Sensitivity Enhancement of Surface Plasmon Resonance (SPR) Sensor Assisted by BlueP/MoS$_2$ Based Composite Heterostructure

PURNENDU SHEKHAR PANDEY$^{1,2}$, (Member, IEEE), AND SANJEV KUMAR RAGHUWANSHI$^{3}$, (Senior Member, IEEE)

$^1$Optical Fiber Sensor Laboratory, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand 826004, India
$^2$Department of Electronics and Communication Engineering, GL Bajaj Institute of Technology and Management, Greater Noida 201306, India
$^3$Department of Electronics Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand 826004, India

Corresponding author: Sanjeev Kumar Raghuwanshi (sanjeevrus77@iitism.ac.in)

This work was supported by the Science and Engineering Research Board, Department of Science and Technology and Government of India, through the Research Grant, with the Project titled “Design of a Web Server-Based Hybrid Physiological Sensor With Optical Cloth for Real-Time Health Specialist Care” under Project SCP/2022/000271.

ABSTRACT This paper addresses a very high sensitivity of surface plasmon resonance (SPR) sensor assisted by novel BlueP/MoS$_2$ based composite heterostructure based on angular interrogation technique. Research on SPR techniques based on angular interrogation system is attracted a lot in recent years due to ease of implementation, robust, reliable and compatibility. These SPR sensors have wide applications in the field of biosensing, biochemical, gas detection, and biological science to mention a few. By these SPR techniques, performance parameters like figure of merit (F.O.M.), detection accuracy (D.A.), and most importantly sensitivity have been tremendously increased. In recent past 2D materials have attracted a massive response in SPR biosensors. Hence in this paper, 2D material like blue Phosphorene/molybdenum disulfide (i.e., BlueP/MoS$_2$) hybrid nanostructure as an integrating layer with the analyte is suggested to improve the sensitivity substantially of SPR sensor. In this connection performance of multilayer structure in conjunction with CaF$_2$ prism, Ag metal layer, Black Phosphorus, BlueP/MoS$_2$ has been analyzed in this paper. The maximum sensitivity of the order of 458$^\circ$/RIU has been obtained in this proposed scheme attributed to BlueP/MoS$_2$ based composite heterostructure at the visible wavelength of 662 nm. The proposed design analysis results in a significant improvement in sensitivity compared to traditional and graphene-based SPR sensors.

INDEX TERMS Blue phosphorene, surface plasmon resonance, chemical sensor, angular interrogation, sensitivity, transfer matrix method.

I. INTRODUCTION

Over the past few decades, in the field of gas sensing, biochemical sensing, and chemical sensing surface plasmon resonance (SPR) sensors have been broadly used [1], [2], [3]. To fabricate SPR sensors, metals like gold (Au)/silver (Ag) are mainly used with Kretschmann configuration [4], [28]. In the proposed structure, we have used Blue Phosphorene/MoS$_2$ heterostructure with silver and black phosphorus (BP) layer. The advent of graphene applications in numerous optoelectronics systems prompted researchers to investigate other two-dimensional (2D) materials, shown their significant contribution to ongoing technologies. Due to the quantum confinement effect, 2D materials exhibit unique physical, chemical, and optical properties as compared to their bulk counterparts. A novel 2D materials have been used to make this SPR biosensor structure while the effect of each layer has been analyzed. In the proposed SPR biosensor different prism comparison and BP and BlueP/MoS$_2$ layers has been theoretically investigated before deciding the proposed
topology. The sensitivity properties of the adapted structure were simulated using Transfer matrix method based on angular interrogation technique, and it was discovered that the sensitivity can be significantly increased with this new structure. Recently 2D materials for applications in optoelectronic devices have been explored recently [5], [6], [7], [8], [31]. Conventional single metal film SPR biosensors have always had a limited sensitivity. Since 2014, BP has been a new promising 2D material, attracting substantial attention for its broadly tunable and direct bandgap, high carrier mobility, and outstanding electrical, optical, and photonic properties [9], [10], [11], [12]. Also, the heterostructure of BlueP and 2D materials have been used to enhance the sensitivity. BlueP is as stable as black phosphorene, and its narrow band gap makes it ideal for sensing applications [13]. However, when number of layers of 2D materials increased the difference in resonance angle get reduced due to angle range limitations, by this sensitivity continuous drop [14]. Angular sensitivity does not affect the metal thickness, and it can be summarized expressively (from 32 nm to 55 nm) though increasing the sensitivity [15]. Higher sensitivity can be achieved with the optimized parameters with the MoS\textsubscript{2} enhanced structure [2]. Exquisite efficiency can be obtained by precisely adjusting the gold film thickness and the number of BP inter-layers [16], [17]. To achieve high sensitivity in the proposed configuration, we used CaF\textsubscript{2} as the coupling prism due to its lower refractive index (R.I.) value [18]. It has been studied that by using an optimized number of the layer of MoS\textsubscript{2}, we will get higher detection accuracy for the system [16]. In this structure, the Blue Phosphorene/MoS\textsubscript{2} heterostructure with a silver metal layer and the BP layer has been taken. The sensitivity properties of the adapted structure were simulated using angular interrogation, and it was discovered that the sensitivity can be significantly increased with this new structure. The proposed SPR biosensor performance realized theoretically through MATLAB software. We assumed in the simulation that prism is uniform in transverse direction and has infinite thickness.

