Influence of Hole Size on Extraordinary Transmission through Periodic Perforated Hole Arrays

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Abstract

The extraordinary optical transmission through two-dimensional periodic perforated Ag film in the far infrared region has been demonstrated. We find that when the squared hole size is larger than the half of the lattice constant *a*/2, the degenerate (±1,0) Ag/Si and (0,±1) Ag/Si mode splits into two peaks. Surface plasmon polaritons (SPPs) dispersion relations with different squared hole size are measured to investigate the different surface charge field at periodic metal array. Experiment results are presented that demonstrated the photonic bandgap opens up when the squared hole size is larger than the half of the lattice constant *a*/2.

Keywords: Surface plasmon, Bragg scattering, bandgap

I. Introduction

Metal films with two-dimensional periodic arrays of subwavelength periodic perforated hole arrays can exhibit extraordinary optical transmission [1-2]. When a single slit in a metallic film is surrounded by periodic surface corrugations, the emitted light field from the slit will concentrate in a specific direction at a confined angle, instead of diverging in all directions represent SP's directional beaming nature [3-4]. If the period of the corrugation is appropriate, the SPP's can Bragg reflect and an energy gap opens up in the SPPs dispersion relation [5-6]. Recently work on the conservation of SPs and light through periodic perforated hole arrays [7] elaborate the SPs propagating nature. Extraordinary optical transmission in middle and far infrared region has been demonstrated [8-9]. They have potential applications in optical filters, optical modulators and light source. In this paper, we investigate the influence of hole size on extraordinary transmission through two-dimensional periodic perforated Ag film in the far infrared region. SPPs dispersion relations with different squared hole size are measured to discuss the different surface charge displacement at periodic perforated Ag film.

II. Experiments

After spinning photoresist onto silicon wafer and pattern transfer, 50 nm thick Ag metal films with different hole size was deposited and lifted off. A Bruker IFS 66 v/s system was used to measure zero-order transmission spectra. The sample is defined to lie in the (x,y) plane, rotating it around the y axis by 1^0 increment up to $\theta=50^0$, allows a study of the dispersion relation in the $\vec{k}_x$ direction. The wavenumber resolution of the measurement was 8 cm^{-1}.

III. Results and Discussion

The SP's momentum conservation law [1] is given by

$$\vec{k}_{sp} = \vec{k}_x + i\vec{G}_x + j\vec{G}_y \qquad (1)$$

, where $\vec{k}_{sp}$ is the surface plasmon wavevector given by

$$\left|\vec{k}_{sp}\right| = \frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \qquad (2)$$

, here ω is the frequency of surface plasmon which is excited by incident radiation, $\vec{k}_x = \left|\vec{k}_0\right|\sin\theta$, $\left|\vec{k}_0\right| = 2\pi/\lambda$ is the wavevector of the incident radiation, λ is the wavelength measurement in vacuum. ε_1 is the dielectric constant of the interface medium, and ε_2 is that of the metal. $\vec{G}_x$ and $\vec{G}_y$ are the reciprocal lattice vectors for a square lattice with $\left|\vec{G}_x\right| = \left|\vec{G}_y\right| = \frac{2\pi}{a}$, and i, j are integers. For a normal incident light, $\vec{k}_x = 0$, Eq.(2) reduced to

$$(i^2 + j^2)^{1/2}\lambda = a\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \qquad (3)$$

