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Role of Prism Materials in The Design of Surface Plasmon Resonance Sensor

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Abstract- This paper introduces a theoretical study of surface plasmon resonance (SPR) based sensor using transfer matrix method (TMM). This work is mainly emphasizes the effect of prism materials on the sensor performance like SPR angle, angular shift, sensitivity, detection accuracy using Kretschmann configuration with angular interrogation mode. The variation of sensitivity of SPR sensor with refractive index of the sensing medium, variation of SPR angle, angular shift and sensitivity with refractive index of the glass prism, the variation of SPR angle, and angular shift with sample refractive index has been investigated. From the investigation we observe that several sensing media can be analyzed lying in the large dynamic range of refractive index 1.33 to 1.45 with the help of observed result. The observed result shows that the sensitivity of the sensor increases with the refractive index of the sensing medium. The SPR angle, angular shift and sensitivity of the sensor decreases with the increase of refractive index of the glass prism.

Key words: Surface plasmon resonance (SPR), Transfer matrix method (TMM), Surface plasmon polariton, Sensitivity, Detection accuracy, MoS2, ZnO

I. INTRODUCTION

Over the last few decades surface plasmon resonance (SPR) based sensors are emerged as an important and useful tool due to its unique feature of highly sensitive, real-time and label-free detection [1]. Label-free detection technique is very easy and time saving which has several applications such as cancer cell detection, antibody analysis, DNA hybridization, protein detection, enzyme detection, corona virus detection, food safety, environmental inspection and safety etc [2-11]. Surface plasmon polaritons or surface plasmons are collective oscillation of free electrons on the metal-dielectric interface with permittivities of opposite sign that causes the phenomena of SPR due to transverse magnetic (p-polarized) incident light [2, 12]. A coupling prism is required to match the momentum of surface plasmon wave with the momentum of incident transverse magnetic (TM) light (p-polarized light) in order to trigger the surface plasmons at the metal-dielectric interface [13]. Under phase matching condition between evanescent wave vector of incident light wave and surface plasmon wave vector, maximum amount of energy transfer from incident light wave to surface plasmon wave is achieved under this condition the resonance curve experiences a steep deep [2,14,15].

SPR based biosensors are capable of detecting small changes in the refractive index of the order of 10^{-7}[16]. SPR biosensors based on only prism and metal cannot detect small molecules such as DNA, RNA and viruses. Two-dimensional (2D) nonmaterial's such as graphene, black phosphorous, quantum dots, transition metal dichalcogenides, MoS_2, MXenes etc. play an important role in order to increase sensitivity and delectability of small molecules when assisted with prism and metal [17,18]. 2D nanomaterials have attracted much attention of the researcher due to their unique physical and chemical properties such as high surface-to-volume ratio which provide additional binding sites in biological samples that leads strengthened optical signals and elevated biosensor functionality [19-22]. Therefore we have used MoS_2 in the proposed structure because of its other unique properties also like large direct and gap (1.8eV), higher optical absorption efficiency (5%) [23,24] and larger work function (5.1eV) as compared to graphene [25-27].

In the present paper, we propose a highly sensitive SPR sensor with high detection accuracy hybrid structure. Zinc oxide (ZnO) is used as an adhesion layer and also plays an important role in the enhancement of detection accuracy and sensitivity performance due to its high isoelectric point, large surface to volume ratio, chemical stability and good optical and electrical properties [28-32]. These properties of ZnO upgrade the light collecting ability as compared to Ni and Cr [33,34]. Sensitivity enhancement is also achieved due to introduction of MoS_2-graphene heterostructure whereas enhancement of detection accuracy is achieved due to introduction of silver metal in the hybrid structure. In comparison to graphene, MoS_2 absorbs more incident light energy because MoS_2 has larger value of imaginary part of dielectric constant which leads enhanced sensitivity.

The broadening of reflectance curve and its shift towards higher angle side increases with the increase in number of MoS_2 layer as well as graphene layer but the broadening and

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shift induced by MoS_2 is more due its high loss. Therefore MoS_2 layer is used to enhance the sensitivity and graphene is used as a biomolecular recognition element because of its carbon based ring structure which enables stable adsorption of biomolecules [35]. Present paper expresses the effect of prism material and refractive index of sensing medium, number of MoS_2 and graphene layer on the sensitivity, detection accuracy of the proposed structure.

