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Design and analysis of micro thermal switch using the near-field effect for space applications

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ABSTRACT

With space developments for diversified missions, intelligent thermal design of spacecraft is essential. This report proposes an active thermal radiation control device, which consists of an array of thermal switch that is enhanced by the near-field radiation. Suspended diaphragms are snapped down by electrostatic force, when the driving voltage is applied to the top electrode. The present simulation for parallel plates of Au (lower electrode) and Cu (upper electrode) at 300 K shows that the effective emittance of 0.02 for a 1 μm separation is dramatically increased to 0.89 for a 10 nm gap. A MEMS (Micro Electro Mechanical Systems)-based active radiator was designed based on the requirements for the driving voltage and resonant frequency. The fill factor of the proposed radiator is as large as 61%. In this study, an analysis based on thermal resistance of various heat paths was conducted. It was found that the thermal resistance of the near-field effect was lower than that of contact heat conduction, indicating that the ON-OFF switching performance is largely improved by near-field radiation. The heat flux in the ON state can be enhanced by a factor of 28.5 (T_1 = 400 K, T_3 = 3 K).

1. Introduction

Smart thermal control that can actively manipulate heat flux on demand has been investigated in recent years. Particularly for thermal management of satellites, thermal radiation is a dominant heat transfer mode in space environments that don't support convection or conduction. Thus, higher-quality radiators have been demanded by diversified space missions. Furthermore, with the focus on micro-, nano-, and pico-satellites, the use of conventional thermal control devices faces some limitation. Next-generation radiators for small satellites must be lightweight, consume low power, exhibit good emittance control, etc. To satisfy these requirements, we focus on thermal control devices that use MEMS technology [1–8].

Beasley et al. [1] proposed a space radiator with high emissivity membrane suspended over the substrate via the SU-8 support posts. The membrane comes into contact with the substrate when the driving voltage is applied. However, the temperature change between ON-OFF states is less than 1 K due to parasitic heat loss through the SU-8 post, which has a thermal conductivity of 0.2 W/(m K). Gong et al. [2] reported on a thermal switch that used EWOD (electrowetting-on-dielectric) principles. The experimental results achieved a switching ON-OFF ratio 2.8 times higher. However, the researchers tested thermal conductivity with water or glycerin, which are not suitable for a space environment under low vapor pressure. Biter et al. [3] proposed a radiator suitable for satellite missions in which the heat transfer mode can switch between thermal radiation and heat conduction. However, the active radiator demands high power consumption of 400 V as the driven voltage. Cho et al. [4] proposed a MEMS thermal switch by using heat conduction between two surfaces. They investigated five types of switches with different materials, with the result that surfaces with liquid-metal micro droplets of Hg and Si proved to be the best, with an ON-OFF ratio that was 224 times higher. However, Hg is a highly toxic material. Osiander et al. [5] prototyped a MEMS thermal shutter array, in which the effective radiation area is changed by opening and closing the shutter. However, in principle, its fill factor (ratio of the actual radiation area to the projection area of the device) cannot exceed 50%, because the shutters occupy 50% of the surface area. Thus, it is desirable to develop a MEMS-based thermal radiator with a large change in the effective emissivity, and with a high fill factor. In Ueno & Suzuki [9], we proposed a MEMS active radiator with a low parasitic heat loss. An array of micro-diaphragms suspended with polymer springs are electrostatically driven in the out-of-plane direction, and the heat flux is increased at the ON state via the contact heat resistance change. We have demonstrated radiation heat flux enhancement as large as 42% with an early prototype developed with parylene MEMS technologies.

One problem for this type of active radiator, which is based on the contact resistance change between the membrane and the substrate, is that high contact pressure is required for low contact resistance in the

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ON state, and thus a high ON-OFF heat flux ratio is achieved. On the other hand, if the contact pressure is too high, unwanted permanent stiction may occur between the membrane and the substrate.