Figures 1 and 2 show the zero-order transmission spectra at normal incidence with different squared hole size. The lattice constant *a* is 7 μm, square length L varies from 3.8 ~ 4.5 μm in Fig. 1, and a is 9 μm, square length L varies from 3.3 ~ 5.8 μm in Fig. 2. Figures 1 and 2 show that when the squared hole size is larger than the half of the lattice constant *a*/2, the degenerate (±1,0) Ag/Si and (0,±1) Ag/Si mode splits into two peaks at 25 and 30 μm, respectively. Different structure with different lattice constant exhibits the similar results. In Fig. 1, left and right peaks are degenerate modes composed of (0,±1) Ag/Si and (±1,0) Ag/Si modes, respectively. This is because when the normal incident light propagate through the sample, Bragg scattering of SPP's on periodic perforated hole arrays and different charge distributions in two standing wave (ω_+ and ω_-) will be estabished and cause different surface charge energy and the gap becomes wider [5-6]. This will cause the ω_+ and ω_- splits into two peaks. The transmission intensity of ω_+ becomes larger than ω_- when the hole size becomes larger. This is because the formation of a greater amount of surface charge density of ω_+ that can be tunnel through the periodic perforated hole arrays as compared toω_- with larger hole size, i.e. narrower metal line width. Figure 3 shows the SPPs dispersion relation with squared hole size L= 6, 5.8, 4.7, 4.3 μm, respectively. At normal incidence ($\theta=0^0$), there is fourfold degeneracy at 0.04 and 0.058 eV which comes from Ag/Si (±1,0) plus Ag/Si (0,±1), and Ag/Si (±1,±1), respectively. When increasing incident angle θ at x direction, the (1,0) Ag/Si mode will go to shorter wavelength , the (-1,0) Ag/Si mode will go to longer wavelength due to the SP's momentum conservation law. Similar results holds for (1, ±1) and (-1,±1) mode. At small θ, the (0, ±1) Ag/Si mode remains unchanged because of the sample is rotated around y axis. The contrast for transmission and the bright area of (1,0) Ag/Si changes to higher energy with larger squared hole size L, which indicates that the mode changes between (0,±1) Ag/Si and (-1,0) Ag/Si mode. Detailed transmission spectra at different angles are shown in Fig. 4 (a) and (b). The lattice constant *a* is 9 μm, square length L varies from 4.3 ~ 6 μm. When light incident angle increase as shown in Fig.4 (a), where the squared hole size is larger than the half of the lattice constant *a*/2, (0,±1) Ag/Si, (-1,0) Ag/Si and (1,0) Ag/Si mode will separate and the intensity of (0,±1) Ag/Si is larger than that of the (-1,0) Ag/Si and (1,0) Ag/Si. This is because $\vec{k}_{sp}$ (0,±1) lies in the (x,y) plane, $\vec{k}_{sp}$ (-1,0) and $\vec{k}_{sp}$ (1,0) lie in the x axis, when light incident angle at x direction increased, $\vec{k}_x$ increases. $\vec{k}_{sp}$ (-1,0) lying in the x axis will become less negative according to Eq. (1), $\vec{k}_{sp}$ (1,0) will become more positive, (-1,0) Ag/Si mode will shift to longer wavelength and lower energy, but opposite results holds for (1,0) Ag/Si mode. $\vec{k}_{sp}$ (0,±1) lie in the (x,y) plane, (0,±1) Ag/Si mode will go to shorter wavelength and higher energy. Surface charge field $\vec{k}_{sp}$ (-1,0) and $\vec{k}_{sp}$ (1,0) mode are formed more difficult than $\vec{k}_{sp}$ (0,±1) mode. At small incident angle at x direction, because of Bragg scattering results in both forward and backward SPP's waves that interfere to set up a two standing wave, the $\vec{k}_{sp}$ (1,0) is more difficult to be excited than that of the $\vec{k}_{sp}$ (-1,0) . Figure 4 (b) shows the transmission spectra when the squared hole size is smaller than the half of the lattice constant *a*/2, (0,±1) Ag/Si and (-1,0) Ag/Si mode will split up and the intensity of (-1,0) Ag/Si is larger than that of the (0,±1) Ag/Si at $\theta<10^0$. When $\theta>12^0$, the intensity of (0,±1) Ag/Si becomes larger than that of the (-1,0) Ag/Si and (1,0) Ag/Si mode appears. The (1,0) Ag/Si mode occurs at smaller angle in Fig. 4 (b) compared to larger hole size in Fig. 4 (a). Surface charge field of larger squared hole size $\vec{k}_{sp}$ (1,0) mode is formed more difficult than that of smaller squared hole size, and it needs more $\vec{k}_x$, i.e., larger θ, to support $\vec{k}_{sp}$ (1,0) mode. For some θ range, $\vec{k}_{sp}$ (-1,0) mode is easier to form as compared with $\vec{k}_{sp}$ (0,±1) mode, which indicate surface charge field changes between (0,±1) Ag/Si and (-1,0) Ag/Si mode.

