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# Enhanced thermal radiation observed in metal-dielectric-metal thermal emitter by surface plasmon resonance

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***Abstract*-The emission spectra of $Ag/SiO_2/Ag$ tri-layer plasmonic thermal emitters were investigated. It is found that the top silver film perforated with periodic hole array acts not only as a filter but also as an optical amplifier. The enhancement of thermal radiation at specific wavelength was induced by the strong surface plasmon resonance. Furthermore, the energy dispersion relation of the surface plasmon and the polar emission of the plasmonic thermal emitter were found.**

## 1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic excitations generated at a metal/dielectric interface. These SPPs have attracted much attention recently due to their interesting physics and wide applications, such as extraordinary optical transmission (EOT) through the periodic subwavelength holes [1], Tsai et. al. [2] opened a door to develop a high power, room temperature operated, narrow band plasmonic thermal emitter in the mid-infrared region, the ratio of the full width at half maximum (FWHM) to the emission peak wavelength is only about 0.1. The emission peak came from the coupling between thermal radiation and surface plasmon (SP) mode.

The question arises that in $Ag/SiO_2/Ag$ plasmonic thermal emitter [2], what is the role that the top silver film perforated with periodic holds arrays plays, a filter or an amplifier? In this paper, it is demonstrated that the top silver film perforated with periodic hole arrays plays a role to enhance the thermal emission at a specific wavelength.

## 2. Experiments and results

The 400 nm Mo film was deposited by sputtering on the back of the double-polished Si substrate as heating source. 20 nm Ti and 200 nm Ag metal film were deposited on the front side of the Si substrate followed by a $SiO_2$ layer deposited by electron beam evaporation. Then a negative photoresist was spun on the $SiO_2$ layer and a hexagonal rod array with the lattice constant a of 3 μm and diameter d of 1.5 μm was formed on photoresist by photolithography. Finally a 200nm-thick silver film was deposited on the photoresist rod array and lifted off to form a silver film perforated with periodic hole arrays on $SiO_2$ layer. The top silver films of emitter A was made up of the hexagonal lattice arrays. The schematic side and top views of the plasmonic thermal emitters were shown in Fig. 1(a) and (b), respectively.

A PERKIN ELMER 2000 Fourier Transform Infrared Spectrometer (FTIR) system was adopted to measure the thermal radiation spectra. The thermal radiation spectra were measured at emitter temperature of 200 ℃, and the resolution of the spectra is 8 $cm^{-1}$.

Figures 2(a) display the emission spectra of two emitters at 200 ℃, i.e., (1) $Ag/SiO_2/Ag$ tri-layer structure (200nm/100nm/200nm) with top plane Ag without any hole shown the black line, (2) $SiO_2/Ag$ double layer structure (100nm/200nm) shown the red line. In Fig. 2(b), the emitter A with top silver film perforated with hexagonal hole arrays. Also shown in Figs. 2(b) is the expected emission spectra by weighted sum of Fig. 2 (a) spectra according to the exposed area ratios of the silicon dioxide to silver, i.e., 0.23 to 0.77 and 0.20 to 0.80 in the emitters A. In Fig. 2(c), the peak at 4.2 μm in emitter A was composed of six degenerated modes, i.e., (±1, 0) $Ag/SiO_2$, (0, ±1) $Ag/SiO_2$, (-1, 1) $Ag/SiO_2$, (1, -1) $Ag/SiO_2$ modes, designated as (1, 0) $Ag/SiO_2$ mode. Obviously the enhancement of the thermal radiation is independent of lattices type, and the emitters with different silicon dioxide thickness from 100 to 700 nm were all demonstrated the enhanced phenomenon (not shown). In contrast, the extra thick $SiO_2$ layer was also considered, the $SiO_2$ layer was replaced by a 500 μm thick glass substrate in the emitter structure with top silver film perforated with hexagonal hole arrays, denoted as emitter B.

As shown in Fig. 3, the expected emission spectrum was constructed similar to Fig. 2 by weighted sum of two measured spectra according to the exposed area ratios of glass to silver. The emission spectrum of emitter B was measured at same temperature of 200 ℃ which revealed weak emittance than theoretical value.

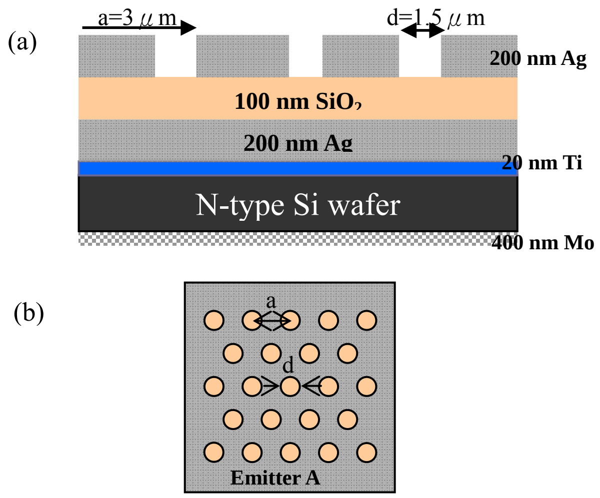


Fig. 1 Schematic diagram of the (a) side and (b) top views of the emitter A , the top metal is perforated with hexagonal array of holes.

