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带状波导表面等离子激元的透射特性

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摘　要:为了深入探讨带状波导的表面等离子激元透射特性,采用衍射光栅耦合方式实现表面等离子激元激发,通过改变金属薄膜厚度和入射光角度,得到薄膜厚度、入射光角度与透射率的变化特性.结果表明:金属薄膜厚度的减少会导致透射带宽迅速降低,同时透射率也随之降低;而入射光角度的改变导致透射光效率的变化.这一研究对于半导体设备的纳米等离子激元耦合具有一定的意义.

关键词:表面等离子体;带状波导;仿真;光栅;金属薄膜
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Transmission Characteristics of Surface Plasmon Polariton Based on Strip Structure

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Abstract: In order to depth study transmission characteristics of surface plasmon polariton based on strip structure, surface plasmon polariton excitation was achieved by using grating coupling. The transmission characteristics which is relation to film thickness and incident angle were obtained though adopting to change he metal film thickness and angle of incident light. The results show that reduction of the metal film thickness will result in rapid transmission bandwidth reduction to a lower transmission rate. Moreover, the incident light angle changes as the efficiency of light transmission varies. The results are significant of nanoplasma polarization couple of semiconductor equipment research.

Key words: Surface plasmon polariton; Strip waveguide; Surface plasmon; Simulation; grating; Metal film
OCIS Codes: 160.3918; 140.39480 160.4236

0 Introduction

Surface Plasmon Polaritons (SPP) are transverse electromagnetic waves that are supported by and coupled with electromagnetic oscillation in a metal-dielectric surface. They are a form of a resonance that propagates along this interface. Research on SPP applications has rapidly developed in recent years[1-2]. In nano-circuits, SPPs exhibit a series of significant properties, such as resonance, amplification, localization, and subwavelength restrictions. Thus, SPPs may be applied in spectroscopy, nano-optics, imaging, bio-sensing, and many other fields [3-8]. Metal-Insulator-Metal (MIM) waveguides with single subwavelength apertures based on optical Surface Plasmon (SP) have ganed significant research attention because of their low transmission loss. Radko et al. reported Au doped Polymethyl Methacrylate (PMMA) with a PbS quantum dot structure and predicted that the transmission length of SPPs increases by 32% [9].

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Chen et al. simulated a Au-InGaAs-Au structure and presented the SPP lossless transmission and performance of nano-ring lasers when the thickness of this structure is 75 nm. Grandidier et al. studied Ag film doped PMMA stripes and analyzed the propagation of SPPs. Robert et al. [9-10] injected Au into the SiO_2 substrate and formed an SP metal channel, as also acquiring an SP waveguide in the process. The SP on the metal membrane surface of the structure can also be coupled to form long range SPPs (which have smaller decay and can be used in SPP amplifiers and lasers). Yano et al. [11] published Raman scattering techniques related to SPP in Nature magazine in 2009, the probe spatial resolution of these techniques reached 80%. Volkov et al. [12-13] combined SP waveguides and nano-focusing technology to yield a fivefold increase in light signal enhancement. Through these technologies, the transmission loss of SPPs is compensated and propagates long. Nevertheless, researchers have discovered that the coupling properties of SPP obstruct its propagation and thus need improvement. [14-17] In this paper, we propose a new type of band waveguide structure and analyze the transmission property of SPP to realize SP waveguide integration, we get transmission characteristics which is relation to film thickness and incident angle though adopting to change the metal film thickness and angle of incident light.

2 Theory model of stripe SPP

Fig. 1 shows the electric field distribution of SPPs in the metal-dielectric interface. The magnetic field (***H***) is along the y direction and the electric field ***E*** is vertical to the surface. SPPs can only couple with TM (p) and not with TE(s). By analyzing the dispersion properties of SPPs, their excitation conditions can be acquired. Using certain boundary conditions for solving Maxwell's equations, the relevant dispersion equation can be obtained.