IV. Conclusions

In conclusion, it is found that when the squared hole size is close to the half of the lattice constant a/2, the split of the degenerate the (0,±1) Ag/Si and (±1,0) Ag/Si modes into two peaks becomes apparent. Surface plasmon polaritons (SPPs) dispersion relations with different squared hole size were measured to investigate the different surface charge field at periodic metal array. The number of surface charge density of (0,±1) Ag/Si mode is larger than that of the (-1,0) Ag/Si mode with narrower metal line width. The transmission intensity of (0,±1) Ag/Si and (-1,0) Ag/Si is determined by which mode can stand more surface charge field.

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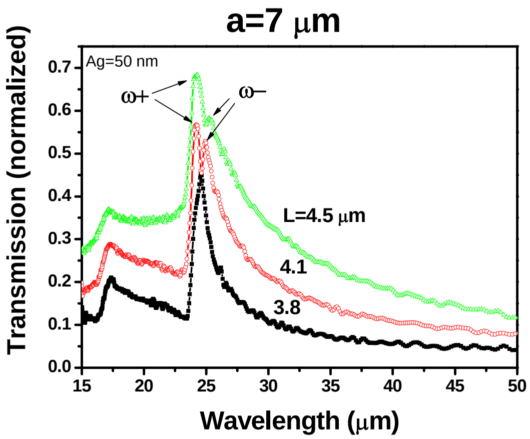


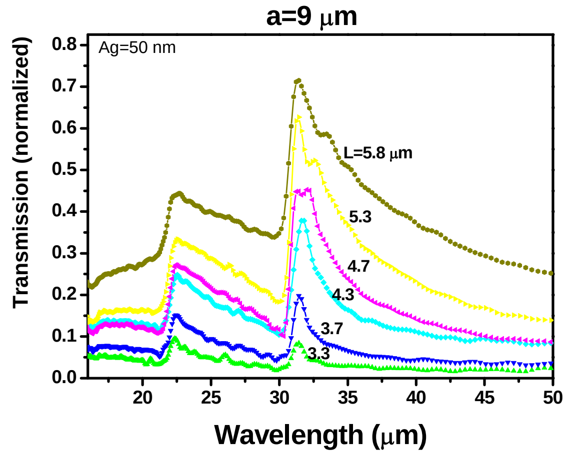
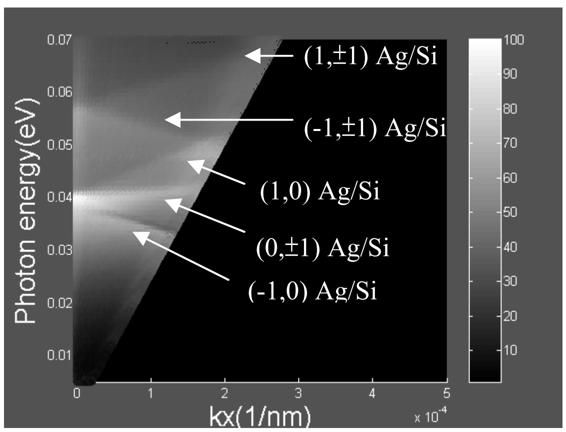
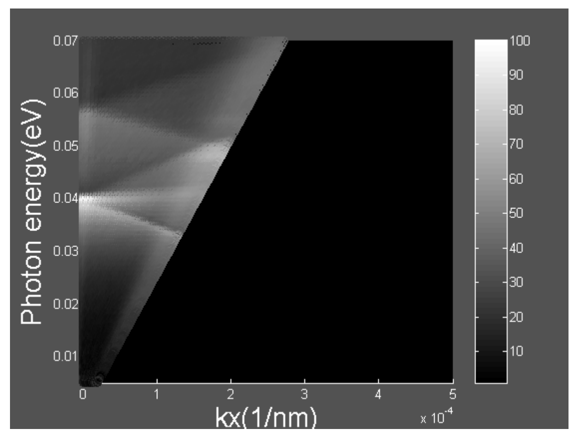


Fig. 1 Zero-order transmission spectra at normal incidence with different squared hole size. The Ag film thickness is 50 nm.

