requires more discrete thermal signals.

Fig. 1 Schematics of the proposed thermal switch composed of thin W-doped VO₂ layer (blue), undoped VO₂ layer (gray), and Au layer (yellow). Red lines indicate the infrared light. “M” and “I” indicate the metal and insulator states, respectively. The thermal switch is at the “ON” mode when $T_1 < T_W$. The thermal switch is at the “OR” mode when $T_W \leq T_1 < T_N$ (341 K), while it turns to the “OFF” mode when $T_1 \geq T_N$ (341 K).

2. Physical system and mathematical formulations

Let us consider a system composed of two multilayer structures composed of W-doped and undoped VO₂ brought into close proximity with a vacuum gap size of d as sketched in Fig. 1. The top thin layer is W-VO₂ with the lower MIT temperature T_W , the middle layer is undoped VO₂ (N-VO₂) with the MIT temperature T_N , and the bottom layer is Au, as shown in Fig. 1. The thickness of the W-doped VO₂ film and the undoped VO₂ film are t_1 and t_2 , respectively. We maintain the two bodies at the temperatures of T_1 and T_2 , respectively, and T_2 is equal to 270 K throughout this work. Subscripts 1

and 2 represent the media above and below the vacuum, respectively. Heat, which is supplied by an electric current or a laser pulse, is used to change temperature T_1 of emitter to trigger a reversible phase transition of W-doped VO₂ film and undoped VO₂ film.

Fig. 2 (a) Real parts and (b) imaginary parts ϵ of dielectric functions for VO₂. Red regions and blue regions are related to frequency bands for HPPsI and HPPsII, respectively. Green regions are related to frequency bands where only SPPs are able to be excited at the vacuum/insulating VO₂ surface.

The undoped VO₂ undergoes an insulator-metal phase transition at 341 K.^[24] When the temperature is lower than 341 K, N-VO₂ shows the insulating behaviors and can be modelled as a uniaxial medium related to the crystal orientation (that is, an electric field vector E perpendicular or parallel to the optical axis). N-VO₂ shows the metallic behaviors with an isotropic dielectric function at the temperatures greater than 341 K. Moreover, the low-level W-doped has little influence on the optical response of VO₂.^[25] Namely, when the doping density is less than 1%, the influence of tungsten doping on the optical properties of vanadium dioxide can be ignored.^[25] When the optical axis of insulator VO₂ is parallel to the z -axis, the dielectric function or relative permittivity of insulator VO₂ can be represented as Equation (1):^[26]

$$\epsilon(\omega) = \begin{bmatrix} \epsilon_O & 0 & 0 \\ 0 & \epsilon_O & 0 \\ 0 & 0 & \epsilon_E \end{bmatrix} \quad (1)$$

where ϵ_O is called the ordinary dielectric function, corresponding to the electric field vector E perpendicular to its optical axis, and ϵ_E is called the extraordinary dielectric function, corresponding to the electric field vector E parallel to its optical axis. Both ordinary and extraordinary dielectric functions are modeled by Lorentz model as shown in Equation (2):^[26]

$$\epsilon(\omega) = \epsilon_\infty + \sum_{j=1}^N \frac{S_j \omega_j^2}{\omega_j^2 - i\gamma_j \omega - \omega^2} \quad (2)$$

where ϵ_∞ is the high-frequency constant, ω is the angular frequency, ω_j is the phonon vibration frequency, γ_j is the scattering rate, S represents the oscillation strength, and j is the

mode index. The experimentally fitted parameters from Barker *et al.*^[27] are used to obtain the ordinary (ϵ_0) and extraordinary (ϵ_E). Moreover, a Drude model can give the dielectric function or relative permittivity of metallic VO₂ as Equation (3):^[26]

$$\epsilon_m(\omega) = \frac{-\omega_p^2 \epsilon_\infty}{(\omega^2 - i\omega\Gamma)} \quad (3)$$