II. DESIGN CONSIDERATION AND THEORETICAL ANALYSIS WITH MATHEMATICAL EXPRESSION

To investigate the effect of prism materials on the sensitivity and detection accuracy of the SPR sensor we consider the set-up with as given in figure 1. In figure 1 the base of the prism is coated with zinc oxide (ZnO) as a high index dielectric and it is further deposited by plasmonic metal silver (Ag), molybdenum disulfide (MoS_2), graphene as a biomolecular recognition element and sensing medium respectively. Graphene is kept in direct contact of biomolecules due to its strong adsorption power of biomolecules on its large surface area. Optimized thickness of these layers is deposited on the prism to get the efficient excitation of surface plasmons (SPs). In order to excite SPs, a monochromatic light of He-Ne laser of wavelength 633 nm is used and incident on the multilayer structure through one face of prism at an angle greater than critical angle. The reflected light is collected through other face of the prism as depicted in figure 1.

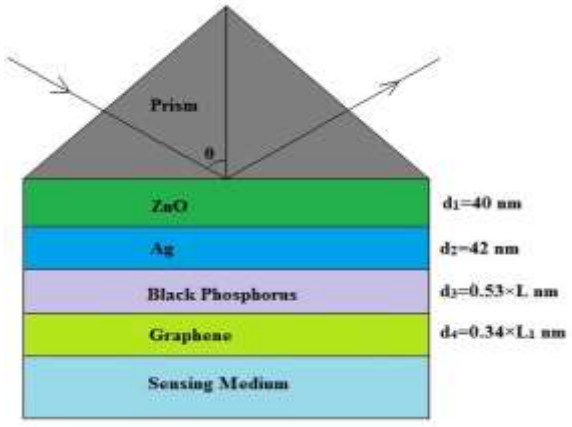

Fig. 1 Schematic representation of SPR sensor set-up

In the present paper angular interrogation method is used to study the information regarding sensitivity, detection accuracy etc. The optimized thicknesses and refractive indices of different layers of the material at 633 nm wavelength of light are given in table 1. The thickness of single layer of MoS_2 and graphene are 0.65 nm and 0.34 nm respectively with L and L_1 as the number of layers of MoS_2 and graphene as given in table 1. Experimentally obtained refractive index of MoS_2 at 633 nm, is $5.9 + 0.8i$ [36-38], whereas the refractive index of graphene is calculated by $3.0 + i(C/3)\lambda_0$ [39, 40], where $C \approx 5.446\ \mu m^{-1}$ is implied by the opacity measurement and λ_0 is the vacuum wavelength in μm.

Table 1. Refractive indices and optimized thicknesses of materials used

Materials	Refractive indices	Optimized thicknesses (nm)
BK7 glass	1.51508	-
BAK1 glass	1.57040	-
BAF10 glass	1.66707	-
SF5 glass	1.66846	-
SF10 glass	1.72312	-
SF11 glass	1.77858	-
ZnO	1.98	40
Ag	0.13511+3.985137i	42
Black Phosphorus (BP)	3.5+0.01i	0.53×L
Graphene	3.0+1.1491i	0.34×L1

We have applied transfer matrix method (TMM) to study different characteristics of the proposed structure [41]. The tangential components of electric and magnetic fields can be represented by the relation:

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = M \begin{bmatrix} E_{N-1} \\ H_{N-1} \end{bmatrix} \quad (1)$$

Where, M is the matrix of whole (N-layered) structure, can be evaluated in terms of its consecutive layer matrix given by

$$M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \prod_{l=2}^{N-1} M_l \quad , \quad (2)$$

with

$$M_l = \begin{bmatrix} cosq_l & \frac{1}{jp_l} sinq_l \\ jp_l sinq_l & cosq_l \end{bmatrix} \quad , \quad (3)$$

$$p_l = \frac{n_l}{cos\theta_l} \quad , \quad (4)$$

$$q_l = \frac{2\pi n_l d_l cos\theta_l}{\lambda_0} \quad , \quad (5)$$

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The reflectance of the proposed multilayered structure can be evaluated by the expression [42-44]

$$R = |r|^2 \quad , \quad (6)$$

where, r is the reflection coefficient can be expressed as

$$r = \frac{(m_{11}+m_{12}p_N)p_1-(m_{21}+m_{22}p_N)}{(m_{11}+m_{12}p_N)p_1+(m_{21}+m_{22}p_N)} \quad , \quad (7)$$