Moreover, the number of Blue Phosphorene/MoS\textsubscript{2} layers for best simulation results are also clarified [19], [20]. Ag possesses remarkable optical features, including a low optical damping, the absence of interband transmission at visible light frequencies, a more prominent resonance peak, and a narrower SPR curve, amongst other attributes. For this reason, it has the potential to be an advantageous material choice when developing SPR sensors. Therefore, a higher level of sensitivity is attainable with the utilisation of silver as a plasmonic material [26], [29], [30]. Also, BP used another material that helped the proposed SPR sensor be more sensitive. This material was phosphorus, which has a single pair on each atom, which makes it very reactive to air. This arrangement of atoms make two different directions in the black phosphorus lattice: the zigzag, which runs parallel to the atomic ridges, and the armchair, which runs perpendicular to the atomic ridges (perpendicular to the ridges) [27]. This strong structural anisotropy is what gives it its unique electrical and optical properties in the same plane. MoS\textsubscript{2} monolayer and BlueP have hexagonal lattice structures, so stacking BlueP on top of MoS\textsubscript{2} can readily create a heterostructure. Covalent bonds ensure in-plane stability. This heterostructure prevents external phosphorene degradation. Direct contact between heterostructure and sensor layer increases adsorption and enhances the interface field. This work explores improving sensitivity with heterostructure layers over Ag. BlueP/MoS\textsubscript{2} prevents Ag layer oxidation. BlueP/MoS\textsubscript{2} heterostructure is the analyte-contacting fourth layer [2]. In the proposed SPR biosensor different prism comparison and BP and BlueP/MoS\textsubscript{2} layers selection has been theoretically investigated for achieving the maximum sensitivity.

II. DESIGN CONSIDERATION OF PROPOSED SPR SENSOR AND ITS IMPLEMENTATION

The proposed structure of the SPR sensor is considered with the Kretschmann configuration. The proposed sensor is a six-layer (BK\textsubscript{7}/Ag/BP/Ag/BlueP/Sensing medium) structure as
shown in Figure 1. At one face of the prism, TM polarized light from the source with an operating wavelength (λ) of 662 nm is applied, and the reflected light is obtained using appropriate photodetector arrays instruments. The SPR sensor is used of a Caf₂ prism [18] with a silver-metal coating (refractive index n₀ = 1.43286 at λ = 662 nm). The refractive index taken for the metal film (Ag) nAg = 0.04944+i × 4.5027, for BP nBP = 3.8337 + i × 0.015215. The refractive index of Blue Phosphorene/MoS₂ heterostructure is considered as nBlueP/MoS₂ = 2.7915+i × 0.335. Sensing layer refractive index was chosen as nS = 1.33 at the wavelength of 662 nm. The BP layer is sandwiched between two layers of Ag films in this proposed arrangement. The Ag first and third layer thickness are considered to be 40 nm and 8 nm respectively. The width of the BP has been determined to be D₀ = M × 0.65 nm. The thickness of Blue Phosphorene/MoS₂ has been calculated as Blue Phosphorene/MoS₂ = N × 0.75 nm, where M and N are the number of BP and Blue Phosphorene/MoS₂ layers respectively [16].

The reflectivity of proposed multi-layered structure is calculated using the expression:

\[
r_{pm1d1m2d2} = \frac{r_{pm1}}{1 + r_{pm1}} \cdot \frac{r_{m1d1m2d2} e^{2iKm1d1m2}}{1 + r_{m1d1m2d2} e^{2iKm1d1m2}}
\]

where:

\[
K_{is} = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 \epsilon_i - K_c^2}; \quad i = p, m, d, m, 2, d.
\]

\[
r_{pm} = \frac{(\epsilon_m K_{px} - \epsilon_p K_{mx})}{(\epsilon_m K_{px} + \epsilon_p K_{mx})} ; \quad r_{md} = \frac{(\epsilon_d K_{mx} - \epsilon_m K_{dx})}{(\epsilon_d K_{mx} + \epsilon_m K_{dx})}
\]

\[
p, m and d denoted as the prism, metal and dielectric respectively. As in the above process when the resonance condition is satisfied then the resonance dip in the reflectance curve is achieved as per Eq. (1). Thus, as seen in Eq. (1), the coupling equation for incident light and SPs at the metal-dielectric interface is as follows:

\[
k_c = k_p = \frac{2\pi}{\lambda} n_p \sin \theta_{spr} = \text{real} \left(\frac{2\pi}{\lambda} \sqrt{\frac{\epsilon_m \epsilon_s}{\epsilon_m + \epsilon_s}}\right)
\]