where $\epsilon_\infty = 9$, the plasma frequency $\omega_p = 0.99$ eV/h and collision frequency $\Gamma = 1.24$ eV/h.^[27] As shown in Fig. 2, the metallic VO₂ has no phonon modes in the considered infrared region, and the imaginary part of the dielectric function decreases with increasing frequency towards its plasma frequency. Red regions and blue regions are related to frequency bands for hyperbolic phonon polaritons of type I (HPPSI) and hyperbolic phonon polaritons of type II (HPPSII), respectively. Green regions are related to frequency bands where only surface phonon polaritons (SPhPs) are able to be excited at vacuum/insulating VO₂ surface. According to the Ref.,^[25] the VO₂ phase transition usually is across a temperature change around 14 K from complete insulating to complete metallic phase. We describe the transition region with T_W and, in such a way, it takes place in the temperature range between T_W and $T_W + \Delta$. The state of the material in the transition region can be described by introducing a volume fraction $f(T)$ such as $f(T_W) = 0$ and $f(T_W + \Delta) = 1$. In real situations, this volume fraction depends on the actual working conditions of the device and can be estimated, for instance, by combining conductivity measurements in the transition region and an effective-medium theory.^[28] Here, to keep our theoretical description as simple as possible, we model the volume fraction as a smooth step function given by Equation (4):^[28]

$$f(T) = 6x^5 - 15x^4 + 10x^3, \quad x = \frac{(T - T_W)}{\Delta} \quad (4)$$

This volume fraction is used to compute the radiative heat fluxes by means of an effective-medium theory,^[29] quantifying the permittivity of VO₂ in the transition region.

In the framework of fluctuation electrodynamics, the radiative heat flux (RHF) is given by Equation (5):^[30, 31]

$$q = \int_0^\infty (\theta(\omega, T_1) - \theta(\omega, T_2)) \Phi(\omega) d\omega = \int_0^\infty (\theta(\omega, T_1) - \theta(\omega, T_2)) d\omega \int_0^{2\pi} \int_0^\infty \frac{k \xi(\omega, k, \varphi)}{8\pi^3} dk d\varphi \quad (5)$$

where $\theta(\omega, T) = \frac{\hbar\omega}{[\exp(\frac{\hbar\omega}{k_B T}) - 1]}$ is the mean energy of a Planck oscillator. $\hbar$ and k_B are the reduced Planck constant and the

Boltzmann constant, respectively. $\Phi(\omega)$ is the spectral energy transfer function. $\xi(\omega, k, \varphi)$ is the photonic transmission coefficient (PTC) that describes the probability of photons excited by thermal energy, which can be written as Equation (6):^[32]

$$\xi(\omega, k, \varphi) = \begin{cases} \text{Tr}[(\mathbf{I} - \mathbf{R}_2^* \mathbf{R}_2) \mathbf{D} (\mathbf{I} - \mathbf{R}_1 \mathbf{R}_1^*) \mathbf{D}^*] & , k < k_0 \\ \text{Tr}[(\mathbf{R}_2^* - \mathbf{R}_2) \mathbf{D} (\mathbf{R}_1 - \mathbf{R}_1^*) \mathbf{D}^*] e^{-2|k_z|d} & , k > k_0 \end{cases} \quad (6)$$

for propagating ($k < k_0$) and evanescent ($k > k_0$) waves where k is the surface parallel wavevector, $k_0 = \omega/c$ is the wavevector in vacuum and φ is the azimuthal angle. $k_z = \sqrt{k_0^2 - k^2}$ is the tangential wavevector along z direction in vacuum and * signifies the complex conjugate. The 2×2 matrix $\mathbf{D}$ is defined as $\mathbf{D} = (\mathbf{I} - \mathbf{R}_1 \mathbf{R}_2 e^{2ik_z d})^{-1}$, which describes the usual Fabry-Perot-like denominator resulting from the multiple scattering between the two interfaces. Subscripts 1 and 2 represent the multilayer structures above and below the vacuum, respectively. The reflection matrix $\mathbf{R}$ is a 2×2 matrix in the polarization representation.