The refractive index sensitivity and of the proposed structure is evaluated with the help of the relation

$$S_{RI} = \frac{\Delta\theta}{\Delta n} \quad , \quad (8)$$

III. RESULTS AND DISCUSSIONS

In this work transfer matrix method is used to study different characteristics of the proposed structure. The proposed multilayer structure mainly emphasizes the effect of different prism materials, number of MoS_2 layer, number of graphene layer on the sensitivity for different sensing medium. The optimized thicknesses of different layers of the proposed structure are given in table 1. Fig. 2, fig. 3, fig. 4, fig. 5, fig. 6 and fig. 7 show the variation of SPR angle with sample refractive index for BK7, BAK1, BAF10, SF5, SF10 and SF11 glass prisms respectively. From these figures, we observe that as the value of refractive index of the sample increases the SPR angle as well as angular shift increases for all the prism materials but the proportion of SPR angle and angular shift increment is more for lower refractive index prism material than higher refractive index prism materials which are most obvious from fig. 8 and fig. 9 that causes the enhancement of sensitivity with decrease in prism refractive index. The evaluated sensitivity of the proposed structure for different prism materials are 188.75 deg./RIU (BK7), 157 deg./RIU (BAK1), 96.417 deg./RIU (BAF10), 95.917 deg./RIU (SF5), 82.417 deg./RIU, 73.25 deg./RIU.

From these figures, it can also be concluded that as the refractive index of the prism increases the sensitivity decreases but the efficiency of excitation of surface plasmon as well as detection accuracy increases because most of the incident light is transferred to excite surface plasmons. Whereas dynamic range is another factor that decides the maximum value of refractive index of the sample that can be sensed by a sensor, which is decreases with decreasing the refractive index of the prism because as the value of refractive index of the sample increases for lower value of refractive index of the prism the amount of light used to enhance the surface plasmons decreases that causes the weak enhancement of surface plasmons. Due to this phenomenon sensing ability of sensor for sensing sample refractive index decreases with increasing sample refractive index for lower refractive index prism material, whereas increases for higher refractive index prism materials.

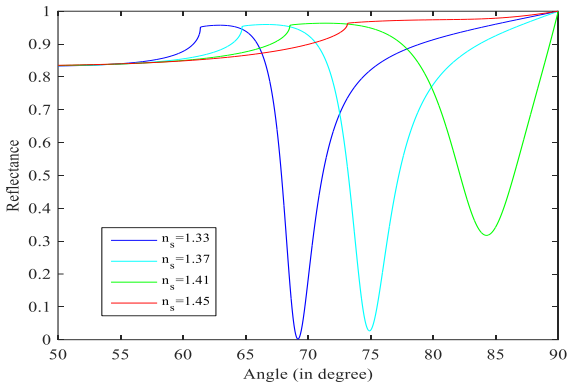

Fig.2 Reflectance versus angle of incidence curve for different values of refractive index of sensing medium for fixed value of refractive indices of BK7 glass prism (n_p=1.51508), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), BP (n_3=3.5+0.01i), graphene (n_4=3+1.1491i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), BP (d_3=0.53×L nm), graphene (d_4=0.34× L_1 nm).