In above Eq. (4), \(n_p\) refers as a refractive index of the substrate medium (glass/prism), \(\lambda\) is the wavelength of light. Here \(\epsilon_m\) and \(\epsilon_s\) are the dielectric constants of the metal layer and the sensing (analyte) layers respectively, also signifies the coupling of incident light and SPs at the metal-dielectric interface. The angle at which the SPR curve has dipped (\(R_{min}\)), that angle is referred to as the resonance angle (SPR angle), for a transition in the R.I. of the analyte, the SPR dip shifts. In Figure 2, a comparative analysis of several prisms in terms of their reflectance curves indicates that Caf₂ prisms have the largest SPR angle for the proposed structure, and thus Caf₂ prisms are chosen as a light coupling glass at 662 nm wavelength. The proposed structure having Ag, BP and BlueP/MoS₂ on the top of the coupling prism, out of them Ag is used as an SPR-active metal layer. BlueP/MoS₂ heterostructure has been considered as the last layer, which interacts with the analyte directly. The dielectric constants of BlueP/MoS₂, Ag, Caf₂, and BP at 662 nm wavelength are extracted from [18], [21] and [22] respectively. The sensitivity (S) and detection accuracy (D.A.) of the sensor have been investigated [16] and calculated as:

\[
S = \frac{\Delta \theta_{spr}}{\Delta n_s}
\]

\[
D.A. = \frac{1}{FWHM}
\]

Sensitivity is defined as the change in resonance angle proportional to the change (n_s) in analyte R.I. and calculated mathematically as per Eq. (5). The D.A. defined in Eq. (6) as the inverse of the SPR curve’s angular FWHM (full width at half maximum) [19]. The six layer design parameters for the proposed sensor at a wavelength of 662 nm are shown in Table 1, along with the layer thicknesses and refractive indexes. The SPR requirement is met by a metal-dielectric contact satisfying the following equations. Transfer matrix method (TMM) has been used to quantify the reflectance of the data. In TMM method a N-layer approximation method has been devised to theoretical analyze of reflectance data. The schematic of a six-layer structure is shown in Figure 1, where \(n_k\) represents the complex values of the refractive index, \(\epsilon_k\) represents as permittivity of the \(k^{th}\) layer with thickness \(d_k\). As shown in Eq. (7), the N-layer structure can be represented using the characteristic matrix [23]:

\[
M = \prod_{k=2}^{N} M_k = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}
\]

\[
M = \begin{bmatrix} \cos(\beta_k) & -\sin(\beta_k)/q_k \\ -iq_k \sin(\beta_k) & \cos(\beta_k) \end{bmatrix}
\]

where:

\[
\beta_k = \left(\frac{2 \pi d_k}{\lambda}\right) \sqrt{\frac{\epsilon_k - n_i^2 \sin^2 \theta_i}{\epsilon_k}}
\]

\[q_k = \sqrt{\frac{\epsilon_k - n_i^2 \sin^2 \theta_i}{\epsilon_k}}\]

The reflection coefficient (\(r_p\)) and transmission coefficient (\(t_p\)) of the incident TM polarized (p-polarized) light is given

| Layers | Material used | Refractive Index (λ=662 nm) | Thickness (nm) |
|--------|--------------|-----------------------------|---------------|
| I      | Prism (Caf₂) | 1.43286                     | -             |
| II     | Metal (Ag)   | 0.04944+i×4.5027            | 40            |
| III    | 2D material (BP) | 3.8337+i×0.015215     | 0.65          |
| IV     | Metal (Ag)   | 0.04944+i×4.5027            | 8             |
| V      | Heterostructure (BlueP/MoS₂) | 2.7915+i×0.335 | 0.75          |
| VI     | Analyte      | 1.33 to 1.336               | -             |
by Eq. (9):

\[
\frac{H_y\text{ref}}{H_y\text{inc}} = \frac{(M_{11} + M_{12}q_N)q_1 - (M_{21} + M_{22}q_N)}{(M_{11} + M_{12}q_N)q_1 + (M_{21} + M_{22}q_N)}
\] (9)

and Eq. (10):

\[
\frac{H_yN_0}{H_yN} = \frac{2q_1}{(M_{11} + M_{12}q_N)q_1 + (M_{21} + M_{22}q_N)}
\] (10)

and then the reflectance \( R_P \) for p-polarized light is calculated as:

\[
R_P = |r_p|_2^2
\] (11)

Eq. (9) and Eq. (10) have been used to estimate the reflection coefficient and transmission coefficient respectively of this paper.