In this section, a generalized 4×4 T-matrix formalism for anisotropic metasurfaces and hyperbolic media with an arbitrary number of layers is developed, from which the general relations for the surface waves dispersions and reflection matrix $\mathbf{R}$ are derived. Let us first consider a single anisotropic metasurface attached to a semi-infinite hyperbolic media. Within the homogenization approach, the electromagnetic (EM) response of such a metasurface, in general, can be described by a fully populated conductivity tensor $\hat{\sigma}''$ in the wave-vector space. Besides, $\hat{\sigma}''$ denotes the conductivity tensor in the wave-vector space and it is expressed by Equation (7):^[33]

Following Refs. ^[34-36] let us write separately the EM field of the p -polarized (TM) and s -polarized (TE) components of the EM wave, which then will be mixed by the nondiagonal response of a metasurface. The p wave with the magnetic field perpendicular to the plane of incidence possess the EM field components $E_p = \{E_x, 0, E_z\}$, $H_p = \{0, H_y, 0\}$. For the s wave, with the electric field perpendicular to the plane of incidence, the EM field components are $E_s = \{0, E_y, 0\}$, $H_s = \{H_x, 0, H_z\}$. Substituting p -wave and s -wave into boundary conditions of metasurface,^[36] one obtain the 4×4 T-matrix, which gives the relations between all the electric field components in the media above and below the metasurface as shown in Equation (8):

$$\hat{\sigma}'' = \begin{pmatrix} \sigma''_{xx} & \sigma''_{xy} \\ \sigma''_{yx} & \sigma''_{yy} \end{pmatrix} = \frac{1}{k^2} \begin{pmatrix} k_x^2 \sigma_{xx} + k_y^2 \sigma_{yy} + k_x k_y (\sigma_{xy} + \sigma_{yx}) & k_x^2 \sigma_{xy} - k_y^2 \sigma_{yx} + k_x k_y (\sigma_{yy} - \sigma_{xx}) \\ k_x^2 \sigma_{yx} - k_y^2 \sigma_{xy} + k_x k_y (\sigma_{yy} - \sigma_{xx}) & k_x^2 \sigma_{yy} + k_y^2 \sigma_{xx} - k_x k_y (\sigma_{xy} + \sigma_{yx}) \end{pmatrix} \quad (7)$$

$$\begin{bmatrix} H_{p1}^+ \\ H_{p1}^- \\ E_{s1}^+ \\ E_{s1}^- \end{bmatrix} = \hat{T}_{1 \rightarrow 2} \begin{bmatrix} H_{p2}^+ \\ H_{p2}^- \\ E_{s2}^+ \\ E_{s2}^- \end{bmatrix} \quad (8)$$

where the sign of + and - represent the forward and backward waves, respectively. $\hat{T}_{1 \rightarrow 2}$ is derived by Equation (9):

$$\hat{T}_{1 \rightarrow 2} = \frac{1}{2} \begin{bmatrix} \frac{k_{zp2}}{\varepsilon_{02}} \begin{bmatrix} P^{++} & P^{--} \\ P^{+-} & P^{-+} \end{bmatrix} & \sqrt{\frac{\mu_0}{\varepsilon_0}} \sigma_{xy} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \\ \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{k_{zp2}}{\varepsilon_{02} k_{zs1}} \sigma_{yx} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} & \frac{1}{k_{zs1}} \begin{bmatrix} S^{++} & S^{+-} \\ S^{--} & S^{-+} \end{bmatrix} \end{bmatrix} \quad (9)$$

where the p -waves components are expressed as Equation (10):

$$P^{++} = \frac{\varepsilon_{01}}{k_{zp1}} + \frac{\varepsilon_{02}}{k_{zp2}} + \frac{\sigma_{xx}''}{\omega \varepsilon_0}; \quad P^{--} = -\frac{\varepsilon_{01}}{k_{zp1}} + \frac{\varepsilon_{02}}{k_{zp2}} - \frac{\sigma_{xx}''}{\omega \varepsilon_0} \quad (10)$$

$$P^{+-} = -\frac{\varepsilon_{01}}{k_{zp1}} + \frac{\varepsilon_{02}}{k_{zp2}} + \frac{\sigma_{xx}''}{\omega \varepsilon_0}; \quad P^{-+} = \frac{\varepsilon_{01}}{k_{zp1}} + \frac{\varepsilon_{02}}{k_{zp2}} - \frac{\sigma_{xx}''}{\omega \varepsilon_0}$$

where the s -waves components are expressed by Equation (11):

$$S^{++} = k_{zs1} + k_{zs2} + \omega \mu_0 \sigma_{yy}''; \quad S^{+-} = k_{zs1} - k_{zs2} + \omega \mu_0 \sigma_{yy}'' \quad (11)$$

