Remotely coupled surface plasmons in a metal/insulator/Si structure perforated with periodic square hole arrays

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The zero-order transmission of radiation through a metal/dielectric structure perforated with square hole arrays is strongly enhanced when incident light resonates with surface plasmons (SPs). Surprisingly, when a metal/dielectric double layer, such as Ag/SiO₂, is fabricated on a silicon substrate, the Ag/Si SP mode by coupling Ag and Si across the intermediate dielectric film has been found. It is named the remotely coupled surface plasmon. The transmission intensity is investigated as a function of the intermediate SiO₂ thickness. The coupling lengths between Ag and Si in order to form the Ag/Si SP mode are determined as well, and they turn out to be 500 and 130 nm for couplings through air and a SiO₂ layer, respectively. © 2006 American Institute of Physics.
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Surface plasmons (SPs) are longitudinal waves that propagate along the surface of a conductor, usually a metal. When a metal film is perforated with two-dimensional periodic square hole arrays, it exhibits extraordinary optical transmission because of SP resonance.^{1,2} Numerous studies have explored the fundamental properties of the SPs and their potential applications in devices.^{3–13} Experimental and analytical results indicate that tunneling through surface plasmons formed on each metal-dielectric interface enhances transmission.^{3–8} According to theoretical analyses, if the perforated metal film has symmetric interfaces, then SPs at the top and bottom interfaces are coupled via evanescent waves.⁹ Extraordinary optical transmission in the middle and far infrared regions has been demonstrated.^{10–13} Our results further indicate that when a metal/dielectric double layer, such as Ag/SiO₂, is fabricated on the silicon substrate, the Ag/Si SP mode is established by coupling Ag and Si across the SiO₂ thin film in the middle infrared region. This mode is called the remotely coupled surface plasmon (RCSP) mode. The intensity of the Ag/Si RCSP mode is investigated as a function of the intermediate SiO₂ thickness and the coupling length between Ag and Si is extracted. Additionally, the multipeak transmission through a triple layer, such as Ag/SiO₂/TiO₂ fabricated on the silicon, is also demonstrated.

The photoresist was spun on the silicon wafer and the square hole array was defined and opened. Then, SiO₂ and Ag films were deposited and then lifted off. The thickness of the Ag film was fixed at 100 nm and the lattice constant of the hole arrays was 5 μm. A Bruker IFS 66 v/S system was used to measure the zero-order transmission spectra. The wave number resolution of the measurement was 8 cm⁻¹. The sample was defined to lie in the (x,y) plane, and the light was incident in the z direction.

The momentum conservation law of SPs is given by

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

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

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

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 wavelength in 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 frequency ω , and ϵ_1 , and ϵ_2 are the dielectric constants of the insulator and the metal, respectively. For normally incident light, $\mathbf{k}_x = 0$, 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 5, 8, and 17 μm are -1.31×10^3 , -3.32×10^3 , and -1.44×10^4 ,¹⁴ respectively. The dielectric constants of SiO₂ and Si at those wavelengths are 2.45 and 11.7. Therefore, theoretically, the degenerate ($\pm 1, 0$) and ($0, \pm 1$) of air/Ag, Ag/SiO₂, and Ag/Si modes are at 5, 7.8, and 17.1 μm when the lattice constant of the hole arrays is 5 μm. Figure 1(a) shows the optical transmission of the Ag/SiO₂/Si periodic hole array of sample A in which the SiO₂ is also perforated, as shown in the inset. The diameter of each hole is 3.5 μm. Three main transmission peaks are observed at 5, 7.8, and 17.2 μm in Fig. 1(a). They correspond to the air/Ag, Ag/SiO₂, and Ag/Si SP modes, respectively. The Ag/Si SP mode is red-shifted by 0.1 μm from its theoretical values, as will be discussed later. The transmission dip at 9.3 μm (1070 cm⁻¹) is caused by SiO₂ absorption. Although a SiO₂ layer is present between the Ag and Si films, the Ag/Si SP mode clearly exists when the SiO₂ layer thickness is thin enough. Thus, it is called remotely coupled SP. The SP waves are not only excited by light 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 light can remotely induce charges on the dielectric at a distance and satisfy the dispersion relation of the SP. The transmitted intensity of the Ag/Si RCSP

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FIG. 1. (Color online) Zero-order transmission spectra of (a) sample A and (b) sample B with different SiO_2 thicknesses. The lattice constant a is $5\ \mu\text{m}$ and the hole diameter L is $3.5\ \mu\text{m}$. In sample B, the perforated holes are only in the top metal layer.

