Effect of silver film thickness on the surface plasma resonance in the rectangular Ag-Si-SiO₂ cavity

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Abstract
The effect of silver film thickness on the surface plasma resonance was investigated in the rectangular Ag-Si-SiO₂ cavity by FDTD. The resonant intensity, the quality factors and the extinction ratios, the intensity and the decay length of electric field, and the amplitude E₀ of far field Re(E) are closely related to the silver film thickness t, especially the electric field and the magnetic field at t ≤ 5 nm. By fine tuning the thickness of silver film, this structure can be used as wave filter and good laser resonator when t ≥ 8 nm, phase regulator when t ≤ 10 nm and electromagnetic field monitor of far field.

1. Introduction
The diffraction anomaly of the metal grating was found in the experiment and a new diffraction peak was observed in the normal diffraction angle distribution spectrum [1]. The peak of the diffraction spectrum is actually the result of the coupling between the diffraction pattern and the surface plasma of the metal surface [2]. When the high-energy electrons pass through the metal thin film, there is energy loss not only at the plasma frequency but also at the lower frequency, which is also related to the energy loss of the metal film [3], which is considered to be surface plasma resonance near the two interfaces. In parallel direction to the surface, the field can propagate. The surface plasma (SP) oscillation can easily be excited by the light waves from the far field. Surface plasma is a very interesting phenomenon. There are many directions worth studying and many exciting results. Since 1990 s, the surface plasma has been greatly concerned and has been applied to many fields, including biochemical sensing, solar cell, optoelectronic integrated devices [4–15].

As efficient and low cost effective noble metal nanomaterials (NMs), Ag NMs are considered as one of the most promising functional materials in electronic, chemical, bio-logical, solar cells and catalytic field [16–30]. In recent years, research on the surface plasma of silver/Si is very popular with researchers [16–25], such as sub-monolayer silver loss [17], photo absorption [18], fiber optic ethanol sensor [19], the blue light phosphorescent organic light emitting diodes [20], electron energy-loss spectroscopy [21], photoluminescence in the plasma coupling of the silvered silicon quantum dots [22] and surface plasma resonance [23, 24]. Plasma with silicon-based silver chips for protein and nucleic acid assay can enhance fluorescence imaging [25]. Absorption peak of ultrafine Ag NPs in SiO₂ nanosphere shifts [29]. The properties of surface plasmas (such as transmission reflection, etc) may be different while the structure size and shape of metal materials are different [10–33]. In recent years, the phenomenon of surface plasma has been paid great attention in different cavities with the shapes of square [34], rectangle [35], ellipsoidal plasmonic crystal [36], nanoring [37], nanobeam [38], microspheric [39], photonic crystal nanobeam [40] and GaAs 2D photonic crystal [41], in which Fano resonances can be observe. At present, most of the rectangular cavities are rectangular waveguide cavities of metal because of its wide use while there are relatively few reports about rectangular cavity that is composed of nanometal film and semiconductor as an optical device. Furthermore, the characteristics of plasma resonance in the cavity are also closely related to the structure of the cavity. For a cavity with one or a few sides in the nanometer range, not all sides have an effect on the surface plasma resonance of the plasma wave. So, in this paper, we will take rectangular cavity as an example to investigate the surface plasma resonance in Ag-Si-SiO₂ cavity under polarized light incident by Finite-Difference Time-Domain (FDTD) and explore the factor
affecting it, such as the thickness $d$ of the silver film in the rectangular cavity which is surrounded by silver film, two rectangular nanoscale silicons and silicon dioxide. From the resonant intensity and position of resonance wavelength, the quality factors and the extinction ratios, the intensity, electric field, and the width of rectangular silicon is $w = 25$ nm. The middle layer is composed of two small cuboid silicons with exactly the same size (30 nm high along y direction). The distances to the corresponding edges and that between the two silicons are $w_1$ and $w_2$. In this article, we set $w_1 = 175$ nm and $w_2 = EF = 600$ nm. Along the x direction, the symmetry point is located at $x = 0$, as is shown in figure 1(b). The bottom layer is silicon dioxide (1 $\mu$m long, 200 nm wide and 2 $\mu$m high along x, z and y direction, respectively). The medium outside the three materials is air. The rectangular cavity of region M (RCM) filled with air is named as guided-wave cavity. Periodic boundary conditions are applied along the x directions. A plane wave (polarized light) with the electric field parallel to the x axis illuminates normally the periodic structure. We use the non-uniform mesh and the minimum mesh size inside RCM was adjusted according to the actual situation. The devices with different silver film thickness of 3, 5, 8, 10, 15 and 20 nm are labeled as letters A, B, C, D, E and F.

