Remotely coupled surface plasmons in a two-colored plasmonic thermal emitter

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A two-colored plasmonic thermal emitter is fabricated with a multilayer structure, in which the dielectric layers are sandwiched between two Ag films. The top Ag film is perforated periodically with holes in a squared array. The thermal radiation of the dielectric layer resonates between two metal films, and surface plasmon polaritons are induced on the top Ag film and then converted to light radiation. Furthermore, if the single dielectric layer is replaced with double layers, then an emission peak that corresponds to the remotely coupled surface plasmon is found in the plasmonic thermal emitter, and the coupling length is less than 500 nm. © 2006 American Institute of Physics. [DOI: 10.1063/1.2370329]

Extraordinary transmission, which is caused by the resonance of surface plasmons (SPs) through a periodic array of metal holes, has been reported.^{1,2} SPs are longitudinal waves that propagate along the surface of a conductor. Recently, many investigations on the dispersion relation of the surface plasmon polariton^{3–5} and time domain analysis^{6,7} have focused on the coupling mechanism of SPs with periodic structures. Extraordinary optical transmission in the middle and far infrared regions has also been demonstrated.^{8–11} The maximum transmission of a cascaded metallic structure, when a dielectric layer is sandwiched between two metal films, can exceed that of a corresponding single metallic structure by over 400%.¹² Additionally, a narrow-band emitter has been demonstrated by applying the features of SPs.¹³ In this study, a two-colored plasmonic thermal emitter is fabricated using a cascaded metallic structure. When double dielectric layers, such as SiO₂/TiO₂, are deposited between two metal films, the Ag/TiO₂ SP mode is established by coupling Ag and TiO₂ across the SiO₂ thin film in the middle infrared region. This mode is called a remotely coupled surface plasmon (RCSP) mode.¹⁴ Additionally, when the SiO₂ thickness exceeds the coupling length of the Ag/TiO₂ RCSP mode, this RCSP mode simply vanishes.

Double metal films that consist of a 50 nm layer of Cr followed by 100 nm Au are thermally evaporated on the back of the double-polished Si substrate as a heating source. A 100-nm-thick Ag film with very low emissivity is deposited on the front side of the Si substrate to retard the substrate radiation; then, a 100-nm-thick SiO₂ or TiO₂ insulator layer or SiO₂/TiO₂ double layers are deposited on the top of the Ag film. Then, another 100-nm-thick Ag metal film is deposited on the insulator layer and perforated with an array of squared holes by photolithography with a lattice constant a of 3 μm and a side length L of the holes of 2 μm . The insets in Figs. 1 and 3 display side views of the devices. The inset of Fig. 1(a) presents the top view of the device. A Perkin Elmer 2000 fourier transform infrared spectrometer (FTIR) system is adopted to measure the thermal radiation spectra. Then, a dc current is sent into the back metal contact and heats up the sample. A thermocouple is put on the top of

the sample to measure the temperature. When the sample is heated, the thermal radiation from the sample passes through the KBr window and is reflected into the FTIR by an off-axis mirror. The irradiated area of the sample is 1 cm². The wave number resolution of the measurement is 8 cm⁻¹. The sample is defined to lie in the (x, y) plane, and the light is incident in the z direction.

The conservation of momentum of SPs is

$$\mathbf{k}_{\text{sp}} = \mathbf{k}_x + i\mathbf{G}_x + j\mathbf{G}_y, \quad (1)$$

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

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

Here, $\mathbf{k}_x = |\mathbf{k}_0| \sin \theta$, $|\mathbf{k}_0| = 2\pi/\lambda$ is the wave vector of the incident radiation, λ is the wave length in a vacuum, and θ is the angle between the incident radiation and the z direction. $\mathbf{G}_x$ and $\mathbf{G}_y$ are the reciprocal lattice vectors of a square lattice with $|\mathbf{G}_x| = |\mathbf{G}_y| = 2\pi/a$, where a is the lattice constant, and i and j are integers. In Eq. (2), ω is the frequency of the SP that is excited by the incident radiation with the same frequency ω , and ϵ_1 and ϵ_2 are the dielectric constants of the insulator and the metal, respectively. For normally incident light, $\mathbf{k}_x = 0$, and Eq. (2) is reduced to

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

The real parts of the dielectric constant of Ag at 3, 5, and 6 μm are -1.31×10^3 , -3.32×10^3 , and -1.44×10^4 ,¹⁵ respectively. The dielectric constants of SiO₂ and TiO₂ at those wavelengths are 2.45 and 4.0. Therefore, theoretically, the degenerate ($\pm 1, 0$) and ($0, \pm 1$) modes designated as (1,0) Ag/air, Ag/SiO₂, and Ag/TiO₂ SP modes are at 3, 4.7, and 6 μm when the lattice constant of the hole arrays is 3 μm .

When the device is heated, the thermal radiation generated in the dielectric layer resonates between the two metal films, and the Ag/dielectric and Ag/air surface plasmon polaritons are induced and then converted to light radiation. The emission spectra are measured at various temperatures from 200 to 300 °C. Figure 1(a) shows the temperature-dependent emission spectra of device A with a single SiO₂ intermediate layer, as shown in the inset. The thickness of the

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FIG. 1. (Color online) Emission spectra of devices (a) A and (b) B. Inset shows the structures of the devices. The hole array has a lattice constant a of 3 μm , and the length of the sides of the square holes L is 2 μm . The thickness of both the SiO₂ and the TiO₂ layers is 100 nm.

