Coupling of surface plasmons between two silver films in a Ag/SiO₂/Ag plasmonic thermal emitter with grating structure

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The reflection and emission spectra of Ag/SiO₂/Ag trilayer plasmonic thermal emitters with different SiO₂ thicknesses are investigated. The top Ag film is perforated with periodic slits. It is found that the coupling of surface plasmons at the top and bottom Ag/SiO₂ interface results in the redshift in thermal emission peaks. In this Ag/SiO₂/Ag plasmonic thermal emitter, the electromagnetic field exhibits either Fabry-Pérot resonance or propagating surface plasmons depending on the thickness of SiO₂ layer. By varying the thickness of SiO₂ layer, transition from localized to grating-coupled propagating surface plasmon modes is observed. © 2008 American Institute of Physics. [DOI: 10.1063/1.3058767]

Surface plasmons (SPs) are electromagnetic excitations that occur at the metal/dielectric interface and result from the interaction between light and free electrons of metal.¹ One of the applications of SPs is in light emitting device, which has been demonstrated by using one-dimensional gratings²⁻⁵ and two-dimensional periodic metal hole array.⁶⁻⁹ Theoretical studies based on plasmonic thermal emitter have also been reported.^{10,11} For plasmonic thermal emitter with one-dimensional metallic grating, nonpropagating localized surface plasmon polariton (LSPP) mode, which resulted from the coupling of SPs at the top and bottom metal/dielectric interface are observed.^{3,12} In this letter, the reflection and thermal radiation spectra of the narrow-bandwidth Ag/SiO₂/Ag trilayer plasmonic thermal emitters with top metallic grating structure are studied. A transition between LSPP and propagating SP modes is experimentally shown by varying the thickness of SiO₂ layer. Moreover, the coupling effect of top and bottom SPs at the Ag/SiO₂ interface is revealed.

The fabrication processes of the Ag/SiO₂/Ag trilayer plasmonic thermal emitter are described as follows: a 300 nm Mo layer was deposited by sputtering on the back of the double-polished *n*-type Si substrate as a heating source. 20 nm Ti used as an adhesive layer followed by 200 nm Ag film were deposited on the front side of the Si substrate by electron beam evaporation. Then SiO₂ layers with different thicknesses were deposited on top of Ag layer by plasma enhanced chemical vapor deposition. After photolithography, a negative photoresist layer was patterned with a grating-shape array. Then a 100 nm Ag film was deposited onto the patterned photoresist layer and lifted off to complete the processes. The lattice constant *a* of the grating is 3 μm and the metal line width *d* is 1.6 μm. Figures 1(a) and 1(b) show the side and top views of device structure, respectively. The radiation area of the device is 1 cm². By sending adequate dc current through the back Mo metal contact, the plasmonic thermal emitter was heated up and radiated infrared in vacuum chamber. A PerkinElmer 2000 Fourier transform in-

frared spectrometer was adopted to measure the radiation spectra of thermal emitters at 260 °C. The reflection spectra were measured by a Bruker IFS 66 *v/s* with a spectral resolution of 8 cm⁻¹. The incident angles *θ* of light to the normal of the metal surface were scanned from 12° to 65° in 1° step in the *xz*-plane as shown in Fig. 1(a).

Figures 2(a)–2(d) show the dispersion relations of SPs in plasmonic thermal emitters with different SiO₂ layer thicknesses *t* (*t*=0, 20, 60, and 170 nm). The dispersion relations of SPs along the *x* axis (dark lines) are extracted from the minima of the reflection spectra at various incident angles (from 12° to 65°). The grayscale from dark to bright represents the reflectivity from low to high. For an ideal planar silver layer, the reflectivity should be near unity in the mid-infrared spectral range, therefore no reflection dips exist. When silver film is perforated with periodic slits, incident light, which satisfies that the momentum conservation law for SPs can couple with SPs at the metal/dielectric interface. Therefore less light is reflected, which causes the reflection dips in measurement. The momentum conservation law for SPs in grating structure is given by $k_{sp} = k_x + iG$, where k_{sp} is the SP wave vector, $k_x = (2\pi/\lambda)\sin\theta$ is the in-plane wave vector, $G = 2\pi/a$ denotes the reciprocal lattice vector, and *i* is an integer. In Fig. 2(a), two grating-coupled SP modes, Ag/air [+1] and Ag/air [−1], intersect with the *y* axis at about

FIG. 1. (Color online) The schematic diagrams showing the (a) side and (b) top views of plasmonic thermal emitter. The top Ag metal is perforated with grating array with a lattice constant *a* of 3 μm and Ag line width *d* of 1.6 μm.

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FIG. 2. The dispersion relations of SPs in plasmonic thermal emitters with SiO₂ thicknesses of (a) 0 nm, (b) 20 nm, (c) 60 nm, and (c) 170 nm.