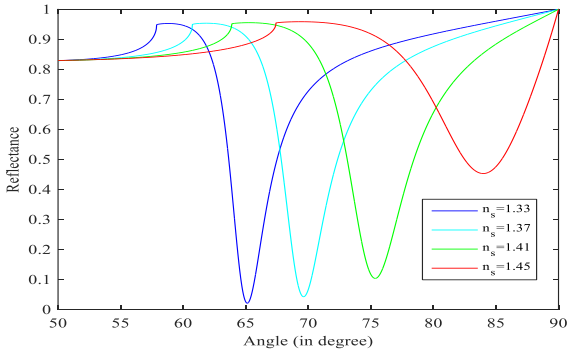

Fig.3 Reflectance versus angle of incidence curve for different values of refractive index of sensing medium for fixed value of refractive indices of BAK1 glass prism (n_p=1.5704), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

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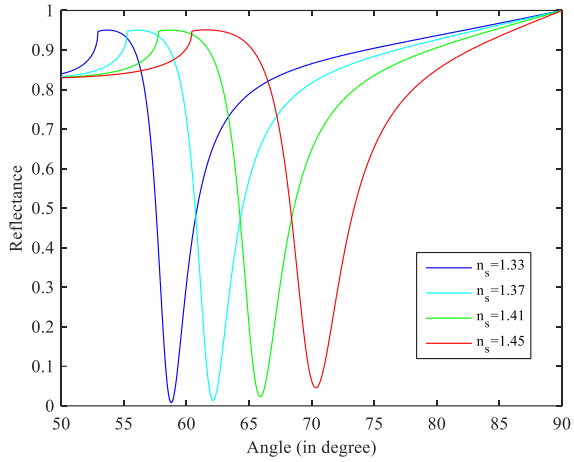

Fig.4 Reflectance versus angle of incidence curve for different values of refractive index of sensing medium for fixed value of refractive indices of BAF10 glass prism (n_p=1.66707), ZnO (n_1=1.98), Ag(n_2=0.13511+3.985137i), MoS_2(n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

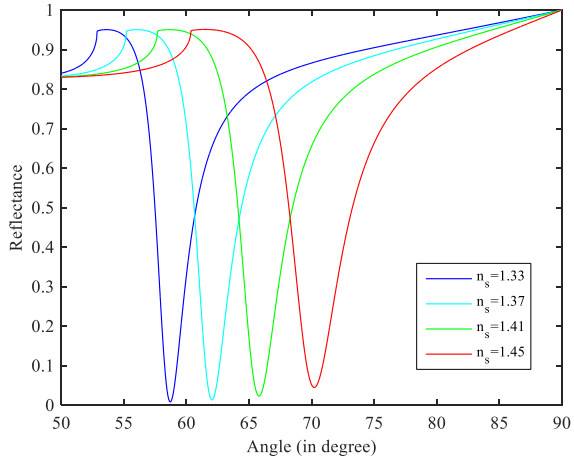

Fig.5 Reflectance versus angle of incidence curve for different values of refractive index of sensing medium for fixed value of refractive indices of SF5 glass prism (n_p=1.66846), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

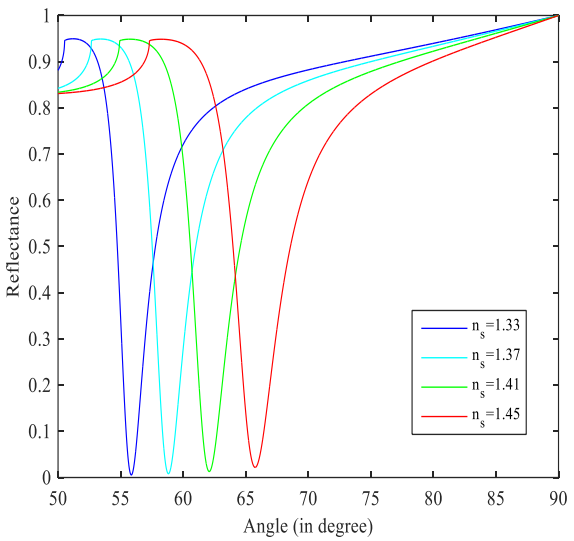

Fig.6 Reflectance versus angle of incidence curve for different values of refractive index of sensing medium for fixed value of refractive indices of SF10 glass prism (n_p=1.72312), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

