Ag-Ni bimetallic film on CaF_2 prism for high sensitive surface plasmon resonance sensor

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Abstract—We present a surface plasmon resonance (SPR) structure based on the Kretschmann configuration incorporating bimetallic layers of noble (Ag) and magnetic materials (Ni) over a CaF_2 prism. Extensive numerical analysis based on transfer matrix theory has been performed to characterize sensor response considering sensitivity, full width at half maxima, and minimum reflection. Notably, the proposed structure, after suitably optimizing the thickness of bimetallic layer provides consistent enhancement of sensitivity over other competitive SPR structures. Hence, we believe that the proposed SPR sensor could find a new platform for medical diagnosis, chemical examination, and biological detection.

The surface plasmon resonance-based biosensor attains much interest due to its extraordinary sensing techniques; generally, SPR based sensors are used to analyze the characteristics of specific chemical and biological samples [1-2]. Sensitivity is one of the most critical parameters of an SPR sensor, and sensitivity enhancement using various methods, including the usage of bimetallic films, is suggested [3]. Between them, a bimetallic configuration utilizing the advantages of both metals seems to be a simple and most credible method to improve the overall performance of the sensors [4-9]. Au-Ag bimetallic configurations are the most common and attracted considerable attention for SPR excitation. This is because such bimetallic configurations utilize the advantages of gold that shows a high shift in resonance dip corresponding to the change in the refractive index (RI) of the sensing medium, which improves the sensitivity of the sensor, whereas the narrow full width at half maximum (FWHM) of silver provides a good signal-to-noise ratio (SNR) for the sensor [10-13]. Several researchers have illustrated the advantage of utilizing bimetallic configurations, however Au and Ag is found to have weak adherence to a prism, hence a thin coating of (Cr), teflon and InP are used to improve adherence and suggested [14-17]. Dmitry *et al*. analyzed the sensitivity of the SPR sensor that utilizes different double layers of Cr/Au, Ag/Au, Ti/Au, Cu/Au and Al/ Au combinations and reported that selecting a suitable bimetallic configuration protects the plasmonic layer from oxidation and other chemical reactions when operating in an aqueous environment [18]. Recently, the ferromagnetic metal of Ni has drawn much attention due to its remarkable magnetooptical properties [19-21]. Lately, utilizing Ni as a plasmonic metal has been suggested to reduce the cost and improve the sensitivity of SPR sensors [22-24]. Over the last years, SF10, BK7, SF11, and CaF_2 prisms have been frequently used in SPR sensors, but out of the entire prisms, CaF_2 has a lower minimum RI, which has enormous effects on the sensitivity of the sensor [25-26]. In this study, we propose the design of a high sensitive SPR sensor structure with enhanced sensitivity utilizing bimetallic layers of magnetic material Ni over Ag on a CaF_2 prism. The reflectance curve, resonance angle, FWHM, Deduction Accuracy (DA), Quality Factor (QF), and the corresponding sensitivity are analyzed theoretically using the Fresnel equation and transfer matrix method. The results show that such a hybrid configuration with a well-optimized thickness of the bimetallic layer over a CaF_2 prism in the Kretschmann configuration can significantly enhance sensitivity than a conventional sensor.

The schematic diagram of the proposed SPR sensor configuration is shown in Figure. 1.

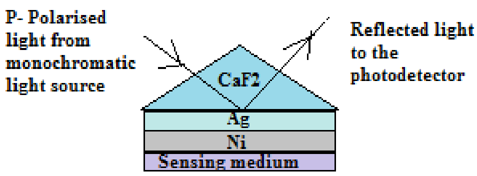

Fig. 1. Schematic diagram of the proposed SPR biosensor.

