Coupling of surface plasmons between two silver films in a plasmonic thermal emitter

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The emission spectra of Ag/SiO₂/Ag trilayer plasmonic thermal emitters with various SiO₂ thicknesses were investigated. By analyzing the relationship between emission peaks and thicknesses of SiO₂, the coupling of surface plasmons between two silver films in a plasmonic thermal emitter is demonstrated and the coupling length is determined as well. Furthermore, the dispersion relation of plasmonic thermal emitter is detected by measuring the reflection spectra with various incident angles. This confirms that the main mechanism involved in the emission of a plasmonic thermal emitter is due to the excitation of surface plasmons. © 2007 American Institute of Physics. [DOI: 10.1063/1.2824389]

Surface plasmons (SPs) have been studied for years because of their potential applications in biosensor, photolithography,^{1,2} and light-emitting device.^{3–6} By using thermal radiation and the coupling of surface plasmons with light in periodic metal structure, midinfrared narrow-bandwidth plasmonic thermal emitter was demonstrated by Tsai *et al.*³ Theoretically, surface plasmons are induced at the interface between the top patterned silver film and neighboring dielectric materials; thus, the emission peak position can be predicted from the momentum conservation equation and the dispersion relation of surface plasmons. The peak position, however, will deviate from the theoretical value when the thickness of SiO₂ is finite. It is because the surface plasmons induced at top and bottom Ag/SiO₂ interfaces are coupled when the SiO₂ layer is not thick enough.⁷

In this work, the thermal radiation spectra and reflection dispersion relation of Ag/SiO₂/Ag trilayer plasmonic thermal emitters with different SiO₂ thicknesses are investigated. By analyzing the shift of peak position, the coupling length of surface plasmons between top and bottom Ag/SiO₂ interfaces is deduced.

The 300 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 films were deposited on the front side of the Si substrate followed by a SiO₂ layer deposited by electron beam evaporation. Then, a negative photoresist was spun on the SiO₂ 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 100-nm-thick silver film was deposited on the photoresist rod array and lifted off to form a silver hexagonal hole array on SiO₂ layer. The side and top views of the device are shown in Figs. 1(a) and 1(b), respectively. The devices were heated by sending electric current through the back Mo metal on Si substrate. A thermal couple is put on the top of the sample to measure the temperature. The thermal radiation generated in the SiO₂ layer resonates between the two metal films and the Ag/SiO₂ and Ag/air surface plasmon polaritons are induced and then converted to light radiation. A

PerkinElmer 2000 Fourier transform infrared spectrometer system was adopted to measure thermal radiation spectra. The wave number resolution of the measurement was 8 cm⁻¹. Furthermore, by measuring the reflection spectra with incident angles of light from 12° to 65°, the dispersion relations of plasmons in this emitter can be measured clearly. The dispersion relations are measured along the ΓK direction, where the position of K in the reciprocal space is shown in Fig. 2.

Figures 3(a)–3(c) show the thermal radiation spectra of emitters at 280 °C with SiO₂ thicknesses of 500, 100, and 60 nm, respectively. In Fig. 3(a), peaks at 3.8 μm are due to the degenerate modes composed of ($\pm 1, 0$) Ag/SiO₂, ($0, \pm 1$) Ag/SiO₂, ($-1, 1$) Ag/SiO₂, and ($1, -1$) Ag/SiO₂ modes,³ designated as (1,0) degenerated Ag/SiO₂ mode. It is almost the same as the theoretical peak position at 3.79 μm . The peak located at 3 μm is due to the cross coupling of the

FIG. 1. (Color online) Plasmonic infrared emitter structure, (a) side and (b) top views.

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FIG. 2. (Color online) The definition of ΓK direction with respect to the surface structure geometry in reciprocal lattice.

Ag/SiO₂ mode and Ag/air mode.³ When the thickness of SiO₂ reduces from 500 to 100 nm, the emission peak shifts from 3.8 to 4.56 μm , as shown in Fig. 3(b). As the thickness of SiO₂ becomes 60 nm, the emission peak shifts further to 5.34 μm , as shown in Fig. 3(c), which is far away from the theoretical value. More light is generated in the thicker SiO₂ layer and the degenerate (1,0) Ag/SiO₂ modes are easier to distinguish. The redshift of emission peaks with the reduction of SiO₂ thickness results from the coupling of surface plasmons between top and bottom metal plates. It is because the surface plasmons are also induced at the interface between the bottom silver film and SiO₂ by the field of surface plasmons in top silver film when the thickness of SiO₂ is not thick enough.

Figures 4(a)–4(d) display the reflection dispersion relations of emitters with SiO₂ thicknesses of 500, 100, 60, and 0 nm, respectively, for light propagating in ΓK direction with different incident angles. Dark lines on dispersion relation represent the dips in reflection spectra. Light which satisfies the momentum conservation and the dispersion relation of surface plasmons can couple with the surface plasmons.

FIG. 3. Measured emission spectra of emitters with $a=3 \mu\text{m}$ and $d=1.5 \mu\text{m}$, and the thicknesses of SiO₂ are (a) 500, (b) 100, and (c) 60 nm.