Therefore, in this paper, we propose a novel near-field-enhanced MEMS radiator to improve the ON-OFF heat flux ratio.

Polder and Van Hove [10] theoretically reported enhancement of radiation heat flux between two metal layers by the near-field effect. Pendry [11] obtained maximum heat flux between two identical parallel surfaces, while Ben-Abdallah and Joulain [12] investigated for two different surfaces. Fu and Zhang [13] investigated the near-field radiation for semi -infinite parallel plates of doped Si depended on dopant concentrations at different temperature by using Drude model as the dielectric function. Basu et al. [14] improved the dielectric function model for doped Si and investigated the effect of doping level and polarization for nanoscale thermal radiation heat transfer at the gap distance from 1 nm to 10 μm. They show that the enhancement of near-field radiation at the room temperature is insensitive to the doping level ($10^{18}\,\mathrm{cm}^{-3}$-$10^{21}\,\mathrm{cm}^{-3}$).

More recently, theories on the near-field radiation for thin film [15–17] and multilayered films [18] are developed. Francoeur et al. [19] studied the transition of thermal radiation from near-field to far-field. Chiloyan et al. [20] investigated the boundary condition between radiation by photons and the heat conduction by phonons in the near-field region. As far as experimental works in the near-field radiation, Hu et al. [21] reported radiation heat transfer in micron gaps between two parallel plates by using micron-order polystyrene particles as spacers. Narayanaswamy et al. [22] investigated thermal radiation between a sphere and a substrate within 1 μm gap with an AFM cantilever. Shen et al. [23] made more accurate experiments between a sphere and a substrate up to a 30 nm gap. The experiments for parallel plates in the near-field radiation was also conducted by St-Gelais et al. [24] and Song et al. [25]. Bernardi et al. [26] experimentally demonstrated the tunnel effect of evanescent modes with silicon planar surfaces of two $5 \times 5\,\mathrm{mm}^2$ for temperature differences up to 120 K.

As the applications of near-field radiation, thermophotovoltaic (TPV) [27,28], thermal transistor [29], thermal memory/logic gates [30] are proposed.

In this study, we investigate the near-field effect between two parallel metal layers in order to estimate the thermal radiation between the substrate and the diaphragm. The optical constant is measured by a spectroscopic ellipsometer for accurate calculation. We then design a new device model that can utilize the near-field effect, and estimate the driving-voltage and the resonant frequency for practical applications in satellites. Finally, we examine the feasibility of the proposed radiator based on heat transfer analysis.

2. MEMS active radiator using near-field effect

The effect of the evanescent wave, which is the non-propagative wave responsible for near-field radiation, is localized in an area within sub-micron range from the heat source. Near-field radiation can exceed far-field radiation heat flux as described by Stefan-Bolzmann's law.

In this study, the space MEMS radiator was proposed as shown in Fig. 1. The diaphragm is supported with the tethers. The heat flux on the radiation surface from the diaphragm q_3 is given by

$$q_3 = \varepsilon_3\sigma(T_2^4 - T_3^4) \approx \varepsilon_3\sigma T_2^4, \tag{1}$$

where ε_3, σ, T_2, and T_3 are the emittance of the outer surface, the Stefan-Boltzmann constant, and the temperatures of the inner surface and outer surface of the diaphragm, respectively. Furthermore, the space temperature T_3 is $\sim 3\,\mathrm{K} \ll T_2$.

In the OFF state, the separation distance between the parallel plates is longer than the characteristic wavelength, and the heat flux $q_{2,\,\mathrm{far}}$ is also given by the far-field radiation for two parallel plates, i.e.,

$$q_{2,far} = \frac{\sigma\varepsilon_1\varepsilon_2}{1-(1-\varepsilon_1)(1-\varepsilon_2)}(T_1^4 - T_2^4), \tag{2}$$

Note that the view factor is assumed to be unity and the edge effect is neglected in Eq. (2), because the separation distance is sufficiently smaller than the size of the diaphragm. In the OFF state, the heat flux of the far-field radiation remains small, when low emittance materials are employed on the opposite surfaces of the substrate and the diaphragm. Using Eqs. (1) and (2), T_2 and the net heat flux in the OFF state are derived as a continuity equation for the heat flux $q_3 = q_{2,\mathrm{far}}$.