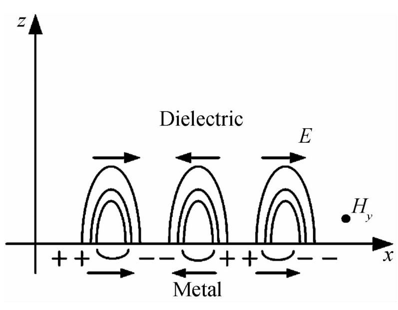

Fig. 1 Curve of SPP propagation characteristics

2.1 Structural analysis

As shown in Fig. 2, the structure design uses a diffraction grating embedded in the metal layer to couple and stimulate SPP. In Fig. 2(b), the incident wave is p-polarized (magnetic field vector along a dimension grating of narrow sewing direction), the diffraction grating is located in the x-y plane, d is the period, a is the metal grating blade spacing, and the grating axis is vertical to the y axis. The period grating is embedded in a high permittivity waveguide, electromagnetic waves are polarized in the x axial electric field; finally, the plasma in the outer surface of the metal is obtained [13,15]. The angle p-polarized microwave, the incidence angle of which is θ, is coupled to the SPP through a diffraction grating, and strong absorption and scattering peaks appear in the spectrum bandwidth [16]. The period grating arrangement provides momentum, and coherent scattering surface plasmon resonance is coupled to the waveguide mode [17]. A coupled waveguide mode is formed and tuning is achieved by plasma resonance. For a given waveguide thickness t, the grating period can determine the coupling frequency. We have calculated the resonance frequency of local SPPs and obtained system and plasma density parameters by changing the grating size and the dielectric permittivity.

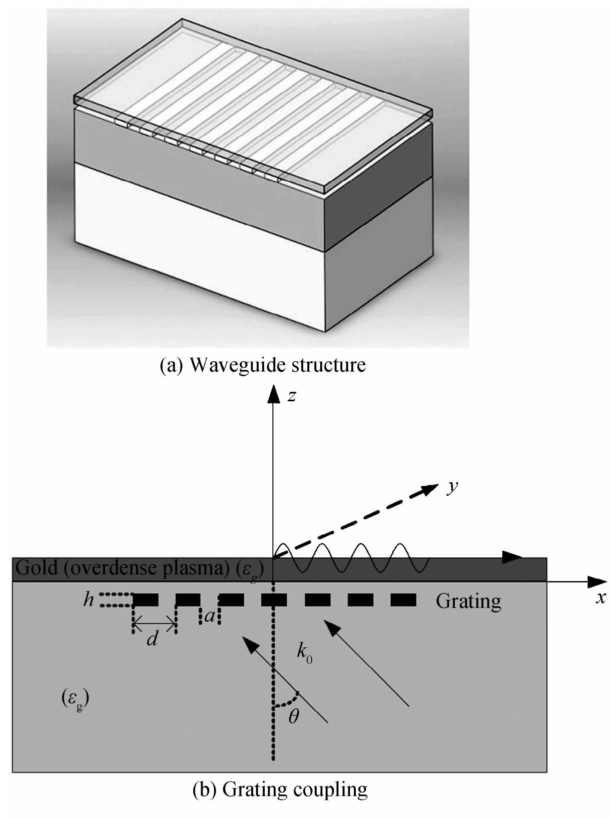

Fig. 2 Model of the grating-embedded strip waveguide

2.2 Theoretical model analysis

Assume that the incident electromagnetic waves can cause total reflection in the grating-dielectric surface and that the evanescent wave, the wave vector k_x of which is equal to the vector of total reflection of electromagnetic waves tunneling into the dielectric, which is stimulated by incident electromagnetic waves through the grating, propagates along the x direction [19]. When the distance between the grating and the plasma surface is sufficiently small, part of the evanescent wave tunnels into the glass-plasma surface ($z=0$). If the resonant coupling condition of SPPs is $k_x=k_{sp}=k_0\sqrt{\varepsilon_g\varepsilon_p/(\varepsilon_g+\varepsilon_p)}$, we can get

$$\frac{\omega}{c}\sin\theta_0\pm vg=\frac{\omega}{c}\sqrt{\frac{\varepsilon_p}{\varepsilon_p+1}}=k_{sp} \tag{1}$$