**III. RESULTS AND DISCUSSION**

In the proposed novel structure the refractive index sensor characteristic has been simulated assisted by BlueP/MoS\(_2\) heterostructure, silver metal and BP layers by the Kretschmann configuration. The proposed refractive index sensor has revealed a better sensitivity to capable enough for the detection of biofluids dissolved in water, biochemicals dissolved with water molecules, hard water detection, softwater detection to mention a few. In this connection, reflectance graph of the proposed structure as a function of an incident angle has been studied to precisely estimate the sensitivity improvement. The parameters in the proposed SPR sensor have been extracted from the literature and optimized thickness of the layers \( D_1, D_2, D_3 \) and \( D_4 \) have been considered layer by layer basis followed by simulation results to achieved the maximum sensitivity of the proposed SPR structure. In the proposed sensor the thickness of the Ag = 40 nm and 8 nm for first and third layer respectively, BlueP/MoS\(_2\) = 0.75 nm and BP = 0.65 nm is considered at

---

**FIGURE 3.** (a) Variation of reflectance with respect to the incident angle for refractive index ranges 1.332 to 1.336 with BP layer and (b) without BP layers.

**FIGURE 4.** Sensitivity (o/RIU) graph for the number of BP layers (M) with constant \( N = 1 \).

**FIGURE 5.** (a) Variation of Reflectance with respect to incident angle for different number of BlueP/MoS\(_2\) \( (N) \) heterostructure layers in the condition of constant BP layer \( (M) \), (b) Reflectance graph for different numbers of BP layers \( (M) \) and single BlueP/MoS\(_2\) \( (N) \) heterostructure layer, (c) Sensitivity of the 9 layers of BP and single layer of BlueP/MoS\(_2\) heterostructure layers.
visible 662 nm wavelength. Due to the excitation of SPR, it has been observed a sharp dip in reflectance graph at a certain angle due to the excitation of SPR wave energy which is adsorbed by the sensing layer or substance. Despite of a small shifts in SPR angle due to slight change in the sensing layer’s refractive index, still the resonance dip has a significant excursion of about $\delta \theta = 2.29^\circ$. Apparently this is due to insignificant molecular interaction on sensing head. The sensitivity parameter can be consistently calculated with the help of Eq. (5). It has been found that sensitivity parameter enhanced upto 458$^\circ$/RIU of the proposed structure while properly optimization of the number of layers and thickness of each layer. In all the calculations of this paper the range of refractive index taken for the simulation is between 1.331 to 1.336. Since the prism and gold layer are traditionally used in past SPR structures, hence similar prism-based structure in conjunction with novel 2D material has been chosen to achieve the optimum refractive index sensor’s sensitivity. Structure has been improved over previous structures with the considering the BP and a BlueP/MoS$_2$ heterostructure layer with Ag as the metal layer. The refractive index of the sensing layer can be used to monitor the sensitivity of the proposed refractive sensor study.

Figure 3 illustrates the relationship between the chemical sensor’s sensitivity and the refractive index of the sensing layer in the proposed BP and BlueP/MoS$_2$ heterostructure. Figure 3(a) shows the reflectance versus incidence angle curve for the R.I. range from 1.332 to 1.336 with the Ag + BP + Ag + BlueP/MoS$_2$ heterostructure. Infact as the refractive index value of the substance changed, SPR dip changed, and FWHM (full width at half maximum) value increased, leading to decreased detection accuracy. Figure 3(a) reveals the responses for two layers of BlueP/MoS$_2$ heterostructure and single BP layers along with change of analyte R.I. Figure 3(b) reveals the results when two BlueP/MoS$_2$ heterostructure and without BP layers are incorporated. The effect of thickness for the layers on the sensing properties when considering the evanescent fields in a typical SPR sensor is that if number of layer will increase the value of RI will increase as well as in complex Ri (real part of refractive index) term and $k$ (imaginary part of refractive index) term will increase hence maximum light will absorb and high penetration depth will appear in evanescent wave but at the same time due to enhancement in damping evanescent field will drop very earlier. So first the SPR angle will get wide and $R_{\text{min}}$ value will reduce so FWHM will hard to calculate. Sensitivity has been tremendously increased with every increment of BlueP/MoS$_2$ heterostructure layers. Sensitivity is significantly increased with incorporating few numbers of BlueP/MoS$_2$ heterostructure layers upto some limit however on the account of increment of FWHM parameter. Hence there is a trade off between the sensitivity and FWHM parameters in connection with the increment of BlueP/MoS$_2$ heterostructure layers. It has been found that sensitivity enhanced with BP layers too with stable FWHM values while keeping fix BlueP/MoS$_2$ heterostructure layers.

