Journal of
Nanoscience and Nanotechnology
Vol. 9, 985–989, 2009

The Coherence Effect of Surface Plasmons on Optical Transmission in Silver Subwavelength Hole Arrays

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We study the optical transmission through a silver film with subwavelength hole arrays, which is sandwiched by super-thin SiO_2 layers. Based on finite-difference time-domain method, optical transmission and dispersion relation of surface plasmons are obtained. It is shown that surface plasmons are coherent in the top layer of the sandwich, which affects optical transmission in this subwavelength system. As a result, transmission modes can be tuned by changing the thickness of top layer. Resonant modes are also demonstrated by the electric field distribution. Besides, anti-resonances induced by Fano interference are also observed in this system. These properties may provide a peculiar approach to manipulate the propagation of electromagnetic wave in subwavelength microstructures.

Keywords: Subwavelength Holes, Coherence of Surface Plasmons, Optical Transmission.

1. INTRODUCTION

Nanostructured metallic films have shown many fascinating optical properties in recent years. Since Ebbesen et al.[1] reported the extraordinary optical transmission (EOT) through a two-dimensional (2D) array of sub-wavelength holes perforated on the silver film, the underlying physics has been studied in detail and one acceptable mechanism is that EOT relates to surface plasmons (SPs), which are waves that propagate along the surface of a conductor or doped semi-conductor,[2–5] usually a metal. When the incident light irradiates a metal, due to the interaction between the light waves and free electrons of the metal, the surface charge oscillates following the electromagnetic fields of the light and interacts with the electromagnetic fields. Therefore, there exists the elementary excitation in the system, so called the surface plasmon polariton (SPP). In the community of subwavelength optics, the SPP is usually called the surface plasmons (SPs). There are several ways to excite SPs, and one of approaches is to perforate periodic subwavelength holes in the surface of noble metal.

Nowadays, it has become possible to tailor the SPs by adjusting the sub-wavelength structures on metal surface, including altering the type and the thickness of metal, and the size and geometry of the hole,[6–12] in order to generate various novel materials and potential devices, such as the left-hand materials.[13–14] Assisted by the holes in metal film, SPs at different metal-dielectric surfaces can couple with each other. The kind of SPs excited in the system is determined by the type of the metal-dielectric interface.[15] Very recently, we have studied the coupling effects of SPs in a Ag/SiO_2 multilayer film and found that the coupling of SPs plays an important role on optical transmission. And Kubo et al. have investigated the coupling between an incident light pulse and a SPs mode, and its effect on the transmission spectra.[16] In this work, by introducing an interference layer on the top of a silver film with subwavelength hole arrays, we try to investigate the coherence of SPs at the same metal-dielectric interface. The coherence of SPs will influence the optical transmission in the system.

2. THEORETICAL MODEL

We consider the propagation of electromagnetic wave through a silver film with subwavelength hole arrays, which is sandwiched by super-thin SiO_2 layers. In detail, a SiO_2 layer (bottom-layer) is formed on the K9 glass substrate, then a silver film grows on the SiO_2 bottom-layer. The silver film is perforated with subwavelength square holes and the hole is filled in by SiO_2. Then an additional SiO_2 layer (i.e., a top layer) is coated on the silver film. In this system, the silver film is sandwiched by two SiO_2 layers, therefore, there is only one kind of metal-dielectric

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interface, and the same kind of SPs will be excited at the interface. We try to study how the super-thin top layer influences optical transmission in this sandwich.

It is known that, when a beam of incident light is impinged on the metal dielectric interface, the interaction between light and the surface plasmon (SP) obeys momentum conservation:[1]

$$\vec{k}_{sp} = \vec{k}_0 \sin\theta + (i\vec{G}_x + j\vec{G}_y) \quad (1)$$

where $\vec{k}_{sp}$ is the wave vector of the SP, $\vec{k}_0 \sin\theta$ is the in-plane component of the incident wave vector, $\vec{G}_x$ and $\vec{G}_y$ are the reciprocal lattice vectors with the same value as $|\vec{G}_x| = |\vec{G}_y| = 2\pi/a_0$, and i, j are both integers. Also we can write the dispersion relation of SPs at metal-dielectric interface as following:

$$k_{sp} = k_0\sqrt{\frac{\varepsilon_d \cdot \varepsilon_{eff}}{\varepsilon_d + \varepsilon_{eff}}} \quad (2)$$