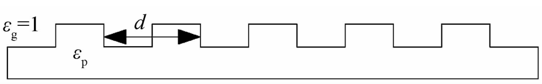

Fig. 3 Model of metal grating

Fig. 3 shows a schematic diagram of the metal grating. Assume $\varepsilon_g=1$ and $\frac{\omega}{k}\sqrt{\frac{\varepsilon_p}{\varepsilon_p+1}}=k_{sp}$, where $\frac{\omega}{c}\sin\theta_0=k$, v is a positive integer, and $g=2\pi/d$. When the metal film thickness is t, the permittivity and permeability are ε_1 and μ_1, respectively, in the $z<0$ section, ε_2 and μ_2, respectively, in the $0<z<t$ section, and ε_3 and μ_3, respectively, in the $z>t$ section. For surface plasmons, which are simulated by TM polarization of electromagnetic waves, the electric and magnetic fields can be expressed as follows

$$\boldsymbol{H}^{(1)}=(0,H_{1y},0)\mathrm{e}^{-\mathrm{i}k_{1z}z}\mathrm{e}^{\mathrm{i}(k_x x-\omega t)},z<0 \tag{2}$$

$$\boldsymbol{E}^{(1)}=-\frac{H_{1y}}{\omega\varepsilon_0\varepsilon_1}(k_{1z},0,k_x)\mathrm{e}^{-\mathrm{i}k_{1z}z}\mathrm{e}^{\mathrm{i}(k_x x-\omega t)},z<0 \tag{3}$$

$$\boldsymbol{H}^{(2)}=[(0,H_{2y}^{+},0)\mathrm{e}^{-\mathrm{i}k_{2z}z}+(0,H_{2y}^{-},0)\mathrm{e}^{-\mathrm{i}k_{2z}z}]\cdot \mathrm{e}^{\mathrm{i}(k_x x-\omega t)},\ 0<z<t \tag{4}$$

$$\boldsymbol{E}^{(2)}=-\frac{1}{\omega\varepsilon_0\varepsilon_2}[H_{2y}^{+}(-k_{2z},0,k_x)\mathrm{e}^{-\mathrm{i}k_{2z}z}+ H_{2y}^{-}(k_{2z},0,k_x)\mathrm{e}^{-\mathrm{i}k_{2z}z}]\mathrm{e}^{\mathrm{i}(k_x x-\omega t)},\ 0<z<t \tag{5}$$

$$\boldsymbol{H}^{(3)}=(0,H_{3y},0)\mathrm{e}^{-\mathrm{i}k_{3z}z}\mathrm{e}^{\mathrm{i}(k_x x-\omega t)},\ z>t \tag{6}$$

$$\boldsymbol{E}^{(3)}=-\frac{H_{3y}}{\omega\varepsilon_0\varepsilon_3}(-k_{3z},0,k)\mathrm{e}^{-\mathrm{i}k_{3z}z}\mathrm{e}^{\mathrm{i}(k_x x-\omega t)},\ z>t \tag{7}$$

where $k_{az}=\left[\varepsilon_a\left(\frac{\omega}{c}\right)^2-k_x^2\right]^{1/2}$; $\alpha=1,2,3$. Through analysis of the boundary conditions of the electromagnetic field at $z=0$ and $z=t$, nonzero solutions at $(0,t)$ may be obtained

$$(\varepsilon_2k_{1z}+\varepsilon_1k_{2z})(\varepsilon_3k_{2z}+\varepsilon_2k_{3z})+(\varepsilon_2k_{1z}-\varepsilon_1k_{2z})\cdot (\varepsilon_3k_{2z}-\varepsilon_2k_{3z})\mathrm{e}^{\mathrm{i}2k_{2z}}t=0 \tag{8}$$

Surface plasmon resonance frequency of stripe waveguide

$$\omega=\frac{\omega_{pe}}{\sqrt{1+\omega_1}}\left(1\pm\frac{2\varepsilon_1}{1+\varepsilon_1}\mathrm{e}^{-k_x t}\right) \tag{9}$$

For dielectric films surrounded by a medium, the surface plasma resonance frequency, which is stimulated by coupling effects, decreases as the sheet thickness increasest. For SPP stimulation, this result is a generalization.

