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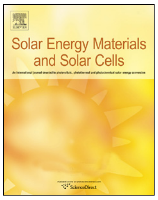

Thermal radiation from silicon microcavity coated with thermochromic film

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ABSTRACT

A high thermochromic performance is required for the thermochromic film application in space radiator. The performance can be improved by material selection or structure design. Here, we constructed a two-dimensional structure composed of silicon microcavity array coated with thermochromic film. From detailed numerical simulation, we found that periodic microcavity array plays a key role in enhancing the spectral emittance. For 1.5 μm deep microcavity with a 500 nm thick thermochromic film, an emittance peak appears at the wavelength of 12.7 μm, which corresponds to the Fabry–Perot (FP) resonance mode. Another microcavity excitation was observed in the shorter wavelength region, which matches well with its resonance wavelength. Based on the simulations, the optimal structure was fabricated by etching and sputtering methods. The fabricated structure shows a high tunable emittance behavior with emittance increment reaching 0.41. Both the experiment and simulation identified that the microcavity beneath thermochromic film can improve its thermochromic performance.

1. Introduction

Thermochromic materials based on manganese oxides are attractive for radiator application in space. They are characterized by tunable thermal radiative properties with the variation of their own temperature, as a result of a metal-insulator (MI) phase transition [1–3]. Since their emittance is small at temperature below the phase transition and large at higher temperature, emittance adjustment can be achieved automatically by temperature change. If a radiator composed of thermochromic material is fitted on a spacecraft surface, the emissive heat transfer from spacecraft can be automatically controlled without additional power consumption and moving parts [4,5]. Thermochromic materials $La_{1-x}A_xMnO_3$ (A is alkaline earth), therefore, have been investigated deeply as a smart radiative device over the past 10 years. These investigations involve the method of device fabrication [2,5,6], the evaluation of device thermal radiative properties (i.e., emittance and solar absorptance) [7–10], and the stability of device in space environment [3,11]. Although numerous efforts have devoted to the thermal radiation enhancement of thermochromic material, the emittance modulation in thermochromic film is still moderate.

With the development of spectral control of thermal radiation, the emittance enhancement has been reported using a periodic surface structures with scale on the order of the wavelength of light such as tungsten microcavities, FP resonance cavity, and two-dimensional W gratings [12,15,16]. Simultaneously, some enhancement mechanisms were presented including the excitation of surface plasmon or phonon polaritons (SPPs) [17], the FP resonance [15,18], the microcavity resonance [19], and the photonic bandgap effect [20]. Recently, Huang et al. also reported that the emittance performance of thermochromic film can be enhanced by utilizing microstructure [21–23]. Huang et al. [21] calculated the spectral emittance of $La_{1-x}Sr_xMnO_3$ ($x = 0.175$) with one-dimensional grating structured surfaces using the finite difference time domain method. The results showed that the thermochromic performance was improved by the structured surface, which have been demonstrated experimentally by means of photolithographic technique to construct a similar structured surface [22]. Then, a structure containing $La_{0.825}Sr_{0.175}MnO_3$ thermochromic film and gratings was proposed to enhanced thermal radiation due to the near-field effect [23,24], which motivated this study to provide additional knowledge on the emittance properties of thermochromic film.

In this work, we constructed a structure with $La_{0.8}Sr_{0.2}MnO_3$ (LSMO) thermochromic film upon silicon microcavity array to investigate its selective thermal radiation properties. The optical constants of LSMO film were obtained from its experimental reflectance data using the Kramers–Kronig(K–K) relationship. The

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optical properties of the structured film were simulated in the infrared region (2.5–25 μm) by using the rigorous coupled-wave analysis (RCWA) method. The effects of microcavity parameters on the optical properties of the structured films were discussed. Based on the computational results, we prepared a similar structure by etching and sputtering method. Silicon microcavity array was etched by plasma etching technique on silicon wafer surface. LSMO film was then sputtered on the microcavity array. The surface morphology, temperature-dependent reflectance, and emittance properties of the structured surface were investigated. Finally, the experimental and simulated results were comparatively analyzed.

2. Calculation of thermal radiation in microcavity array structure

2.1. Calculation model and method

Fig. 1 schematically shows a typical structure under investigation. Silicon microcavity array is coated with a LSMO film. The silicon layer thickness is 0.5 mm, which is thick enough to ensure the whole structure opaque. The depth and period of the microcavity with a side length of $l=4$ μm is h and Λ, respectively. The thickness of LSMO film is d. By adjusting the microcavity parameters, four calculation cases were obtained in this work and their structural parameters were listed in Table 1.