0.42 eV ($\sim 3 \mu\text{m}$), i.e., there exists a reflection dip at 0.42 eV for normal incidence. These two SP modes result from the interaction between incident light and reciprocal lattice vectors, $+G$ and $-G$, at the Ag/air interface. When $t=20$ nm, the Ag/air grating-coupled SP modes are still observable, as shown in Fig. 2(b). Furthermore, the dark line around 0.15 eV is attributed to the asymmetric longitudinal optical (AS₁ LO) phonon vibration mode of the SiO₂ layer.¹³ No Ag/SiO₂ grating-coupled SP mode is observed. However, there exist five additional dark lines at about 0.12, 0.19, 0.31, 0.47, and 0.6 eV. These five dark lines are $m=1$, $m=1$, $m=2$, $m=3$, and $m=4$ Ag/SiO₂/Ag LSPP modes, which exhibit the Fabry-Pérot resonance;^{3,12} i.e., the wavelength of incident light λ and the Ag grating line width d satisfy $2d \approx m\lambda/n_{\text{eff}}$, where m is integer and n_{eff} is the effective refractive index of Ag/SiO₂/Ag LSPP mode. Two $m=1$ LSPP modes (could be denoted as $m=1_a$ and $m=1_b$) exist at 0.12 and 0.19 eV, which is due to the obvious difference in the refraction index n of SiO₂ at wavelength of incident light $\lambda=10.65 \mu\text{m}$ (0.12 eV, $n=2.14$) and $\lambda=6.5 \mu\text{m}$ (0.19 eV, $n=1.20$).¹⁴ From Fig. 2(c), as t increases to 60 nm, the dispersion relation of Ag/air grating-coupled SP modes is the same as that in Fig. 2(b) since the Ag/air grating-coupled SP modes are determined by the lattice constant of periodic metallic film. Besides Ag/air $[\pm 1]$ SP modes, there also exists Ag/air $[-2]$ SP mode. However, the dispersion relations of the LSPP modes all shift to higher energies. When t increases to 170 nm, $m=1_a$ and $m=1_b$ LSPP modes shift further to 0.13 and 0.25 eV and other high order LSPP modes shift to higher energies as shown in Fig. 2(d). The shift in the dispersion lines of Ag/SiO₂ LSPP modes is due to the coupling effect of SPs, which will be discussed later.

Figures 3(a)–3(c) show the thermal radiation spectra of the plasmonic thermal emitters at 260 °C with $t=20$, 60, and 170 nm, respectively. In Fig. 3(c), the emission peaks at 10 and 4.93 μm correspond to the $m=1_a$ and $m=1_b$ Ag/SiO₂/Ag LSPP modes shown in Fig. 2(d). When the emitter is heated, the thermal radiation generated in the SiO₂ layer resonates between top and bottom Ag films. Then Ag/SiO₂/Ag LSPPs are induced and converted to light radiation. As t decreases to 20 nm, the emission peaks shift to

FIG. 3. Measured emission spectra of plasmonic thermal emitters at 260 °C and the thicknesses of SiO₂ are (a) 20 nm, (b) 60 nm, and (c) 170 nm.

FIG. 4. The dispersion relations of SPs in plasmonic thermal emitters with SiO₂ thicknesses of (a) 500 nm and (b) 1.4 μm .

10.65 and 6.5 μm . In our Ag/SiO₂/Ag plasmonic thermal emitter, the induced SPs at the top Ag/SiO₂ interface will couple with the SPs at the bottom Ag/SiO₂ interface,¹⁵ which will increase the effective refractive index.^{12,16,17} The wavelength λ_p of emission peak resulting from the resonance of LSPPs is expressed as $\lambda_p \approx 2n_{\text{eff}}d$, therefore the redshift in emission peaks represents the increase in n_{eff} , which is consistent with the work demonstrated by Miyazaki *et al.*¹² According to the above result, the position of thermal emission peak is not only determined by the Ag grating line width d but also influenced by the thickness of intermediate SiO₂ layer.