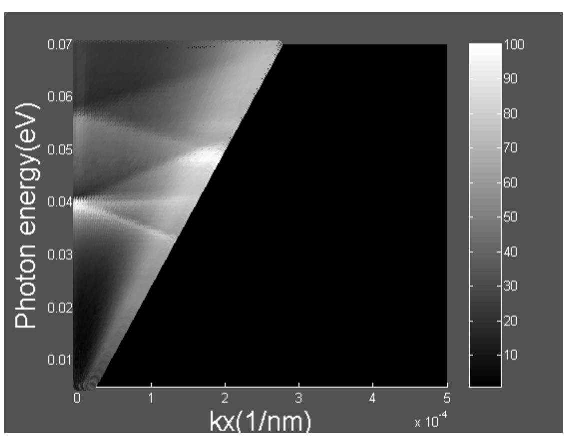
Fig. 2 Zero-order transmission spectra at normal incidence with different squared hole size. The Ag film thickness is 50 nm



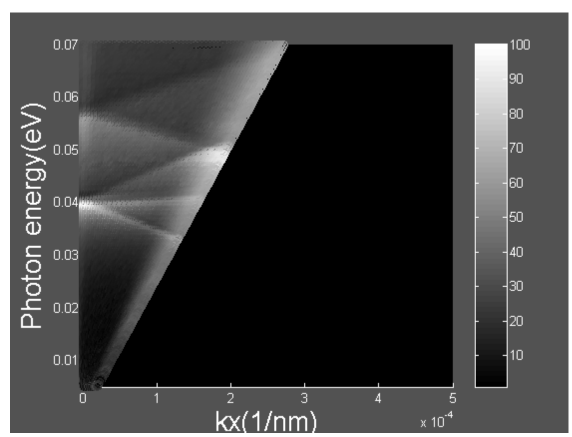
(a) a=9 μ m, L=6 μ m



(b) a=9 μ m, L=5.3 μ m

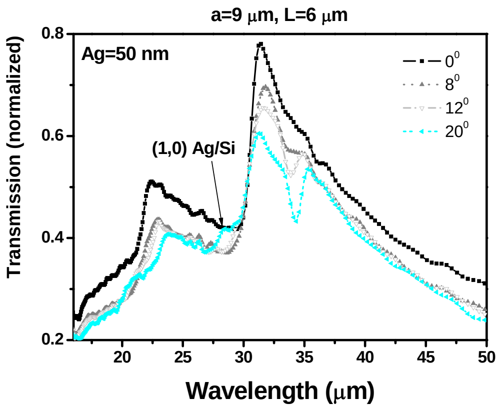


(c) a=9 μ m, L=4.7 μ m

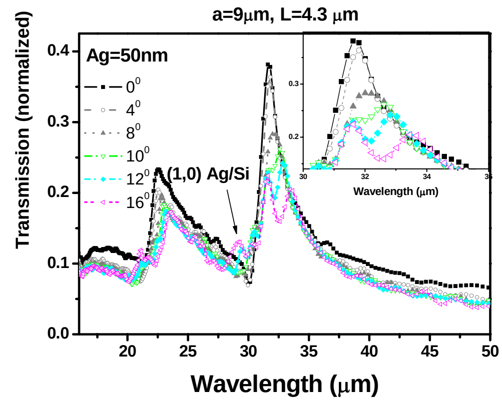


(d) a=9 μ m, L=4.3 μ m

Fig.3 Energy dispersion relation of SPPs, transmission intensity (gray scale) as function of photon energy and $\vec{k}_x$.



(a) Varies angle transmission spectra, a=9, L=6μm.



(b) Varies angle transmission spectra, a=9, L=4.3μm.

Fig. 4