Localized surface plasmons in Al/Si structure and Ag/SiO₂/Ag emitter with different concentric metal rings

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This paper reports the optical properties of Al/Si structure and trilayer Ag/SiO₂/Ag plasmonic thermal emitter with different concentric metal rings on top metal film. It is found that when the metal width is smaller than 40% of the period (=gap+metal width), the (1,0) Al/Si surface plasmon leads to a maximum in the transmission spectra; otherwise, the opposite is observed. The dispersion relations and emission spectra of the plasmonic thermal emitters were investigated. The emission peaks are independent of the gap width and redshift as annular metal width increases. This phenomenon suggests the excitation of Fabry-Pérot type resonance within cavity of Ag/SiO₂/Ag structure. No (1,0) Ag/SiO₂ surface plasmon was observed. © 2008 American Institute of Physics. [DOI: 10.1063/1.2938879]

The excitation of surface plasmons (SPs) in the extraordinary transmission of periodic metal hole array is well accepted,^{1–6} and it has been comprehensively applied to biosensor,⁷ quantum dot infrared photodetector,² etc. For the plasmonic thermal emitter,^{3,4} the emission peak can be theoretically identified from the momentum conservation law and dispersion relation of SPs in periodic hole array. It is interesting to know the hole shape effect on the extraordinary transmission phenomena. In this paper, the transmission spectra of the Al/Si structure and the dispersion relations of SPs and emission spectra of the Ag/SiO₂/Ag plasmonic thermal emitter (ASA-PTE) with various concentric metal rings on top metal film are investigated. It is found that in contrast to propagating surface plasmon polaritons (SPPs), the nonpropagating localized SPPs were observed.

The top view of concentric metal-ring structure is displayed in Fig. 1(a). The side views of Al/Si and ASA-PTE structures are shown in Figs. 1(b) and 1(c), respectively. Two sets of samples are prepared for this study. In the first set of samples, the diameter of central metal disk is 2 μm , the gap between concentric metal rings g is fixed at 2 μm , and the width of annular metals w is changed from 2, 3, 4 to 5 μm . In the other set of samples, the diameter of central metal disk is also 2 μm , the w is fixed at 2 μm , and g is changed from 3, 4, 5 to 6 μm . A 200-nm-thick Al film was prepared by thermal evaporation on a doubly polished n -type silicon wafer, and then the photoresist was spun onto Al films for lithography. Following pattern transfer, annular metal gratings were formed in a size of 1 $\times$ 1 cm.² The sample is defined to lie in the (x , y) plane as displayed in the inset of Fig. 2(a), and the zero-order transmission spectra of the Al/Si structure under unpolarized incident light in the z direction are measured and analyzed; the samples are rotated around the y axis in 1° step allowing the dispersion relation of SPs in the x direction to be determined. The transmission spectra were measured by a Bruker IFS 66 v/s Fourier transform infrared (FTIR) spectrometer. The fabrication processes of the ASA-PTE are described as follows: A 400-nm-thick molybdenum (Mo) film was deposited by sputtering on the top of the Si

wafer; a 200-nm-thick Ag film was deposited on Mo followed by an e-beam evaporation of 100-nm-thick SiO₂ film. After a negative photoresist film was spun onto SiO₂ film for lithography, another 100-nm-thick Ag film was deposited onto the patterned photoresist layer and lifted off. The ASA-PTEs with annular Ag grating were completed as displayed in Fig. 1(c), and the reflection spectra of ASA-PTEs which represent the dispersion relation of SPs were examined as well. A dc is sent into the Mo metal through contact pads on two sides of the sample, the emitter was heated up and emitted infrared light. A Perkin-Elmer 2000 FTIR system was used to measure the thermal emission spectra. The widths of the annular metals w and gaps g between concentric metal

FIG. 1. (Color online) (a) Top view of Al/Si structure and ASA-PTE. The diameter of the central metal disk is 2 μm in concentric metal rings; the gap g between concentric metal rings and the width w of concentric metal rings are independent parameters; side view of (b) Al/Si structure and (c) ASA-PTE.

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FIG. 2. (Color online) The transmission spectra of Al/Si structure perforated with different concentric metal rings. (a) The gap g between metal rings is fixed at $2 \mu\text{m}$, whereas the metal ring width w is an independent variable from 2, 3, 4 to $5 \mu\text{m}$. (b) The widths of annular metals w are fixed at $2 \mu\text{m}$, whereas the gap g is an independent variable from 3, 4, 5 to $6 \mu\text{m}$.

rings are varied to examine their effect on the emission spectra of ASA-PTEs.

