Effect of Silicon Carbide on Surface Plasmon Resonance (SPR) Sensor: A Theoretical Approach

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Abstract: This study delivers a comprehensive computational analysis of a Surface Plasmon Resonance (SPR) sensor engineered in the Kretschmann configuration. The design integrates a calcium fluoride (CaF_2) prism, a thin copper (Cu) film, a silicon carbide (SiC) layer, and an active sensing interface. Optical characterization was carried out via the Transfer Matrix Method (TMM) combined with angular interrogation at a 633 nm excitation wavelength. The optimized sensor exhibits an angular sensitivity of 194 deg./RIU, a detection accuracy of 1.38 deg^{-1}, a quality factor of 269.44 RIU^{-1} and a limit of detection of 5.1×10^{-6} RIU over a refractive index window of 1.330–1.350. To assess analytical performance and selectivity, metrics such as detection accuracy, quality factor, figure of merit (FOM) and dip-based FOM (DOFOM) were evaluated. The results underscore the device's significant potential for next-generation biomedical diagnostics and contribute valuable insights to materials science and plasmonic sensor technology.

Keywords: *Silicon Carbide, Kretschmann Configuration, Angle Interrogation, Black Phosphorus.*

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I. INTRODUCTION

Surface Plasmon Resonance (SPR) continues to play a pivotal role in the advancement of next-generation sensing technologies based on optical and photonic principles [1–2]. Due to their straightforward design, real-time analytical capabilities, and outstanding sensitivity, SPR-based sensors are extensively employed in a wide range of applications, including biomedical diagnostics, biochemical analysis, environmental monitoring, and medical research [3-4]. An array of SPR sensor configurations has been developed for interdisciplinary use in fields such as healthcare, agriculture, defense, and environmental assessment. These sensors enable real-time kinetic analysis, facilitate label-free detection, and offer rapid and accurate measurements [5-6]. SPR sensing operates by detecting minor changes in the resonance angle that occur due to variations in the refractive index of materials adsorbed on the sensor surface [7-8]. When p-polarized light is directed through a glass prism and encounters the metal-dielectric interface at a specific angle, it stimulates the excitation of surface plasmons, collective oscillations of free electrons confined to the metallic surface. These electron oscillations are highly responsive to even minimal variations in the adjacent refractive index [9-10]. The resonance condition results in a characteristic reduction in the intensity of the reflected light, producing a well-defined minimum in the reflectance spectrum referred to as the SPR curve due to light absorption at resonance [11-12]. Even slight changes in the refractive index produce measurable angular shifts, thereby allowing label-free and highly sensitive detection of biomolecular interactions. Among the various SPR configurations, prism-coupled designs using the Kretschmann arrangement are particularly favored for their rapid response and enhanced sensitivity, surpassing the performance of the Otto configuration [13–14]. Sensor performance is typically characterized using parameters such as sensitivity, detection accuracy, limit of detection (LOD), and the quality factor. The Transfer Matrix Method (TMM) is a widely utilized computational approach for modelling and optimizing SPR sensor behaviour across different structural architectures. Recent developments in biochemistry and genetic engineering have further propelled the evolution of SPR biosensors, facilitating their integration into the broader domains of plasmonics and photonics [15–16]. SPR detection techniques primarily rely on two interrogation methods: angular and wavelength interrogation. Angular interrogation,

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which involves the use of monochromatic light at varying incidence angles, enhances the signal-to-noise ratio and improves measurement precision. Typically, SPR sensors consist of a glass prism coupled with a plasmonic metal film, wherein the prism ensures efficient coupling of incident light with surface plasmons [17–20].