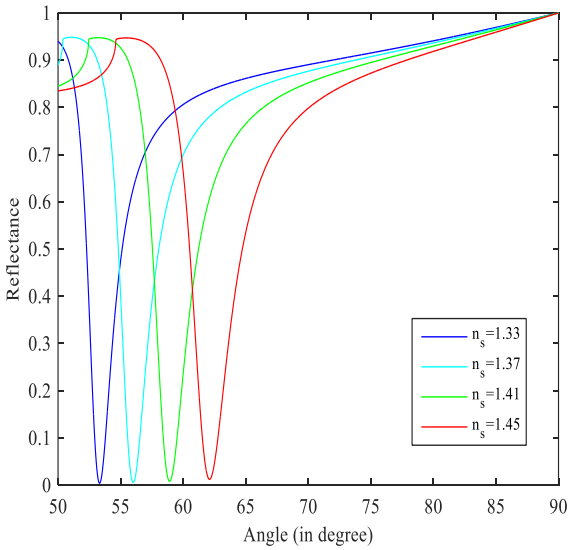

Fig.7 Reflectance versus angle of incidence curve for different values of refractive index of sensing medium for fixed value of refractive indices of SF11 glass prism (n_p=1.77858), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

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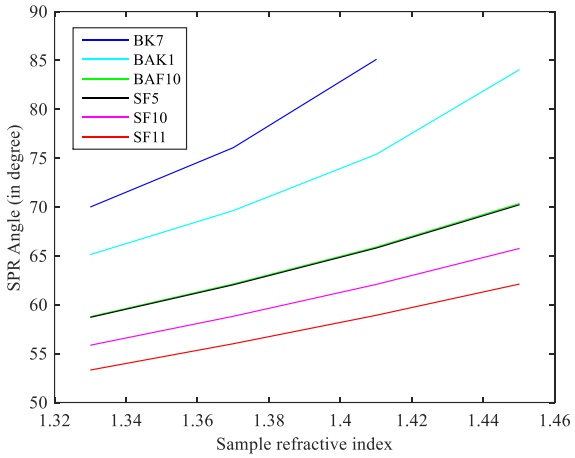

Fig.8 SPR angle versus sample refractive index curve for different glass prism materials for fixed value of refractive indices ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

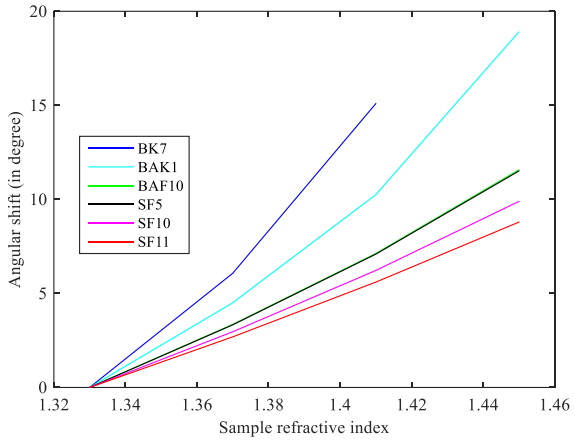

Fig.9 Angular shift versus sample refractive index curve for different glass prism materials for fixed value of refractive indices ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

Fig. 10 depicts the resonance curve for all the prism materials (BK7, BAK1, BAF10, SF5, SF10 and SF11), from these curves we observe that as the value of refractive index of the prism material increases the value of resonance angle decreases but the efficiency of excitation of surface plasmon and detection accuracy increases with the increase of refractive index of prism materials. Efficient excitation of surface plasmon occurs only when most of the incident light is transferred to excite surface plasmon that leads zero reflectance whereas the accuracy of measurement i.e. detection accuracy increases as the width of the reflectance curve decreases. From fig. 10, we can conclude that the efficiency of excitation and detection accuracy is maximum for SF11 and minimum for BK7.