The RCWA method is used to analyze the optical properties of the structured surface. This approach is one of the most effective theories to investigate the diffraction of periodic structures [25,26]. The detailed algorithm is not described here, it can refer to Ref. [25]. The reflectance $\rho(\lambda)$ of the structured surface can be calculated from the RCWA method. According to Kirchhoff's law, the spectral emittance $\epsilon(\lambda)$ is equal to the spectral absorptance $\alpha(\lambda)$. Consequently, for the opaque structure in this work, the spectral emittance without considering anisotropy requirement can be obtained as $\epsilon(\lambda)=\alpha(\lambda)=1-\rho(\lambda)$. Then, total emittance $\epsilon(T)$ in the wavelength region of 2.5–25 μm is also determined from the following equation:

$$\epsilon(T)=\frac{\int_{2.5}^{25}[1-\rho(\lambda,T)]E_{\lambda,b}(\lambda,T)\,d\lambda}{\int_{2.5}^{25}E_{\lambda,b}(\lambda,T)\,d\lambda}, \qquad (1)$$

where $E_{\lambda,b}(\lambda,T)$ is blackbody radiative intensity. In experiment, the measured reflectance $\rho(\lambda,T)$ is a normal total reflectance due to a smaller incident angle of 15° near the normal incidence and a wider wavelength range (2.5–25 μm). Consequently, the emittance $\epsilon(T)$ derived from the measured reflectance using Eq. (1) can be considered as the normal total emittance based on the knowledge of thermal radiation heat transfer [27].

2.2. About LSMO film

The LSMO film was deposited on (100) orientation As-doped silicon wafer (Hefei Crystal Technical Material Co., Ltd., China) through magnetron sputtering technique. In order to improve the oxygen content, the LSMO films were annealed ex situ at 700 °C in flowing oxygen for 2 h. Fig. 2 shows the XRD pattern of LSMO target and LSMO film deposited on Si substrate. The film thickness is 500 nm. The XRD pattern of film is corrected for Si substrate. Only peaks related to the film are presented without Si substrate peaks. The samples are perovskite structure. Compared with the LSMO target, film diffraction angle shifts toward larger angle direction, which means the lattice constant of film is smaller than that of the target. The result is similar with the report that the thinner LSMO film is prone to show a larger diffraction angle [28]. The experimental near-normal (15° incident angle) reflectance of LSMO film on silicon plane is shown in Fig. 3. In order to detect the

Table 1
Microcavity size with μm unit in simulation model.

Simulation cases	Λ	h	d
Case 1	12	1.5	0.5
Case 2	12	2	1
Case 3	12	5	1
Case 4	12	8	1

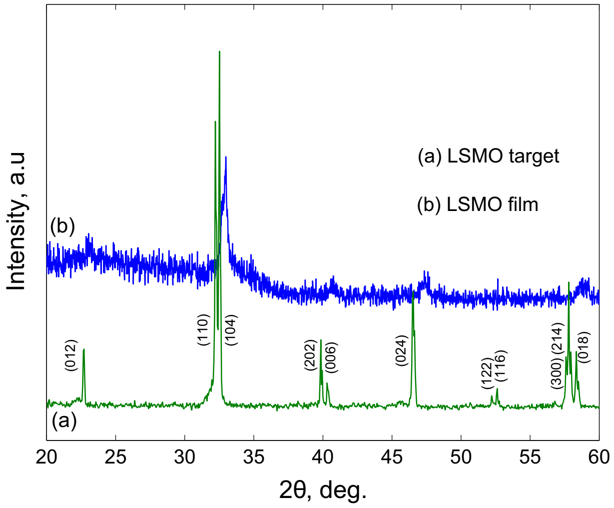

Fig. 2. XRD pattern of LSMO target and LSMO film.

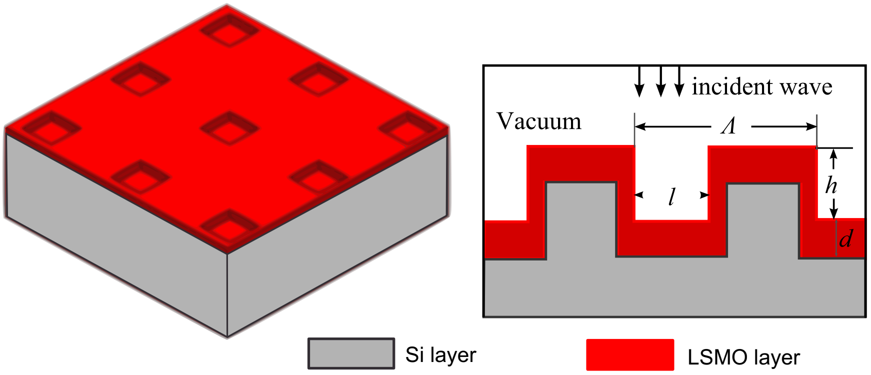

Fig. 1. Schematic diagram of the proposed structure.