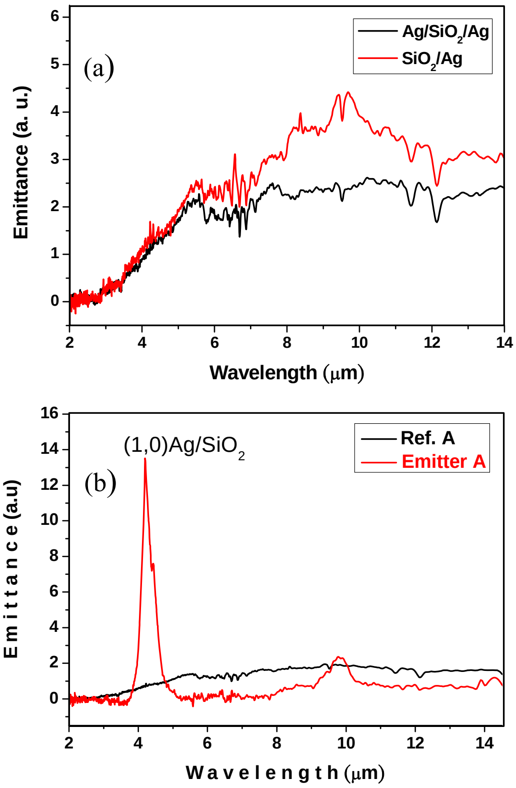


Fig. 2 Measured emission spectra of the (a) 200 nm $Ag/SiO_2/Ag$ (black line) and 100 nm $SiO_2/Ag$ (red line), (b) Emitter A with hexagonal lattice of holes. All the samples were measured at the temperature of 200 $^0$C. Theoretical curves are the weighted sum of Fig. 2(a) according to the exposed area ratio of the silicon dioxide to silver.

The peak wavelength at 4 μm was attributed to Ag/glass mode, the intensity ratio between SP peak and background was not much higher than unity. The background signal arisen from the propagating wave reflected between two metal films and filtered through the periodic holes in the top metal film. The similar result was also observed in Al/Si based thermal emitter [3].

The enhanced behavior can be considered from the spectral density of total energy at near-field and far-field zone, followed as equation (1) [4]:

Where the first and second terms represents the density of energy in far-field and near-field zone of electromagnetic emission, respectively.

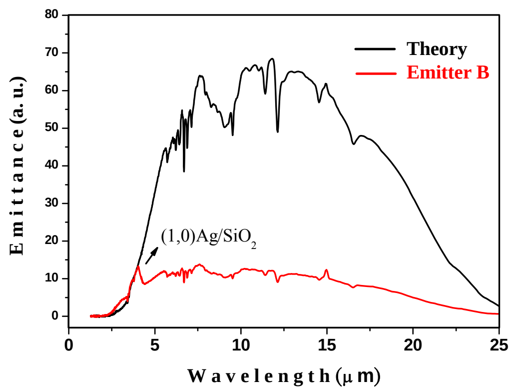


Fig. 3 Measured emission spectra of emitter C with hexagonal lattice of holes, compared with theoretical curves.

$$u_{tot}(z,w)=\frac{\Theta(w,T)w^2}{2\pi^2c^3}\left\{\int_0^{w/c}\frac{KdK}{k_0^3|\gamma_1|}\frac{(1-|r_{12}^s|^2)+(1-|r_{12}^p|^2)}{2}\right. \qquad (1)$$

$$\left.+\int_{w/c}^{\infty}\frac{4K^3dK}{k_0^3|\gamma_1|}\frac{\mathrm{Im}(r_{12}^s)+\mathrm{Im}(r_{12}^p)}{2}e^{-2\mathrm{Im}(\gamma_1)z}\right\}$$

The $\Theta(w,T)=\hbar w/[\exp(\hbar w/k_BT)-1]$ is the thermal energy of the quantum oscillator, and $r_{12}^s$ and $r_{12}^t$ are the coefficient of s- and p-polarized reflection between two mediums, respectively. The far-field zone is dominated by propagating wave, which leaves the surface of the emitter and radiates freely into the space, however, the near-field zone is dominated by evanescent wave, which do not radiate into free space. The weak emittance of theoretical spectra shown in Fig. 2(c) and 2(d) were attributed to the thin $SiO_2$ layer, leading to less propagating emission to evanescent wave intensity ratio. For tri-layer plasmonic thermal emitter, surface plasmon provided a route to convert the evanescent wave to propagating mode, resulting in the enhancement of radiation. For the plasmonic thermal emitter with thick $SiO_2$ layer, the surface to bulk energy ratio substantially decreased, the theoretical spectra shown in Fig. 3 was dominated by propagating modes reflecting between top and bottom metals, the converted emission from evanescent wave at 4 μm becomes small, leading to a low emittance ratio of SP peak to background [3]. In $Ag/SiO_2/Ag$ tri-layer emitter, the thin silicon dioxide (~ 100 nm) sandwiched between two Ag metals, because the penetration depth of (1, 0) $Ag/SiO_2$ SP modes at peak wavelength of 4.2 μm and 4.74 μm are 8.74 and 11.86 μm, respectively, it is larger than the thickness of silicon dioxide film, which cause the coupling of the evanescent waves between top and bottom metal/$SiO_2$ interfaces and stored energy in the $SiO_2$ film.

## 3. Conclusion

In conclusion, it is demonstrated that the top metal film perforated with periodic hole array of the $Ag/SiO_2/Ag$ tri-layer plasmonic thermal emitter acts not only as a filter but also as an optical enhancer due to the surface plasmon resonance. A ten-fold enhancement of radiation at a specific wavelength was observed as compared to the expected weighted sum of measured thermal radiation. The enhanced observation was attributed to the surface plasmon oscillation between two metal films which converted the confined evanescent wave to the propagating mode.

## References


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