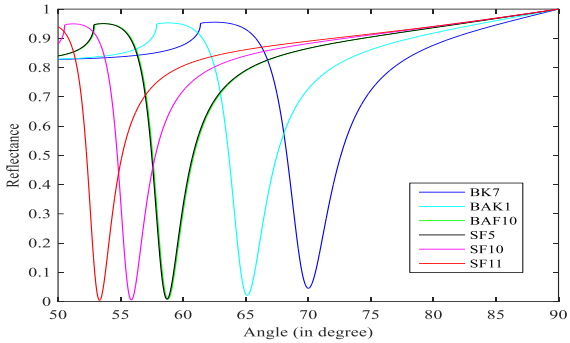

Fig.10 Reflectance versus angle of incidence curve for different glass prism materials for fixed value of refractive indices ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i), analyte (n_5=1.33) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

Fig. 11 shows the variation of SPR angle with prism material refractive index for different sample refractive index. From these curves we observe that as the value of refractive index of the prism material increases the resonance angle decreases for all the sample refractive index but the rate of reduction of SPR angle is different for different sample. The rate of reduction is maximum for high refractive index sample and minimum for low refractive index sample. Fig. 12 depicts the variation of angular shift with refractive of prism materials for different refractive of the sample. From this figure, we observe that as the value of refractive index of the prism material increases the angular shift decreases for all the refractive index of the sample but the rate of reduction of the angular shift is maximum for higher refractive index sample and minimum for lower refractive index sample.

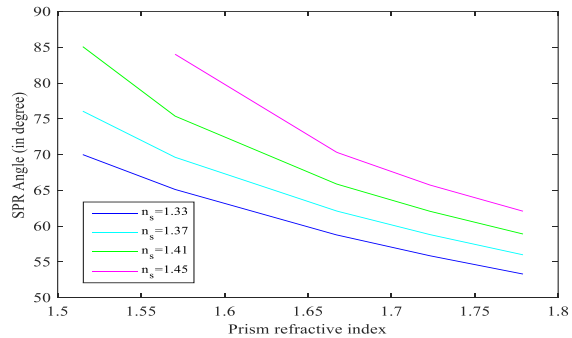

Fig.11 SPR angle versus prism material refractive index curve for different sample for fixed value of refractive indices ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2

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(n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

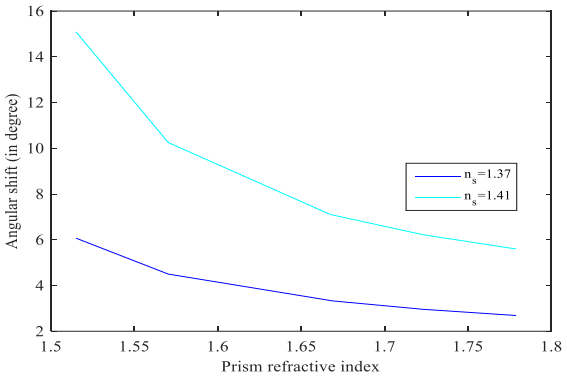

Fig.12 Angular shift versus prism material refractive index curve for different sample for fixed value of refractive indices ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

Fig 13 shows the variation of sensitivity of the proposed sensor for different refractive index of prism material. From this curve we can conclude that the sensitivity of the proposed sensor decreases as the refractive index of the prism material increases and has maximum value for BK7 glass prism because shift in resonance is maximum and minimum for SF11 glass prism because shift in resonance is minimum. In this way we can get the desired value of sensitivity by adjusting the refractive index of the prism material.

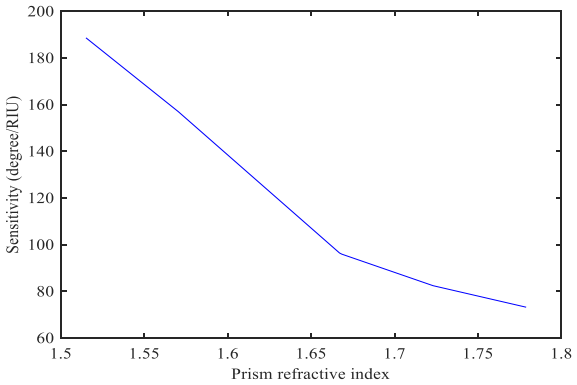

Fig.13 Sensitivity versus prism material refractive index curve for fixed value of refractive indices ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i), analyte (n_5=1.33) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

Fig. 14 and fig. 15 show the variation of reflectance with angle of incidence for different number of MoS_2 and graphene layers respectively for BK7 glass prism. From these curves we observe that as the number of MoS_2 layer and graphene layer increases the resonance angle increases for both, but the shift in resonance angle is more in case of MoS_2 layer in comparison to graphene layer, it means the sensitivity of the sensor is more for MoS_2 for the same number of layer but the detection accuracy and dynamic range is more for graphene. The efficiency of excitation of surface plasmons is more affected by graphene than MoS_2. Thus the control over efficiency of excitation of surface plasmons, detection accuracy and dynamic range mostly dominated by graphene and sensitivity mostly controlled by MoS_2.