Despite significant advancements, conventional SPR configurations often exhibit limitations in detecting trace-level analytes. To address these challenges, researchers have focused on developing multilayer sensor structures and incorporating novel materials such as two-dimensional (2D) nanomaterials, perovskites, advanced plasmonic elements, and semiconductors. Prisms with lower refractive indices and broader resonance angles have demonstrated improved sensitivity. Among plasmonic metals, copper (Cu) exhibits superior signal-to-noise performance and sharper resonance dips compared to gold and silver. However, its susceptibility to oxidation necessitates the use of protective coatings made from 2D materials or metal oxides [21–28]. Silicon carbide (SiC) has emerged as a highly promising candidate for enhancing SPR sensor performance. It offers a high refractive index, excellent thermal and mechanical stability, chemical inertness, and broad optical transparency. These attributes collectively contribute to improved sensor sensitivity, robustness, and operational longevity, making SiC particularly suitable for challenging environments, industrial monitoring, chemical analysis, and biological detection. Additionally, SiC demonstrates superior structural stability, adaptability, and cost-effectiveness compared to conventional metallic layers [29–30]. The structure of this research article is organized as follows: the section entitled **"Numerical Modeling of the Proposed SPR Sensor"** outlines both the design and theoretical framework of the sensor. To develop an optimized sensor configuration, various design alternatives are explored and evaluated in the **"Results and Discussion"** section, where the sensor's performance is assessed based on sensitivity, detection accuracy, quality factor, and limit of detection (LOD). Finally, the key findings of this study are summarized in the **"Conclusion"** section.