$$S^{--} = k_{zs1} - k_{zs2} - \omega \mu_0 \sigma_{yy}''; \quad S^{-+} = k_{zs1} + k_{zs2} - \omega \mu_0 \sigma_{yy}''$$

here, subscripts 1 and 2 represent the media above and below the metasurface, respectively. k_z , and ε are tangential wavevector along z direction in media and dielectric function of media. Subscripts p and s represent the p -polarized (TM) and s -polarized (TE), respectively. ε_0 is the vacuum permittivity; μ_0 is the vacuum permeability. In general, for any 4×4 T-matrix, it is used to link all the electric field components by Equation (12):

$$\begin{bmatrix} H_{p1}^+ \\ H_{p1}^- \\ E_{s1}^+ \\ E_{s1}^- \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{bmatrix} \begin{bmatrix} H_{p2}^+ \\ H_{p2}^- \\ E_{s2}^+ \\ E_{s2}^- \end{bmatrix} \quad (12)$$

The reflection matrix $\mathbf{R}$ is defined and expressed in terms of the T-matrix elements as following Equation (13):^[36]

$$r_{pp} = \frac{H_{p1}^-}{H_{p1}^+} \Big|_{E_{s1}^+ = 0} = \frac{T_{21}T_{33} - T_{23}T_{31}}{T_{11}T_{33} - T_{13}T_{31}}, \quad r_{ps} = \frac{E_{s1}^-}{H_{p1}^+} \Big|_{E_{s1}^+ = 0} = \frac{T_{41}T_{33} - T_{43}T_{31}}{T_{11}T_{33} - T_{13}T_{31}} \quad (13)$$

$$r_{sp} = \frac{H_{p1}^-}{E_{s1}^+} \Big|_{H_{p1}^+ = 0} = \frac{T_{11}T_{23} - T_{13}T_{21}}{T_{11}T_{33} - T_{13}T_{31}}, \quad r_{ss} = \frac{E_{s1}^-}{E_{s1}^+} \Big|_{H_{p1}^+ = 0} = \frac{T_{11}T_{43} - T_{13}T_{41}}{T_{11}T_{33} - T_{13}T_{31}}$$

The formalism developed above can be generalized easily for an arbitrary number of layers by multiplying the T-matrices corresponding to each layer. For a multilayer metasurface consisting of N 2D-layers with effective conductivity tensors $\hat{\sigma}_j''$ ($j = 1, 2, \dots, N$). One obtains the 4×4 T-matrix, which gives the relations between all the electric field components in the multilayer metasurface as shown in Equation (14):

$$\begin{bmatrix} H_{p1}^+ \\ H_{p1}^- \\ E_{s1}^+ \\ E_{s1}^- \end{bmatrix} = \hat{T}_{1 \rightarrow N} \begin{bmatrix} H_{pN}^+ \\ H_{pN}^- \\ E_{sN}^+ \\ E_{sN}^- \end{bmatrix} \quad (14)$$

$$\hat{T}_{1 \rightarrow N} = \hat{T}_1 \hat{T}_{t_{1,1}} \hat{T}_2 \hat{T}_{t_{1,2}} \dots \hat{T}_{t_{i,N-1}} \hat{T}_N \hat{T}_{t_{i,N}} \quad (15)$$

where $\hat{T}_j$ is obtained from $\hat{T}_1$ [Eq. (8)] by replacing $\hat{\sigma}_1''$ with $\hat{\sigma}_j''$, $\hat{T}_{t_{i,j}}$ is the T-matrices for a light propagating through the vacuum between two adjacent 2D layers with corresponding thicknesses $t_{i,j}$ ($j = 1, 2, \dots, N$):^[36]

$$T_{t_{i,j}} = \begin{bmatrix} e^{-ik_{zp}t_{i,j}} & 0 & 0 & 0 \\ 0 & e^{ik_{zp}t_{i,j}} & 0 & 0 \\ 0 & 0 & e^{-ik_{zs}t_{i,j}} & 0 \\ 0 & 0 & 0 & e^{ik_{zs}t_{i,j}} \end{bmatrix} \quad (16)$$

The T-matrix allows us to obtain all necessary characteristics (the reflection and the dispersion relation) using general Eqs. (7)–(15).

