Thickness optimization of a monometallic plasmonic structure for a surface-plasmon resonance biosensor

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Surface-plasmon resonance (SPR) effect in thin metal films is highly sensitive to the dielectric refractive index changes in the vicinity of metal interface and the conventional Kretschmann configuration has been widely used in the SPR measurement. In this work we have presented the thickness optimization for a monometallic plasmonic structure using the prism-based Kretschmann configuration in angular and spectral interrogation. He-Ne laser with wavelength of 632.8 nm as an optical source, a thin gold layer deposited onto the glass substrate and a BK7 glass prism were applied for this studies.

Based on the numerical analysis with variation of metallic layer thickness, angle of incidence and wavelength we will obtain the resonance parameters, such as reflectivity and phase. Experimentally, the SPR spectra of a pure gold sensing surface has been studied. With functionalizing with specific antigen molecules on the surface of the gold layer, this optimized settings can be further used as biosensing purpose for detection of certain analytes.

Keywords: Surface-plasmon resonance, Kretschmann configuration, biosensor.

I. INTRODUCTION

Surface plasmon resonance (SPR) is one of the widely used optical phenomena for the development of label-free, rapid and sensitive sensing devices [1]. The SPR is able to detect small variations of the index of refraction at the metal-coated interface caused by changes in a few monolayers above the surface [2].

Surface plasmons (SPs) are collective oscillations of conduction electrons at the surface of a thin metallic film adjacent to a dielectric layer. Exciting a surface plasmon wave (SPW) propagates along the interface between a metal and a dielectric medium. The well-known prism-based configuration which is proposed by Kretschmann [3] is frequently used for the SPs excitation. Small changes in optical properties of adjacent dielectric medium can be detected by this technique with a high precision. In this configuration of the attenuated total reflection (ATR) method p-polarized light (TM mode) beam is reflected at the interface between a prism and a very thin metal layer, being captured by a sensitive detector. Under the phase matching condition is satisfied, all the energy of the incident beam is totally transferred to the SPW, producing a reflectance dip in the reflected light intensity. This sharp dip in the SPR response curve indicates the minimum reflectivity based on the total internal reflection at the metal-dielectric interface. The dielectric function of the noble metal have a negative real part at the chosen wavelength of the light [4]. Thus, the SPR occurs therefore in the visible region in so-called free electron-like metals such as silver and gold.

With a gold or a silver layer, resonance can be observed at any wavelength above 500 nm to the near IR, where the specific resonance angle corresponding to a particular wavelength will always be above the total internal reflection angle of the glass/dielectric interface. The thickness of the metallic layer is critical in this matter. If the metallic layer is too thick, the entire incident light is absorbed before reaching the upper surface of the metal; if it is too thin, not enough energy is absorbed by the free electrons and the SPR effect is negligible [5].

Outside the metal there exists an evanescent electric field, a field decays exponentially with distance from the metal surface with decay length of the order of 0.2 to 0.3 of the wavelengths of light [4]. This evanescent field interacts with the close vicinity of the metal. Changes in the optical properties of this region will therefore influence the resonance angle, which is the use of the SPR for biosensing purposes. Therefore, the shift in the

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incident angle or the optical wavelength indicates as the presence of analyte in the sample [6].

In this paper we will obtain the resonance parameters, such as reflectivity and phase based on the numerical analysis with variation of metallic layer thickness, angle of incidence and wavelength. The metallic thickness optimization is performed for the monometallic plasmonic structure using the prism-based Kretschmann configuration in angular and spectral interrogation. Experimentally, the SPR spectra of a pure gold sensing surface has been studied.