II. NUMERICAL MODELLING OF PROPOSED SPR SENSOR

➢ *Refractive Index of Different Layers*

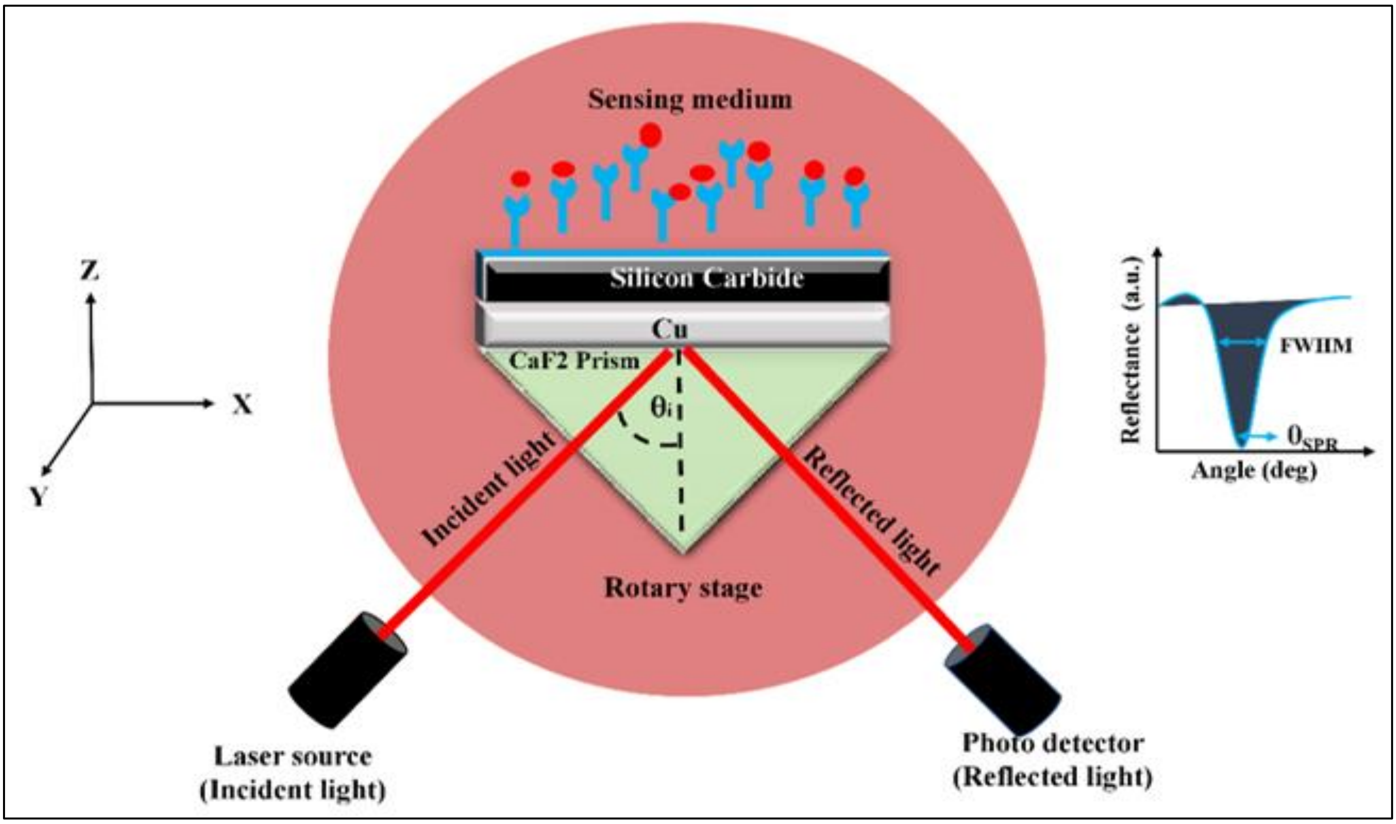

Fig 1 Proposed SPR Sensor Device Structure

A schematic representation of the suggested multilayer sensor based on the Kretschmann configuration is presented in Figure 1. The design consists of four distinct layers arranged in sequence: a calcium fluoride (CaF_2) prism, copper (Cu), silicon carbide (SiC), and the sensing medium. Each layer is precisely engineered with nanometre-scale thickness to enhance the sensor's performance characteristics, utilizing an operational wavelength of 633 nm. In particular, the CaF_2 prism serves as the optical substrate. The refractive index of the CaF_2 prism is calculated in accordance with the well-established dispersion formula.31].

$$n_{CaF_2} = \left(1 + \frac{0.5675888\lambda^2}{\lambda^2 - 0.050263605} + \frac{0.4710914\lambda^2}{\lambda^2 - 0.1003909} + \frac{3.8484723\lambda^2}{\lambda^2 - 34.649040}\right)^{1/2} \quad (1)$$

The refractive index of Copper (Cu) is ascertained employing the Drude model [45]

$$n^2 = [1 - \frac{\lambda^2 \lambda_c}{\lambda_p{}^2(\lambda_c + i\lambda)}] \quad (2)$$

The thickness and refractive index of various Nano materials have been optimized at 633 nm are shown in Table 1.

Table 1 Refractive Index & Optimized Thickness of Various Nanomaterials.

Layer	Material	Optimized Thickness	RI at 633nm	Reference
1.	CaF_2 Prism	100nm	1.43290	[44]
2.	Cu	55nm	0.0369+i4.5393	[32]
3.	SiC	1-6 nm	2.6342	[29]

➢ *Theoretical Modelling of the Proposed Sensor*

The refined Kretschmann configuration for Surface Plasmon Resonance (SPR) analysis is evaluated utilizing a four-layer conceptual model, as depicted in Figure 1. In this arrangement, transverse magnetic (TM) polarized light enters via one side of the prism and is directed toward its base. Upon incidence at the base, the light experiences total internal reflection (TIR) before exiting through the opposite side, where a photodetector captures and evaluates the reflected beam. SPR detection is carried out at an excitation wavelength of 633 nm. This sensing structure consists of a calcium fluoride (CaF_2) prism, a copper (Cu) thin film, a silicon carbide (SiC) buffer layer, and an outer analyte medium. The target analyte is introduced into the detection chamber through a designated inlet, facilitating interaction with antibodies immobilized on the sensor interface to specifically bind the molecule of interest. Surplus or unreacted analyte is effectively removed via an outlet, thereby ensuring high analytical fidelity.

