Propagation of surface plasmon waves at metal thin film/air interface using modified optical waveguiding assembly

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Surface Plasmon Resonance (SPR) spectroscopy is a surface-sensitive technique that has been extensively studied in sensing applications. For the optimization purpose of data collection, the SPR setup becomes more costly due to the employment of expensive optical apparatus. In this study, we proposed a modified optical waveguiding assembly to observe the plasmon mode coupling phenomenon. By employing the Kretschmann configuration, the effect of various thicknesses of silver thin films to the strength of SPR signal was investigated. The experimental results show an excellent agreement with the Fresnel equation from simulated results which verify the stability and the accuracy of our setup to observe the SPR phenomena. The optimum thickness of thin film for the excitation of strong SPR signal is 50 nm which results in minimum reflectance of 0.136 at a resonant angle of 56°. As the thicknesses increased to 70 nm and 90 nm, the SPR dip became shallower considering the absorption of surface plasmon polaritons in a silver layer. A good verification between both experimental and simulated results with small percentage difference of 0.90% proves the capability of our proposed modified optical waveguiding setup to be used in SPR experiments.

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1. Introduction

Surface plasmon resonance (SPR) has been utilized in chemical and biological sensing applications due to its high sensitivity technique. Metal nanoparticles [1,2] and bulk thin films exhibiting wide variety of nonlinear optical properties have attracted much attention relying to their potential applications in SPR. Owing to the resonant interaction between the surface charge oscillation and the electromagnetic field of light, surface plasmons can trap light energy into a nanoscale volume.

Nowadays, most SPR spectrometers consist of a laser (He-Ne, broadband source, etc), half or quarter wave plate, a beam splitter, mirrors, an optical stage driven by a stepper motor, a light attenuator, a polarizer, an optical chopper, an amplifier, a digital storage oscilloscope , a CCD camera and a glass prism in contact with a thin metal layer [3-8]. The reflected beam is detected by a sensitive photodiode and then processed by the lock-in-amplifier [9, 10]. Thirstrup et al. developed the SPR sensor integrated with the diffractive optical coupling elements (DOCEs) to the traditional prism and focusing optics for the purpose of obtaining reliable use to enable multiple sensor element analyses [11]. All these methods have been developed to increase the sensitivity and resolution of biosensors based on different SPR modes. In order to collect spectral information, two techniques have been commonly used, namely the wavelength interrogation and angle interrogation method. The angular interrogation is more desirable due to its simple and cost effective setup. By varying the incident angle and fixing the wavelength of the light source, the spectra of SPR can be observed [12-16].

In this paper, we seek to determine the capability of our simple and low cost experimental setup to excite the surface plasmon polaritons (SPP) and to detect the plasmonic mode coupling accurately using the optical waveguiding assembly. Basically, the optical waveguiding assembly which consists of a laser diode with wavelength of 632.8nm, a polarizer, a convex lens, a prism, waveguides and a rotational stage is used to examine the modal structure and the waveguide parameters (i.e. refractive index and thickness). By modifying the optical waveguiding assembly (Brand: OPTOSci), we have developed our in-house SPR setup which only employs basic optical equipments namely, a linearly polarized He-Ne laser, convex lens, rotational stage, prism and photodetector to investigate the plasmon coupling phenomenon. It is expected that the differences in SPR peaks depth can be observed as the thicknesses of thin films are varied. For the results verification, the experimental and simulated outputs are compared.

2. Methodology

We started the experiment by pre-depositing a layer of 5 nm thick of chromium which acts as an adhesive material onto the borosilicate microscope glass slide (Fisher Scientific, 0.25cm x 0.25cm x 1cm with refractive index of 1.513) using DC magnetron sputtering technique. The chromium film was used to increase the silver thin film adhesion onto the glass slide and to ensure sufficient film stability [17]. We performed a tape test by stripping off the chromium-silver thin film layers using a commercial cellotape to determine the adhesion strength of the sputtered silver thin film which is coated on the glass slide [18]. The transmittance spectra for the pre-deposited 5nm chromium with 50nm silver thin metal film before and after the tape test were observed using a UV-Vis spectrophotometer (Perkin Elmer/Lamda 35). Silver thin films with thicknesses of 50 nm, 70 nm and 90 nm were deposited onto the chromium coated borosilicate glass by DC magnetron sputtering (Brand: Kurt J. Lesker PVD 75) from a silver target (99.99%). By varying the thicknesses of thin films, the different in SPR peaks depth can be observed [19-21]. The chamber was evacuated to 0.02 miliTorr before introducing an Ar gas inside the chamber. During the deposition process, the gas pressure was set at 3 miliTorr, meanwhile the power was maintained at 100W. We set the rotational rate of the sample holder at 10rpm during the sputtering process. The temperature of chamber was set within 23° C to 25°C.