Figures 2(a) and 2(b) show the transmission spectra of Al/Si structure with various parameters of concentric metal rings, i.e., gap $g=2 \mu\text{m}$, metal width $w=2-5 \mu\text{m}$, metal width $w=2 \mu\text{m}$, and gap $g=3-6 \mu\text{m}$, respectively. The left figure displays the transmission spectra from 2.5 to $25 \mu\text{m}$, whereas the right figure extends the wavelength range from 15 to $200 \mu\text{m}$. At normal incidence, the wavevector at the x -direction k_x is zero, for a square periodic hole array, and the (1,0) metal/dielectric SP mode appeared at wavelength $\lambda_{\text{SP}} \approx a \times \sqrt{\epsilon_d}$, where a is the period of hole array and ϵ_d is the real part of dielectric constant of the material ($\epsilon_d=11.9$ for Si and 1 for air). When gaps g are fixed at $2 \mu\text{m}$ as shown in Fig. 2(a), the theoretical values of the (1,0) Al/Si SP mode with period $a=g+w=4, 5, 6$, and $7 \mu\text{m}$ are 13.8, 17.3, 20.7, and $24.2 \mu\text{m}$ and those of the (1,0) Al/air SP modes are 4, 5, 6, and $7 \mu\text{m}$, respectively. It is interesting to note that these theoretical values are located at the dips instead of peaks of the transmission spectra, as indicated by short arrows in Fig. 2(a). This is opposite to what is observed in the traditional periodic hole array.¹⁵ When the metallic widths w are fixed at $2 \mu\text{m}$ as shown in Fig. 2(b), the theoretical values of the (1,0) Al/Si SP mode with periods $a=g+w=5, 6, 7$, and $8 \mu\text{m}$ are 17.3, 20.7, 24.2, and $27.6 \mu\text{m}$ and those of the (1,0) Al/air SP modes are 5, 6, 7, and $8 \mu\text{m}$, respectively. The theoretical value of $17.3 \mu\text{m}$ is also located at the minimum of the transmission spectra.

FIG. 3. (Color online) Emission spectra of ASA-PTE with different gaps and annular metal widths at various temperatures. The widths of annular metal widths are fixed at $2 \mu\text{m}$; the gaps between metallic rings are (a) 3, (b) 4, and (c) $5 \mu\text{m}$. The gaps between metallic rings are fixed at $2 \mu\text{m}$, and the widths of annular metals are (d) 2, (e) 4, and (f) $5 \mu\text{m}$. The dip at $5.8 \mu\text{m}$ indicated by short dashed line is due to the absorption of H_2O in the ambient (Ref. 8). The numbers n indicate the position of FP modes of order n .

However, the next higher values of (1,0) Al/Si SP modes with $a=g+w=6, 7$, and $8 \mu\text{m}$ locate at the maximum of the transmission spectra, as shown in Fig. 2(b). Figures 2(c) and 2(d) display the transmission spectra of $g=2 \mu\text{m}$, $w=3 \mu\text{m}$ and $g=5 \mu\text{m}$, $w=2 \mu\text{m}$ samples, respectively. The angles of rotation Ω around the y axis are the independent variable, as displayed in the inset of Fig. 2(c). It is clear that the peak (dip) positions do not move as Ω increases, and the group velocity in the x -direction is zero ($\partial\omega/\partial k_x=0$), which implies that these induced SPPs are localized modes. It is concluded that when the metal width is smaller than 40% of the period $a=g+w$, the (1,0) Al/Si localized SP mode leads to a maximum of the transmission spectra; otherwise, the opposite transmission minimum is observed. This result suggests that as the gap g increases to more than 60% of the period, the localized modes excited by the surface charges underneath neighboring Ag rings can be easily scattered out through annular apertures which leads to transmission maximum.