The optical response of the multilayer sensor structure is meticulously studied employing the Transfer Matrix Method (TMM), integrated with Fresnel reflection coefficient calculations and the N-layer theoretical approach. In this framework, each constituent layer is precisely positioned along the z-axis, characterized by unique parameters such as thickness, complex dielectric permittivity, and refractive index. The simulation presumes that all layers are uniform, isotropic, and non-magnetic to preserve theoretical rigor and optimize analytical performance. Through the application of the boundary condition, the tangential field at $Z= Z_1= 0$ is presented in terms of the tangential field at $Z= Z_{N-1}= 0$. [33-35].

$$\begin{bmatrix} G_1 \\ L_1 \end{bmatrix} = A_{ij} \begin{bmatrix} G_{N-1} \\ L_{N-1} \end{bmatrix} \quad (3)$$

Let G_1, G_{N-1}, L_1, and L_{N-1} represent the tangential components of the magnetic and electric fields at the interfaces of the first and last layers, respectively. The matrix X denotes the characteristic matrix corresponding to the composite structure, which is obtained from the following equation.

$$X = \prod_{k=2}^{N} X_k = \begin{vmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{vmatrix} \quad (4)$$

$$X_k = \begin{vmatrix} \cos\gamma_k & -i\sin\gamma_k/\delta_k \\ -i\sin\gamma_k & \cos\gamma_k \end{vmatrix} \quad (5)$$

Here γ_k and δ_k are

$$\delta_k = \frac{(\varepsilon_k - n^2\sin^2\theta_1)^{1/2}}{\varepsilon_k}, \quad \gamma_k = \frac{2\pi d_k}{\lambda}(\varepsilon_k - n^2\sin^2\theta_1)^{1/2}$$

In this context, θ_1 denotes the angle at which the light is incident, and λ signifies the wavelength of the incoming light. The parameters ε_k and d_k correspond to the dielectric permittivity and the thickness of the kth layer, respectively.

The total reflection coefficient for p-polarized light (r_p) is computed as follows:

$$r_p = \frac{(X_{11} + X_{12}Y_N)Y_1 - (X_{21} + X_{22}Y_N)}{(X_{11} + X_{12}Y_N)Y_1 + (X_{21} + X_{22}Y_N)} \quad (6)$$

The reflectivity of the multilayer configuration is given as:

$$R_p = |r_p|^2 \quad (7)$$

III. PERFORMANCE PARAMETERS

The efficacy of a Surface Plasmon Resonance (SPR) sensor is chiefly determined by fundamental metrics including sensitivity (S), detection accuracy (DA), and quality factor (QF). Additionally, the Full Width at Half Maximum (FWHM) serves as a vital criterion for assessing the sensor's operational performance. Attaining favorable values for these parameters is crucial to improving the reliability and measurement precision of SPR-based detection systems.

Sensitivity is defined as:

$$S = \frac{\Delta\theta_{res}}{\Delta n_a} \quad \text{(deg./RIU)}. \quad (8)$$

Detection Accuracy (DA) is defined as:

$$DA = \frac{1}{FWHM} \quad \text{(1/deg.)} \quad (9)$$

Quality Factor is defined as

$$QF = \frac{\text{Sensitivity}}{\text{FWHM}} \quad (10)$$

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To ensure reliable sensing capabilities, it is imperative to enhance sensitivity (S) while simultaneously reducing the Full Width at Half Maximum (FWHM). Attaining this balance necessitates that the SPR reflectance profile presents a pronounced and distinct resonance trough. Nonetheless, there is frequently an inherent compromise between detection accuracy (DA) and sensitivity (S) within SPR sensor platforms. Consequently, the primary aim is to establish an optimal balance among material selection, structural configuration, and operational parameters in order to design an SPR system that offers superior sensitivity, minimal reflectance at resonance (Rmin), and adequate detection accuracy, thereby improving the overall quality factor (QF). The functional response of the SPR sensor has been computationally analysed using MATLAB.