Table 3 shows the effect on the performance parameter by changing the number of BP layer (M) while keeping constant BlueP/MoS$_2$ heterostructure (N = 1) layer. It has been found that sensitivity increased to maximum value 458$^\circ$/RIU for the 9 number of BP layers there after it start decreasing with further increasing of BP layers. It has been found that at $\Delta n_\text{f}=0.007$ the maximum sensitivity touched down to a value of 471.42$^\circ$/RIU, which opens a new era to the researcher for the several applications. Figure 4 shows the sensitivity (o/RIU) graph for different BP layers with constant BlueP/MoS$_2$. Figure 5 (a) shows the schematic diagram of reflectance with incidence angle for the different number of BlueP/MoS$_2$ heterostructure layers with the condition of constant BP layer (M). Figure 5(b) shows the reflectance graph for different numbers

| Configuration (Cal2+) | $\Delta t_{SPR}$ (Degree) | Sensitivity (o/RIU) | Analyte RI range (n=0.005) |
|-----------------------|--------------------------|---------------------|--------------------------|
| Ag                    | 0.93                     | 186                 | 1.331 to 1.336           |
| Ag+BP                 | 0.99                     | 198                 | 1.331 to 1.336           |
| Ag+BP+Ag              | 1.00                     | 200                 | 1.331 to 1.336           |
| Ag+BP+BlueP/MoS$_2$    | 1.07                     | 214                 | 1.331 to 1.336           |

Table 3. Variation of the BP layer (M) and a constant BlueP/MoS$_2$ heterostructure has an impact on the output parameter.
of BP layers and single BlueP/MoS$_2$ heterostructure layer. Figure 5(c) shows the sensitivity of 458 °RIU by the 9 layers of BP and single layer of BlueP/MoS$_2$ heterostructure layers. Figure 5(a) shows the simulated results for increasing BlueP/MoS$_2$ heterostructure (N) layers and single BP layer for fixed refractive index media. It is observed that BlueP/MoS$_2$ heterostructure layers increasing the sensitivity improved layer by layer. At the same time, its detection accuracy is decreasing because FWHM of reflectance wave rises with a growing BlueP/MoS$_2$ heterostructure layer. It cannot randomly increase the BlueP/MoS$_2$ heterostructure layers because when FWHM increases sensitivity decreases. Apparently large FWHM and less reflectance dip more than 0.5 (a.u.) are not suitable for sensing application. Figure 5(b) shows the simulated results for only single layer of BlueP/MoS$_2$ heterostructure with varying BP layers up to 10 layers. It has been observed that up to 9 layers of BP the FWHM value is not less than 0.5 and also very sharp reflectance dip is obtained while after 9 layers of BP the FWHM increases and so as sensitivity starts decreases. Due to this observation optimum 9 layers of BP has been considered in the proposed structure for achieving highest sensitivity (458 °RIU) parameter. Sensitivity at different R.I. has been shown in Figure 6 by the theoretical analysis for the proposed structure layer by layer of Ag + BP + Ag + BlueP/MoS$_2$ heterostructure. The maximum sensitivity is obtained 214 °RIU at R.I. = 1.336 of analyte when single layer of BP and BlueP/MoS$_2$ heterostructure has been introduced. In Figure 6 the layer-by-layer analysis has been done for the R.I. range of 1.332 to 1.336. In this analysis firstly at 1.332 R.I., with only Ag layer SPR performance has been seen and similarly added a single layer of BP and BlueP/MoS$_2$ layer sensitivity calculated. Table 4 shows the sensitivity comparison with some recent paper works with the proposed work. It has been investigated that by the proposed configuration sensitivity enhancement achieved to be 471.42 °RIU for a small change of analyte refractive index Δn$=\approx$0.007.

Figure 7 shows the performance parameters of the proposed SPR sensor, at 9 layers of BP the FWHM achieved 4.45°, sensitivity 458 °RIU, D.A. = 0.22472 and F.O.M. 102.9 RIU$^{-1}$. After layer number 09 (9 x 0.65 nm thickness), the evanescent filed penetration depth decreases to the outer medium due to noncompliance of the SPR condition hence in the proposed SPR sensor sensitivity would decreased after layer number 09.

