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Surface Plasmon Resonance Sensor of Silver Film Based on Kretchmann Configuration

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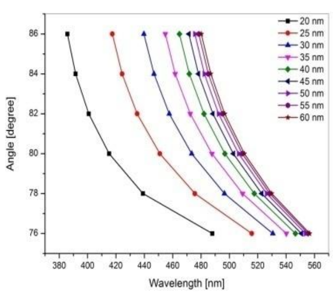
Hood-Hong Ley, Asiah Yahaya, Yusof Munajat*

Applied Optics Research Group, Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author
yusofm@utm.my

Graphical abstract



Abstract

Performance of a surface plasmon resonance (SPR) sensor based on Kretchmann configuration for silver (Ag) film is evaluated via theoretical simulation. The film thickness and incident angle are varied to obtain the SPR wavelength in the range of 500-550 nm. Shift of SPR wavelength with refractive index of the dielectric defines the sensitivity whereas the resolution is obtained from the ratio of the instrumental resolution to the sensitivity. The SPR sensor shows increasing sensitivity for thicker film however the absorption magnitudes of such films are high and unfavourable for data acquisition. Film thickness of 45 nm and 50 nm which has good sensitivity and resolution with high absorbance magnitude of the SPR wavelength is the best thickness to be employed for sensing purpose.

Keywords: Surface Plasmon resonance, refractive index, sensor, Fresnel equation

Abstrak

Prestasi penderia permukaan plasmon resonans (SPR) berdasarkan konfigurasi Kretchmann untuk filem tipis perak (Ag) dinilai melalui simulasi berangka. Ketebalan filem dan sudut tuju dimanipulasikan untuk mendapatkan gelombang SPR dalam nilai 500-550 nm. Penderia SPR menunjukkan peningkatan dalam kesensitifan untuk filem yang lebih tebal. Namun begitu, magnitud penyerapan untuk filem tebal amat rendah dan tidak sesuai untuk tujuan perolehan data. Didapati filem dengan ketebalan 45 nm dan 50 nm paling sesuai untuk digunakan sebagai penderia indeks pembiasan kerana mempunyai magnitud penyerapan yang tinggi serta panjang gelombang SPR dalam nilai yang dikehendaki.

Kata kunci: Resonans plasmon permukaan, index pembiasan, penderia, persamaan Fresnel

1.0 INTRODUCTION

Surface plasmon is an electromagnetic wave generated by the surface electrons of a conductor. The resonance phenomenon refers to the excitation of surface plasmon wave by incident photons specifically the transverse magnetic polarised (TM) or p-polarised. Hence, surface plasmon resonance (SPR) is observed when the light which reflects off the metal surface exhibit an abrupt decrease in the intensity of specific wavelength known as the SPR wavelength [1-3]. The resonance condition depends on the incident wavelength, dielectric of the metal film, and the refractive index of the surrounding. Such properties of SPR is appealing as a sensitive method for measuring the change in refractive index and thus has ushered in various researches with promising applications in the field of biosensor.

The surface plasmon resonance is generally achieved by employing the experimental configuration known as prism coupling, grating coupling or waveguide coupling [4]. Prism coupling method is further specified into two configurations known as Kretchmann's configuration and Otto's configuration. In this paper, our simulation construct is based on Kretchmann's schematic for silver film. The film thickness and the photon's incident angle is varied in order to design a sensor with corresponding SPR wavelength in the region of 500-550 nm. This study serves as preliminary result as part of our optimisation process of SPR sensor in the case of optical fibre sensor. Hence, the incident angles are chosen to be similar as the angle at which the rays would propagate in a fibre. Performance of the sensor is characterised in terms of its sensitivity and resolution.

2.0 THEORETICAL SIMULATION

Kretchmann's configuration is shown in Figure 1. Metal film in this study is silver film and the dielectric layer is the medium at which the refractive index is to be measured. Condition for excitation of surface plasmon wave is dependent on the wave vector of the incident light, such that the resonance condition will occur when equation 1 and 2 is equal [1-4].