where ε_d is the permittivity of the dielectric. Because the SPs might be coherent in the top dielectric layer and they could also couple with each other in the sandwich, we use ε_{eff} to denote the effective permittivity of the silver film perforated with square array of subwavelength holes. If both Eqs. (1) and (2) are satisfied, the SPs can be excited at the interface. When the incident angle is $\theta = 0$, we can obtain the maximum transmission satisfying

$$\lambda_{max} = \frac{a_0}{\sqrt{i^2 + j^2}}\sqrt{\frac{\varepsilon_d \cdot \varepsilon_{eff}}{\varepsilon_d + \varepsilon_{eff}}} \quad (3)$$

Therefore, the transmission peaks can be indexed with integers (i, j) in the optical spectra. The effective permittivity of the structured metal ε_{eff} can be obtained from the reflectivity and transmittivity of light in the metal-dielectric system.

3. RESULTS AND DISCUSSION

Based on the full-vectorial three-dimensional (3D) finite-difference time-domain (FDTD) method,[17] the transmission spectra of electromagnetic waves through the sandwich structures can be calculated. For simplicity, we consider the case when incident light is perpendicular to the surface of the sandwich. Figures 1(a–d) show the transmission spectra of several sandwiches, where the thickness of top layer is different. In each case, the thickness of the silver film is $t_{Ag} = 100$ nm, the period of the hole array is $a_0 = 600$ nm, the length of the square hole is $d = 150$ nm, and the bottom layer has a thickness of $t_b = 100$ nm. Yet the thickness of the top layer decreases gradually from $t_s = 120$ nm to $t_s = 60$ nm. It is obvious that extraordinary optical transmission indeed happens in the sandwich (as shown in Figs. 1(a–d)). According to Eq. (3), we are able to label the transmission peaks by using indices (i, j).

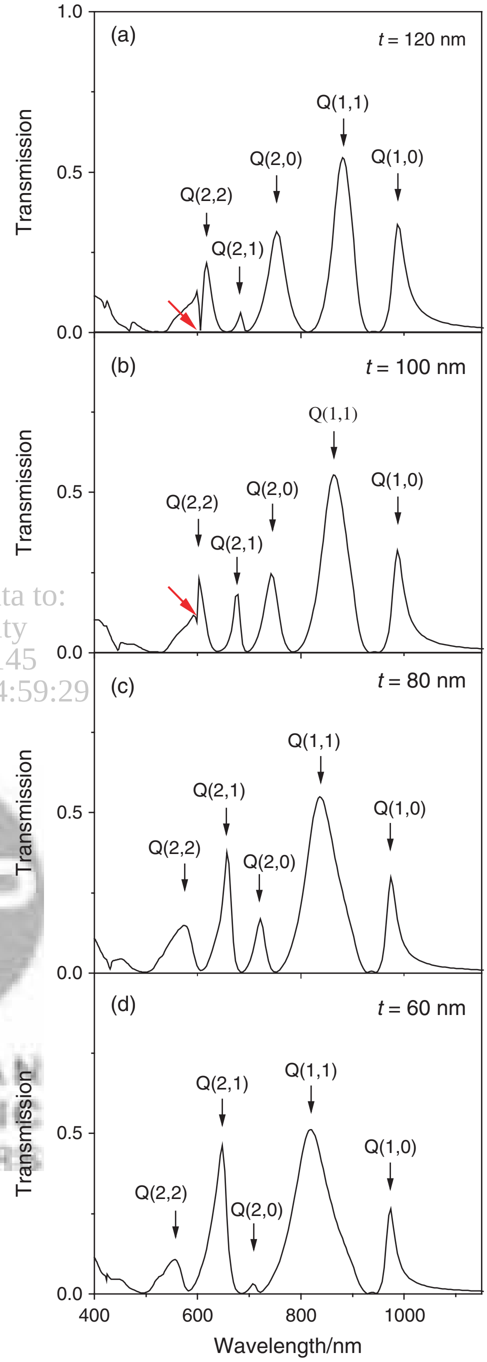

Fig. 1. Transmission spectra of several structured silver films sandwiched by SiO_2 layers, where the top SiO_2 layer has different thickness t_s: (a) $t_s = 120$ nm, (b) $t_s = 100$ nm, (c) $t_s = 80$ nm, (d) $t_s = 60$ nm, respectively. In each case, the thickness of the silver film is $t_{Ag} = 100$ nm, the period of the hole array is $a_0 = 600$ nm, the length of the square hole is $d = 150$ nm, and the bottom layer has a thickness of $t_b = 100$ nm. The incident light is perpendicular to the surface of the sandwich.