IV. FABRICATION PROSPECT

The proposed sensing chip is developed with different deposition materials on top of a multi-layered structure made of high-refractive-index glass. The Ag layer will be deposited on top of the prism or glass substrate by the e-beam deposition machine. Then, the index-matching gel is used to stick the SPR chip (glass substrate) to the flat side of the prism. After the deposition of the Ag layer other materials will be deposited layer by layer. On the top of the sensing chip, the sensing analyte was moved to the flow cell. Light can be launched on one side of the prism, and on the other side reflected light can be collected through a spectrophotometer.
and the spectrophotometer is connected to the PC/laptop by
the help of the ASPIRE-SPECTRA- 21 (compatible with
the Windows) software where absorbance, reflectance, and
transmittance spectrum can be obtained. Given all of these
options and the current state of material technology, we are
optimistic that the suggested SPR sensor for testing can be
used in real life. The prism needs to be put between the source
and detector of the spectrophotometer. A spectrophotometer
has two light sources: white light (tungsten halogen) and LED
light (wavelength range 200-1100 nm). After that, there is a
need to set a reference value in a dark room so that the lab
environment can be done in natural light. After getting the
reference value from the surrounding environment, the LED
light source on one side of the prism was used to send light
through the prism must land on the top of the prism, where the
sensing material is positioned. In the coating process, we can
use field emission scanning electron microscopy (FESEM)
to look at the deposition of layers on a glass substrate from
a cross-sectional view, and this is done to make sure that the
layers are deposited correctly as per the required thickness of
the layers.

V. CONCLUSION

A BlueP/MoS$_2$ heterostructure has been suggested for use
in an SPR-based sensor. In comparison to conventional SPR
sensor schemes and graphene-based SPR sensor schemes, it is
demonstrated that the proposed system with this structure
will achieve enhanced sensitivity. The maximum sensitivity is
obtained when a 9-layer BP (black phosphorous) heterostruc-
ture and a single-layer BlueP/MoS$_2$ heterostructure are used.
Additionally, the identification accuracy is within reasonable
limits. We analyzed the sensor’s performance by considering
the cumulative effect of the wavelength and the varying BP
and heterostructure layers. Owing to the extremely sensitive
nature of the proposed scheme, it could be a competitor to
graphene-based SPR sensors.

