Transmission enhancement properties of double-layered metallic hole arrays

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We report experimental results on enhanced light transmission through double-layered (Ag/Au) metallic hole arrays within a skin-depth. Zero-order transmission spectrums are characterized as a function of Ag film's thickness, which extends from $\delta/15$, $\delta/6$ to approximately δ, where δ is a skin-depth. In contrast with other reported results (Refs. [11 − 13]) in single-layered metallic hole arrays, our experimental results show much more dramatic properties of transmission process dependent on sub-δ thickness. It is shown that there is no negligible transmission enhancement at $\delta/15$. At $\delta/6$, much higher transmission efficiency can be achieved. With film's thickness being close to δ, the transmission efficiency declines contrarily. Simultaneously, the corresponding resonant peak also slightly moves toward the shorter wavelength. It is proposed that the coupling of surface plasmon polaritons (SPPs) at Ag/Au interface within δ is involved in the process.

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Since extraordinary optical transmission (EOT) through metallic hole arrays has been reported by Ebbesen *et al.*[1,2], it has stimulated significant interest recently. Until now, much work both theoretically and experimentally[2−4] has been carried out not only to understand the mechanism of EOT but also to explore the potential applications in flat-panel displays, tunable optical filters, etc[5−8].

EOT is generally interpreted as the interaction of the incident radiation with surface plasmon polaritons (SPPs)[9,10] at the metal-dielectric interface of the two-dimensional metallic hole arrays (2D-MHAs). Thereinto, the issue has been demonstrated that the EOT process is associated with metal film's thickness[1]. More recently, there have been several experimental studies examining the EOT as a function of metal film's thickness in single-layered metallic hole arrays[11−13]. For multilayer metallic hole arrays, though the crucial role of outer metal surface (being insensitive to inner metal surface) on enhanced transmission above δ was pointed out by Grupp *et al*[4]. According to experimental results, to our knowledge, there is little information available about EOT properties of double-layered metallic hole arrays within δ.

In this letter, the Ag/Au double-layered metallic hole arrays within δ were fabricated respectively. Zero-order transmission spectrums are characterized as a function of Ag film's thickness, which extends from $\delta/15$, $\delta/6$ to approximately δ. But the Au has the same thickness much thicker than δ. The results show dramatic properties of light transmission enhancement process dependent on Ag film's sub-skin-depth thickness, which are different from other reported results previously[11−13]. Our experimental results show the discernable transmission enhancement at $\delta/15$, the EOT being gained at $\delta/6$ and the transmission efficiency declining contrarily at δ.

Yet, other results (Refs. [11 − 13]) showed a negligible transmission enhancement at $\delta/15$, the weak transmission enhancement at $\delta/6$, and the EOT was gained at δ. Simultaneously, the corresponding resonant peak also slightly moves to the shorter wavelength. It is proposed that the coupling of SPPs at Ag/Au interface within δ is involved in the process. Further, the presence of 'skin effect', as suggested by Marion and Scalora *et al.*[14,15], is further validated by our experimental results presented here. We think that both the outer metal surface (Ag) and inner metal surface (Au) operate within δ in Ag/ Au double-layered metallic hole arrays.

In Fig. 1, the Ag/Au metallic hole arrays residing in SiO$_2$@Si substrate were fabricated by conventional technology. In the first step, a layer of silicon dioxide (700 nm) was deposited on the n-doped silicon wafers with resistance of approximately $6 - 8$ Ω·cm. Experimentally, after a familiar cleaning process involving ultra sonic treatment, the 2D-MHAs were prepared on a SiO$_2$@Si substrate by using a lithography process with reactive ion etching (RIE). A reactive DC sputtering system (20 W DC power and 3 mTorr of chamber pressure with an Ar reactive gas at room temperature) was used to deposit
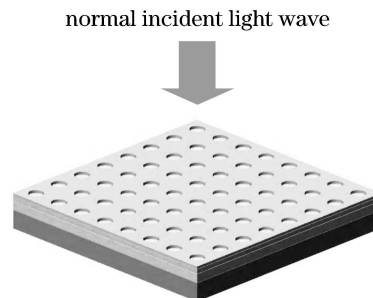
normal incident light wave

Fig. 1. Schematic diagram of Ag/Au double-layered metallic hole square arrays.

Ag/Au films. The deposition rate has been characterized to have a fairly linear relation to the deposition time. Au film were deposited on the $SiO_2@Si$ substrate by the same thickness (100 nm) more than δ firstly. Then, three samples (A, B, and C) with different Ag film' thicknesses, 1.5 nm ($\delta/15$), 3.8 nm ($\delta/6$), and 23 nm (δ) were deposited using different deposition times of 6, 16, and 95 s, respectively. The air round hole arrays have been etched through Ag/Au layer into the silicon substrate to a total depth of 6 μm. Each set of samples keeps the same lattice type of round hole consisting of 3.5 μm diameter with a periodic spacing of 7 μm and a total arrays size is of 3×3 (mm^2). Zero-order transmission spectra of samples were performed by the Fourier-transform spectroscopy using Varian 4100 FT-IR. Transmission amplitude is depicted by the ratio between the sample and the reference spectra.