3. Results and discussions

Fig. 3 (a) The total radiative heat fluxes with different emitter temperatures T_1 at the gap distance of $d = 50$ nm with the receiver temperature fixed at $T_2 = 270$ K. The dotted lines in different colors represent transition of this thermal signals with different doped concentrations from “ON” mode to “OR” mode. (b) The spectral energy transfer function at different modes.

To show the character of multiple discrete thermal signals in the thermal switch, as shown in Fig. 3(a), we simulated the radiative heat flux of thermal switch with different W-doped MIT temperatures, when the emitter temperature T_1 changes from 300 to 370 K. The MIT temperatures of thin W-doped

VO₂ layer are fixed as 310, 315, 320, 325, 330 and 341 K. The corresponding doped concentrations are 10.3, 8.9, 7.4, 5.5, 3.6 and 0 %.^[22, 23] The vacuum gap d is equal to 50 nm. The thickness t_1 of W-doped VO₂ layer and the thickness t_2 of non-doped VO₂ layer are 30 and 1000 nm, respectively. In Fig. 3(a), the emitter is insulating at the beginning when $T_1 < T_W$, while the receiver, whose temperature is fixed at $T_2=270$ K, is always an insulator. The radiative heat flux is 11.8 kW/m² at $T_1=300$ K and it increases almost linearly with increasing the emitter temperature until it reaches the maximum at the MIT temperature of W-doped VO₂. When the emitter temperature exceeds T_W , the top layer becomes metallic, which in turn forms a Fabry-Perot cavity. The phonon modes of the insulator VO₂ at the receiver cannot be effectively coupled to the metallic interface of emitter that does not support any phonon modes to enhance the heat transfer. Therefore, it can be clearly seen that, for different doping densities (from 5.5 to 10.3 %), when the emitter temperature T_1 exceeds the phase transition temperature of W-doped VO₂, these radiative heat flux all drop significantly.

Meanwhile, for different doping densities, these differences in radiative heat flux resulting from the phase transition are located within the range from 10.3 to 6.5 kW/m². This also shows that this thermal switch has a stable working performance, and from “ON” mode to “OR” mode, a large discrete degree of the thermal signal can be obtained. Nevertheless, as shown in Fig. 3(a), it can be clearly seen that when the MIT temperature of W-doped VO₂ layer is 330 K, since the transition regions of W-doped VO₂ and undoped VO₂ overlap, the device cannot provide multi-level discrete signals. Namely, only when the transition regions of W-doped VO₂ and undoped VO₂ do not overlap, the device can provide steady multi-level discrete signals. Therefore, it is very necessary to select reasonably the doping concentration of the W doped layer.

For the thickness of W-VO₂ smaller than the penetration depth, the phonon mode of N-VO₂ can pass through the metallic layer of emitter to couple with the phonon modes of receiver. Meanwhile, the F-P resonance caused inside the N-VO₂ layer film of emitter also increases the heat transfer between the emitter and the receiver.^[37] Thus, due to these above reasons, the RHF of “OR” mode is greater than the RHF between insulating-VO₂ and metallic-VO₂ (“OFF” mode). When the emitter temperature exceeds 341 K, the emitter becomes metallic. As a result, the radiative heat flux first decreases abruptly from 13.9 kW/m² at $T_1=341$ K to 8.4 kW/m² at $T_1=355$ K, and then increases slightly to 8.9 kW/m² at $T_1=360$ K. It can be clearly seen that, when the port is switched from “OR” mode to “OFF” mode, the resolution of thermal signal is about 5.5 kW/m². Consequently, a stable and significant transition of this thermal signal can be also observed when the discrete thermal signal changes from “OR” mode to “OFF” mode.

To visualize the RHF transition of the thermal switch, in Fig. 3(b), we calculate the energy transfer function $\Phi(\omega)$.