Conversely, in the ON state, the diaphragm snaps down to the substrate when electrostatic force is applied between the upper and lower electrodes. The distance between the diaphragm and substrate then becomes smaller than the characteristic wavelength, and the heat flux between the parallel plates is greatly enhanced by near-field radiation [13,17,19].

The near-field effect is caused by the random motion of dipoles in the solid material, which produce time-dependent electric and magnetic fields near its surface. Spectral energy flux is derived by projecting the ensemble-averaged Poynting vector in a direction normal to the surface [10,13–16]. The total heat flux $q_{2,\mathrm{near}}$ is given by

$$q_{2,near} = \frac{1}{\pi^2}\int_0^\infty \left[\{\Theta(\omega, T_1) - \Theta(\omega, T_2)\}\int_0^\infty Z_{12}(\beta)\beta d\beta\right] d\omega, \tag{3}$$

where β and Θ are the parallel wavevector components, and the mean energy of a Planck oscillator in thermal equilibrium is given by

$$\Theta = \frac{\hbar\omega}{\exp(\hbar\omega/k_B T) - 1}, \tag{4}$$

where $\hbar$, ω and k_B are Planck's constant, the frequency and the Boltzmann constant, respectively. The exchange function Z_{12} in Eq. (3) is given by

$$Z_{12}(\beta, d) = \frac{4Re(\gamma_1)Re(\gamma_2)|\gamma_0^2 e^{i2\gamma_0 d}|}{|(\gamma_0+\gamma_1)(\gamma_0+\gamma_2)(1 - r_{01}^s r_{02}^s e^{-2i\gamma_0 d})|^2} + \frac{4Re(\varepsilon'_1\gamma_1^*)Re(\varepsilon'_2\gamma_2^*)|\gamma_0^2 e^{i2\gamma_0 d}|}{|(\varepsilon'_1\gamma_0+\gamma_1)(\varepsilon'_2\gamma_0+\gamma_2)(1 - r_{01}^p r_{02}^p e^{-2i\gamma_0 d})|^2}, \tag{5}$$

where the first and the second terms are transmission of the energy carried by each mode in polarization for the TE and TM modes respectively. The Fresnel reflection coefficients r of s- and p-polarizations are given by Eqs. (6) and (7), and the wavevector component in the z-direction γ are given by Eqs. (8) and (9):

$$r_{0j}^s = \frac{\gamma_0 - \gamma_j}{\gamma_0 + \gamma_j}, \tag{6}$$

$$r_{0j}^p = \frac{\varepsilon'_j\gamma_0 - \gamma_j}{\varepsilon'_j\gamma_0 + \gamma_j}, \tag{7}$$

$$\gamma_0 = \sqrt{k_0^2 - \beta^2}, \tag{8}$$

$$\gamma_j = \sqrt{k_j^2 - \beta^2} = \sqrt{\varepsilon'_j k_0^2 - \beta^2}, \tag{9}$$

where $k_0 = \omega/c$. It is important to accurately estimate the dielectric function ε' for the materials used. In the present study, ε' is estimated by the optical constants of the materials, i.e., the refractive index n and the extinction coefficient k, as follows,

$$\varepsilon' = \varepsilon'_R - i\varepsilon'_I, \tag{10}$$

$$\varepsilon'_R = n^2 - k^2, \tag{11}$$

$$\varepsilon'_I = 2nk. \tag{12}$$

Note that Eq. (3) gives the far-field radiation heat flux when the separation distance is large. Using Eqs. (1) and (3), T_2 and thus the net heat flux in the ON state are derived as a continuity equation for the heat flux $q_3 = q_{2,\mathrm{near}}$.