II. THEORETICAL PART

2.1 Numerical approach based on the ATR method

To excite the SPs, the wavevector of the incident light in the prism must phase match to the wavevector of the SPs at the metal-dielectric interface. The matching condition can be written as [7]

$$k_x^{prism} = k_x^{SP} \quad (1)$$

$$\sqrt{\varepsilon_1}\frac{\omega}{c}sin\vartheta_1 = \frac{\omega}{c}\sqrt{\frac{\varepsilon_2\varepsilon_3}{\varepsilon_2+\varepsilon_3}} \quad (2)$$

where, ε_1, ε_2, and ε_3 are the dielectric permittivity of prism, metal film, and dielectric layer, respectively, and ϑ_1 is the incident angle of light in the prism. The refractive index of prism is estimated by using the Sellmeier's dispersion formula,

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (3)$$

where the coefficients $B_1, B_2, B_3, C_1, C_2,$ and C_3 numeric values are given in Table I, and λ is the wavelength in μm. With a help of the Drude model, the dielectric function (ε_m) of metal layer is expressed as

$$\varepsilon_m(\lambda) = \varepsilon_{mr} + i\varepsilon_{mi} = 1 - \frac{\lambda^2\lambda_c}{\lambda_p^2(\lambda_c + i\lambda)} \quad (4)$$

where, λ_p is the plasma wavelength and λ_c is the collision wavelength, respectively. As shown in Figure 1, the conventional Kretschmann configuration consists of a metallic film (Au film) coated on a BK7 glass prism and a sensing medium. In angular interrogation the wavelength was chosen at 632.8 nm (He–Ne laser source).

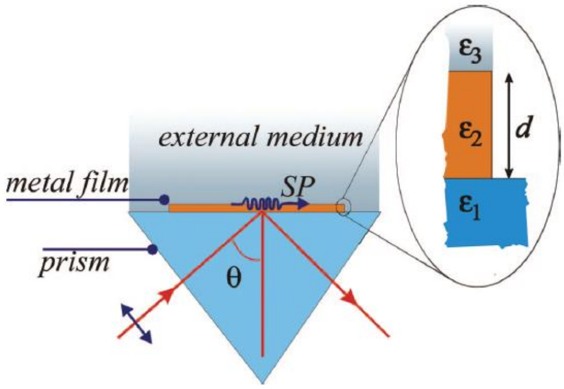


Figure.1 Schematic diagram of conventional Kretschmann configuration [8].

In this work the characteristic transfer matrix method (CTM) is applied to find reflectance of the multilayers structure is given by [9]

$$M_k = \begin{pmatrix} cos\beta_k & -isin\beta_k/q_k \\ -iq_k sin\beta_k & cos\beta_k \end{pmatrix} \quad (5)$$

where q_k for transverse magnetic (TM) incident light are given by

$$q_k^{TM} = \sqrt{\left(\frac{1}{\varepsilon_k}\right)} cos\vartheta_k \quad (6)$$

The phase factor is

$$\beta_k = \left(\frac{2\pi}{\lambda}\right) n_k cos\vartheta_k (z_k - z_{k-1}) \quad (7)$$

where $(z_k - z_{k-1})$ is the thickness of the kth layer. The reflection coefficient for a multilayer structure is given by [10]

$$r = \frac{((M_{11}+M_{12}q_N)q_1 - (M_{21}+M_{22}q_N))}{((M_{11}+M_{12}q_N)q_1 + (M_{21}+M_{22}q_N))} \quad (8)$$

where

$$M_{ij} = \left(\prod_{k=2}^{N-1} M_k\right)_{ij}, i,j = 1,2 \quad (9)$$

where i,j denote row and column indices and k is the layer index. q_1 and q_N are calculated for incident (prism) and the final medium (air or analyte). Now the reflectance of a multilayer system is given by

$$R = |r|^2 = rr^* \quad (10)$$

where *denotes the complex conjugate. The complex amplitude reflection coefficient is

$$r = R^{1/2}e^{i\varphi_r} \quad (11)$$

which can be written as

$$r = |r|(\lambda,\vartheta,n,d)e^{i\varphi_r(\lambda,\vartheta,n,d)} \quad (12)$$

where $\lambda, \vartheta, n,$ and d are the working wavelength, incident angle, refractive index, and thickness of the layers of the plasmonic structure, respectively, and φ_r is the phase shift of the reflected wave [10].

$$\varphi_r = \arg(r) = tan^{-1}\left[\frac{Im(r)}{Re(r)}\right] \qquad (13)$$

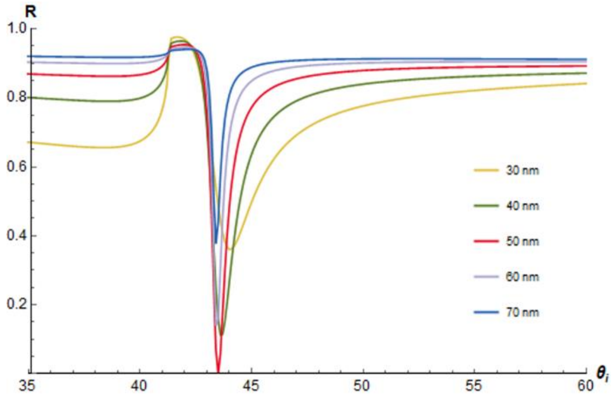
Table I. The constants of the dispersion and Drude model.