REFERENCES

[1] J. Homola, “Surface plasmon resonance sensors for detection of chemical
and biological species,” Chem. Rev., vol. 108, no. 2, pp. 462–493, 2008.
[2] A. K. Sharma and A. K. Pandey, “Blue phosphorene/MoS$_2$ heterostructure
based SPR sensor with enhanced sensitivity,” IEEE Photon. Technol. Lett.,
vol. 30, no. 7, pp. 595–598, Feb. 8, 2018.
[3] H. Tan, M. Zhou, L. Zhuge, C. Jin, and X. Wu, “Study on the surface
plasmon polarizations in nonuniform plasma,” IEEE Trans. Plasma Sci.,
vol. 48, no. 12, pp. 4112–4118, Dec. 2020.
[4] E. Kretschmann and H. Raether, “Radiative decay of non radiative surface
plasmons excited by light,” Zeitschrift Naturforsch A, vol. 23, no. 12,
pp. 2135–2136, 1968.
[5] S. Sun, T. Hussain, W. Zhang, and A. Karton, “Blue phosphorene mono-
layers as potential nano sensors for volatile organic compounds under point
defects,” Appl. Surf. Sci., vol. 486, pp. 52–57, Aug. 2019.
[6] B. Karki, S. Sharma, Y. Singh, and A. Pal, “Sensitivity enhancement of
surface plasmon resonance biosensor with 2-D fractalene nanostructures,”
Plasmonics, vol. 17, pp. 1–8, Jul. 2021.
[7] Y. Singh, M. K. Paswan, and S. K. Raghuvanshi, “Sensitivity enhance-
ment of SPR sensor with the black phosphorous and graphene with bi-
layer of gold for chemical sensing,” Plasmonics, vol. 16, pp. 1–10,
Apr. 2021.
[8] S. K. Raghuvanshi, S. Kumar, and Y. Singh, 2D Materials for Surface
Plasmon Resonance-Based Sensors, 1st ed. Boca Raton, FL, USA: CRC
Press, 2021, doi: 10.1201/9781003190738.
[9] H. O. H. Churchill and P. Jarillo-Herrero, “Phosphorus joins the family,”
Nature Nanotechnol., vol. 9, no. 5, pp. 330–331, May 2014.
[10] L. Li, Y. Yu, G. J. Ye, Q. Ge, X. Ou, H. Wu, D. Feng, X. H. Chen, and
Y. Zhang, “Black phosphorus field-effect transistors,” Nature Nanotech-
nol., vol. 9, no. 5, pp. 372–377, 2014.
[11] A. S. Rodin, A. Carvalho, and A. H. C. Neto, “Strain-induced gap
modification in black phosphorus,” Phys. Rev. Lett., vol. 112, p. 176801,
May 2014, doi: 10.1103/PhysRevLett.112.176801.
[12] L. Wang, S.-C. Tian, and L. Li, “Research on evaluation index system of
safety culture construction in oilfield teams,” in Proc. 7th Int. Conf. Intell.
Comput. Technol. Autom., Oct. 2014, pp. 517–521.
[13] D. Sarkar, X. Xie, J. Kang, H. Zhang, W. Liu, J. Navarrete, M. Moskovits,
and K. Banerjee, “Functionalization of transition metal dichalcogenides
with metallic nanoparticles: Implications for doping and gas-sensing,”
Nano Lett., vol. 15, no. 5, pp. 2582–2586, 2015.
[14] A. K. Sharma, A. K. Pandey, and B. Kaur, “Simulation study on com-
prehensive sensing enhancement of BlueP/MoS$_2$- and BlueP/WSe$_2$-based
fluoride fiber surface plasmon resonance sensors: Analysis founded on
damping, field, and optical power,” Appl. Opt., vol. 58, no. 16,
p. 4518–4525, 2019.
[15] L. Wu, J. Guo, Q. Wang, S. Lu, X. Dai, Y. Xiang, and D. Fan, “Sensitiv-
ity enhancement by using few-layer black phosphorus-graphene/TMDCS
heterostructure in surface plasmon resonance biochemical sensor,” Sensors
Actuators B, Chem., vol. 249, pp. 542–548, May 2017.
[16] A. Srivastava and Y. K. Prajapat, “Performance analysis of silicon and
blue phosphorene/MoS$_2$ hetero-structure based SPR sensor,” Photon. Sen-
sors, vol. 9, no. 3, pp. 284–292, Sep. 2019.
[17] Y. Singh and S. K. Raghuvanshi, “Sensitivity enhancement of the surface
plasmon resonance gas sensor with black phosphorus,” IEEE Sensors Lett.,
vol. 3, no. 12, pp. 1–4, Dec. 2019.
[18] I. H. Malitson, “A redetermination of some optical properties of calcium
fluoride,” Appl. Opt., vol. 2, no. 11, pp. 1103–1107, Jul. 1963.
[19] S. Aksimsesk, H. Jussila, and Z. Sun, “Graphene–MoS$_2$–metal hybrid
structures for plasmonic biosensors,” Opt. Commun., vol. 428,
p. 233–239, Aug. 2018.
[20] Q. Ouyang, S. Zeng, D. Dinh, P. Coquet, and K.-T. Yong, “Sensitivity
enhancement of MoS$_2$ nanosheet based surface plasmon resonance biosen-
ror,” Proc. Eng., vol. 140, pp. 134–139, Dec. 2016.
[21] Q. Peng, Z. Wang, B. Sa, B. Wu, and Z. San, “Electronic structures and
enhanced optical properties of blue phosphorene/transition metal dichalco-
genides van der Waals heterostructures,” Sci. Rep., vol. 6, no. 1, pp. 1–10,
Aug. 2016.
[22] Z. Lin, L. Jiang, L. Wu, J. Guo, X. Dai, Y. Xiang, and D. Fan, “Tuning
and sensitivity enhancement of surface plasmon resonance biosensor with
graphene covered Au-MoS$_2$-Au films,” IEEE Photon. J., vol. 8, no. 6,
pp. 1–8, Dec. 2016.
[23] P. S. Pandey, Y. Singh, and S. K. Raghuvanshi, “Theoretical analysis of
the Irssr sensor with enhance forom for low refractive index detection
using mxene and fluorinated graphene,” IEEE Sensors J., vol. 21, no. 21,
p. 23979–23986, Nov. 2021.
[24] L. Wu, Y. Jia, L. Jiang, J. Guo, X. Dai, Y. Xiang, and D. Fan, “Sensitiv-
ity improved SPR biosensor based on the MoS$_2$/graphene–
aluminum hybrid structure,” J. Lightw. Technol., vol. 35, no. 1,
p. 82–87, Jan. 1, 2017.
[25] B. Meshgingalam and J. Barvestani, “Performance enhancement of SPR
biosensor based on phosphorene and transition metal dichalcogenides
for sensing DNA hybridization,” IEEE Sensors J., vol. 18, no. 18,
p. 7537–7543, Sep. 2018.
[26] B. Hossain, A. K. Paul, M. A. Islam, M. M. Rahman, A. K. Sarkar,
and L. F. Abdulrazak, “A highly sensitive surface plasmon resonance
biosensor using SnSe allotrope and heterostructure of BlueP/MoS$_2$ for
cancerous cell detection,” Optik, vol. 252, Feb. 2022, Art. no. 168506.
[27] A. Castellanos-Gomez, “Black phosphorus: Narrow gap, wide applica-
tions,” J. Phys. Chem. Lett., vol. 6, pp. 4280–4291, Oct. 2015.
[28] S. K. Raghuvanshi and P. S. Pandey, “A numerical study of different metal
and prism choices in the surface plasmon resonance biosensor chip for
human blood group identification,” IEEE Trans. Nanobiosci., early acces,
Jun. 23, 2022, doi: 10.1109/TNAN.2022.3185806.
[29] P. S. Pandey, S. K. Raghuvanshi, and Y. Singh, “Enhancement of the sensi-
tivity of a surface plasmon resonance sensor using a Nobel structure based
on barium titanate–graphene –silver,” Opt. Quantum Electron., vol. 54,
no. 7, pp. 1–15, Jul. 2022.
P. S. Pandey, S. K. Raghuwanshi: Sensitivity Enhancement of SPR Sensor Assisted by BlueP/MoS$_2$ Based Composite Heterostructure