According to the colored stripe in Fig. 3(b), the effects of surface phonon polaritons (SPhPs) and hyperbolic phonon polaritons (HPPs) on the spectral radiative heat flux can be easily recognized. On the “ON” mode, the peaks of energy transfer function increase drastically by these phonon modes. When the thermal switch enters the “OR” mode, it can be clearly seen that the energy transfer functions keep smaller values in all regions of phonon modes. Especially, since the attenuation length ($\delta_z = 1/\text{Im}(k_z)$) is smaller in the region of higher frequency,^[38] the metallic W-VO₂ tremendously suppress the HPPsI from 0.048 to 0.072 eV/h and the HPPsII from 0.075 to 0.101 eV/h, which in turn results in the dramatic decline of RHF from “ON” mode to “OR” mode. When the temperature further increases and the emitter completely becomes metallic, since the phonon modes of the insulator VO₂ cannot be coupled to the other metallic interface that does not support any phonon modes, the energy transfer function of “OFF” mode is greatly suppressed as shown in Fig. 3(b).

Fig. 4 Contour plots of photonic transmission coefficient for (a) “ON” mode, (b) “OR” mode, and (c) “OFF” mode. Black dash lines are dispersion curves. Dispersion relationship in this system can be obtained by zeroing the denominator of PTC as $\mathbf{I} - \mathbf{R}_1 \mathbf{R}_2 e^{2ik_z d} = 0$. Yellow, green and blue dash dot lines are contour curves for PTC equal to 0.6, 0.3 and 0.1, respectively.

The photonic transmission coefficient (PTC) and dispersion relations can visually reveal the physics behind the effect of surface state on the near-field radiative heat transfer. As shown in Fig. 4(a), with the strong coupling of the SPhPs and HPPs generated at the vacuum-surface interface from VO₂, we can clearly see that the bright band appears. In particular, at the

high frequency region ($\omega > 0.04$ eV/h), thanks to strong SPhPs and HPPs, the thermal switch can obtain the brighter band of photon transmission coefficient in the area of higher wavevector, which is very helpful to the energy transmission of the system in the “ON” mode. When W-VO₂ undergoes an insulator-metal transition with increasing temperature, the switch begins to enter the “OR” mode. At this time, the N-VO₂ in the middle layer can still support the strong phonon mode. Nevertheless, the phonon mode supported by the middle layer N-VO₂ of emitter would be depleted by the metallic W-VO₂ of emitter before coupling with the phonon mode of receiver. As shown in Fig. 4(b), by comparing to Fig. 4(a), it can be visually observed that as the model changes from “ON” mode to “OR” mode, the PTC of “OR” mode no longer supports energy transmission at a large wavevector. Meanwhile, this loss will increase significantly as the wave vector and frequency increase. It is particularly clear that as the frequency increases, the attenuation of this bright band gradually increases. The contour curves for PTC equals to 0.6 at $\omega = 0.096$ eV/h significantly decrease from 40 k_0 for “ON” mode to 16 k_0 “OR” mode. When the emitter becomes completely metallic as the temperature further increase, which is the case for the “OFF” mode, the PTC between an insulating VO₂ and a metallic VO₂ is suppressed greatly as shown in Fig. 4(c). The phonon modes of the insulating VO₂ could not constructively couple to the other metallic interface that does not support any phonon modes. Furthermore, due to the highly reflective nature of the metallic VO₂ in emitter, the PTC for the “OFF” mode shown in Fig. 4(c) is weaker than that for the “OR” mode presented in Fig. 4(b).

Moreover, the higher resolution of thermal signal can effectively improve the identification of discrete thermal signals, that is, makes the difference of radiative heat flux between two adjacent discrete thermal signals more obvious. The introduction of two-dimensional (2D) materials may be a good solution. In this section, we show that the combination of metasurfaces such as graphene and graphene grating can further increase the difference of radiative heat flux between two discrete thermal signals. The graphene conductivity can be written as a sum of intra-band (Drude) and inter-band contributions, i.e., $\sigma = \sigma_D + \sigma_I$, as shown in Equations (17&18), respectively: [39]

$$\sigma_D = \frac{i}{\omega + i/\tau} \frac{2e^2 k_B T}{\pi \hbar^2} \ln \left(2 \cosh \frac{\mu}{2k_B T} \right) \quad (17)$$

$$\sigma_I = \frac{e^2}{4\hbar} \left[G \left(\frac{\hbar\omega}{2} \right) + i \frac{4\hbar\omega}{\pi} \int_0^\infty \frac{G(\xi) - G(\hbar\omega/2)}{(\hbar\omega)^2 - 4\xi^2} d\xi \right] \quad (18)$$