Materials	Constants [11]		
	B_1	B_2	B_3
BK7 Glass	1.03961212	0.231792344	1.01046945
	C_1	C_2	C_3
	0.00600069	0.020017914	103.560653
	Parameters [12]		
Gold	λ_p in μm		λ_c in μm
	0.16826		8.9342

III. SIMULATION PART

The resonance parameters, reflectance and phase, are numerically computed using the three-layer Kretschmann configuration with variation of metallic layer thickness, angle of incidence and wavelength, respectively. In this work the dielectric medium was set to air.

(a)



(b)

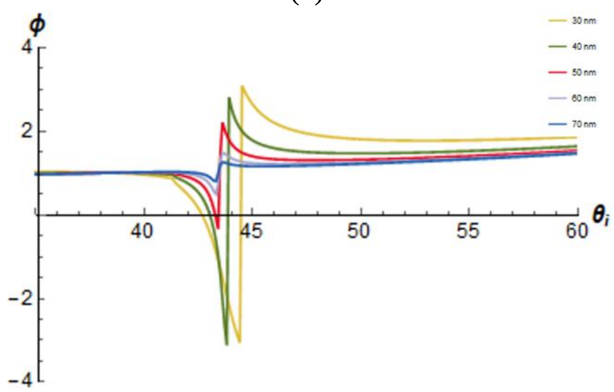


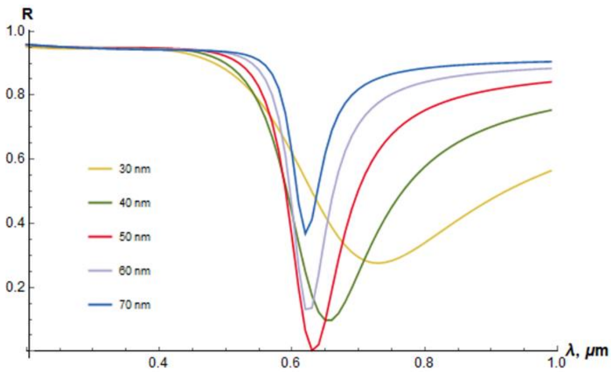
Figure 2. Resonance parameters a) reflectance and b) phase in angular interrogation.

As shown in Figure 2 and 3, the resonance curves have been plotted for different gold film thicknesses from 30 to 70 nm. From the shape of these resonance curves one can find the value of the gold thin layer thickness required for the optimum coupling of the incident energy in the prism to SPW.

For two resonance parameters the angle or wavelength at resonance remains almost unchanged due to the variation of the metal layer thickness for both spectral and angular interrogation.

From the reflectance curves of gold thin film, we can see the minimum values at the thickness of 50 nm with a Heaviside phase jump. In angular interrogation the wavelength is fixed at 632.8 nm for monometallic SPR configurations using gold thin film. But in spectral interrogation, the resonance angle is fixed at 43.47° for gold thin film.

(a)



(b)

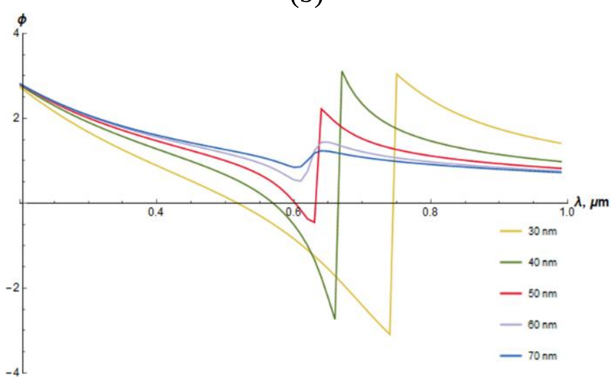


Figure 3. Resonance parameters a) reflectance and b) phase in spectral interrogation.

