Cavity mode in trilayer Ag/SiO$_2$/Au plasmonic thermal emitter
Ming-Wei Tsai, Yu-Wei Jiang, Chia-Yi Chen, Yi-Han Ye, and Si-Chen Lee
Department of Electrical Engineering
Graduate Institute of Electronics Engineering, National Taiwan University
No. 1, Sec. 4, Roosevelt Road, Taipei, 10617 Taiwan
E-mail: sclee@cc.ee.ntu.edu.tw

1. Introduction
Infrared light source is valuable in the studies of the light induced reaction of biological system, environmental protection, industrial and the defense industries. Three-dimensional metallic photonic crystal with emission in the infrared region has been reported by Lin et al. [4-5]. The two dimensional narrow-band infrared thermal emitter was demonstrated by Pralle et al. [6], strong resonance of the air/Au surface plasmon polariton (SPP) (1,0) degenerate modes resulted in the light radiation at the wavelength equal to the lattice constant. A two dimensional sandwiched Ag/SiO$_2$/Ag plasmonic thermal emitter was shown to exhibit strong Ag/SiO$_2$ and the Ag/air SPPs resonance and converted to narrow bandwidth light radiation [6]. Several theoretical and experimental studies based on plasmonic thermal emitter have been reported [1-11]. In this letter, an ultra-narrow bandwidth thermal emitters due to cavity mode instead of surface plasmon (SP) were demonstrated. Their emission spectra and the dispersion curves were characterized as a function of the SiO$_2$ layer thickness. The interaction between the Ag/SiO$_2$/Au cavity and SP were investigated.

2. Experiments and results
A metal film consist a 400 nm Mo films is thermally deposited on the back of the double-polished Si substrate as a heating source. Ti and Au metal film was deposited on the front side of the Si substrate followed by a SiO$_2$ layer deposited with the plasma enhanced chemical vapor deposition (PECVD). Bottom Au layer is used as reflection layer instead of silver because the SiO$_2$ growth temperature is 350 °C, surface silver aggregate together that cause SiO$_2$ layer to come off. The thicknesses of the SiO$_2$ layer in devices A, B, C, D and E are 1, 1.5, 1.67, 2 and 2 μm, respectively. Then a hexagonal hole array of 100 nm-thick silver film was deposited and lifted-off on SiO$_2$ layer. The radiation area of the sample is 1 cm$^2$. The schematic diagrams showing the side and top views of the device structure are depicted in Figs.1(a) and (b), respectively. A PERKIN ELMER 2000 Fourier Transform Infrared Spectrometer (FTIR) system was adopted to measure the thermal radiation spectra. The wavenumber resolution of the measurement is 8 cm$^{-1}$.

The devices are heated by sending electric current through the back Mo metal on Si substrate. A two dimensional sandwiched Ag/SiO$_2$/Ag plasmonic thermal emitter with very thin SiO$_2$ layer which shows strong Ag/SiO$_2$ and the Ag/air SPPs resonance has been reported elsewhere [6]. The emission spectra were measured with increasing SiO$_2$ thickness shown in Fig. 2 (a), (b), (c) and (d) for devices A, B, C and D, respectively, with lattice constant $a = 3$, diameter $d = 1.5$ μm. The emission spectrum of device E was shown in Fig. 2 (e), with lattice constant $a = 5$, diameter $d = 2$ μm, the same SiO$_2$ thickness as compared with device D. In Fig. 2 (a), the peak at 4.11 μm is composed of six degenerate modes, i.e., $(\pm 1,0), (0, \pm 1), (-1,-1)$ and $(1,-1)$ Ag/SiO$_2$ modes denoted as $(1,0)$ Ag/SiO$_2$ mode. The full width at half maximum (FWHM) of the Ag/SiO$_2$ (1,0) degenerate mode at the temperature of 120 °C is 0.21 μm. The ratio $(\Delta \lambda / \lambda)$ of the FWHM to the peak wavelength is 0.051. The ultra narrow bandwidth of Ag/SiO$_2$ (1,0) SP mode is due to low temperature operation and good quality of PECVD oxide. The peak at 3.08 μm is due to the cross coupling between the $(1,0)$ Ag/SiO$_2$ and $(1,0)$ Ag/air modes.

In Fig. 2 (b), the peaks at 3.27, 3.87, 4.92 μm are $(1,0)$ Ag/SiO$_2$ modes, $(1,0)$ Ag/SiO$_2$ modes and cavity mode (CM), respectively. Ray optics may occur when SiO$_2$ is thick enough, the dispersion curves intermixing may cause the (1,0) Ag/SiO$_2$ SPP mode to split. The FWHM of the CM resonance at the temperature of 140 °C is 0.20 μm. The CM resonance is the Fabry-Perot (F-P) resonance generated in SiO$_2$ layer between the parallel metal plane. Ag/SiO$_2$/Au waveguide is regarded as a cavity and varies with the SiO$_2$ layer thickness. The interaction between the Ag/SiO$_2$/Au cavity and SP were investigated.

The cut-off wavelength $\lambda_{c}$ of the two parallel Ag/SiO$_2$/Au waveguide can be approximately described as

$$\lambda_{c} = \frac{4\pi \times n_d \times h}{2m\pi - \phi},$$  \hspace{1cm} (1)
where $n_d$ is the refractive index of the dielectric material; $h$ is the SiO$_2$ thickness; $\phi$ is the phase shift on the top periodic Ag structure; $m$ is integer.

Calculated result shows that the phase shift due to top periodic structure is 44.5°. CM resonance generated in SiO$_2$ layer resonance in Ag/SiO$_2$/Au waveguide propagated along the direction parallel to plane waveguide.

3. Conclusion

In conclusion, narrow bandwidth infrared thermal emitters were fabricated. As the SiO$_2$ layer is thin, the Ag/SiO$_2$ and Ag/air SPPs are clearly seen, while that become thick, CM resonance determined by waveguide cut-off frequency related to the SiO$_2$ layer thickness display on the emission spectra. The hybrid C/SP mode is influenced by the film thickness and the periodicity of top Ag film. This infrared light source can be used in long wavelength optical communication and to explore the interaction of electromagnetic wave and the plants in the infrared region. From the biological response of plants, the genes that are responsible to the infrared light can be identified. This work is supported by the National Science Council of Republic of China under Contract No. NSC 95-2120-M-002-007.

Reference