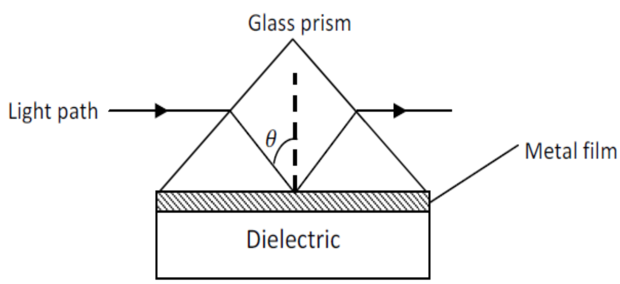


Figure 1 Kretchmann prism coupling schematic

$$k_{sp} = k_0 \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (1)$$

$$k_x = k_0 n_{prism} \sin\theta \quad (2)$$

where ε_m is the dielectric constant of metal film, ε_d is the dielectric constant of the surrounding dielectric layer, ε_{prism} is the dielectric constant of the prism, k_0 is the wave vector in free space and θ is the incident angle from the normal of the interface.

Applying Fresnel's equation according to the configuration in Figure 1, for a three layer system, the reflectance magnitude of the light is given by equation (3) [1-3,5,6];

$$R = |r_{123}^p|^2 = \left|\frac{r_{12}^p + r_{23}^p e^{2ik_2d_2}}{1 + r_{12}^p r_{23}^p e^{2ik_2d_2}}\right|^2 \quad (3)$$

where r_{123}^p is the reflection coefficient for layer 1 to 3, r_{ij}^p is the reflective coefficient at the boundary of layer i and j, d_2 is the thickness of the gold film, $k_{i(j)}$ is the wave vector propagating from medium i to j given by equation 4 and 5 respectively [4,5].

$$r_{ij}^p = \frac{k_i/n_i^2 - k_j/n_j^2}{k_i/n_i^2 + k_j/n_j^2} \quad (4)$$

$$k_{i(j)} = k_0\sqrt{\varepsilon_{i(j)} - \varepsilon_{prism}\sin^2\Theta} \quad (5)$$

The SPR spectrum is simulated for silver film of several thicknesses to obtain the corresponding thickness which gives the SPR wavelength in the range of 500 – 550 nm. Film thickness of 20 – 60 nm was simulated with the step of 5 nm where its SPR wavelength is plotted for incident angle 76° to 86° with 2° increment. For the selected film thickness of desired SPR wavelengths, the SPR variation with refractive index is investigated for dielectric medium of refractive index 1.3300 to 1.3360 RIU with 0.0005 RIU increment. The performance of the sensor is then evaluated by determining the sensitivity as the ratio of the shift in SPR wavelength with refractive index of the dielectric layer, where as the resolution is given by the instrumental resolution divided by the sensitivity, where in this simulation the wavelength resolution is set to be 0.13 nm

3.0 RESULTS AND DISCUSSION

Plot of incident angles versus SPR wavelength for several film thicknesses in search for the SPR wavelength in the range of 500 – 550 nm is illustrated in Figure 2. The graph in Figure 2 suggests that films of thickness 45, 50, 55 and 60 nm has suitable SPR wavelength. Other reason to select the film thickness in this range is also due to the angle of incidence that achieve the resonance condition is in the desired range. A plot of reflectance magnitude with incident angle is shown in Figure 3.

