Journal of Quantitative Spectroscopy & Radiative Transfer 218 (2018) 171–177

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Effective modulation of the near-field heat flux with radiative thermal switch based on electrochromic effects of tungsten trioxide

Yong Chen[a], Zhiheng Zheng[a,b], Yimin Xuan[a,c,*]

[a] School of Energy and Power Engineering, Nanjing University of Science and Technology, 210094 Nanjing, China
[b] School of Environmental and Materials Engineering, College of Engineering, Shanghai Polytechnic University, 201209 Shanghai, China
[c] School of Energy and Power, Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, China

ARTICLE INFO

Article history:
Received 13 March 2018
Revised 20 July 2018
Accepted 22 July 2018
Available online 27 July 2018

Keywords:
Electrochromic material
Near-field radiative heat flux
Surface plasmon polaritons
Switching factor

ABSTRACT

In this work, we theoretically demonstrate the method to effectively modulate the near-field radiative heat flux by the radiative thermal switch made of electrochromic material tungsten trioxide (WO_3). The thermal switch is composed of two gates separated by vacuum gap d_0. The heat flux tunneling the thermal switch can be modulated through changing the optical state of the gates by exerting a voltage. The impacts of the vacuum gap distance and the film thickness on the switching factor of the radiative thermal switch are investigated. When the vacuum gap d_0 is less than 500 nm, the switching factor is increased with the decrement of d_0 and can be as high as 98%. On the other hand, at the vacuum gap $d_0 \geq 500$ nm, the switching factor can be increased up to 85% with the increment of the vacuum gap. Additionally, the thickness effect of the WO_3 film on the switching factor is investigated at $d_0 = 100$ nm and $d_0 = 10$ µm, respectively. The switching factor can be decreased with the increment of the thickness of the WO_3 films at $d_0 = 100$ nm, whereas the switching factor at $d_0 = 10$ µm can realize the extreme value in the case that the thickness of WO_3 films amounts to 160 nm. This work can pave the way for the nanoscale thermal management and has potential applications for thermal based recording technology.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Heat flux control is a key issue of the modern technology in thermal management, energy conversion and thermal based information processing. The studies on thermal diodes (rectifier), thermal transistor and thermal switch have been rapidly growing because these components can be used for controlling thermal transport that cannot be supported by the traditional thermal resistors and capacitors [1]. The control of the heat flow carried by phonons is investigated during the past years [2–5]. Recent decades, extensive studies have demonstrated the thermal rectifier which can achieve the asymmetry of the near-field radiative heat fluxes by using temperature dependent polar materials [6–9] and the phase transition material vanadium dioxide [10–16].

Recent years, the radiative thermal switch, which can effectively modulate the radiative heat flux between two objects, is explored by using the materials whose optical properties can be adjusted by exerting a voltage [17–19]. Cui et al. [17] obtained thermal modulation effect by controlling the size and sign of the magnetoelectric response in metamaterials. The maximum modulation factor of the near-field radiative heat flux in their study could be 70%. Yang and Wang (18) presented electrically controlled near-field thermal modulator based on graphene-coated silicon carbide plates. By properly tuning the chemical potential of the graphene on the surface of the silicon carbide plates, the switching factor could exceed 90% at the vacuum gap 10 nm. The researches above achieved the remarkable switching effects by tuning the surface polaritons (SPs) coupling between the two objects. Once the vacuum gap further increases, on the other hand, the SPs cannot dominate the radiative heat transfer and the switching effect will be greatly diminished.

Electrochromic materials are also called color changing materials, whose optical properties can be altered by exerting a voltage. Numerous types of electrochromic materials were proposed and widely applied to the smart windows [20], satellite thermal control [21], optical recording technology [22], diffraction based imaging [23] and camouflage [24,25]. During the past decades, extensive efforts of the researchers were concentrated on the electrochromic material WO_3. The optical states of the WO_3 based electrochromic device can be controlled easily by applying a voltage pulse because the WO_3 film can sustain the optical state when the applied voltage removed [21]. The responding speed of the WO_3 based electrochromic device is limited by the color changing speed of WO_3

* Corresponding author at: School of Energy and Power Engineering, Nanjing University of Science and Technology, 210094 Nanjing, China.
E-mail address: ymxuan@nuaa.edu.cn (Y. Xuan).

https://doi.org/10.1016/j.jqsrt.2018.07.015
0022-4073/© 2018 Elsevier Ltd. All rights reserved.

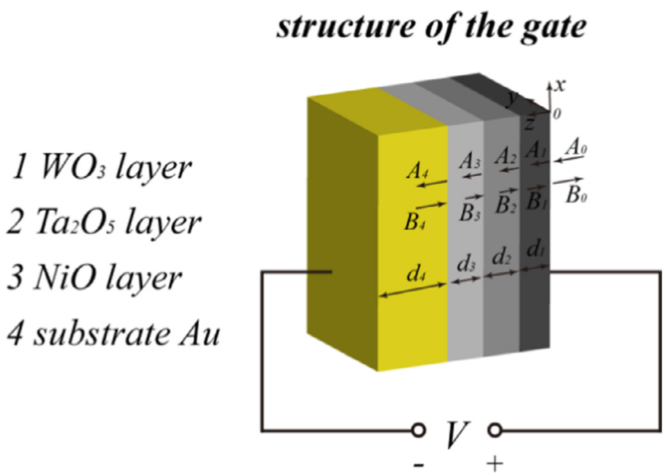

Fig. 1. The schematic diagram of the gate. A_l and B_l ($l = 1, 2, 3, 4$) are the amplitudes of the waves at the interfaces.