2. Simulated device

Figure 1(a) is the Ag-Si-SiO$_2$ schematics of simulated device with periodic structure of transversal translation. The upper layer is covered with Ag film. The length along the x direction is $l = 1 \mu$m and the width along the z direction is 200 nm. The adjustable thickness along the y direction of the Ag film is $d$ (3, 5, 8, 10, 15 and 20 nm) and the width of rectangular silicon is $w = 25$ nm. The middle layer is composed of two small cuboid silicons with exactly the same size (30 nm high along y direction). The distances to the corresponding edges and that between the two silicons are $w_1$ and $w_2$. In this article, we set $w_1 = 175$ nm and $w_2 = EF = 600$ nm. Along the x direction, the symmetry point is located at $x = 0$, as is shown in figure 1(b). The bottom layer is silicon dioxide (1 $\mu$m long, 200 nm wide and 2 $\mu$m high along x, z and y direction, respectively). The medium outside the three materials is air. The rectangular cavity of region M (RCM) filled with air is named as guided-wave cavity. Periodic boundary conditions are applied along the x directions. A plane wave (polarized light) with the electric field parallel to the x axis illuminates normally the periodic structure. We use the non-uniform mesh and the minimum mesh size inside RCM was adjusted according to the actual situation. The devices with different silver film thickness of 3, 5, 8, 10, 15 and 20 nm are labeled as letters A, B, C, D, E and F.

3. Results and discussion

Figure 2 shows reflectance spectra of region R in Ag-Si-SiO$_2$ with different thickness $t$ of silver nanofilms. The lowest reflectivity is located at around 1321 nm for A and C-F and at about 1374 nm for B, respectively. The higher the reflectivity is, the less the electron absorbs. The reflection peak is also called the resonance absorption peak and each peak corresponds to a vibration mode ($m_j, j = 1, 2, 3$). The position of the resonance mode is related to the thickness of the silver film. There are three resonance modes ($m_j, j = 1, 2, 3$) for A and B and two modes ($m_j, j = 1, 2$) for C-F. The modes $m_1$ are at about 1192 nm. The location of the mode $m_2$ of B (at about 1252 nm) is different from those of the other five (at about 1321 nm). Especially, when $t = 3$ nm and 5 nm the modes $m_3$ are observed at 1347 nm and 1584 nm, respectively. The resonance intensity of the modes ($m_j, j = 1, 2, 3$) increase with the increase of the silver film thickness. The results above show that the silver film has the characteristic of selective absorption to the incident light. The greater the thickness of the silver film is, the more
obvious the choice of absorption is. The device and rectangular cavity with thicker silver film \((t \geq 8\ \text{nm})\) can be used as wave filter and good laser resonator.

Under the incidence of near-infrared polarized light, the transmittance spectrum in RCM is shown in figure 3. In the simulated normal-incidence transmission spectrum, three resonant modes can be observed for the films of 3 nm and 5 nm and two resonance modes in the other four films. The location of mode \(m_1\) is also independent of the thickness of silver films and those of the modes \(m_j\) \((j = 2\ \text{and} \ 3)\) are closely related to the silver film thickness. The absorption of the three modes increases with the increase of the silver film thickness, which is the same as in figure 2. The surface plasma resonance mode is related to many factors, such as the size, structure and type of the materials, polarization angle, Fermi energy and magnetic resonance, etc [36–41]. In this paper, the sharp resonances mainly come from surface plasma polarization, which is electromagnetic excitation at the interface between a metal and a dielectric material [42].

