High performance midinfrared narrow-band plasmonic thermal emitter

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The blackbody radiation spectrum is fundamental to any thermal emitter. However, by properly designing the emitter structure, a narrow bandwidth and high power infrared source can be achieved. This invention consists of a triple layer structure by sandwiching a dielectric SiO₂ layer between two Ag metal films on the Si substrate. The top Ag layer is perforated by periodic holes. When the device was heated, the background thermal radiation was suppressed by the bottom Ag whose emissivity is very low. The thermal radiation generated in the SiO₂ layer resonant between two metal films and the Ag/SiO₂ and the Ag/air surface plasmon polaritons are induced and converted to light radiation. Strong resonance at Ag/SiO₂ (1,0) degenerate modes results in the coherent light radiation at the wavelength associated with the dielectric constant of SiO₂ and the lattice constant of the perforated hole array. The ratio of the full width at half maximum to the peak wavelength is 0.114. This narrow bandwidth and high power infrared light source can be used to explore the biological response of cells and plants. © 2006 American Institute of Physics. [DOI: 10.1063/1.2364860]

Extraordinary transmission through periodic subwavelength perforated hole arrays in metallic films has been reported by Ebbesen and co-workers.^{1,2} In recent years, experimental and theoretical works on near-field image,³⁻⁵ dispersion relation of the surface plasmon polariton (SPP),⁶⁻⁸ and time domain analysis^{9,10} are focused on the investigation of the coupling mechanisms of surface plasmons (SPs) with the periodic structure. Extraordinary optical transmission through two-dimensional periodic, corrugated metallic films without holes has been reported theoretically and experimentally,^{11,12} which reveals the coupling of surface plasmon waves excited simultaneously on both sides of the metallic thin film. A thermal emitter with narrow bandwidth emission property is very useful in the studies of the reaction of a biological system, environmental protection, and industrial environment.¹³⁻¹⁹ The maximum transmission of a cascaded metallic structure, the dielectric layer sandwiched between two metal films, can be more than 400% greater than that of a corresponding single metallic structure.²⁰ In this letter, the high performance plasmonic thermal emitters were proposed and fabricated. Their thermal radiation and the coupling mechanism with SPs were investigated in detail.

A double layer consisting of a 50 nm Cr followed by 100 nm Au films is thermally deposited on the back of the double-polished Si substrate as a heating source. Ag metal film was deposited on the front side of the Si substrate followed by a SiO₂ layer deposited with the electron beam evaporator. The thicknesses of the SiO₂ layer in devices A, B, and C are 100, 300, and 500 nm, respectively. Then a hexagonal hole array of 100 nm thick silver film was deposited and lifted-off on SiO₂ layer with the lattice constant a of 3 μm and diameter d of 1.5 μm . The radiation area of the sample is 1 cm². The schematic diagrams showing the side and top views of the device structure are depicted in Figs. 1(a) and 1(b), respectively. A Perkin Elmer 2000 Fourier transform infrared spectrometer (FTIR) system was adopted

to measure thermal radiation spectra. The wave number resolution of the measurement was 8 cm⁻¹.

In a two-dimensional hexagonal lattice, the conservation of momentum for SPs is given by

$$\mathbf{k}_{\text{SP}} = \mathbf{k}_x + i\mathbf{G}_1 + j\mathbf{G}_2, \quad (1)$$

where $\mathbf{k}_{\text{SP}}$ is the wave vector of the surface plasmon given by

$$|\mathbf{k}_{\text{SP}}| = \frac{\omega}{c} \left(\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} \right)^{1/2}, \quad (2)$$

where ω is the frequency of the surface plasmon that is excited by the incident radiation with frequency ω , $\mathbf{k}_x = |\mathbf{k}_0| \sin \theta$, $|\mathbf{k}_0| = 2\pi/\lambda$ is the wave vector of the incident radiation, and λ is the wavelength of the radiation in vacuum. θ is the incident angle with respect to the normal direction of the surface. ϵ_1 and ϵ_2 are the dielectric constants of the insulator SiO₂ and the metal Ag, respectively. $\mathbf{G}_1$ and $\mathbf{G}_2$ are the reciprocal lattice vectors of a hexagonal lattice, and i and j are integers. For normal incident light, $\theta=0^\circ$ and $\mathbf{k}_x=0$, Eq. (2) reduces to

FIG. 1. (Color online) Schematic diagram of the (a) side and top views of the devices. The thicknesses t of SiO₂ layer in devices A, B, and C are 100, 300, and 500 nm, respectively. The hexagonal hole array has a lattice constant a of 3 μm and diameter d of 1.5 μm .

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$$\lambda = a \left(\frac{4}{3} (i^2 + ij + j^2) \right)^{-1/2} \left(\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} \right)^{1/2}. \quad (3)$$

The real parts of the dielectric constants of Ag at 2, 3, 4, and 5 μm are -2.1×10^2 , -4.71×10^2 , -8.34×10^2 , and -1.31×10^3 ,²¹ respectively. That of SiO_2 is 2.13 at all of these wavelengths. The calculation results show that the $(\pm 1, 0)$, Ag/ SiO_2 , $(0, \pm 1)$ Ag/ SiO_2 , $(-1, 1)$ Ag/ SiO_2 , and $(1, -1)$ Ag/ SiO_2 modes are degenerate and located at 3.79 μm , the Ag/ SiO_2 $(1, 1)$ mode at 2.19 μm , and the Ag/air $(1, 0)$ modes at 2.6 μm , assuming that the SiO_2 layer is infinitely thick.