3 Simulation results and discussion

Fig. 4 shows the SPP vibrations of this structure in Courant, Friedrichs, and Lewy (CFL) conditions. In the $z=0$ plane, the collective oscillation of free electrons is in the dozens of nanometers range and close to the border, hence the oscillation effect is more obvious. Research indicates that as the medium thickness increases, the transmission rate gradually decreases and the transmission bandwidth narrows, which the metal film of outgoing light field is weak and disperse to all direction, surface plasma stimulated by period grating has compensated the near-field intensity of metal film surface, while surface wave from the metal film and surface plasma in translucent structure are in phase interference, and produces transmission phenomenon.

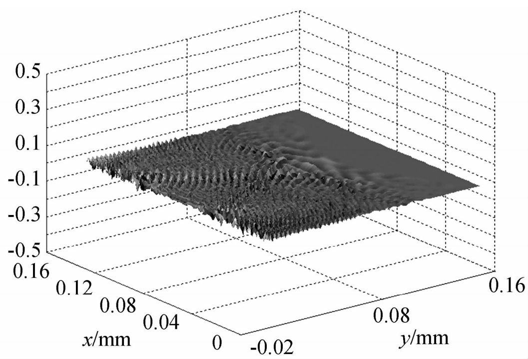

Fig. 4 Schemes of SPP vibration

As shown in Fig. 5, when the metal medium thickness decreases, the transmission bandwidth is quickly reduced and the transmission peaks are gradually reduce.

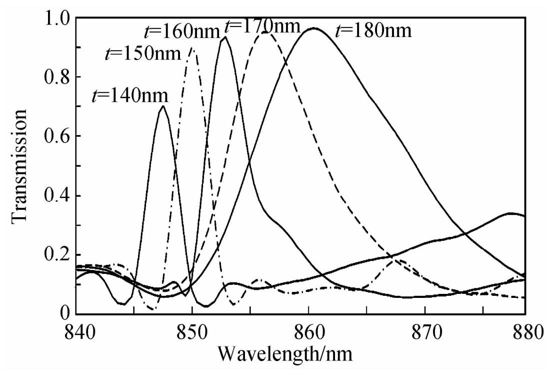

Fig. 5 Transmission rate

When the incident light has different angles $\theta=0°$, $30°$, $60°$, and $90°$, the scattered light intensity may change and the transmitted light efficiency may differ. When the propagation loss of the plasma wave is considered, the transmission efficiency is defined as the ratio between the output light intensity from the metal film and the incident light intensity. The expression of transmission efficiency f is

$$f=[1/(1+e^{-l/L}I_{in}/I_{out})][(P_{in}-P_{out})/P_{in}] \quad (10)$$

where l is the grating length, L is the length of the plasma wave, I_{in} is the light intensity of the metal film collection, and I_{out} is the output light intensity. When the dielectric thickness is 140 nm, 160 nm, and 180 nm, transmission efficiency decreases as θ increases, as shown in Fig. 6.

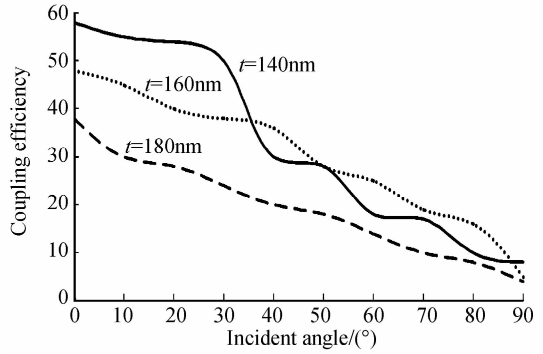

Fig. 6 Curve of transmitted light efficiency

4 Conclusion

When the sheet metal thickness is nanoscalar in nature, the SPPs of the electromagnetic field are distributed on both sides of the metal. In the dielectric system of the sheet metal, the transmission rate varies as the metal film thickness changes. When the metal film thickness decreases, the transmission bandwidth becomes significantly narrower and the transmission peak is lower. The effect of grating-coupled, causes the ratio of output light intensity from both sides of the metal film as well as the incident light intensity to change as the incidence angle changes. When the film thickness is 140 nm and the incident light is vertical to the metal thin film, light transmission efficiency is highest.

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