IV. RESULTS AND DISCUSSIONS

In this study, a Surface Plasmon Resonance (SPR) sensor is developed utilizing the Kretschmann configuration, which incorporates a prism to provide the necessary momentum for surface plasmon excitation. Calcium fluoride (CaF_2) is chosen as the prism substrate owing to its comparatively low refractive index, thereby improving the efficiency of optical coupling. The system operates with p-polarized light at a wavelength of 633 nm to optimally excite surface plasmons at the metal-dielectric boundary, as illustrated in Fig. 1. The primary objective of this research is to examine reflectance variations in response to changes in the refractive index (RI) of the analyte. At the resonance condition, a distinct and sharp reduction in the reflectance spectrum is observed, indicating the point of maximum excitation and energy transfer to the surface plasmons.

➢ *Effect of Prism and Metal Layer*

The four-layer architecture of the proposed surface plasmon resonance (SPR) sensor is pivotal in influencing the device's overall functional efficacy. Consequently, a meticulous optimization of the structural parameters is imperative to maximize performance. This refinement is executed through a methodical, sequential adjustment of each constituent layer. The initial stage involves evaluating the reflectance dependency on the angle of incidence, where the minimum reflectance value (Rmin) directly relates to the transfer of momentum from the incoming light to the surface plasmons. Greater momentum transfer results in a lower Rmin, signifying more effective excitation of surface plasmons. Among the various prism substrates analysed, calcium fluoride (CaF_2) distinguishes itself as an optimal coupling material due to its comparatively low refractive index, which enhances angular sensitivity and expands the spectrum of reflectance variation. The comparative evaluation encompasses prism substrates such as CaF_2, CsF, FK51A, BK7, and B270, possessing refractive indices of 1.4329, 1.4768, 1.4853, 1.5151, and 1.520, respectively. The refractive index of the sensing environment is maintained at 1.33. Reflectance and sensitivity metrics are derived using Equations (5) and (8). As depicted in Figure 3(a), the configuration based on CaF_2 demonstrates the lowest reflectance among the materials tested. Precise modulation of the metallic layer's thickness is crucial for optimizing surface plasmon (SP) excitation, aiming for a reflectance value nearing zero. Figure 3 illustrates the optimization of the copper (Cu) thin film deposited on the CaF_2 prism, where, at an adjusted thickness of 55 nm, the reflectance reaches a minimum of 0.0147 at the resonance angle. This low level of reflectance is attributed to diminished energy dissipation during the optical energy transfer to the SPs. Furthermore, the copper layer presents a narrow full width at half maximum (FWHM), substantially enhancing the sensor's detection fidelity. An ideal FWHM of 1.33° is attained with a Cu thickness of 55 nm. Taking into account the balance between minimized reflectance and reduced FWHM, the 55 nm Cu film is established as the most advantageous configuration, resulting in a reflectance of 0.01177 and an FWHM of 0.96°.

Nevertheless, copper's predisposition to oxidation can negatively impact the sensor's durability and operational consistency. To mitigate this drawback, a protective silicon carbide (SiC) coating is applied. SiC is chosen for its exceptional physical and electronic characteristics, including ferroelectricity, piezoelectricity, and a high dielectric constant. The elevated dielectric constant increases the electrical flux density, thus enhancing charge retention within the detection interface an attribute particularly beneficial for advanced biosensing applications.