The devices are heated by sending electric current through the back Cr/Au metal on Si substrate. The thermal radiation generated in the SiO_2 layer resonates between the two metal films and the Ag/ SiO_2 and Ag/air SPPs are induced and then converted to light radiation. The emission spectra were measured at different temperatures from 220 to 300 $^\circ\text{C}$ and shown in Figs. 2(a)–2(c) for devices A, B, and C, respectively. In the inset of Fig. 2(a), the 300 $^\circ\text{C}$ emission spectrum is enlarged. The peak at 4.16 μm is the degenerate modes composed of $(\pm 1, 0)$ Ag/ SiO_2 , $(0, \pm 1)$ Ag/ SiO_2 , $(-1, 1)$ Ag/ SiO_2 , and $(1, -1)$ Ag/ SiO_2 modes. The degenerate modes around 2.45–2.8 μm are composed of $(\pm 1, 0)$ Ag/air, $(0, \pm 1)$ Ag/air, $(-1, 1)$ Ag/air, and $(1, -1)$ Ag/air modes. The bottom 100 nm thick Ag film has very small emissivity which generates very small blackbody radiation, yet it can completely block the background radiation from the Si substrate. The Ag/ SiO_2 and Ag/air SPPs are induced in the top Ag layer. The full width at half maximum (FWHM) of the Ag/ SiO_2 $(1, 0)$ degenerate mode is 0.48 μm . The ratio of the FWHM to the peak wavelength is 0.114 which is small. The power consumption is about 18.52 W at the temperature of 300 $^\circ\text{C}$, total output power measured at the FTIR system is 384 mW, and the output power to input power ratio is 2.1%. The narrow-band emitter has been demonstrated by Pralle *et al.*;¹³ strong resonance at air/Au SPP $(1, 0)$ degenerate modes results in the light radiation at the wavelength equaling the lattice constant. However, in Figs. 2(a)–2(c), much stronger resonance at Ag/ SiO_2 $(1, 0)$ degenerate modes at 4 μm as compared to Ag/air $(1, 0)$ degenerate modes at 2.45 μm was demonstrated. The peak wavelengths at the Ag/air and Ag/ SiO_2 modes in devices A, B, and C remain unchanged when the temperature increased from 220 to 300 $^\circ\text{C}$, implying that the SP coupling mechanisms are the same. More light is generated in the thicker SiO_2 layer and the degenerate $(1, 0)$ Ag/ SiO_2 modes are easier to distinguish. The peak located at 3 μm shown in Fig. 2(c) is due to the cross coupling²² of the Ag/ SiO_2 and Ag/air modes which become distinguishable in the thicker SiO_2 layer. Figure 2(d) displays the band structure of the Ag/ SiO_2 and Ag/air plasmon modes along the ΓM and ΓK directions, where M is located at $2\pi/a(1, 0)$ and K is located at $2\pi/a(1, -1/\sqrt{3})$ in the reciprocal space. It can be seen that the $(0, 1), (1, 0)$ Ag/ SiO_2 degenerate modes cross over the $(-1, 0), (0, -1)$ Ag/air degenerate modes at 0.4 eV along the ΓM direction. Similarly, the $(1, 0)$ and $(-1, 0), (0, -1)$ Ag/ SiO_2 modes cross over the $(-1, 0)$ Ag/air mode at 0.4 eV along the ΓK direction. This means that the Ag/ SiO_2 modes resonate with the Ag/air modes at a specific direction. The FTIR experiment is a far-field measurement. The emission solid angle collected in the system is about 30° , therefore, in

FIG. 2. (Color online) Measured emission spectra of devices (a) A, (b) B, and (c) C at different temperatures. The inset in (a) shows the enlarged spectrum of device A at the temperature of 300 $^\circ\text{C}$. (d) Calculated energy dispersion relation of SPPs as a function of $\mathbf{k}$ along ΓM and ΓK . Blue solid lines indicate the Ag/ SiO_2 modes and red dotted lines indicate the Ag/air modes.

a thicker SiO_2 layer the resonant modes have a chance to be observed in the emission spectra.

The $(1, 0)$ Ag/ SiO_2 degenerate modes in devices A, B, and C at a temperature of 300 $^\circ\text{C}$ emit at 4.16, 3.98, and

3.8 μm , respectively. When the SiO_2 thickness is thin, the infrared thermal radiation is generated in this layer and resonant between the upper and bottom Ag films. This coupling of SPs moves (1,0) Ag/ SiO_2 degenerate modes to longer wavelength. When the thickness of the SiO_2 layer is greater than the SP coupling length of Ag/ SiO_2 mode, the transmission peak wavelengths are close to the predicted value. The (1,0) Ag/air degenerate modes around 2.45–2.8 μm slightly shift to the opposite.

In conclusion, narrow bandwidth infrared thermal emitters were fabricated. The bottom 100 nm thick Ag film with very small emissivity can completely reflect the background radiation of the Si substrate and the thermal radiation generated in the SiO_2 layer. The FWHM of the Ag/ SiO_2 (1,0) degenerate mode is 0.48 μm . The ratio of the FWHM to the peak wavelength is 0.114 which is small. When the SiO_2 thickness exceeds the SP coupling length of Ag/ SiO_2 mode, the transmission peak wavelengths are close to the predicted value. The thick SiO_2 cause the degenerate (1,0) Ag/ SiO_2 modes to split. It can be used as a high temperature operated, narrow bandwidth, and high power infrared light source.

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