For the optical excitation of surface plasmon polaritons, it is compulsary to excite *p*-polarization light because no solutions exist for the case of s-polarization light. Since we used a linearly polarized He-Ne laser source, the *p*-polarized beam was achieved by rotating the orientation of the laser into the TM polarization state to 90°. The TM polarization state was confirmed by observing the behaviour of the reflected light which struck the bare prism as reported in our previous paper [22].

The next procedure is to create the SPR phenomenon by coating a metal layer on the hypothenus side of the bare prism. For the excitation of surface plasmon at the metal/air interface, an evanescent wave created at the glass/metal interface has to penetrate through the metal layer. The SPR experiment was performed using a modified optical waveguiding assembly (Brand: OptoSci) as displayed in Fig. 1. Instead of using a laser diode as the light source, we used a linearly polarized He-Ne laser (Brand: Uniphase) for the light excitation due to its well collimated output. A mounted lens with 15.4cm focal length was placed between the glass prism and the He-Ne laser to focus the laser beam. The linearly polarized He-Ne laser with wavelength of 632.8nm stroke the right angle prism (refractive index of 1.33) to match the evanescent wave from the surface plasmon excitation. In comparison with the optical waveguiding assembly, we added a silicon photodetector on the rotational arm to detect the reflected power. The prism was coupled to a silver coated glass slide via index matching gel under the Kretschmann configuration. We deposited silver nano thin films with various thicknesses directly on the microscope glass slides, so that the effect of thin films thicknesses to the SPR can easily be examined by changing the sputtered glass slides.

To perform an angular interrogation technique, the prism was rotated in a counter clockwise direction with an increment of 1° for each reading. Incident angles in the range of $40° < \theta_i < 85°$ were analysed while employing a fixed incident wavelength of 632.8 nm. An output value was obtained using a power meter (Newport). After each reading, the rotational stage was manually rotated in a counter clockwise direction. The resonant excitation of surface plasmons was characterized by a dip in the reflectance curves which refers to the energy of the incident light that is partially transferred to plasmons. We measured the reflectance as a function of the angle of incidence. Power reflectance is defined as the ratio of power flow of the reflected power to that of the incident wave as expressed in Eq. 1 as follows:

$$R = \frac{P_{reflected}}{P_{incident}} \tag{1}$$

where R is the reflectance, $P_{reflected}$ is the reflected power and $P_{incident}$ is the incident power [23]. We performed a simulation to compare the experimental and the calculated result to observe the capability and the accuracy of our system in SPR phenomenon using WINSPALL 3.02 simulator which is based on Fresnel equation developed by Knoll group [24-27].

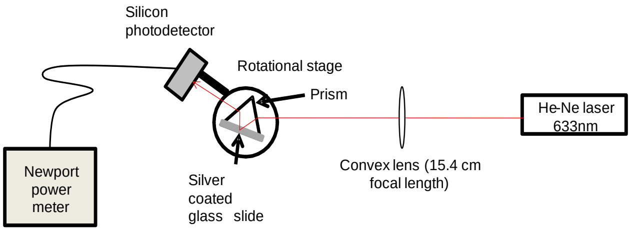

Fig. 1. Modified optical waveguiding assembly for the excitation of surface plasmon polaritons.

3. Results

Prior conducting the SPR experiment, the adhesive property of the silver thin films which was co-sputtered with chromium to strengthen the adhesion between the thin film and the glass slide, was explored. Fig. 2 depicts the results of the UV-Vis spectroscopy for the pre-deposited 5 nm chromium and 50 nm silver thin film sputtered on the glass. The UV-Vis transmittance spectra show similar transmittance characteristics for silver before and after the test which reveals that the silver thin film is attached strongly to the glass slide. This justifies the need of an addition layer of chromium to provide a strong adhesion and stability of the silver thin films.