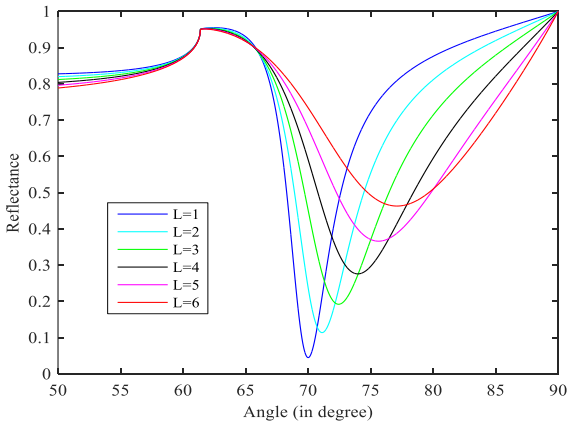

Fig.14 Reflectance versus angle of incidence curve for different number of MoS_2 layer for fixed value of refractive indices of BK7 glass prism (n_p=1.51508), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40 nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

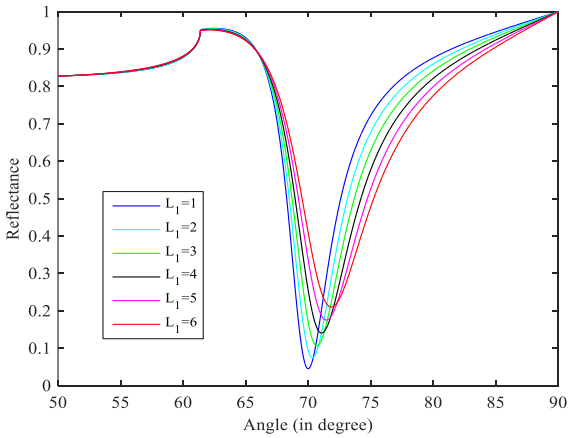

Fig.15 Reflectance versus angle of incidence curve for different number of graphene layer for fixed value of refractive indices of BK7 glass prism (n_p=1.51508), ZnO (n_1=1.98), Ag (n_2=0.13511+3.985137i), MoS_2 (n_3=5.9+0.8i), graphene (n_4=3+1.1487i) and thicknesses of ZnO (d_1=40

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nm), Ag (d_2=42 nm), MoS_2 (d_3=0.65×L nm), graphene (d_4=0.34× L_1 nm).

IV. CONCLUSIONS

In this paper we have theoretically reported the effect of different prism materials refractive indices on the different parameters of the SPR based sensor such as SPR angle, angular shift, sensitivity, efficiency of excitation of surface plasmons, detection accuracy, and dynamic range using transfer matrix method for sample of different refractive index. These parameters are found to be greatly influenced by the refractive index of the glass prism material. From the simulation curves it is obvious that for lower refractive index prism material SPR angle, angular shift and sensitivity are larger than higher refractive index prism materials, whereas higher refractive index prism material gives very sharp resonance curve that leads greater precision of measurement that means greater detection accuracy in measurements. A higher refractive index prism material also leads zero reflectance that causes efficient excitation of surface plasmons i.e. efficiency of excitation of surface plasmons increases for higher refractive index glass prism materials. From the investigations, we can conclude that in order to get higher SPR angle, angular shift and sensitivity we should select lower refractive index glass prism material as well as the more number of MoS_2 layer whereas in order to get efficient excitation of surface plasmons, greater detection accuracy and greater dynamic range we should select the glass prism of higher refractive index as well as the more number of graphene layer while operating the sensor at 633 nm wavelength of light. In this way we may choose the prism material in accordance with the application concerned by keeping in mind the trade-off between the sensitivity and dynamic range required.

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