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Optical Excitation of Surface Plasmon Polariton in Thin Gold, silver and Copper Metal Layers and Measuring the Metal Layer

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Abstract

In this paper, we employed the attenuated total reflection (ATR) technique to theoretically and experimentally measure the thickness of metal thin films and compare together them. The computations of the present study were carried out using characteristics matrix method. The ATR technique is based on the excitation of surface polaritons. In the ATR spectra, the surface polaritons manifest themselves as sharp reflectivity minima. We used this minimum to measure the thickness of a silver layer coated on the surface of a prism. We observed that the measured value has a good agreement with the real thickness of the layer

Keywords: Attenuated Total Reflectance (ATR), Reflection spectrum, Surface Polaritons , Surface Waves , Transfer Matrix

1. Introduction

Surface plasmons are excited the collective oscillations of the electron gas at the interface of metal – dielectric [1]. Oscillation of electrons in the common border of two media is coupled with an electromagnetic field. This electromagnetic field is called surface polariton which has a maximum value at the surface of metal and decays exponentially with away from the surface. Having a maximum field at the interface between the two media made surface polariton as very sensitive and proper tool for studying the physical and optical properties of the surface [2]. Surface polariton at the interface between two media are excited only when the dielectric displacement vector has a component normal to the surface. In this case, the dielectric displacement vector can induce the below surface charge density [3]:

$$\left(\vec{D}_m - \vec{D}_d\right).\hat{z} = 4\pi\sigma \qquad (1)$$

Where z unit vector is perpendicular on the interface between the two media and d and m respectively represents the dielectric and the metal media. If the incident light is as a transverse electric wave with TE polarization, in this case, this can't excite the surface modes; because the electric field has not a normal component on the common interface of these two media. But transverse magnetic wave with TM polarization can be couple with surface polaritons [4]. Because of in this polarization, the electric field has a normal component to the interface of two media. Excitation of surface polaritons can occur in several ways. The easiest way is optical excitation to excite surface polaritons at the thin metal layers [5, 6]. Since the surface modes aren't propagated in the perpendicular direction to the interface, so these excitations couldn't establish by a light beam which directly radiate with the metal surface. To excite the surface plasmons on the metal surface, the incident light with linear polarization under the suitable angles respect to the surface should be radiated. Also a grating and prism should be used to match the momentum of incident light with surface plasmons polarization momentum [7]. The basic condition for the formation of a transverse magnetic surface waves is given by the following equation [8, 9]:

$$\frac{k_{zd}}{k_{zm}} = -\frac{\varepsilon_d}{\varepsilon_m} \qquad (2)$$

This equation is established when the electrical permittivity of two environments have opposite signs. Therefore it is possible to excite surface polaritons in metal - dielectric border.

2. Excitation of Surface Polaritons by Light

To excite the surface polaritons is used a prism such as arrangement of Figure (1). In this arrangement, a light beam with linear polarization is radiated under the θ angle as perpendicular to the surface of the prism coated metal layer. Under these conditions, the parallel component of the wave vector of the incident beam to the surface is:

$$k_x = \frac{\omega n_p}{c} \sin\theta \qquad (3)$$

Where n_p and θ are the refractive index of the prism and the incident beam angle. While the angle of incident beam is larger than the critical angle, so the parallel component of the momentum of the incident photons is large enough to allow excitation of surface modes. With the proper choice of the incident angle, in this case the reflected light from the boundary of the prism and the metal is included to the Attenuated Total Reflection (ATR), and reflectivity of the system largely decreases [10]. Under these conditions, the parallel component of the momentum of the incident photons will be equal to the momentum of surface waves which is given by the following equation:

$$k_{xspw} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \cdot \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \qquad (4)$$

3. Experimental arrangement to observe atr spectra by the Prism

One of the ways that have been proposed to excite of surface polaritons was prism – metal – air Kretschmann experimental configuration [11]. In this arrangement i.e. Figure (1) the first dense environment is a prism, the second, metal layer and the third is dielectric (air) environment. In this arrangement, incident photons aren't coupled directly to the interface of metal and dielectric. But those are coupled by the damped field caused by total internal reflection using the prism by with high refractive index on the boundaries of metal – dielectric. In this case, the value of electric permittivity of the prism medium is larger than the dielectric medium. So the incident light photons momentum was larger than the direct radiation momentum on the surface of the metal and in particular spectral region can provide necessary momentum to excite surface polaritons on the boundary of metal – dielectric. However, with choosing the appropriate incident beam angle (θ) the best resonant coupling raised between the photons of damped field and surface modes. Experimentally, this measured reflectivity spectrum of resonance coupling of the prism manifest itself as a sharp minimum in the reflectivity spectrum [12-16].