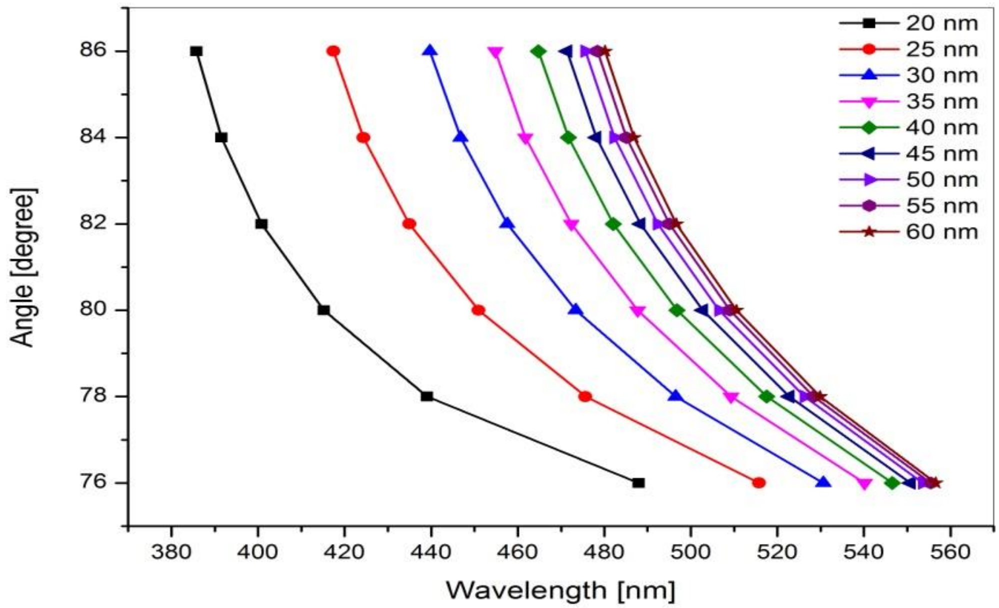


Figure 2 SPR wavelength for various film thicknesses

Extending the analysis for selected film thicknesses, the plot of the reflectance as a function of wavelengths obtained from equation (3) for selected incident angles is shown in Figure 3 for film thickness 45 nm and 60 nm to demonstrate the shift in the minimum of the reflectance curve with incident angle. Flexibility of SPR sensor allows the SPR wavelength to be tuned into the desired wavelength region by varying the film thickness and the incident angle. However, another point to consider is that for thicker film at higher incident angle shows a shallow dip in the reflectance which may pose difficulties in terms of data acquisition as for detector which are subjected to electronic noise, the SPR wavelength measured will be erroneous. For that matter, it is best to design the sensor such that its reflectance magnitude of the SPR wavelength is lower than 50%. Decrease in the absorption for thicker film is due to the lower field amplitude of the evanescent wave that is able to penetrate the metal film. Figure 4 and 5 are plotted for the same refractive index of the dielectric layer which is set to 1.3300. Figure 4 illustrate the variation of reflectance curve as a function of wavelength for the selected film thicknesses.

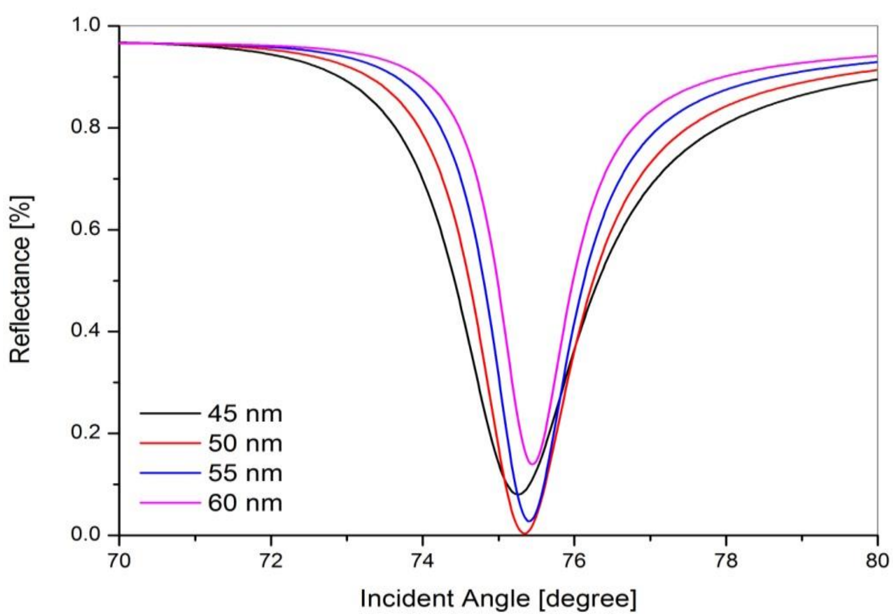


Figure 3 Plot of reflectivity against incident angle

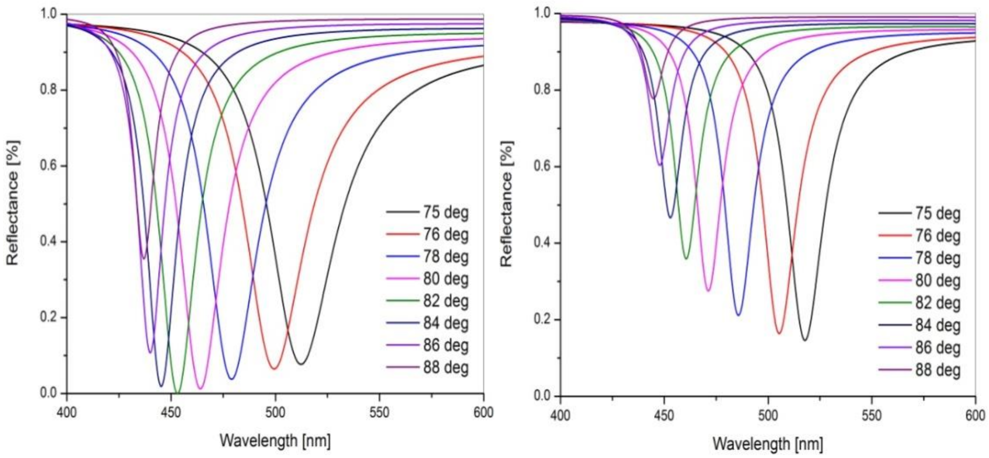


Figure 4 Variation of SPR wavelength with incident angle (left) 45 nm and (right) 60 nm film thicknesses.