Figures 4(a) and 4(b) show the dispersion relations of SPs in plasmonic thermal emitters with $t=500$ nm and 1.4 μm , respectively. The dark lines at about 0.15, 0.13, and 0.10 eV are attributed to the AS₁ LO, asymmetric transverse optical, and symmetric stretching phonon vibration modes of the SiO₂ layer, respectively.¹³ In Fig. 4(a), $m=1_a$ and $m=1_b$ Ag/SiO₂/Ag LSPP modes become indistinct and Ag/SiO₂ grating-coupled SP modes (Ag/SiO₂ [± 1] and Ag/SiO₂ [-2]) appear. The Ag/SiO₂ [± 1] modes intersect with the y axis at about 0.34 eV, which is higher than the theoretical value (0.3 eV). In Fig. 4(b), as the thickness of SiO₂ in-

creased to 1.4 μm , the Ag/SiO₂ LSPP modes totally disappear. Moreover, the dispersion relation of Ag/SiO₂ [± 1] modes is almost the same as the theory. When the SiO₂ layer is thin, the electromagnetic field exhibits the Fabry-Pérot resonance underneath the Ag lines due to strong coupling of top and bottom SPs. Therefore Ag/SiO₂ LSPP modes, instead of Ag/SiO₂ grating-coupled SP modes, dominate at this stage. As the thickness of SiO₂ increases, it is found that Ag/SiO₂ LSPP modes and grating-coupled SP modes exist simultaneously. Furthermore, the interaction between LSPPs and SPs results in the blueshift in Ag/SiO₂ grating-coupled SP modes. When the thickness of SiO₂ is thick enough, coupling of top and bottom SPs can be neglected and Ag/SiO₂ LSPP modes totally disappear, whereas Ag/SiO₂ grating-coupled SP modes become dominant.

In summary, the dispersion relations and emission spectra of Ag/SiO₂/Ag trilayer plasmonic thermal emitters with various SiO₂ thicknesses are investigated experimentally. The top and bottom SPs will couple together when SiO₂ layer is thin, which increases n_{eff} and results in the redshift in the thermal emission peak. As the thickness of SiO₂ continues to increase, the Ag/SiO₂ LSPP modes become weaker and finally disappear. When the SiO₂ layer is thick enough, the Ag/SiO₂ grating-coupled SP modes become dominant and the dispersion relation of Ag/SiO₂ [± 1] modes almost coincides with the theory.

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¹H. Raether, *Surface Plasmons* (Springer, Berlin, 1988).

²M. Laroche, C. Arnold, F. Marquier, R. Carminati, J.-J. Greffet, S. Collin, N. Bardou, and J.-L. Pelouard, *Opt. Lett.* **30**, 2623 (2005).

³C.-M. Wang, Y.-C. Chang, M.-W. Tsai, Y.-H. Ye, C.-Y. Chen, Y.-W. Jiang, Y.-T. Chang, S.-C. Lee, and D. P. Tsai, *Opt. Express* **15**, 14673 (2007).

⁴K. Ikeda, H. T. Miyazaki, T. Kasaya, K. Yamamoto, Y. Inoue, K. Fujimura, T. Kanakugi, M. Okada, K. Hatade, and S. Kitagawa, *Appl. Phys. Lett.* **92**, 021117 (2008).

⁵M. Kreiter, J. Oster, R. Sambles, S. Herminghaus, S. Mittler-Neher, and W. Knoll, *Opt. Commun.* **168**, 117 (1999).

⁶M.-W. Tsai, T.-H. Chuang, C.-Y. Meng, Y.-T. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **89**, 173116 (2006).

⁷M.-W. Tsai, C.-Y. Chen, Y.-W. Jiang, Y.-H. Ye, H.-Y. Chang, T.-H. Chuang, and S.-C. Lee, *Appl. Phys. Lett.* **91**, 213104 (2007).

⁸H. L. Tam, K. F. Li, K. W. Cheah, J. B. Xia, R. Huber, W. H. Wong, and Y. B. Pun, *Appl. Phys. Lett.* **89**, 131123 (2006).

⁹S. A. Kalele, N. R. Tiwari, S. W. Gosavi, and S. K. Kulkarni, *J. Nanophotonics* **1**, 012501 (2007).

¹⁰R. Biswas, C. G. Ding, I. Puscasu, M. Pralle, M. McNeal, J. Daly, A. Greenwald, and E. Johnson, *Phys. Rev. B* **74**, 045107 (2006).

¹¹D. L. C. Chan, M. Soljacic, and J. D. Joannopoulos, *Opt. Express* **14**, 8785 (2006).

¹²H. T. Miyazaki and Y. Kurokawa, *Phys. Rev. Lett.* **96**, 097401 (2006).

¹³C. T. Kirk, *Phys. Rev. B* **38**, 1255 (1988).

¹⁴D. E. Palik, *Handbook of Optical Constants of Solids* (Academic, Boston, 1985), pp. 749–763 and 1067.

¹⁵S. A. Darmanyan and A. V. Zayats, *Phys. Rev. B* **67**, 035424 (2003).

¹⁶S. Collin, F. Pardo, and J.-L. Pelouard, *Opt. Express* **15**, 4310 (2007).

¹⁷C.-Y. Chen, M.-W. Tsai, Y.-W. Jiang, Y.-H. Ye, Y.-T. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **91**, 243111 (2007).