Main peaks in Figure 1 are indexed by low integers, such as $Q(1, 0)$, $Q(1, 1)$, $Q(2, 0)$, $Q(2, 1)$, and $Q(2, 2)$. The capital letter "Q" in "$Q(i, j)$" represents the silver-SiO_2 interface, which means these resonant modes originate from the SPs at the silver-SiO_2 interface. With decreasing the thickness of the top layer, both intensity and position of the resonant mode are strongly influenced. This phenomenon may be understood as following. First, due to the periodic lattice structure in silver film, the reciprocal lattice vector provides the additional momentum to excite the SP modes. Second, the incident light is scattered by the subwavelength holes. The scattered light is then reflected by the SiO_2-Air interface, and the reflected light regenerates SPs at the silver-SiO_2 interface. The regenerated SPs may coherence with the SPs produced directly by the incident light, and finally affects the optical transmission, such as tuning the intensity of transmission peaks. Third, the thickness of the top-layer influences the dispersion relation of SPs at the silver-SiO_2 interface, which immediately induces a positional shift of the resonant mode.

Now we consider the coherence of SPs in the top SiO_2 layer of the sandwich. When a beam of incident light irradiates the sandwich, a SP mode with momentum $\vec{k}_{sp1}$ is generated at the silver-SiO_2 interface. Simultaneously, the light is scattered near the square holes at the silver-SiO_2 surface. We suppose that the scattered light has a wave vector $\vec{k}_1$ and the scattering angle is ϕ. When ϕ is large enough, the scattered light will be completely reflected by the SiO_2-Air interface, then the reflected light generates another SP mode with momentum $\vec{k}'_{sp1}$ at the silver-SiO_2 interface. The additional optical path of the scattered light leads to the phase difference between the two SPs modes. This phase difference can be written as:

$$\Delta\varphi = 2nk_1 t_s / \cos\phi \qquad (4)$$

where n is the refractive index of SiO_2, t_s is the thickness of the top SiO_2 layer coated on the surface of silver film, and ϕ is the scattering angle. Those two SPs modes may coherence within the top layer, and the coherence is tuned by the thickness of the top-layer t_s (as shown in Eq. (4)). As shown in Figures 1(a–d), when we change the thickness of the top layer from $t_s = 120$ nm to $t_s = 60$ nm, the intensity of resonant mode changes accordingly. Because the main peaks are indexed, we are able to count the change of transmittivity for certain single mode. For example, the resonant mode "$Q(2,1)$" has a transmittivity of $T_{Q(2,1)} = 0.064$ when the thickness of the top layer is $t_s = 120$ nm (as shown in Fig. 1(a)). Once the thickness of the top layer decreases to $t_t = 60$ nm, the transmittivity of this mode increases up to $T_{Q(2,1)} = 0.466$ (as shown in Fig. 1(d)). But if we take the resonant mode "$Q(2,0)$" as another example, we find that its transmittivity is $T_{Q(2,0)} = 0.316$ when the thickness of the top layer is $t_s = 120$ nm, and $T_{Q(2,0)} = 0.032$ when the thickness of the top layer is $t_s = 60$ nm. Therefore, the coherence of SPs may enhance or weaken the optical transmission, which depends on the resonant modes. When the resonant mode is in the visible range, the coherence of SPs strongly influences the intensity of the transmission in our system (as shown in Fig. 1). Actually, the coherence of SPs closely relates to the ratio of the top-layer thickness and the wavelength of the resonant mode, t_s/λ_{max}, which induces the phase difference between the coherent SPs modes. On the other hand, the light scattering also generates a non-resonant mode, and non-resonant mode may couple with the SPs resonant mode.[18] Thereafter, the transmission presents a characteristic dip, which originates from the destructive interference effect between the two kinds of modes. Those anti-resonances induced by Fano interference are also observed in this system, which locates at about 600 nm, and is marked by red arrows in Figures 1(a)–(b), respectively.