mode decays as the thickness of SiO_2 increases. Hence, the data can be fitted using an exponential function to determine the decay length of the coupling, as shown in Fig. 2. The respective peak transmissions at different SiO_2 thicknesses are obtained by subtracting the transmission intensity at the off-resonance wavelength of $3\ \mu\text{m}$ from the peak transmission of the Ag/Si mode at $17.2\ \mu\text{m}$. The coupling length of the RCSP is defined as the thickness of the SiO_2 layer, the corresponding peak transmission in the fitting curves of which goes to e^{-1} of the original value at zero SiO_2 thickness. The fitting functions are also shown in Fig. 2, and X and Y represent the SiO_2 thickness and the peak transmission, respectively. The coupling length for sample A is $500\ \text{nm}$. The intensity of the Ag/ SiO_2 mode also decreases as the thickness of SiO_2 increases. The variation is attributed to the strong absorption of SiO_2 at $9.3\ \mu\text{m}$. Figure 1(b) shows the optical transmission of sample B with different SiO_2 thicknesses. In sample B, the SiO_2 layer is not perforated as shown in the inset. The lattice constant and the hole diameter are the same as those of sample A. Similarly, the Ag/Si RCSP mode can still be seen if the thickness of the

FIG. 2. (Color online) Fitting curve of the Ag/Si mode transmission of samples A and B.

SiO_2 layer is less than $440\ \text{nm}$. The Ag/Si RCSP mode also decays as the SiO_2 thickness increases. The coupling length of the Ag/Si RCSP mode is much shorter if the SiO_2 film is not perforated, as shown in Fig. 2. The coupling length of sample B is $130\ \text{nm}$. Therefore, the coupling mechanism of RCSPs primarily involves the holes. Figure 3 shows the optical transmission of sample A with differently sized holes, $L=4, 3.5$, and $3\ \mu\text{m}$. The thickness of the SiO_2 is fixed at $740\ \text{nm}$. The Ag/Si RCSP mode appears when the diameter of the hole exceeds $3.5\ \mu\text{m}$. Thus, the coupling length of the RCSP also depends on the size of the hole.

Figure 4 plots the optical transmission of samples C and D, which have the triple layer structure—Ag/ TiO_2 / SiO_2 for sample C and Ag/ SiO_2 / TiO_2 for sample D—and are fabricated on the Si wafer, as shown in the inset. It also plots the optical transmission of sample E, which has a double-layered Ag/ TiO_2 structure. The dielectric constant of the TiO_2 is 4.0 . The transmission curve of sample E reveals that the air/Ag and Ag/ TiO_2 modes are at 5 and $10\ \mu\text{m}$, values which are consistent with theory. The peak at $19.0\ \mu\text{m}$ is the Ag/Si RCSP mode and will be discussed later. For samples C and D, the TiO_2 and SiO_2 layers are clipped between the Ag film perforated with holes and the Si wafer. Four main peaks on the transmission curve are observed, as shown in Fig. 4. These are identified as air/Ag, Ag/ SiO_2 , Ag/ TiO_2 , and Ag/Si modes. Therefore, the multippeak transmission can be

FIG. 3. (Color online) Zero-order transmission spectra of sample A with holes of various sizes. The thickness of SiO_2 is fixed at $740\ \text{nm}$.

FIG. 4. (Color online) Zero-order transmission spectra of samples C to E. The lattice constant a is $5 \mu\text{m}$ and the hole diameter L is $3.5 \mu\text{m}$.

achieved by clipping appropriate materials with various dielectric constants between the perforated Ag film and Si wafer. The structural difference between samples C and D is the sequence of deposition of the TiO₂ and SiO₂ layers. Clearly, the respective transmission intensities of the Ag/SiO₂ and Ag/TiO₂ modes change little when the deposition sequence of the two layers is interchanged. Therefore, the multipeak transmission intensity achieved by RCSPs is independent of the sequence of the intermediate dielectric material. The Ag/Si RCSP mode is shifted to slightly longer wavelengths when the intermediate layer between Ag and Si is changed to a material with a higher dielectric constant. For example, the larger dielectric constant of TiO₂ (4.0) than that of SiO₂ (2.45) causes a Ag/Si RCSP mode in sample E to yield a peak at $19.0 \mu\text{m}$ rather than at $17.2 \mu\text{m}$ in sample B. If double layers are present between the Ag and Si, the peak transmission wavelength depends on the percentage of double dielectrics or the effective dielectric constant. In sample C, the percentage of the TiO₂ layer in the intermediate is smaller than that of sample D. Therefore, the peak of the Ag/Si RCSP mode in sample C ($17.3 \mu\text{m}$) is at a shorter wavelength than that in sample D ($17.6 \mu\text{m}$).

In conclusion, the Ag/Si SP mode by coupling Ag and Si across the intermediate dielectric thin film through the holes has been found. The decay length of the RCSP is affected by not only the thickness of the dielectric film, whether perforated or not, but also the size of holes in the metal. The peak transmission wavelength of the RCSP is affected by the effective dielectric constant of the material between the Ag and Si substrates. A larger effective dielectric constant corresponds to a larger redshift of the peak trans-

mission wavelength. Furthermore, the Ag/Si RCSP coupling lengths were 500 and 130 nm for couplings through air and a SiO₂ layer, respectively.

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