Therefore, less light is reflected from the emitters when satisfied with the coupling conditions. The six degenerate modes at 3.8 μm (0.326 eV) for normal incidence light split into four dispersion lines, as denoted in Fig. 4(a), when light incident angle increases (vector $\vec{k}_x$ increases). This dispersion relation provides evidence that the main mechanism of the thermal emission peak is due to the coupling of light with surface plasmons. Other dark lines in higher energy region are due to the higher order modes of surface plasmons. When the thickness of SiO₂ is 100 nm, the dispersion relation is still the same but with all bands shift to lower energy slightly. Figure 4(c) shows the dispersion relation of emitter with SiO₂ thickness of 60 nm. Now, the degenerate Ag/SiO₂ modes are at 0.23 eV which is consistent with the radiation emission peak at 5.34 μm (0.23 eV) shown in Fig. 4(c). If

FIG. 4. Energy dispersions of thermal emitters with $a=3 \mu\text{m}$ and $d=1.5 \mu\text{m}$, and the thicknesses of SiO₂ are (a) 500, (b) 100, (c) 60, and (d) 0 nm for light propagating along the ΓK direction.

FIG. 5. (Color online) (a) The relationship between the peak wavelength of (1,0) Ag/SiO₂ mode vs the thickness of SiO₂. Square dots are the experimental results and the red line is the fitting curve. (b) Effective refractive index n_{eff} as a function of normalized SiO₂ thickness w/λ . The blue line is the theoretical curve and red circles are experimental data.

no SiO₂ layer exists in the plasmonic emitter, i.e., thickness of SiO₂ equals to 0 nm, the dispersion curves due to the Ag/SiO₂ surface plasmon modes all disappear except that of the Ag/air mode, as shown in Fig. 4(d). This confirms again that the physical origin involved in the thermal emitter is the excitation of surface plasmons at the Ag/SiO₂ interface. The split behaviors are all the same for emitters with different SiO₂ thicknesses. It means that the coupling of surface plasmons changes the energy of themselves. If the coupling effect is enhanced, surface plasmons can be induced by the light with longer wavelength, even though the periodic structure on top Ag film is the same.

The relation between peak position of degenerate (1,0) Ag/SiO₂ mode and SiO₂ is shown in Fig. 5(a). The peak position can be fitted using an exponential function to determine the coupling length of (1,0) Ag/SiO₂ mode in the Ag/SiO₂/Ag triple layer structure. The fitting curve is $y = 3.6e^{-x/58} + 3.9$, where x is the thickness of SiO₂ in nanometers. As the thickness of SiO₂ x increases to infinity, the peak position y approaches 3.9 μm which is very close to the theoretical value of 3.79 μm . The coupling length in this structure is 58 nm which is much shorter than that of Ag/SiO₂ mode in an Ag/SiO₂/Si triple layer structure.⁸ It is

due to the strong coupling of surface plasmons between the two silver films. It can be seen that when the thickness of SiO₂ is less than 100 nm, the peak position redshifts substantially with the reduction of SiO₂ thickness. The coupling of surface plasmons becomes less apparent when the SiO₂ thickness exceeds 300 nm.

Collin *et al.*⁷ have theoretically calculated the coupling strength of surface plasmons in a metal/dielectric/metal structure. Their conclusion is that the coupling of surface plasmons increases the effective refractive index of the intermediate dielectric medium resulting in the redshift of wavelength. According to their work, the equation of effective refractive index of transverse magnetic mode in a thin dielectric layer sandwiched by two metal layers is given as follows:

$$n_{\text{eff}} = \frac{k_x}{k_0} = \sqrt{\epsilon_d} \left(1 + \frac{\lambda}{\pi w \sqrt{-\epsilon_m}} \sqrt{1 + \frac{\epsilon_d}{-\epsilon_m}} \right)^{1/2}, \quad (1)$$

where w is the thickness of intermediate dielectric layer, λ is the wavelength in free space, and ϵ_d and ϵ_m are the permittivities of dielectric and metal mediums, respectively. By comparing our result to the Eq. (1), the effective refractive index n_{eff} as a function of normalized width w/λ is shown in Fig. 5(b). The blue line is the theoretical curve drawn by Eq. (1) and the red circles are experimental data. With increasing w/λ , the effective refractive index becomes smaller, finally approach the $\sqrt{\epsilon_d}$ value.

In conclusion, the emission spectra and reflection dispersion relations of Ag/SiO₂/Ag thermal plasmonic emitters with different SiO₂ thicknesses were investigated experimentally. The position of thermal emission peak of a plasmonic emitter is not only determined by the periodic structure on top Ag film but is also affected by the thickness of intermediate SiO₂. Surface plasmons at the top and bottom Ag/SiO₂ interfaces couple together if the thickness of SiO₂ is not thick enough. This coupling effect makes the effective refractive index of SiO₂ increase and, therefore, results in the redshift of the Ag/SiO₂ SP modes. The coupling length turns out to be 58 nm.

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