It is interesting to note that the positions of transmission peaks are sensitive to the thickness of the top SiO_2 layer. As the thickness of the top layer decreases, all these resonant modes have a blue shift more or less. For example, compare the mode "$Q(1,0)$" in Figure 1(a) with that in Figure 1(d), the position of this resonant mode

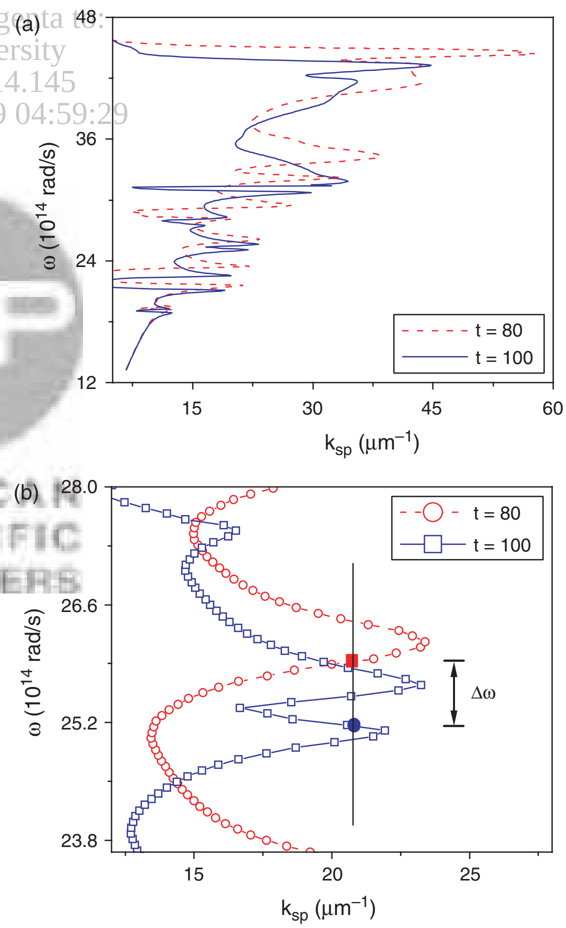

Fig. 2. The dispersion relation of two structured silver films sandwiched by SiO_2 layers, where the top layer of SiO_2 has different thickness t_s. (a) The blue solid curve corresponds to the sandwich with $t_s = 100$ nm, and the red dashed curve corresponds to the sandwich with $t_s = 80$ nm. (b) Enlarged dispersive curves, which shows the SP mode "$Q(2,0)$." The blue curve with hollow square spot corresponds to the sandwich with $t_s = 100$ nm, and the red curve with hollow circle spot corresponds to the sandwich with $t_s = 80$ nm. $\Delta\omega$ represents the difference of frequency for the SP mode "$Q(2,0)$" in these two cases.

moves from 989 nm to 972 nm, which has a blue shift of $\Delta_{Q(1,0)} = 17$ nm. Another example is about the mode "$Q(1, 1)$." When the thickness of the top layer changes from 120 nm to 60 nm, the position of the mode "$Q(1, 1)$" moves from 880 nm to 819 nm, and has a blue shift of $\Delta_{Q(1,1)} = 61$ nm. For other modes, such as $Q(2, 0)$, $Q(2, 1)$, and $Q(2, 2)$, blue shifts indeed occur. We have also calculated the transmission spectra in a series of sandwiches, where the thickness of the top layer is fixed to $t_s = 100$ nm, but the thickness of the bottom layer changes from $t_b = 100$ nm to $t_b = \infty$. In those cases, the optical transmission does not change. It seems that the bottom layer only provides a silver-SiO_2 interface for the optical transmission. Therefore, it is the difference in thickness of the top layer that gives rise to blue shift of the resonant modes. To demonstrate the blue shift of resonant modes, we calculate the dispersion relation of SPs in the sandwich at the visible range. Figures 2(a)–(b) show the dispersion relation of two sandwiches, where the thickness of the top layer is $t_s = 100$ nm and $t_s = 80$ nm, respectively. It is obvious that when the top layer becomes thinner, the dispersion relation moves up. It becomes more evident in the enlarged curves (as shown in Fig. 2(b)). In Figure 2(b), the vertical line corresponds to the wave vector of the SP mode "$Q(2, 0)$." When the thickness of the top layer changes from $t_s = 100$ nm to $t_s = 80$ nm, and the difference in frequency for the SP mode "$Q(2, 0)$" is $\Delta\omega = 22$ nm, which agrees well with the blue shift of transmission peak labeled by "$Q(2, 0)$" in the optical spectra as shown in Figures 1(b and c).