Concerning the physical process of light passing through metal film, it can be explained below. When light is incident on metal film from air, the SPPs on both interfaces can be excited. A surface plasmon wave propagates along metal dielectric interface and decays exponentially into both media. In considering the role of metal surface, it is indispensable as well as useful to discuss two characteristic lengths (δ and δ_{SPP}-SPPs propagation length along metal surface). According to the skin effect of electromagnetic theory, metal skin-depth expression is given by $\delta \approx \lambda_0/2\pi\text{Im}(\sqrt{\varepsilon_m})$[3]. According to alike definition, SPPs propagation length expression is given by $\delta_{SPP} \approx \lambda_0(\varepsilon_{rm})^2/2\pi\varepsilon_{im}$[16]. Where λ_0 is the incident light wavelength; ε_d is the dielectric constant of the medium, in our case, $\varepsilon_d \approx 2.16$ for silicon dioxide. Based on above two relations, we can calculate δ and δ_{SPP} from the published values of the dielectric constants of metals[17].

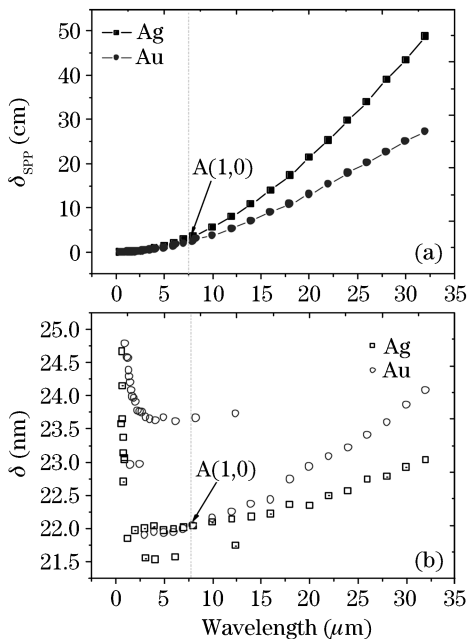For investigating EOT properties of double-layered (Ag/Au) metallic hole arrays within δ, we compare

transmission efficiency in case of the prominent SPPs A (1,0) (A for metal-air interface). In Fig. 2, we have plotted two parameters (δ, δ_{SPP}) as functions of wavelength for Ag and Au. Figure 2(a) shows the diagram dependent on δ_{SPP} for Ag and Au along metal surface. At $\lambda \approx 7.5$ μm, in the case of SPP A (1,0), δ_{SPP} for Ag and Au are almost the same approximately 3.4 cm. Figure 2(b) shows the diagram dependence of δ for Ag and Au for a plane wave impinging at normal incidence on metal surface. At $\lambda \approx 7.5$ μm, in the case of SPP A (1,0), δ for Ag and Au are almost the same approximately 22 nm. The two noble metals (Ag, Au) were chosen for the sameness of SPPs A (1,0) characteristic length scales (δ, δ_{SPP}). This helps evanescent waves to be coupled fully at the double-layered (Ag/Au) metal interface.

Figure 3(a) shows transmission spectra of the Ag/Au metallic hole square arrays as functions of Ag film's thickness. The Rayleigh minima of Wood's anomaly effect[2], clearly appears at $\lambda \approx 7$ μm, with the SPPs A (1,0) maxima ($\lambda \approx 7.5$ μm) occurring at the slightly longer wavelengths than minima. The Rayleigh minimum is given by $\lambda = a_0\sqrt{\varepsilon_d}/\sqrt{i^2 + j^2}$. The resonant wavelength of square arrays at normal incidence is given by $\lambda = a_0\sqrt{\varepsilon_m\varepsilon_d/(\varepsilon_m + \varepsilon_d)}/\sqrt{i^2 + j^2}$, where a_0 is the lattice constant of the arrays, i and j are the mode indices of the SPPs[18]. The Rayleigh minima and the SPPs A (1,0) peaks for square arrays with $a_0 = 7$ μm are calculated at 7 and 7.0011 μm, respectively. We find out that the experiment results are slightly larger than the calculated values. As a case of the SPPs A (1,0),