where $G(\xi) = \sinh(\xi/k_B T) / [\cosh(\mu/k_B T) + \cosh(\xi/k_B T)]$. The conductivity depends explicitly on the temperature T and the chemical potential μ . The relaxation time τ is fixed at 10^{-13} s. [39] The optical conductivity for the array of graphene nanoribbons has been derived using a well-known effective medium theory (EMT) [10-12] that holds true when the unit-cell

period $P = W + G$ is much smaller than the operating wavelength, i.e., $P \ll \lambda_0$. Meanwhile, EMT is valid only when the vacuum gap is larger than the period of the ribbons. [40-42] When the gap distance is several times greater than the period, EMT predicts the real heat flux well, as has been quantitatively shown by others. [41] According to Ref [41] when the vacuum gap d_0 is 50 nm and the period P is 10 nm, the error of EMT is less than 5% compared with rigorous coupled-wave analysis (RCWA). Meanwhile, as the gap distance increases, the accuracy of EMT can be further improved. According to EMT, this technique is based on modeling the strip near-field coupling as an effective capacitance as shown in Equation (19): [43, 44]

$$\sigma_{eff} = \begin{bmatrix} \sigma_{xx} & 0 \\ 0 & \sigma_{yy} \end{bmatrix} = \begin{bmatrix} \frac{W\sigma\sigma_c}{P\sigma_c + W\sigma} & 0 \\ 0 & \frac{W}{P}\sigma \end{bmatrix} \quad (19)$$

where $\sigma_c = -i\omega\epsilon_0 P / \left\{ \pi \ln \left[\csc \left[0.5\pi(P-W)/P \right] \right] \right\}$ is the effective strip conductivity taking into account near-field coupling and nonlocality. In the hyperbolic regime, the metasurface acts as a metal for one transverse field polarization ($\text{Im}[\sigma_{yy}] > 0$) and as a dielectric for the other one ($\text{Im}[\sigma_{xx}] < 0$). ω is the frequency, and ϵ_0 is the vacuum permittivity.

We first discuss the radiative heat flux (RHF) of Case I, where a graphene sheet is interspersed between the top layer comprised of W-doped VO₂ and the middle layer comprised of undoped VO₂ in Fig 5(b). We can see in the Fig. 5(a) that the presence of the graphene sheet significantly modifies the RHF of the thermal switch. In most of the temperatures, the RHF is larger than the absence of the graphene sheet, especially, in the “ON” mode. It can be clearly seen that when the graphene sheets are introduced, the resolution of radiative heat flux from “ON” mode to “OR” mode is increased obviously from 8.54 to 13.38 kW/m² in the Fig. 5(a). The phenomenon can be explained by the plasmons resonance coupling on graphene sheets between the emitter and receiver. Meanwhile, the thinner thickness of W-doped VO₂ allows the evanescent wave supported by graphene to pass through the metal film, thus ensuring that it can still achieve the increase of radiant heat transfer in the “OR” mode. The resolution of radiative heat flux from “OR” mode to “OFF” mode also can be increased from 5.14 to 7.18 kW/m² in Fig. 5(a).

In the nature, the width of graphene stripe should be a multiple of the lattice constant a of graphene of 0.246 nm. We consider that the width W is 10 a (2.46 nm) and the unit-cell period P is 40 a (9.84 nm) to realistically depict graphene grating in Fig. 5(c). In practical applications, the graphene ribbon arrays can be fabricated by electron beam lithography, [45] chemical etching, [45] metal template growth, [46] carbon nanotube cutting shear method, [47] and laser interference. [48] When the graphene grating is introduced, the resolution of radiative heat flux from “ON” mode to “OR” mode is increased from 8.54 to 10.9 kW/m² in Fig. 5(a). It is

well-known that by patterning a single layer of graphene sheet into ribbons, the closed circular dispersion of graphene plasmons is opened to become hyperbolic, leading to a giant enhancement of the near-field radiative heat flux.^[41] But when the graphene grating is placed between W-VO₂ layer and N-VO₂ layer, the RHF of *Case II* is less than the RHF of *Case I*. This is because although the hyperbolic anisotropic plasmons of the graphene grating can support the photon energy at a larger wavevector, the photon energy at the large wavevector is lost through the W-VO₂ layer and cannot make enough contribution to the radiative heat transfer. On the contrary, the photon energy at a lower wavevector can pass through the W-VO₂ layer relatively losslessly, thereby having a good enhancement effect on the radiative heat transfer of this thermal switch. However, in terms of near-field enhancement, there is a drawback of hyperbolic graphene plasmons, that is, the coupling with lower wavevector is rather weak.^[41] The above reasons leading to the RHF for introducing graphene grating is not as good as the introduction of graphene sheets. Therefore, we can draw a conclusion: two-dimensional materials with a more intense photon energy in the lower wavevector range can better help to improve the resolution of thermal switch.