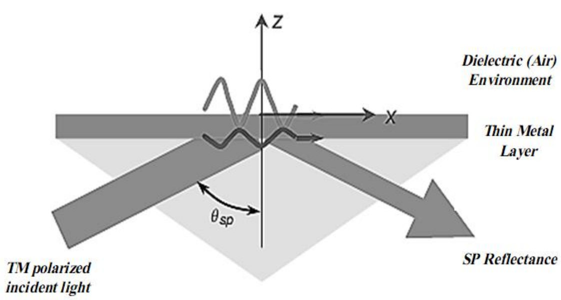

Fig.1. Experimental arrangement of Kretschmann to excite surface plasmon

Reflectivity spectra can be obtained using the transfer matrix [17]. For this arrangement i.e. Figure (1) the intensity of reflectivity is given as following:

$$M = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}^{-1} \begin{bmatrix} 1 & 1 \\ \dfrac{-i\varepsilon_p k_{mx}}{\varepsilon_m k_{px}} & \dfrac{i\varepsilon_p k_{mx}}{\varepsilon_m k_{px}} \end{bmatrix} \times \begin{bmatrix} e^{k_{mx}a} & e^{-k_{mx}a} \\ e^{k_{mx}a} & e^{k_{mx}a} \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ \dfrac{i\varepsilon_m k_{dx}}{\varepsilon_d k_{mx}} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} E_i \\ E_r \end{bmatrix} = M \begin{bmatrix} E_t \\ 0 \end{bmatrix}$$

$$r = \frac{E_i}{E_r} = \frac{M(2,1)}{M(1,1)} \Rightarrow R = |r|^2$$

Where p and a respectively represents the prism environment and the metal layer thickness and k_d, k_m, k_p are respectively the wave vector in the dielectric, metal and prism environments. Also M is the total transfer matrix and E_t, E_i, E_r are respectively the transmitted, incident and reflected electric field amplitudes.

4. Reflectivity spectra of copper, silver and gold metals theoretically and comparing them

In this section we presented the reflectivity spectra diagrams using the experimental configuration of Kretschmann for the incident wavelength of 4348 Å for different thicknesses of thin layers of copper, silver and gold coated onto the surface of a prism against to scanned radiation angles separately [18,19]. In these diagrams we observed that the minimum intensity of reflectivity occurs in incident angles when the phase velocity of incident radiation is parallel to the x-axis is coupled with the phase velocity of surface modes. Measuring width and depth of the minimum reflectivity present respectively the losing and the excitation intensity. Losses of surface plasmons are as a result of losses of phonon electron oscillations mechanism into the metal and reflecting into the prism environment. When surface modes amplitudes will be exponentially damped into the metal toward the prism, radiation losses occur. Because of it has an emission component in the direction of z inside the prism environment, as a result of radiative losses, it will be influenced by the thickness of the metal layers.

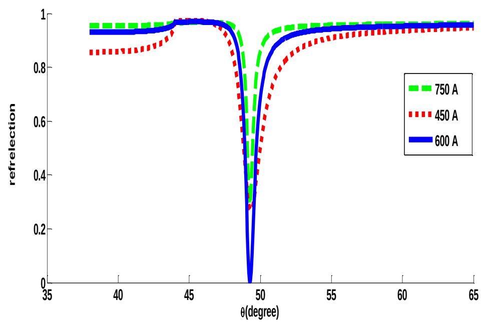

Fig.2.Reflectivity diagram of Kretschmann arrangement is based on radiation angle for different values of thickness 450, 600, 750 Å of silver film with -6.250+i 0.201 permittivity index coated on the prism for the wavelength of 4348 Å in which arrangement, the refractive index of prism is 1.44. The best coupling is observed in this wavelength for the thickness of 600 Å and angle of 48.87 °

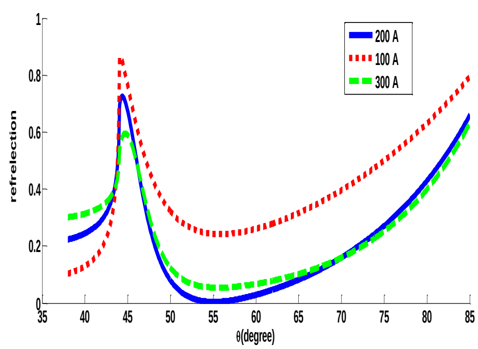

Fig.3. Experimental arrangement for measuring the intensity reflectivity arrangement is based on radiation angle for different values of thickness 100, 200, 300 Å of copper film with -3.842+i 5.799 permittivity index coated on the surface of a prism for wavelength 0f 4348 Å in which arrangement, the refractive index of prism is 1.44. The best coupling is observed in this wavelength for thickness of 200 Å and angle of 55.27 ° .