The quality factor \((Q)\) and the extinction ratio can be calculated according to the main peak of the resonance. A high-quality factor means lower light energy loss in a resonant cavity. Moreover, the better the extinction ratio is, the better the quality of the resonator is. For the different RCMs with the film thickness of 3, 5, 8, 10, 15, and 20 nm, the quality factor \(Qs\) are about 50, 21, 77, 82, 91, and 91, respectively. The Exts obtained are around 1.3, 5.0, 5.8, 6.9, 7.6 and 8.3 dB, respectively. These results show that the quality factor \(Qs\) and the Exts are a function of the thickness of the silver film. Except the silver films of 3 nm and 20 nm, the quality factor increase with

**Figure 2.** Reflectance spectra of region R in Ag-Si-SiO\(_2\) with different nano silver films thickness \((3\ \text{nm}, 5\ \text{nm}, 8\ \text{nm}, 10\ \text{nm}, 15\ \text{nm}\) and \(20\ \text{nm})\).

**Figure 3.** The relationship between the transmittance of the middle region RCM and the thickness of the silver film under the incidence of near infrared light.
increment of the silver film thickness. So is for the variation of the extinction ratio in this study. That is to say, the resonator of \( F \) is better than those of \( A-E \).

In addition, those resonance modes in figure 3 can be verified by the distribution of the electric field, as is shown in figure 4(A). Because the vibration intensity of the mode \( m_1 \) is much weaker than that of the other two modes in \( B \), the mode \( m_2 \) is not shown in the electric field distribution diagram. The resonant intensity at about 1191 nm increases with the increment of silver film thickness. In the other five RCMs except \( B \), we can observe a resonant mode at about 1321 nm whose intensity also increases with the increment of the thickness of silver films. Obviously, in RCM (the region between the two dark line at \( x = -0.3 \) \( \mu \text{m} \) and \( x = 0.3 \) \( \mu \text{m} \)), the maximum intensity of electric field is located around the right and left sides of the rectangular silicon. The intensity of the electric field is related to the thickness of the silver film. The intensity of the electric field gradually diminished with the increment of silver films thickness. Meanwhile, the electric field is symmetric distribution on the local field center \( (x = 0) \), whose location is related to the position of two rectangular silicon. The phase shift can be obtained according to the distribution of electric field. In this study, phase shift \( \Delta \varphi \) may be approximately expressed as \( \Delta \varphi = \frac{2\pi}{\lambda} D \), where \( \lambda \) is resonance wavelength of surface plasma and \( D \) is the distance from the rectangular silicon to the symmetry center \( x = 0 \), as is shown in figure 1(b). The phase shifts of \( E \)-field are around 0.38\( \pi \) for \( A \), 0.44\( \pi \) for \( B \) and 0.46\( \pi \) of \( C-F \), which shows that the plasma resonance wavelength can be obtained by measuring the phase shift according to the electric field distribution and the rectangular

Figure 4. The electric field distribution of silver thin films with different thickness (a) 3 nm (b) 5 nm (c) 8 nm (d) 10 nm (e) 15 nm and (f) 20 nm. in RCM region (A) and in reflection region (B), respectively.
resonator can be used as a phase regulator when $t \leq 10$ nm. Figure 4(B) shows the distribution of the electric field in the reflecting region. With the increase of silver film thickness, the electric field on silver surface becomes weaker. This results indicates that the increase of the thickness of the silver (a plasma) film causes the surface plasma wave enhancement and the electric field near the silver surface decreases under the excitation of polarization wave. In addition, the increase of the surface plasma wave will cause the increase of plasma resonance frequency or resonance wavelengths decrease, which can be the main cause of mode m3 blue shift in figures 2 and 3 for devices A and B, respectively.