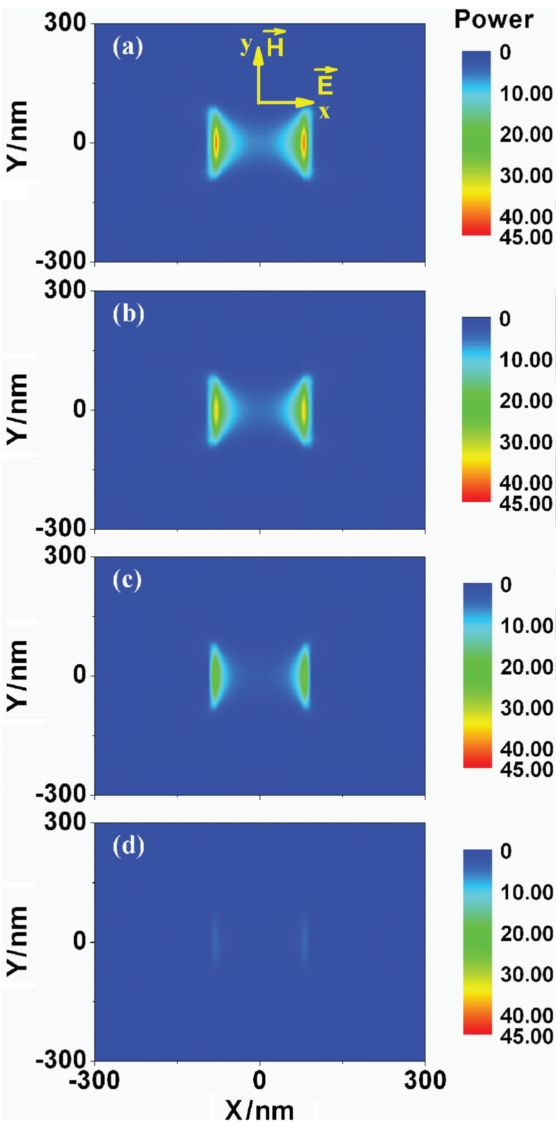

Fig. 3. The electric field density distribution of the resonant mode "$Q(2, 0)$" in the sandwich with different thickness of the top layer, t_s. (a) $t_s = 120$ nm. (b) $t_s = 100$ nm, (c) $t_s = 80$ nm, (d) $t_s = 60$ nm, respectively. In each case, the incident light is p-polarized, and the electric field is along the x direction as shown in Figure 3(a).

In order to show the resonant mode impacted by the top layer, we calculate the distribution of electric field density of the mode "$Q(2, 0)$" in several sandwiches. As shown in Figures 3(a–d), it is obvious that the electric filed is mainly distributed along the edges of the square hole, which is perpendicular to the incident electric field. As the thickness of the top layer decreases, the density of electric field becomes weaker. This result agrees with the variance of transmittivity for the mode "$Q(2, 0)$" in the transmission spectra (as shown in Figs. 1(a–d)). This feature implies that the interference layer, i.e., the top SiO_2 layer, can change the distribution of SPs, which definitely influences the transmission of resonant modes. Thereafter, we can tune the optical transmission by adjusting the top layer in above subwavelength sandwich.

4. CONCLUSIONS

To summarized, optical transmission in a nanostructured silver film, sandwiched by two SiO_2 layers, has been investigated. We demonstrate that the SiO_2 layer covered on the silver film has an important effect on the transmission behavior. The super-thin SiO_2 top layer, which serves as an interference layer, can lead to the coherence of SPs at the silver-SiO_2 interface, and its thickness serves as a phase factor in the effect of coherence. As a result, both the transmittivity and the position of the resonant modes can be tuned by changing the thickness of the SiO_2 top-layer. This property may provide a unique approach to manipulate the propagation of electromagnetic wave in subwavelength microstructures.

Acknowledgments: This work was supported by the grants from National Nature Science Foundation of China (10625417, 50672035, 90601001), the State Key Program for Basic Research from the Ministry of Science and Technology of China (2004CB619005, 2006CB921804), and partly by the Ministry of Education of China (NCET-05-0440).

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Received: 7 June 2007. Accepted: 30 November 2007.