[30] P. S. Pandey, S. K. Raghuwanshi, and S. Kumar, “Recent advances in two-dimensional materials-based Kretschmann configuration for SPR sensors: A review,” IEEE Sensors J., vol. 22, no. 2, pp. 1069–1080, Jan. 2022, doi: 10.1109/JSEN.2021.3133007.

[31] S. K. Raghuwanshi and P. S. Pandey, “Optimum design of surface plasmon resonance (SPR) tapered fiber optic biosensing probe with graphene–MoS$_2$ over layers for DNA hybridization,” IEEE Trans. Plasma Sci., early access, Oct. 18, 2022, doi: 10.1109/TPS.2022.3211645.

PURNENDU SHEKHAR PANDEY (Member, IEEE) received the B.Tech. degree in electronics and instrumentation engineering from Dr. A. P. J. Abdul Kalam Technical University, Uttar Pradesh, India, and the M.Tech. degree in digital communication from Uttarakhand Technical University, Dehradun, Uttarakhand, India, in 2013. He is currently working as an Assistant Professor with the Department of Electronics and Communication Engineering, GL Bajaj Institute of Technology and Management, Greater Noida, India. He has ten years of teaching experience and worked as a JRF under the Indian Space Research Organization (ISRO) sponsored project (Sanction No. ISRO/RES/3/775/18-19) at the Indian Institute of Technology (Indian School of Mines) Dhanbad, India. He has authored or coauthored 35 research papers and a book. He holds nine patents published and one granted patent. His research interests include optical fiber-based surface plasmon resonance (SPR) sensor, prism-based SPR, nanomaterial-coated fiber Bragg grating (FBG) sensor for chemical and biochemical sensing, wireless sensors, and biomedical instrumentation.

SANJEEV KUMAR RAGHUWANSHI (Senior Member, IEEE) received the bachelor’s degree in electronic and instrumentation engineering from the Shri Govindram Seksaria Institute of Technology and Science, Indore, Madhya Pradesh, India, in August 1999, the master’s degree in solid state technology from the Indian Institute of Technology (IIT) Kharagpur, Kharagpur, India, in January 2002, and the Ph.D. degree in optics from the Department of Electrical Communication Engineering. He was a Visiting Scientist at the National United University, Mialoi, Taipei, Taiwan, from June 2014 to July 2014. He worked as a Postdoctoral Research Fellow at the Instrumentation and Sensor Division, School of Engineering and Mathematical Sciences, City University of London, London, U.K., from 2014 to 2015. He was a Visiting Scientist (under INSA Visiting Scientist Fellowship Scheme 2020) with the Department of Electrical Communication Engineering, Indian Institute of Science (IISc), Bengaluru, India, from December 2021 to January 2022. He is currently working as an Associate Professor with the Department of Electronics Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad. In the previous ten years, he has published more than 100 peer-reviewed and indexed international SCI journal articles. He has six books in the field of current optical fibers. Six Indian patents have been filed and published in the last five years. Several central Government funding agencies, including the Department of Atomic Energy (DAE), Government of India (GOI), the Indian Space Research Organization (ISRO), GOI, Council of Scientific and Industrial Research (CSIR), GOI, Defence Research and Development Organisation (DRDO), GOI, and the Science and Engineering Research Board, Department of Science and Technology, GOI, have sanctioned and executed his research and development projects. He is a Life Member of the Institution of Electronics and Telecommunication Engineers (IETE) and the International Academy of Physics Sciences, as well as a fellow of the Optical Society of India (OSI). For his Postdoctoral degree, he was awarded the Erasmus Mundus Scholarship. He has been awarded by the “Best Research Award” (Canara Bank Publication Award) by the IIT (ISM), Dhanbad, in 2016, 2017, and 2018. He was a receipt of the International Travel Grants by the Department of Science and Technology, Science and Engineering Research Board (DST-SERB) to attend one international conference on Photonics, Berlin, Germany, in 2016, and Photonics West SPIE, Sanfrancisco, CA, USA, in 2020. He has contributed to IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, IEEE SENSORS JOURNAL, IEEE PHOTONICS TECHNOLOGY LETTERS, and IEEE JOURNAL OF QUANTUM ELECTRONICS, as a Reviewer. He serves on the editorial boards of various Indian publications and serves as a reviewer for them.

* * *