The proposed configuration consists of four different layers with an operating wavelength of 633nm and is based on the Kretschmann configuration [23]. The refractive index of a CaF_2 prism is 1.4329; the choice of

CaF_2 prism is dictated by its lower RI compared with others, by the fact that acts as an amplifier for enhancing sensitivity and other factors [25]. The RI of the Ag and Ni layers are calculated by the Drude formula [24, 19]. The reflectivity of a given multilayer configuration is expressed by $R_P=|r_p|^2$ The sensitivity (S), detection accuracy (DA) and quality factor (QF) of the SPR sensors are calculated according to the following equations [23, 27]:

$$S=\frac{\delta\theta_{res}}{\delta n_c} \qquad DA=\frac{\delta\theta_{res}}{\delta\theta_{0.5}}, \qquad Q=\frac{S}{\delta\theta_{0.5}},$$

where δn_c is the change in the RI of the sensing medium, $\delta\theta_{res}$ is the resonance angle shift and $\delta\theta_{0.5}$ is the full width at half maximum (FWHM) of the reflectance curve

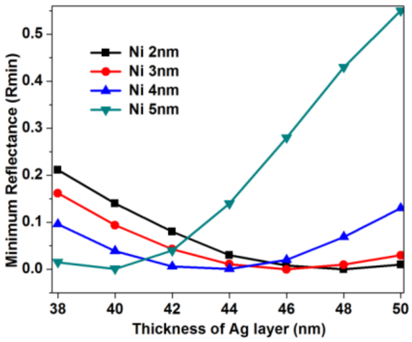

Fig. 3. Reflectance plot for the bimetallic configuration with a CaF_2 prism.

As R_{min} close to zero is essential for the coupling of maximum energy of incident light with surface plasmon wave [28], in the first phase of optimization the variation of R_{min} as a function of thickness of Ag varying from 38nm to 50nm for the fixed thickness of Ni as 2nm, 3nm, 4nm and 5nm is calculated and shown in Fig.2. It is noted from Fig. 3 that initially high R_{min} values are obtained for all the thickness of Ni layers considered when the thickness of Ag is as low as 38nm. However, it is found to approach zero.

AG (d)	NI (d)	R_{MIN}	S	QF	DA
48	2	0.0000	274	93.73	27.80
46	3	0.0000	318	91.04	23.69
44	4	0.0013	387	92.06	20.11
42	4	0.0066	369	84.57	19.31
	5	0.0457	504	103.8	17.88
40	4	0.0394	350	76.75	18.44
	5	0.0017	473	94.97	17.32

Table 1. S, R_{min}, QF and DA obtained for the above R_{min} configurations.

Respectively at 48nm, 46nm, 44nm and 40nm of Ag for the corresponding thickness of Ni as 2nm, 3nm, 4nm and 5nm which, as further found, increased with the increasing thickness of Ag. It is observed from Table 1 that the maximum sensitivity (approx. 473deg/RIU) is obtained for 40nm of Ag with a fixed thickness of Ni as 5nm for the entire configuration considered with the least possible R_{min} values. To further investigate the sensor's sensitivity, the variation of sensitivity of the proposed configuration corresponding to the change in the thickness of Ag for the fixed thickness of Ni is plotted and shown in Fig. 3. As noted from Fig. 4, a 5nm thickness of Ni offers better sensitivity out of all the thicknesses of Ni considered andthe maximum sensitivity (approx. 520deg/RIU) is achieved for 44nm of Ag for a fixed thickness of Ni as 5nm. As 5nm of Ni shows better sensitivity, we fixed the thickness of Ni as 5nm as an optimized value. Figure 5 shows the performance of the sensor corresponding to 5nm of Ni.

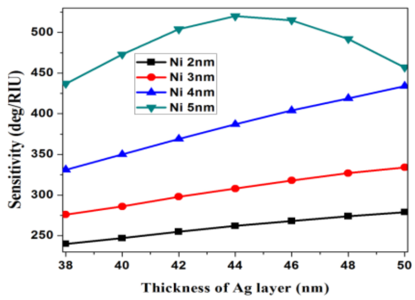

Fig. 4. Sensitivity plot for bimetallic configuration with CaF_2 prism.

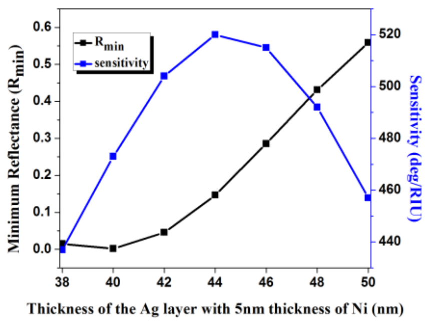

Fig. 5. Variation of R_{min} and S corresponding to a change in the thickness of Ag for the fixed 5nm thickness of Ni.

