Localized surface plasmon polaritons in Ag/SiO₂/Ag plasmonic thermal emitter

Yi-Han Ye, Yu-Wei Jiang, Ming-Wei Tsai, Yi-Tsung Chang, Chia-Yi Chen, Dah-Ching Tzuang, Yi-Ting Wu, and Si-Chen Lee^{a)}
 Department of Electrical Engineering, Graduate Institute of Electronics Engineering, National Taiwan University, Taipei, Taiwan 10617, Republic of China

(Received 2 April 2008; accepted 9 June 2008; published online 25 July 2008)

The reflection dispersion relation and emission spectra of Ag/SiO₂/Ag trilayer plasmonic thermal emitters with different lattice constant and Ag line width were investigated. The top Ag film is perforated with parallel line-shape hole array. The induced Ag/SiO₂ surface plasmons at both top and bottom Ag/SiO₂ interface are found coupled together. The coupling effect results in the localized surface plasmon polaritons confined at the top Ag/SiO₂ interface which exhibit the Fabry-Pérot resonance. The thermal emission peak position coincides with the reflection minimum in the dispersion relation and shifts to long wavelength as the Ag line width increases, which proves that the emission is due to the excitation of localized surface plasmon polaritons. Moreover, the emitted light is polarized perpendicular to the parallel metal lines. © 2008 American Institute of Physics. [DOI: 10.1063/1.2958215]

It has been well known that the metallic film perforated with subwavelength periodic hole array exhibits extraordinary optical transmission, which results from the interaction between light and surface plasmon (SP).¹ Because of the unique properties, SPs have been studied extensively in numerous fields such as solar cell,² quantum dot infrared photodetector,³ and light emitting device.^{4–6} For one-dimensional (1D) metallic grating structure, grating-coupled SP modes and Fabry-Pérot resonance have been reported theoretically and experimentally.^{1,7–10} In this letter, the reflection and thermal radiation spectra of the narrow-bandwidth trilayer Ag/SiO₂/Ag plasmonic thermal emitters with top metallic grating structure were studied. It was found that the localized SP polaritons (LSPs) were excited due to the coupling of SPs between top Ag grating and bottom metal.

The fabrication processes of the trilayer Ag/SiO₂/Ag plasmonic thermal emitter are described as follows. A 300 nm Mo layer was deposited by sputtering on the back of the *n*-type Si substrate as a heating source. 20 nm Ti used as an adhesive layer and 200 nm Ag film were deposited on the front side of the Si substrate followed by a 100 nm SiO₂ layer deposited by electron beam evaporation. After photolithography a negative photoresist layer were patterned with a grating-shape hole array with the lattice constant *a* and the line width *d*. Then a 100 nm Ag film was deposited onto the patterned photoresist layer and lifted off to complete the processes. The side and top view of the Ag/SiO₂/Ag trilayer plasmonic thermal emitters are shown in Figs. 1(a) and 1(b). The structural parameters and emission peaks of Ag/SiO₂/Ag trilayer plasmonic thermal emitters (samples A–E) are listed in Table I. By sending an adequate dc current on the back Mo contact, the plasmonic thermal emitter was heated up in vacuum chamber. A Perkin Elmer 2000 Fourier transform infrared spectrometer was adopted to measure the radiation spectra of emitters at 260 °C. The reflection spectra are measured by a Bruker IFS 66 *v/s*

with incident angles of light to the normal of the metal surface (*z* axis) from 12° to 65° in 1° step in *xz* plane as defined in Fig. 1(a). The dispersion relations of SPs along *x* axis are extracted from the minima of the reflection spectra at various incident angles.

Figure 2(a) shows the dispersion relation of SPs in sample A with lattice constant *a*=4 μm and Ag line width *d*=2 μm. The grayscale from dark to bright represents the reflectivity from low to high. The grating coupled SP modes (Ag/air [±1], Ag/air [−2], and Ag/air [−3]) were observed. The momentum conservation law of SPs in 1D grating structure is given by $\mathbf{k}_{\text{SP}} = \mathbf{k}_x + i\mathbf{G}$, where $\mathbf{k}_{\text{SP}}$ is the surface plasmon wavevector. Here, $\mathbf{k}_x = \mathbf{k}_0 \sin \theta$, $|\mathbf{k}_0| = 2\pi/\lambda$ is the wavevector of the incident light, λ is the wavelength in vacuum, and θ is the incident angle as shown in Fig. 1(a). $\mathbf{G}$ is the reciprocal lattice vector of Ag grating with $|\mathbf{G}| = 2\pi/a$, where *a* is the lattice constant and *i* is integer. The darker line around 0.15 eV representing the reflection dip is attributed to the asymmetric longitudinal optical (AS₁ LO) phonon vibration mode of the SiO₂ layer.¹¹ However, no Ag/SiO₂ grating-coupled SP mode was observed. Moreover, there exists four additional darker lines at about 0.12, 0.19, 0.33, and 0.49 eV instead. Different from the splitting characteristic of Ag/air grating-coupled SP modes, these four lines are almost independent of the incident angles. The

FIG. 1. (Color online) The schematic structure of plasmonic thermal emitter, (a) side and (b) top views.