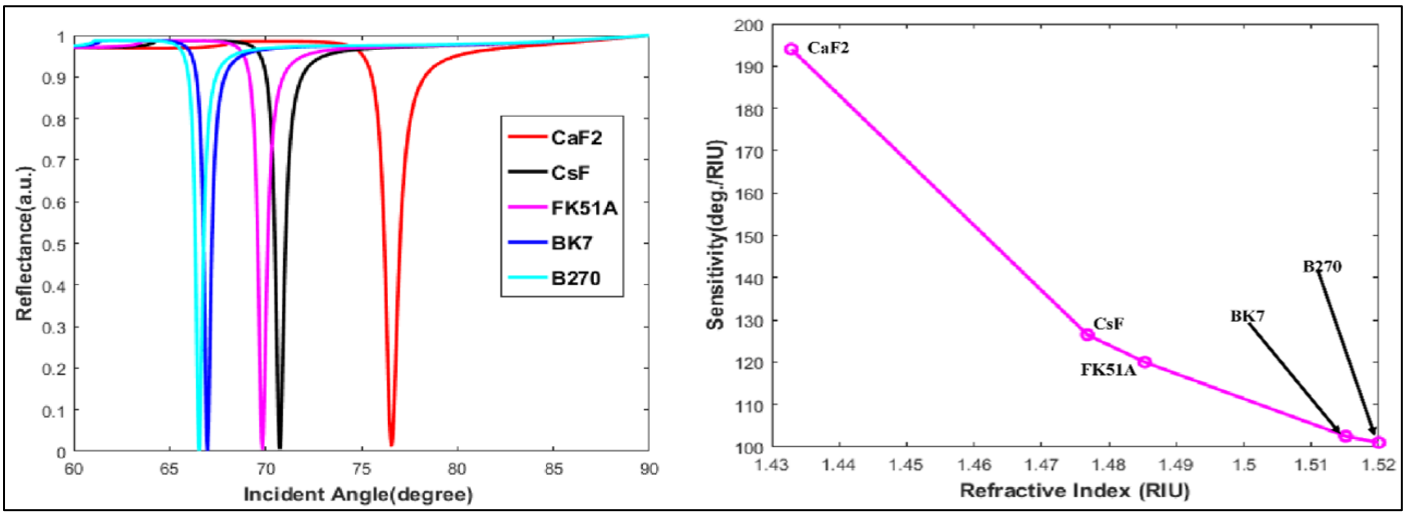

Fig 2 a. Reflectance vs. Incident angle curve for different prisms. b. Plot of Sensitivity vs. various prism materials.

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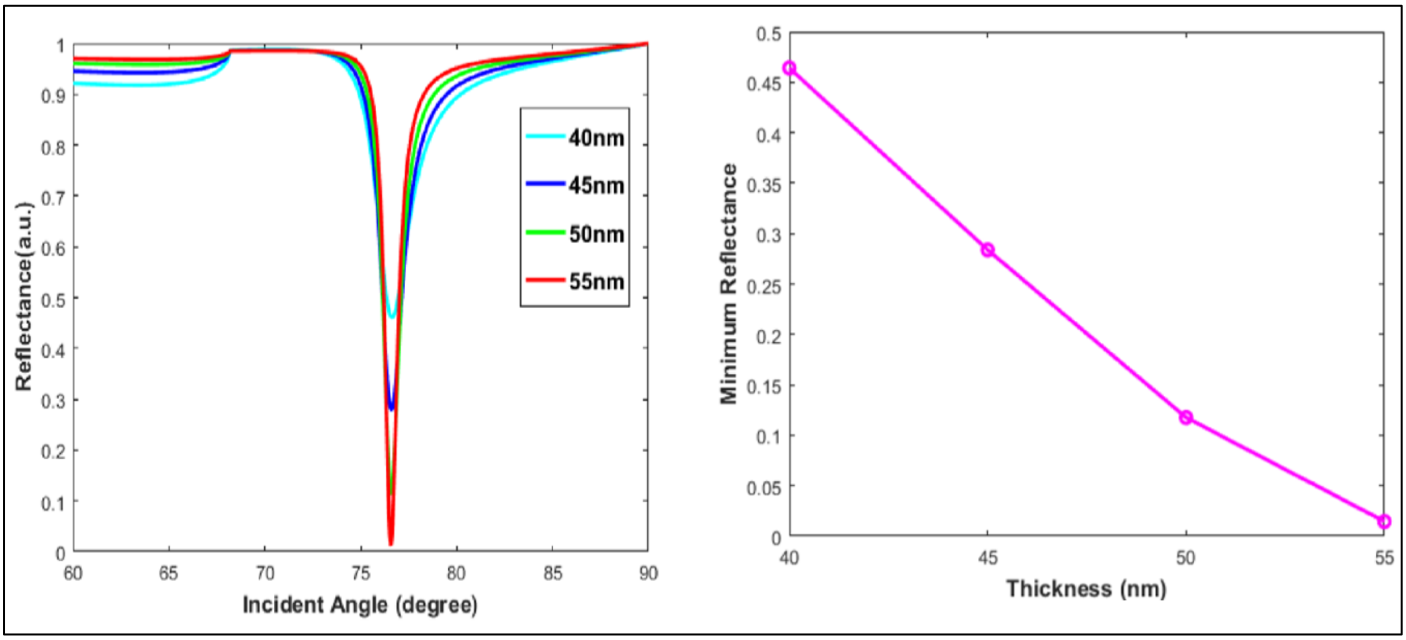