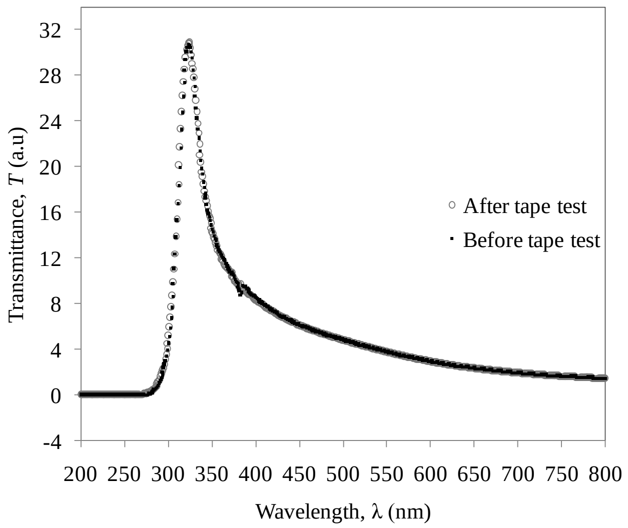

Fig. 2. UV-Vis transmittance spectra of silver thin film before and after the tape test.

The keypoint of this experiment is to observe the SPR phenomenon using the modified optical waveguiding assembly. The variation in minimum reflectance as the metal layer thicknesses vary are clearly seen as captured in Fig. 3. At 50 nm thickness of the silver thin film, the angular excitation spectra of surface plasmon show the deepest peak in the reflectance curve with value of 0.136 at resonance angle of 56°. This phenomenon occurs due to the free electrons in the silver layer that adsorb the incident light and attenuate the intensity of the reflected light rapidly which decrease the value of power detected by the silicon photodetector. As the silver thin film thickness is increased to 70 nm, about 36.4% of the reflected power drops which results in a weak excitation of SPP. The resonance angle is backshifted to 55°. A very shallow dip of the SPR curve at 56° of resonance angle with minimum reflectance of 0.819 was obtained with the increment of thin film thickness to 90 nm.

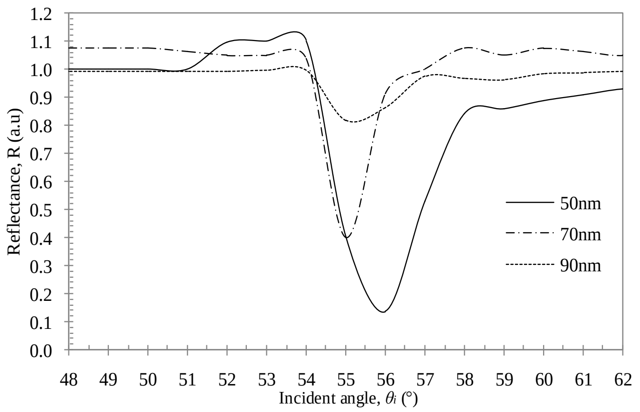

Fig. 3. Excitation of SPP with the effect of silver nano thin films thicknesses using the modified optical waveguiding assembly.

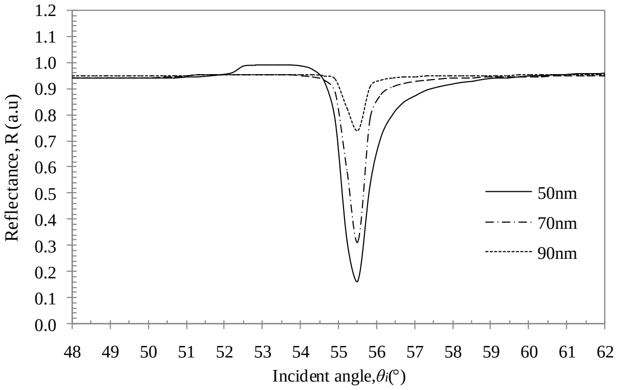

Fig. 4. Simulation results for the excitation of SPP with the effect of silver nano thin films thicknesses.

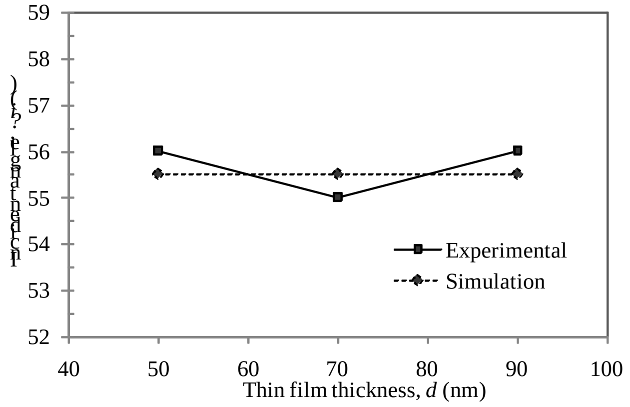

Fig. 5. Characteristics of incident angles during SPR as the thin film thicknesses vary.