IV. EXPERIMENTAL PART

The experimental setup includes the light source, polarizer, half-cylindrical prism and detector. A schematic of our angular-interrogation-based Kretchmman-configuration SPR system is presented in Figure 4. A monochromatic He-Ne laser (power 15mW) was used as the SPR excitation light source. The laser light, collimated and p-polarized, is reflected at the interface between the prism and the gold thin film, being captured by the CCD detector. To control the incidence angle, the prism is placed on the rotation stage. In this work the prism is used to enable plasmon resonance at the metal/air interface (light momentum increase). Note that light-plasmon coupling is only possible if the light momentum is first increased since plasmon excitation by light impinging directly on a metal-dielectric interface is not possible [13], [14].

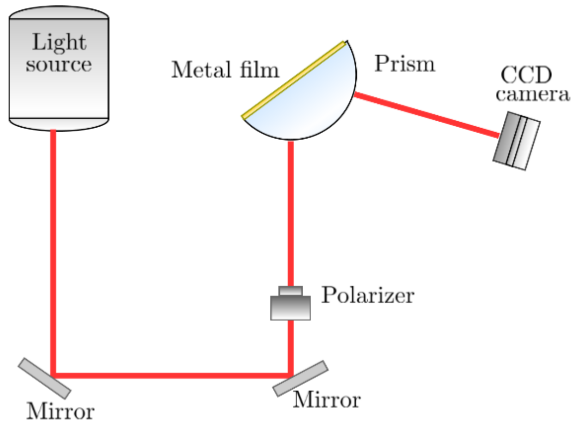


Figure 4. The scheme of the experimental setup for SPR measurement.

The gold thin layer was deposited on the BK7 glass slide with same index of refraction as the prism. An immersion oil is applied to minimize secondary reflections between the prism and glass slide.

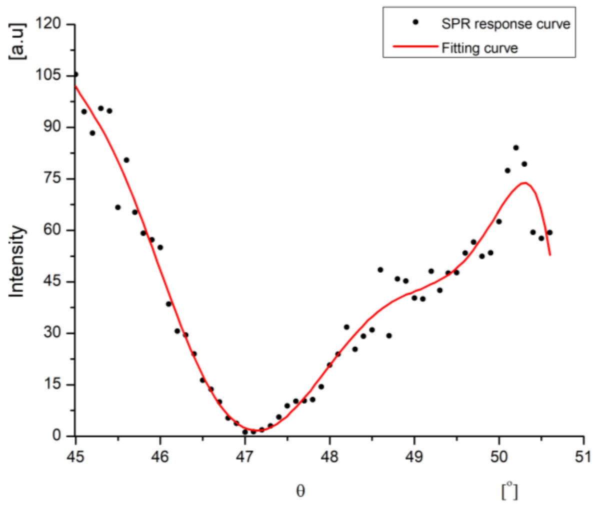


Figure 5. The normalized SPR response curve of a pure gold sensing surface.

In Figure 5 the normalized SPR response curve of a pure gold sensing surface has been plotted. To remove the noise signal in the dark condition, we subtracted the intensity of dark image from the reflected p-polarized beam intensity as well as s-polarized beam intensity. The final intensity is derived by dividing the subtracted p-polarized beam intensity by the subtracted s-polarized beam intensity [15]. With the fitting result of the gold thin film spectra the resonance angle was obtained at 47.18°.

V. CONCLUSION

In this paper, we estimated the resonance parameters, reflectivity and phase with different metallic thickness for monometallic plasmonic structure in angular and spectral interrogation. Furthermore, the resonance angle, laser wavelength and metallic thickness required for our angular-interrogation-based Kretchmman configuration SPR experimental system are introduced. Experimentally, the SPR response curve of gold thin film has been plotted. From this spectrum we observed the SPR effect at 47.18° resonance angle. Further, with functionalizing with specific antigen molecules on the surface of the gold layer, these optimized settings can be used as biosensing purpose for detection of certain analytes.

ACKNOWLEDGEMENT

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