Fig 3 a. Cu metal Layer thickness Optimization Curve b. Minimum Reflectance Vs Sensitivity Plot

➢ *Evaluation of Performance Parameter across Different SPR Sensor Architectures:*

This section presents a detailed comparative analysis of key performance parameters across different Surface Plasmon Resonance (SPR) sensor configurations. Figures 4a and 4 b illustrate two distinct SPR architectures, each accompanied by its corresponding reflectance spectrum, to facilitate direct performance evaluation. Structure-1, comprising a CaF_2 prism, copper (Cu) layer, and the sensing medium, represents the baseline or conventional SPR sensor design. As shown in Figure 3a, this configuration demonstrates a resonance angle shift of 2.93°, yielding an angular sensitivity of 146.5° RIU^{-1}, which is categorized as moderate in terms of responsiveness. Enhanced configurations are explored in subsequent designs. In Structure-2 (CaF_2 prism/Cu/SiC/sensing medium), a silicon carbide (SiC) interlayer is integrated above the copper film. This addition aims to enhance the adsorption efficiency of biomolecules and simultaneously prevent copper oxidation, thereby improving stability and sensitivity. Figure 4b reveals a resonance angle shift of 3.88°, corresponding to a heightened angular sensitivity of 194° RIU^{-1}.

Table 2 Performance Parameter of Various SPR Sensors

Sr. No.	Device Structure	$\Delta\theta_{res}$	Sensitivity (°RIU^{-1})	DA ($deg.^{-1}$)	QF (RIU^{-1})	LOD ($\times 10^{-6}$)
1.	Prism+ Cu+ SM	2.93°	146.5	2.77	406	6.8
2.	Prism+ Cu +SiC +SM	3.88°	194.0	1.38	269.44	5.1