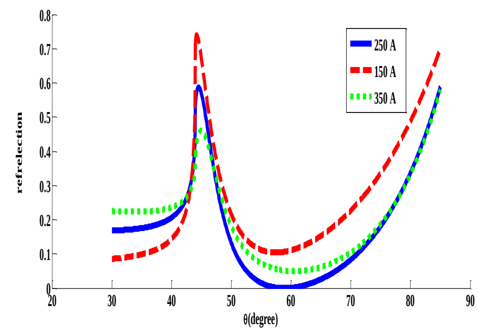

Fig.4. Reflectivity diagram of Kretschmann arrangement is based on the radiation angle for different values of thickness 150, 250, 350 Å of gold film with -1.701+i 5.594 permittivity index coated on the surface of a prism for wavelength 0f 4348 Å .In this arrangement the refractive index of prism is 1.44. The best coupling is observed in this wavelength for thickness of 250 Å and angle of 58.87 ° .

Comparing the above diagrams with each other and also with consider to width size and depth of the minimum of the reflectivity spectrum, respectively present losing and intensity of excitation, therefore, it is concluded that silver metal has less loss than other metals, and greater intensity of excitation and the reflectivity appears better in this metal.

5. Experimental measurement of Silver Metal Thickness

The In this experiment, at first the refractive index of a prism with apex angle of 60 was measured by diode laser with a blue light with wavelength of 4348 Å accurately and the value of 1.44 was obtained. Then an aspect of a prism is coated by a layer of silver metal. Using the arrangement shown in Figure (5), we radiated light with TM polarization of

blue laser on the prism. Incident angles were scanned with specified step size accurately. For scanned angles, the intensity of reflectivity
was measured by an optical detector (photo detector). It continued until at a specific angle, a sharp drop was observed in reflectivity system.

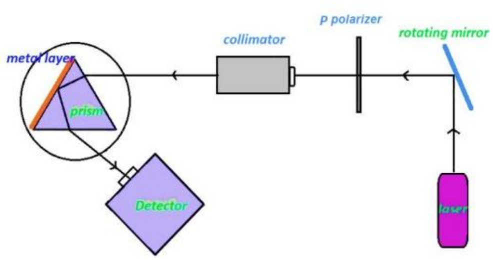

Fig.5. Experimental arrangement for measuring the intensity of reflectivity

Figure (6) is shown the intensity of reflectivity against radiation angle on the interface of prism and silver layer theoretically (full curve) and experimentally (star curve). It is observed that in both curves there is a maximum of intensity in the incident angle before critical angle and a minimum of intensity at the best coupling and after critical angle. Theoretical reflectivity minimum and experimental reflectivity minimum is observed under the 49.32 and 48.35 angles respectively. Using the presented transfer matrix and the determined electric permittivity index of silver for laser with blue light wavelength and the angle of reflectivity minimum, the thickness of silver layer is obtained 450 Å, which had a good agreement with the actual value of 458 Å. In this experiment, the experimental data have been normalized to the theoretical data due to absorption and scattering in the prism.

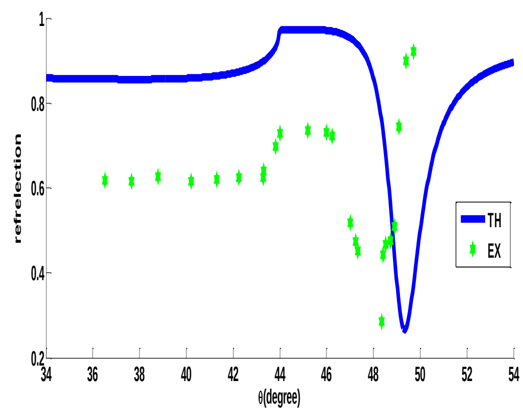

Fig.6. Theoretical (full curve) and experimental (star curve) diagram of reflectivity against radiation angle for blue light laser with a wavelength of 4348 Åonclusion.

6. Conclusion

In this paper, we compared the reflectivity spectra for various metals theoretically and reached this conclusion that silver is the best metal for the excitation of surface waves. Because the thickness is one of the most important parameters of the thin metal layer and various properties of the layer is directly dependent to the thickness. So the measurement of thin film thickness is essential for optical applications and etc. Therefore we could experimentally calculate the thickness of the metal layer using excitation of surface waves in a silver metal layer and measured intensity reflectivity that good agreement was obtained by comparing the theoretical thickness.

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