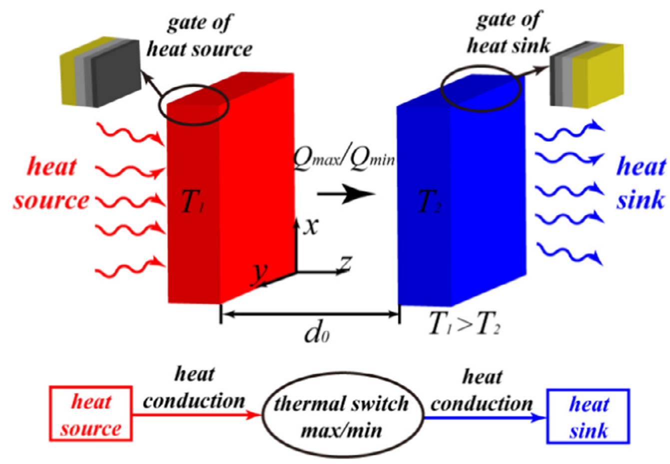

Fig. 2. Schematic diagram of the radiative thermal switch. The flow diagram in the bottom illustrates the working process of the radiative thermal switch.

not by the thermal inertia. Numerous studies had illustrated the method to prepare the WO_3 films of fast color changing speed [26–31] which implied the promising applications based on WO_3. Despite the large amounts of studies on the electrochromic materials, the near-field radiative heat flux between two closely spaced objects made of electrochromic materials was seldom investigated. It is intriguing that whether the electrochromic materials can be applied to the thermal switch for effectively modulating the near-field radiative heat flux.

In the present study, the radiative thermal switch made of electrochromic material WO_3 is theoretically demonstrated to effectively modulate the near-field radiative heat flux. The presented radiative thermal switch is composed of two gates separated by a vacuum gap d_0. The radiative heat flux tunneling the vacuum gap can be modulated when the optical state of the gate varies according to the external voltages. The remaining part of this paper is organized as follows. Section 2 introduces the color changing mechanism of the gate made of WO_3. Section 3 demonstrates the structure of the thermal switch and the calculation model of the near-field radiative heat flux. The switching factor is defined in this section to indicate the capability of the radiative thermal switch to modulate the near-field radiative heat flux. Section 4 presents the calculated results and then discusses the impacts of the vacuum gap distance on the switching factor at the vacuum gap d_0 ranging from 10 nm to 10 µm. Furthermore, the thickness effect of the WO_3 film on the switching factor is studied at the vacuum gap 100 nm and 10 µm. Additionally, the underlying mechanisms of the effects on the switching factor are demonstrated. Finally, Section 5 gives the conclusion.

2. Color changing mechanism of the gate

The electrochromic materials can experience color changing process when ions (hydrogen or lithium ions) insert into or extract from the materials by the voltage bias applied to the electrode layers [21]. Reference [20] has reviewed the general structure of the electrochromic device, which is composed of five layers including electrode layer, ion storage layer, electrolyte layer, electrochromic layer and electrode layer, respectively. The practical electrochromic device can be less than five layers. For example, the electrochromic layer can synchronously serve as the color changing layer and the electrode layer if the electrochromic layer is conductor. In this case, the structure can be reduced to four layers.

Fig. 1 illustrates the schematic diagram of the gate of the radiative thermal switch in the present study. The gate is made of a 4-layer $Au/NiO/Ta_2O_5/WO_3$ electrochromic device. d_1, d_2, d_3 and d_4 are the thicknesses of the corresponding films. In the presented structure, the substrate Au serves as the electrode on the side of NiO layer, meanwhile, the NiO and Ta_2O_5 are respectively ion storage layer and the electrolyte layer. The WO_3 layer functions as the color changing materials of the gate [21]. Simultaneously, the WO_3 layer serves as the electrode due to its benign electrical conductivity in both the bleached state and colored state [32]. The positive direction of the voltage bias V is elucidated in Fig. 1. According to the investigation in Ref. [21], the color changing mechanism of the gate can be illustrated by the electrochemical processes which can be expressed as follows

$$[WO_3]_{bleached\ state} \underset{[-H^+ - e^-]_{V_+}}{\overset{[+H^+ + e^-]_{V_-}}{\rightleftharpoons}} [HWO_3]_{colored\ state} \tag{1}$$

where the H^+ and e^- represent hydrogen ion and electron, respectively. According to expression (1), when the negative voltage $V = -750$ mV applied to the gate, H^+ supplied by the ion storage layer is inserted into WO_3 layer and the gate varies from the bleached state to the colored state. On the contrary, when the positive voltage $V = 300$ mV applied to the gate, H^+ is extracted from the WO_3 layer and the gate is transformed from the colored state to the bleached state. In this work, the equilibrium states (colored state and bleached state) of the gate are employed to serve as two modes of the radiative thermal switch.

3. Calculation model and theoretical method

3.1. Schematic diagram of the radiative thermal switch

The configuration of the radiative thermal switch is depicted in Fig. 2. The two gates are maintained at the temperature $T_1 = 310$ K and $T_2 = 290$ K, respectively. According to the structure in Fig. 2, the gates of the thermal switch experience the opposite configurations. The WO_3 films of the gates are separated by vacuum gap d_0, meanwhile, the substrate Au serves as the medium for absorbing heat from the “heat source” or transferring heat to the “heat sink” by heat conduction. The radiative heat flux tunneling the thermal switch can be modulated when both the two gates vary between the bleached state and the colored state by exerting proper voltages. The diagram in the bottom of Fig. 2 illustrates the procedure of modulating the heat flux between the “heat source” and

Download English Version:

https://daneshyari.com/en/article/7845791

Download Persian Version:

https://daneshyari.com/article/7845791

Daneshyari.com