^{a)}Electronic mail: sclee@cc.ee.ntu.edu.tw.

TABLE I. The structural parameters and emission peaks of samples A–E, the lattice constant of the top metallic grating and Ag line width are a and d , respectively. (unit: μm).

Sample	a	d	Peak 1	Peak 2
A	4	2	6.3	10.5
B	5	2	6.3	10.5
C	6	2	6.3	10.5
D	5	1.4	5	10.1
E	5	2.5	7	11

group velocity of these four modes, $\partial\omega/\partial k_x$, at the x direction is zero, which implies that these induced SPPs are localized. It is because when the thickness of SiO_2 layer is thin enough, the propagating SPs in x direction induced by TM polarized light (electric field perpendicular to metallic lines)^{7,8} at the top Ag/ SiO_2 interface will couple with the SPs at the bottom Ag/ SiO_2 interface.^{12–14} This coupling effect results in the confinement of SPs at the top Ag/ SiO_2 interface and forms LSPPs underneath the metal lines. The LSPPs exhibit the Fabry–Pérot type resonance in x direction, 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 dielectric medium at λ which will be influenced by the coupling effect of SPs.^{12,13} In our plasmonic thermal emitter, the thickness of top Ag grating film is only 100 nm while the measurable spectral range is in MIR range (2–25 μm). Therefore, no Fabry–Pérot resonance in z direction determined by the depth of slit^{9,10} was observed. The darker lines at 0.12, 0.19, 0.33, and 0.49 eV are $m=1$, $m=1$, $m=2$, and $m=3$ LSPP modes, respectively. Two $m=1$

FIG. 2. (a) The dispersion relation of SPPs in sample A. (b) The emission spectrum of sample A.

FIG. 3. The emission spectra of samples (a) A, (b) B, and (c) C. The lattice constants of these samples are 4, 5, 6 μm , respectively, with the same Ag line width $d=2$ μm .

LSPP modes exist at 0.12 and 0.19 eV, which is due to the obvious difference of refractive index of SiO_2 at wavelength of incident light λ of 6.3 μm (0.19 eV) and 10.5 μm (0.12 eV). The refractive index of thick SiO_2 at 6.3 and 10.5 μm are $n=1.23$ and 2.20, respectively.¹⁵ These free space wavelengths in the SiO_2 shrink to 5.12 and 4.7 μm , respectively. In our Ag/ SiO_2 /Ag plasmonic thermal emitter, the SiO_2 is thin, the coupling of Ag/ SiO_2 SPs at both top and bottom metal/dielectric interface will effectively increase the refractive index¹³ 1.23 to 1.17 times, i.e., $n_{\text{eff}} \approx 1.54$ at 6.3 μm , $n_{\text{eff}} \approx 2.63$ at 10.5 μm . Figure 2(b) is the thermal radiation spectrum of sample A at 260 $^\circ\text{C}$. The emission peaks at 6.3 and 10.5 μm are consistent with the two $m=1$ LSPP modes, as shown in Fig. 2(a), which confirms that the mechanism involved in the emission of plasmonic thermal emitter is due to the excitation of LSPPs. When the emitter is heated, the thermal radiation generated in the SiO_2 layer resonates between two silver films. Then Ag/ SiO_2 LSPPs are induced and converted to light radiation.

Figures 3(a)–3(c) show the thermal radiation spectra of samples A–C, respectively. These emitters have the same Ag grating line width d but different lattice constant a . Different from the plasmonic thermal emitters whose emission peaks are determined by lattice constant a demonstrated by Tsai *et al.*,⁴ these emitters have the same emission peaks at about 6.3 and 10.5 μm which correspond to the two $m=1$ LSPP modes. Figures 4(a)–4(c) show the thermal radiation spectra of emitters E, B, and D, respectively. These emitters have the same lattice constant a but different Ag grating line width d . The emission peaks shift from 5 and 10.1 μm , 6.3

FIG. 4. The emission spectra of samples (a) E, (b) B, and (c) D. The lattice constants of these samples are all $5\ \mu\text{m}$ and the Ag line widths are 2.5, 2, and $1.4\ \mu\text{m}$, respectively.

and $10.5\ \mu\text{m}$ to 7 and $11\ \mu\text{m}$ as the Ag grating line width d increases from 1.4 to $2.5\ \mu\text{m}$. According to the above result, the emission peaks attributed to the LSPP modes are independent of lattice constant and shift to long wavelength as the top Ag line width increases, which is consistent with the Fabry-Pérot resonance. The refraction index of thick SiO_2 at 5, 7, 10.1 and $11\ \mu\text{m}$ are $n=1.342$, 1.09, 2.59, and 1.93, respectively. When SiO_2 layer is thin (100 nm), they will be increased 1.17–1.3 times of the original values.