It is noted from Fig. 5, although the sensitivity approx. 520deg/RIU is achieved for 44nm of Ag, that the corresponding R_{min} obtained is much higher and is approx. 0.146. However, for 42nm of Ag and 5nm of Ni, the sensitivity obtained is 504deg/RIU, whereas the R_{min} is still as low as 0.04. Hence, we optimized the sensing configuration with 42nm of Ag thickness and 5nm of Ni thickness as a better configuration that gives maximum sensitivity and still has the R_{min} close to zero. Figure 6 shows the reflectance curve obtained for the same case. It is observed that the shift in the resonance curve corresponding to the change in the RI of the sensing medium from 1.330 to 1.335 improved very much as $\Delta\theta$=1.5136° and the corresponding enhanced sensitivity is calculated as 504deg/RIU. Moreover, the FWHM of the resonance curve is still found to be equal to 4.85°, which is much smaller than that of the conventional Au based SPR sensor [27].The DA and QF are calculated as 17.88/deg and 103.9/RIU respectively. Hence, the proposed simple structure shows much enhanced sensitivity and QF without using any additional 2D layers on the top of metal layers, coating of which seems difficult and yet unavoidable to enhance sensitivity in the competitive SPR structures [29].

References	Configuration	Sensitivity (°/RIU)
Nisha *et al*.[24]	Prism/Au/MoS_2/Ni/G	229
Vibisha *et al*.[23]	Prism/Cu/Ni	480
Bhishma *et al*.[29]	Prism/Franckeite/Ni/G	352
Proposed	Prism (CaF_2)/Ag/Ni	504

Table 2. Comparison of S for selected SPR structures.

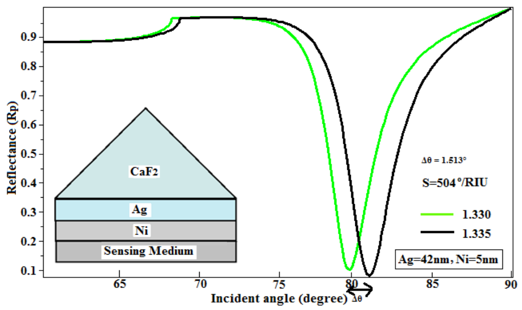

Fig. 6. The reflectance curve obtained for 42nm thickness of Ag and 5nm thickness of Ni.

Figure 7 shows the variation of S and FWHM corresponding to a change in RI of the sensing medium. The obtained results show the sensitivity is found to increasing from 229.29°/RIU to 504.45°/RIU and FWHM from 3.48° to 4.8° while increasing the RI of the sensing medium from 1.33 to 1.335. Notably, the proposed structure, upon suitably optimizing the thickness of a bimetallic layer provides consistent enhancement of sensitivity over other competitive SPR structures and is compared in Table.2

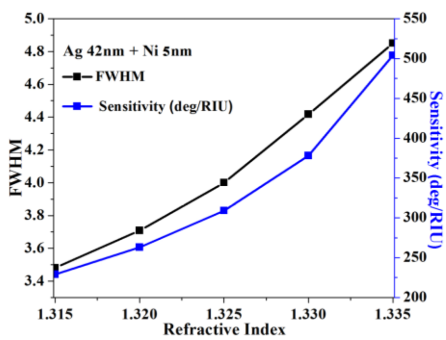

Fig. 7(a). Sensitivity and FWHM of SPR sensor with a varying refractive index.

The SPR biosensor utilizing a bimetallic layer of Ag-Ni on a CaF_2 prism is numerically studied. The results show that the proposed sensor can enhance the sensitivity as high as 504°/RIU and can still keep the FWHM of resonance curve as low as 4.85 and hence enhance the QF as high as 103.9/RIU .We hope that such a simple structure and favorable results will make the proposed sensor an appropriate and potential candidate for recognizing biomolecules organic elements and other samples.

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