Figures 3(a)–3(c) display the emission spectra of ASA-PTEs with fixed $w=2 \mu\text{m}$, and the gap g is changed from 3, 4 to $5 \mu\text{m}$, respectively. For a typically Fabry-Pérot (FP) type resonance, the wavelength of the radiation in the cavity is expressed by λ_{FP} ,

$$\lambda_{\text{FP}} = \frac{2n_{\text{eff}}w}{m}, \quad (1)$$

in which w is the annular metal width on the top Ag film of ASA-PTE, the integer m is the order of the FP resonance, and n_{eff} is the effective refraction index of thin SiO_2 by taking into account the coupling of SPs between top and bottom metal/dielectric interfaces. The refractive indices n of thick SiO_2 at 6.3 and $10.6 \mu\text{m}$ are 1.279 and 2.184,⁸ respectively. It varies a lot in these wavelength ranges, i.e., $5-20 \mu\text{m}$. When $m=1$ and $w=2 \mu\text{m}$, the calculated results using Eq. (1) and the above refraction index n indicate that the localized SP modes should locate at 5.12 and $8.74 \mu\text{m}$, whereas the measurement peaks are redshifted 1.22 times and located at 6.3 and $10.6 \mu\text{m}$. The shift in wavelengths is the result of an effective shift in refractive index n_{eff}

TABLE I. The lattice parameters on top silver layer and experimental emission peak wavelengths of the ASA-PTE due to FP type resonance (unit: μm).

Samples		Experimental emission peaks First order FP mode (μm)
g (μm)	W (μm)	
3	2	6.5, 10.6
4	2	6.1, 10.4
5	2	6.3, 10.6
2	2	6.3, 10.5
2	4	7.8, 14.8
2	5	8, 16.3

$=1.22n$, similar to what Chen *et al.* found.⁹ These modes are defined as FP first order mode, as displayed in Figs. 3(a)–3(d). Two FP first order modes are redshifted owing to coupling of SP modes between top and bottom Ag films when the thickness of SiO_2 layer is thin.^{9,10}

Figures 3(d)–3(f) display the emission spectra of ASA-PTE with fixed gap $g=2\ \mu\text{m}$, the metal widths w are 2, 4, and $5\ \mu\text{m}$, and the emission spectra display two or three emission peaks. Similarly, the FP first order mode for these three samples are located at (6.3, 10.5), (7.8, 14.8), and (8, 16.3) μm , respectively. They redshift with the increasing Ag metal-ring width w , as listed in Table I. The FP order two modes can be seen and located at 3.7 and 6.3 μm , as shown in Figs. 3(d) and 3(e), respectively. When the metal width w reaches $5\ \mu\text{m}$, the FP order three, four, and five modes can be clearly seen in Fig. 3(f). The FP order two mode cannot be observed owing to absorption of H_2O in the ambient. The (1,0) Ag/ SiO_2 SP modes cannot be observed in Figs. 3(a)–3(f), indicating that they are suppressed by the FP modes. Figures 4(a) and 4(b) show the dispersion relations of the ASA-PTEs along the x axis with $g=2\ \mu\text{m}$, $w=2\ \mu\text{m}$, and $g=2\ \mu\text{m}$, $w=4\ \mu\text{m}$, respectively. They are measured with incident angles of light from 12° to 65° due to the measurement limit. The dark line at 0.15 eV owes to Si–O–Si bond and asymmetric stretching longitudinal optical phonon modes of the SiO_2 layer.¹¹ In Fig. 4(a), the dark lines for Ag/ SiO_2 FP modes with $w=2\ \mu\text{m}$ are located at 0.193, 0.12, and 0.33 eV which correspond to the two FP first and second order modes, respectively. For the same reasons, the dark lines shown in Fig. 4(b) for sample $w=4\ \mu\text{m}$ at 0.083, 0.16, 0.21, 0.3, 0.38, and 0.48 eV are localized FP order one, one, two, three, four and five modes, respectively. In addition, no traditional (1,0) Ag/ SiO_2 SP mode is observed in Figs. 4(a) and 4(b). The energies of the dark line in Fig. 4(a) match to those of the emission peaks of Fig. 3(d). Similarly, Figs. 4(b) and 3(e) are matched as well.

In conclusion, the transmittance of Al/Si structure and emission spectra of the ASA-PTE with concentric metal rings on the top Ag film exhibited quite different characteristics. In the Al/Si structure, (1,0) Al/Si and Al/air localized SP modes were excited which leads to transmission maximum when the metal width w is smaller than 40% of the period ($=\text{gap}+\text{metal width}$); otherwise, the transmission minimum was observed. In the ASA structure, no (1,0) Ag/ SiO_2 SP modes were observed. FP modes determined by metal width were excited. The localized FP type cavity resonance SP modes can be shifted to lower energies with the increasing concentric metal-ring width.

FIG. 4. The dispersion relations of ASA-PTE with various parameters of annular metals: (a) $g=2\ \mu\text{m}$, $w=2\ \mu\text{m}$ and (b) $g=2\ \mu\text{m}$, $w=4\ \mu\text{m}$. The arrows indicate the position of the FP modes of different orders.

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