Furthermore, in the vertical direction at two horizontal positions, it can be seen clearly that the exponential decayed E-fields are in the range from the position $-150$ nm (or $150$ nm) to $x = 0$ in each cavity RCM, as is shown in figure 5. The decay length is defined as the variation of the wavelength when the intensity drops to $1/e$ of the maximum intensity. Figure 5(A) shows that the electric field is indeed tightly confined near $x = \pm 150$ nm along the Ag layer, whose decay lengths are about $80.9$ nm, $74.9$ nm, $104.5$ nm, $110.9$ nm and $110.9$ nm for A-F, respectively. These indicate the decay length is dependent of the thickness of silver film. In addition, it is obvious that the intensity of the electric field gradually decreases with the thickness increase of silver film, which is
consistent with the results of figure 4. Figure 5(B) indicates the farfield of electrical field in RCM with different thickness of silver film. The maximum amplitude $E_0$ (the dash line shown) of Re(E) gradually decreases with the increment of the thickness $t$ from 3 nm to 10 nm and then tends to be stable. The relationship between $E_0$ and $t$ can be approximated by an exponential decay curve: $E_0 = 9.17 + 22.5\exp(-t/2.45)$. The position of maximum amplitude is located at about $\theta_0 = -1^\circ$. As a result, the expression of the far field near the surface of silver film in RCM can be approximately expressed as: $\text{Re}(E) = (9.17 + 22.5\exp(-t/2.45))\cos(\theta + 1)$, where $\text{Re}(E)$ is the
real part of the far field of electric field. These results show that the far field of electric field can be monitored by adjusting the thickness of silver film and polarization angle.

Figure 6 shows the magnetic field distribution of silver thin films with different thickness (a) 3 nm (b) 5 nm (c) 8 nm (d) 10 nm (e) 15 nm and (f) 20 nm in reflection region (A) and in RCM region (B), respectively. The distribution of magnetic field tends to be stable when the film thickness $t$ is no less than 8 nm, as is shown in figure 6(A). Except the film of $t = 5$ nm, the magnetic field is weak on the two sides and strong in the middle (right above at $x = 0$). As the distribution of the electric field, the resonance mode can be obtained by the distribution of the magnetic field. The distribution of magnetic field and electric field are complementary. The strongest magnetic field is located in the local electric field and the strongest electric field is lied in the local magnetic field. The strongest magnetic field is in the middle of the rectangular cavity RCM. Moreover, it can be obtained that the magnetic intensity gradually weakens with increasing of silver film thickness in RCM, as is shown in figure 6(B).
4. Conclusions

In summary, after the effect of silver film thickness on the surface plasma resonance was investigated in the rectangular Ag-Si-SiO₂ cavity by FDTD, a series of results have been obtained. The intensity of the resonance mode increases with the increase of the silver film thickness. The quality factor is closely related to the thickness of the silver film and the Exts increase with increment of the silver film thickness. The intensity of electric field and the strongest magnetic field gradually diminished with the thickness increment of silver films and the decay length of electric field is closely dependent of the thickness of silver film. The relationship between the maximum amplitude $E_0$ of $\text{Re}(E)$ and $t$ can be approximated by an exponential decay curve: $E_0 = 9.17 + 22.5\exp(-t/2.45)$ and the expression of the far field near the surface of the silver film RCM can be approximately expressed as: $\text{Re}(E) = (9.17 + 22.5\exp(-t/2.45))\cos(\theta + 1)$. This structure can be used as wave filter and good laser

Figure 6. (Continued.)
resonator when $\tau \geq 8$ nm, phase regulator when $\tau \leq 10$ nm and electromagnetic field monitor of far field whose electromagnetic field near the silver film can be effectively changed by fine tuning the thickness of silver film.

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