In order to measure the polarization of the emitted light, a polarizer is placed between plasmonic thermal emitter and detector. Figure 5 shows the thermal radiation spectra of emitter A with polarizer angles of 0° , 30° , 60° , and 90° . The axis of polarizer is perpendicular to the metallic line when θ is 0° . As the polarizer angle increases, the emittance of the two $m=1$ LSPP emission peaks at 6.3 and $10.5\ \mu\text{m}$ become weaker. Moreover, the emission peaks finally disappear when the polarizer angle reaches 90° . It implies that the emitted light is linearly polarized, and the polarization of the light radiated from such plasmonic thermal emitter is perpendicular to the parallel metal lines. It is because LSPPs exhibit the Fabry-Pérot resonance in the x direction, and the induced SPPs tend to couple with the local charge dipole oscillations between the long edges,¹⁶ i.e., only light generated from SiO_2 layer with polarization perpendicular to metallic lines can induce LSPPs.

FIG. 5. (Color online) Measured emission spectra of sample A with polarizer angles of 0° , 30° , 60° , and 90° .

In summary, the dispersion relation of LSPP and emission spectra of narrow-bandwidth plasmonic thermal emitters with 1D Ag grating are investigated. The SPs induced at the top Ag/ SiO_2 interface will couple with the SPs at the bottom Ag/ SiO_2 interface if the SiO_2 layer is thin enough. Instead of propagating along the top Ag/ SiO_2 interface, the SPs are localized and exhibit the Fabry-Pérot resonance. The thermal emission peaks of plasmonic thermal emitter are independent of lattice constant and redshift as the top Ag line width increases. In addition, the polarization of the emitted light is perpendicular to the metal lines.

The authors would like to thank the National Science Council of the Republic of China for financial support under Contract No. NSC 96-2221-E-002-242.

- ¹H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martin-Moreno, F. J. Garcia-Vidal, and T. W. Ebbesen, *Science* **297**, 820 (2002).
- ²J. K. Mapel, M. Singh, M. A. Baldo, and K. Celebi, *Appl. Phys. Lett.* **90**, 121102 (2007).
- ³C.-Y. Chang, H.-Y. Chang, C.-Y. Chen, M.-W. Tsai, Y.-T. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **91**, 163107 (2007).
- ⁴M.-W. Tsai, T.-H. Chuang, C.-Y. Meng, Y.-T. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **89**, 173116 (2006).
- ⁵D. M. Koller, A. Hohenau, H. Ditlbacher, N. Galler, F. R. Aussenegg, A. Leitner, J. R. Krenn, S. Eder, S. Sax, and E. J. W. List, *Appl. Phys. Lett.* **92**, 103304 (2008).
- ⁶S. Wedge, J. A. E. Wasey, W. L. Barnes, and I. Sage, *Appl. Phys. Lett.* **85**, 182 (2004).
- ⁷H. Lochbihler, *Phys. Rev. B* **50**, 4795 (1994).
- ⁸M. B. Sobnack, W. C. Tan, N. P. Wanstall, T. W. Preist, and J. R. Sambles, *Phys. Rev. Lett.* **80**, 5667 (1998).
- ⁹J. E. Kihm, Y. C. Yoon, D. J. Park, Y. H. Ahn, C. Ropers, C. Lienau, J. Kim, Q. H. Park, and D. S. Kim, *Phys. Rev. B* **75**, 035414 (2007).
- ¹⁰J. W. Lee, M. A. Seo, D. S. Kim, S. C. Jeoung, Ch. Lienau, J. H. Kang, and Q.-Han Park, *Appl. Phys. Lett.* **88**, 071114 (2006).
- ¹¹C. T. Kirk, *Phys. Rev. B* **38**, 1255 (1988).
- ¹²S. Collin, F. Pardo, and J.-L. Pelouard, *Opt. Express* **15**, 4310 (2007).
- ¹³C.-Y. Chen, M.-W. Tsai, Y.-W. Jiang, Y.-H. Ye, Y.-T. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **91**, 243111 (2007).
- ¹⁴S. A. Darmanyan and A. V. Zayats, *Phys. Rev. B* **67**, 035424 (2003).
- ¹⁵E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, New York, 1985), pp. 749–763, 1067.
- ¹⁶M.-W. Tsai, T.-H. Chuang, H.-Y. Chang, and S.-C. Lee, *Appl. Phys. Lett.* **89**, 093102 (2006).