The experimental results were simulated using standard software to check for accuracy from a theoretical point of view. Fig. 4 shows the simulated SPR phenomena for various thicknesses of silver thin films. By using Winspall 3.02 plasmon simulator programme, the effect of silver thin films thicknesses to the SPR phenomena was observed. The resonance angle for these three film thicknesses remain fixed at 55.5°, meanwhile the minimum reflectance increased as the thin film thicknesses increase. The minimum reflectances obtained are 0.157, 0.316 and 0.741 for the thin film thicknesses of 50nm, 70 nm and 90 nm respectively.

4. Discussions

A steep dip in reflectivity curve occurs due to SPR which is very sensitive to the refractive index of the dielectric layer at the surface of the silver film. Fig. 5 reveals the value of incident angles during SPR phenomena at different silver thin films thicknesses. The experimental results are slightly shifted between 55° and 56° as thicknesses of the thin film increased. According to the simulation results, the incident angles shall remain fixed considering only one type of dielectric layer are employed, namely air. Nevertheless, if different dielectric material is utilized such as water, a shifting in the incident angle is expected [11, 15, 28]. It is proved that the experimental incident angles obtained during SPR are nearly precise with the simulated results with small percentange difference of 0.90%.

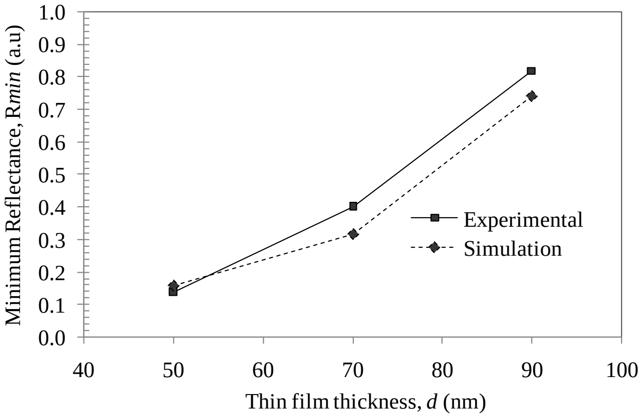

Fig. 6. Relationship between minimum reflectances and thin film thicknesses.

Fig. 6 illustrates the characteristics of the minimum reflectance obtained as the thin films thicknesses are increased from 50 nm to 90 nm. According to the results obtained, the optimum thickness to observe strong SPR signal is 50 nm as proven using both methods, namely the experimental and simulation analysis, which also show an excellent agreement with another related work [28]. As the thin film thicknesses increased to 70 nm and 90 nm, the SPR signals become weak owing to the surface plasmon polaritons can no longer be efficiently excited due to absorption in the silver layer. Conversely, if the silver layer is too thin, the surface plasmon polaritons will be strongly damped due to the radiation damping into the glass [28]. We concluded that the optimum thickness to observe surface plasmon resonance with a steep dip in the reflectivity curve is 50 nm.

The SPR peaks obtained using experimental and simulation is slightly different which reveals the disagreement between the experimental and simulated results. The reason behind this problem is due to the value of the silver dielectric function used during the simulation. The depth of the absorption dip during SPR phenomenon is mostly affected by metal characteristics such as the thickness of thin film and the metal dielectric functions which were discussed experimentally and theoretically in many related works [29-31]. Since the dielectric function of silver used during simulation is an ideal value, it is worth to conclude that the experimental value of the dielectric function is slightly different with the ideal one. This leads to the 0.90% of instability between the experimental and the simulation results.

5. Conclusions

In conclusion, we have briefly reviewed the potential of modified optical waveguiding assembly which is simple and less costly to be used in SPR experiments. As compared with the common SPR setup, this experiment only used the basic optical components for the light source (e.g: He-Ne laser and convex lens) and detector (e.g: silicon photodetector which is located on the rotational arm of the stage). A strong SPR signal was observed using silver thin film with thickness of 50nm. By obtaining a small percentage difference about 0.90%, we prove the capability of this setup for SPR applications.

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