In addition, with the improved functions of control element, the number of discrete thermal signals required is also increasing. A thermal switch with a more discrete thermal

signals is also investigated to adapt to the complex control environment that requires more discrete thermal signals. By reasonably setting the number of film and the W-doped concentration of each film, the discrete thermal signals of the switch can be increased. Fig. 6 shows the total radiative heat fluxes as a function of emitter temperatures for four configurations. Here, we set the number of layers of W-doped VO₂ to two, with $t_1=15$ nm and $t_2=40$ nm, as shown in Fig. 6(b). It is interesting to observe that, by controlling the MIT temperature of each layer of W-VO₂, we can actively define the temperature response threshold of thermal signal to adapt to the work environment. For example, in Fig. 6(a) when we set the MIT temperature of each layer of W-doped VO₂ as 310 and 324 K, we can get four discrete thermal signals, which greatly increases the capacity of the signal channel. The resolution of radiative heat flux at discrete thermal signals is located within the range from 2.98 to 3.25 kW/m². However, considering the interference of the thermal signals between each W-doped VO₂ layer, the number of discrete signals cannot be increased indefinitely. It is because that if the number of thermal signal is further increased, the difference of MIT temperature between each W-doped VO₂ layer would be too small and the transition regions of each W-doped VO₂ layer would overlap, resulting in the device that cannot provide multi-level discrete signals.

Fig. 5 (a) The total radiative heat fluxes with different emitter temperatures T_1 at the gap distance of $d=50$ nm with the receiver temperature fixed at $T_2=270$ K. (b) The graphene sheet and (c) the graphene grating are interspersed between the top layer comprised by W-doped VO₂ and the middle layer comprised by undoped VO₂. The thickness t_1 of W-doped VO₂ layer and the thickness t_2 of undoped VO₂ layer are 30 nm and 1000 nm, respectively. The chemical potential of graphene is 1 eV, the width W of graphene grating is 2.46 nm, and the unit-cell period P of graphene grating is 9.84 nm.

Fig. 6 (a) The total radiative heat fluxes with different emitter temperatures T_1 at the gap distance of $d=50 \text{ nm}$ with the receiver temperature fixed at $T_2=270 \text{ K}$. The number of layers of W-doped VO₂ is two, with $t_1=15 \text{ nm}$ and $t_2=40 \text{ nm}$. The thickness of N-VO₂ in 1000 nm ; and (b) schematics of the proposed thermal switches with multiple discrete signal levels.

4. Conclusion

In summary, the concept of near-field thermal switch with multiple discrete thermal signals is demonstrated theoretically based on near-field radiative heat transfer at nanometer vacuum gaps. Doping tungsten into vanadium dioxide can decrease the metal-insulator transition (MIT) temperature. The combination of layers with different MIT temperatures, employing W-doped and undoped VO₂, provides the possibility to perform multiple discrete thermal signals (“ON”, “OR”, and “OFF” discrete thermal signals) that can be realized at nanometer scale, thereby implementing the higher channel capacity. These results overcome the limitation that the original binary radiative switch only provides two discrete thermal signal (“ON” and “OFF”). Furthermore, we further demonstrate that the introduction of two-dimensional (2D) materials can effectively improve the identification of discrete thermal signals, that is, make the difference of radiative heat flux between two adjacent discrete thermal signals more obvious. Finally, by reasonably setting the number of films and the W-doped concentration of each film, the thermal switch with more-bit states can be further developed. The thermal circuits based on the combination of this switch can promote the development of the thermal computing with multi-state channel to realize more thermal circuit.

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Conflict of interest

There are no conflicts to declare.

Support information

Not applicable

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