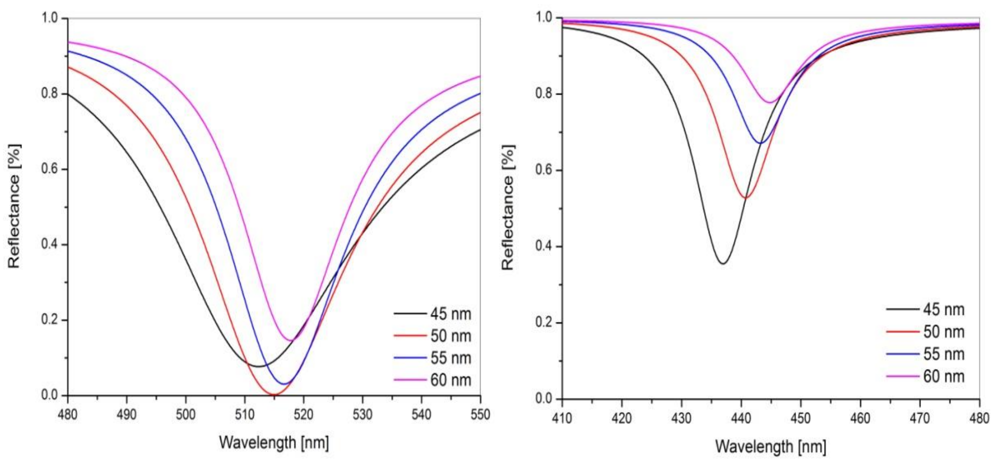


Figure 5 SPR profiles for various film thickness at incident angle 75° (left) and 88° (right).

Table 1 Sensitivity and resolution of the SPR sensor

Film thickness [nm]	Sensitivity [$\mu m/RIU$]	Resolution [RIU]
45	2.109	6.162×10^{-5}
50	2.138	6.079×10^{-5}
55	2.162	6.010×10^{-5}
60	2.163	6.010×10^{-5}

Figure 5 shows that for the same incident angle and the same refractive index of the dielectric value, the SPR profile changes with the value increases for thicker film and the shape of the curve also exhibit distinction in terms of the FWHM. Ideally, the profile with sharper peak is desired for easy identification of SPR wavelength than that of a broader peak. Notice that for incident angle of 75°, the sharpness of the SPR profile increases with film thickness where for all thicknesses the reflectance magnitude is of acceptable value. However for higher incident angle the thicker shows SPR profile with high reflectance percentage such that only the film thickness of 45 nm and 50 nm is acceptable to ensure a sensor designed to give good repeatability of results.

Performance for all the film thicknesses are summarised in Table 1. From Table 1, the sensitivity is increases with film thickness which is expected since for thicker film the amount of electrons available for exciting the surface plasmon wave is higher and thus more sensitive towards any changes in the surrounding dielectrics. The resolution however decreases with film thickness although the difference is less than 1%, thus in this matter the limiting case is the magnitude of the reflectance of the SPR profile which plays an important role for data acquisition. Thus, the film 45 and 50 nm are still the better choice compared to 55 and 60 nm films. The ability of SPR to detect the change in refractive index allows the sample to be in the form of liquid or gas. Since the refractive index of a solution is directly proportional to the amount to solute or the concentration, thus this method can be used to measure the concentration of a solution. Our result is in agreement in terms of the magnitude of sensitivity as compared to the work by [8] who deposited silver film on optical fibre for measuring the refractive index of liquid samples.

4.0 CONCLUSION

The working principle of a SPR sensor based on silver film is demonstrated for measuring the change in refractive index of the surrounding dielectric medium for a Kretchmann's configuration via simulation. Dependence of the SPR profile is studied by manipulating the film thickness and incident angle. Performance of a SPR sensor shows a higher sensitivity and decreasing resolution for higher film. Further increment of the film thickness for high sensitivity is not favourable due to the nature of the evanescent wave. The results suggest that the film thickness of 45 nm and 50 nm is best suitable for measuring change in refractive index in the wavelength region of 500 – 550 nm.

Acknowledgement

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