Fig. 2. Wavelength-dependent (a) δ_{SPP} and (b) δ for Ag and Au. The vertical dashed lines indicate the observed SPPs A (1,0) mode at 7.5 μm.
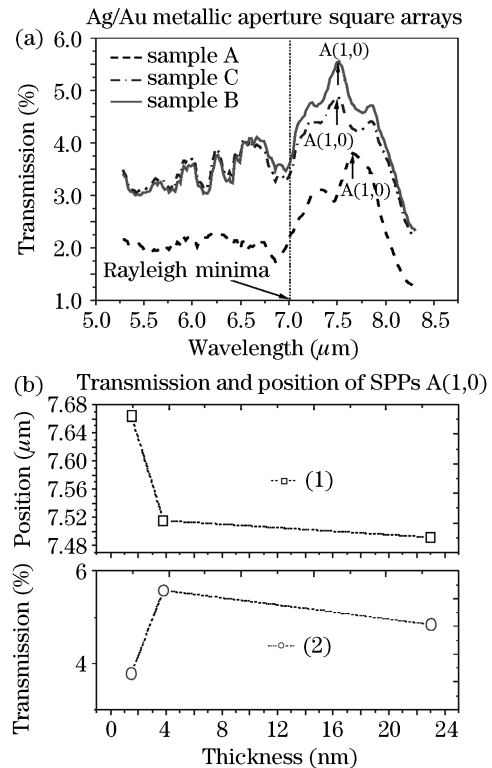
Fig. 3. (a) Zero-order transmission spectra of Ag/Au double-layered metallic hole square arrays and (b) resonant peak (1) positions and (2) amplitude of SPPs A (1,0) as a function of Ag film's thickness. The vertical dashed line indicates the observed Rayleigh minima at 7 μm.

for sample A (dashed curve), resonant peak appears at 7.67 μm. Distinctly, its transmission efficiency is as small as 3.8%, whereas, the other experimental result shows no resonance[11−13]. For sample B (solid curve), its transmission efficiency as high as 5.6% is achieved. Its resonant peak appears at 7.52 μm. For sample C (dashed-dotted curve), its transmission efficiency (as small as 4.9%) declines contrarily. Its resonant peak appears at 7.5 μm.

Figure 3(b) illuminates the resonant peak transmission efficiency and position of the prominent SPPs A (1,0) as functions of Ag film's thickness, which clearly reveals two regions dependent on Ag film's thickness. Above 1.5 nm, the resonant peak amplitude is very sensitive to film's thickness. At 3.8 nm, a strong resonance appears in the spectra, whose amplitude exponentially increases. As film's thickness increases unceasingly, there is no sub-linear increase in the transmission amplitude until Ag film's thickness is equal to δ, as not expected by the other researchers[11−13] [in Fig. 3(b-2)]. Simultaneously, the resonant wavelength decreases monotonically from 7.67 to 7.52 μm as Ag film's thickness increasing from 1.5 to 3.8 μm, with a tendency toward saturation (7.49 μm) in thick region (23 μm). This is called blue-shifted [in Fig. 3(b-1)].

It is worth noting that transmission efficiency as high as 5.6% is achieved at 3.8 nm, only $\delta/6$. The value is more one order of the transmission efficiency 4.9% achieved at 23 nm, approximately δ. In other words, the transmission enhancement is insensitive to the increase in Ag film's thickness. So, it will be meaningful for us to have more particular investigation the problem. For comparison, additional Ag/Au metallic hole hexagonal arrays with the same geometry and material parameters were fabricated respectively. The measured transmission efficiencies are 11.8% at 3.8 nm, only $\delta/6$ and 5.8% at 23 nm, approximately δ, respectively. The former value is two orders of the latter. At 1.5 nm, we also observe SPPs A(1,0) resonance and the transmission efficiency is 4.9%. Simultaneously, the resonant peaks are blue-shifted with Ag film's thickness increasing (not shown in Fig. 3).

The results shows that the SPPs of Ag/Au interface operates within δ which presents a further development of the EOT studies. In this case, such a system (Ag/Au metallic hole arrays within δ) may have a new physics behind the transmission properties. It is proposed that the coupling of SPPs at Ag/Au interface within δ is involved in the process. This is because metal film's thickness is critical to control the coupling of the incident light to the metal surface. When Ag film's thicknesses are adjusted, the degree of SPPs coupling at Ag/Au interface must be changed. The coupling of SPPs at Ag/Au interface within δ might present some new SPPs A (1,0) models for EOT.

In conclusion, we report experimental results on transmission properties of double-layered metallic hole arrays within δ. There are some new and fascinating phenomena to emerge in this work. This is because of the skin effect of Ag and Au surfaces equally[14]. The coupling of SPPs at Ag/Au interface within δ has the same contributions to EOT. According to this opinion, we maybe can find a right metal film's thickness to gain the highest resonant peak amplitude. This is another amusing question out of this paper to explore further for us the next time. The measured resonant wavelength is blue-shifted significantly. It is presumably attributed to the coupling of the localized SPPs inside the holes[13].

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