SiO₂ layer is 100 nm. The spectra include two main peaks at 3.3 and 5.0 μm , which correspond to Ag/air and Ag/SiO₂ (1,0) degenerate SP modes, respectively. The emission peak around 10 μm (1080 cm^{-1}) is attributed to the phonon vibration of the SiO₂ layer. The emission peaks do not shift to shorter wavelength as the temperature increases, confirming that the radiation is from SPs and is not blackbody radiation. The bottom Ag film deposited on the front side of the Si substrate totally blocks the background radiation. The measured peak wavelength of the SP mode is slightly longer than the theoretical value because of the coupling of SPs between the bottom and top Ag films through the thin SiO₂ layer. Additionally, a small peak at 4.1 μm appears in Fig. 1(a), and corresponds to the cross coupling¹⁶ of the Ag/SiO₂ mode and the Ag/air mode. It becomes distinguishable in the thicker intermediate layer. Figure 1(b) displays the emission spectra of device B with a single TiO₂ intermediate layer, as shown in the inset. The thickness of the TiO₂ layer is 100 nm, and its dielectric constant is 4.0. The spectra include two main peaks at 4.6 and 6.6 μm , which correspond to the cross coupling of Ag/air with the Ag/TiO₂ SP mode and the (1,0) degenerate Ag/TiO₂ SP mode, respectively. The strong H₂O absorption at around 6.5 to 7 μm causes the emission peak at 6.6 μm to be not very sharp and the emittance to be

FIG. 2. Emission spectra of device C with SiO₂/TiO₂ double intermediate layers, as shown in the inset. The thickness of both the TiO₂ and the SiO₂ layers is 100 nm.

weaker than that in the cross-coupled mode. The emission peaks of device B are broader than those of device A. Therefore, the Ag/air mode of device B seems to be weaker than that of device A. However, the ratio of the emittance of the

FIG. 3. (Color online) Emission spectra of device (a) D and (b) E with TiO₂ and SiO₂ double intermediate layers. The thickness of the TiO₂ layer is 50 nm and those of the SiO₂ layers are (a) 150 nm and (b) 500 nm.

Ag/air mode to that of the Ag/dielectric mode equals that of device A, as shown in Fig. 1(a).

Figure 2 shows the temperature-dependent emission spectra of device C with SiO₂/TiO₂ double layers, as shown in the inset. Both TiO₂ and SiO₂ layers are 100 nm thick. The spectra have five peaks at 3.5, 3.7, 4.3, 5.1, and 6.0 μm , which correspond to Ag/air (1,0), the cross coupling of Ag/air with Ag/SiO₂, the cross coupling of Ag/air with Ag/TiO₂, Ag/SiO₂ (1,0) degenerate, and Ag/TiO₂ (1,0) degenerate SP modes, respectively. Although a SiO₂ layer is present between the Ag and TiO₂ films, the Ag/TiO₂ SP mode is clearly seen. The SP waves are not only excited at the interface between the metal and dielectric, but also remotely coupled to the other dielectric across the neighboring one. That is, collective charges on the metal surface induced by thermal radiation can remotely induce charges on the dielectric at a distance, satisfying the dispersion relation of the SP. Furthermore, in this double layer structure, the peak positions of each mode are all slightly redshifted with respect to those of the single layer structure because the coupling of SPs across a thicker intermediate layer is weaker.

Figure 3(a) shows the emission spectra of device D with a structure similar to that of device C. The total thickness of the intermediate layer is the same, but the thicknesses of the SiO₂ and TiO₂ layers are 150 and 50 nm, respectively. Each peak position is almost the same as shown in Fig. 2, and the Ag/TiO₂ RCSP modes at 5.7 μm are still present. Figure 3(b) displays the emission spectra of device E with a similar structure, but with a SiO₂ layer that is 500 nm thick. Clearly, the degenerate (1,0) Ag/TiO₂ and the cross coupling of Ag/air and Ag/TiO₂ modes all disappear. Therefore, the coupling length of the Ag/TiO₂ RCSP mode in the plasmonic thermal emitter is less than 500 nm. The remaining peaks are Ag/air (1,0) modes at 3 and 3.2 μm , the Ag/air and Ag/SiO₂ cross coupling mode at 3.8 μm , and the Ag/SiO₂ (1,0) modes at 4.4 and 4.8 μm . The thicker intermediate layer splits the (1,0) modes, which thus become more distinguishable and closer to the predicted positions. This is because the experiment is a far-field measurement. The emission solid

angle collected in the system is about 30°. The different (1,0) modes may emit in a slightly different emission angle with a different wavelength.

In summary, RCSPs in the plasmonic thermal emitter are characterized and are observable if the intermediate insulating layer is thin enough. The coupling length of the Ag/TiO₂ RCSP mode with the SiO₂ layer in between is less than 500 nm. Therefore, a multicolored infrared emitter can be fabricated by clipping materials of different dielectric constants between two Ag films.

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