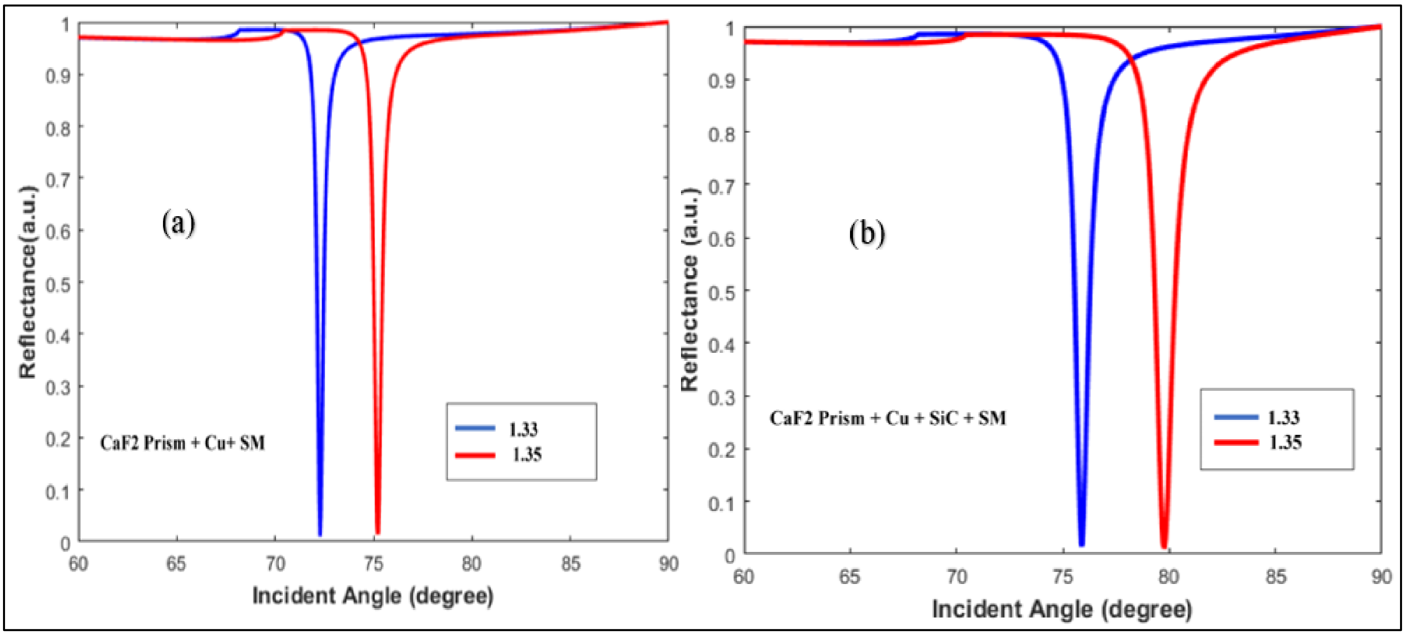

Fig 4 Reflectance Curve of SPR Sensors

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➢ *Comparative Analysis of SPR Sensor*

Table 3 provides a comparative evaluation of the sensitivity of the proposed approach in relation to previously established surface plasmon resonance (SPR) methodologies, along with their corresponding constituent layer materials.

Table 3 Comparative Analysis of SPR Sensor

S. No.	Device Structure of the SPR Sensor	Sensitivity (°RIU^{-1})	References
	Prism N-FK51A/Cu/BP	124.0	[33]
	Prism CaF2 /Cu/ BaTiO3/Graphene	179.0	[5]
	Prism BK7/ZnO/Ag/ BaTiO3/WS2	180.0	[34]
	Prism CaF2/ Cu/ SiC	194.0	Proposed

V. CONCLUSION

This study delivers a comprehensive evaluation of the refractive index (RI) operating range and sensitivity attributes of an innovative Surface Plasmon Resonance (SPR) sensor integrating a CaF_2/Cu/SiC/sensing medium (SM) multilayer arrangement. The sensor reliably functions across a variable RI spectrum of 1.33 to 1.35, exhibiting superior capability in discerning subtle alterations in sensitivity and the dynamic response of biological analytes. Principal performance indicators assessed encompass angular sensitivity, detection accuracy (DA), quality factor (QF), and the limit of detection (LOD). To maximize sensitivity and minimize optical reflectance, an extensive optimization strategy was implemented, focusing specifically on adjusting the thickness parameters of both the prism and copper (Cu) layers. This structural refinement was meticulously performed via the Transfer Matrix Method (TMM) utilizing a MATLAB-based simulation platform. The optimized sensor architecture attained an angular sensitivity of 194.00 deg./RIU, a detection accuracy of 1.38 deg^{-1}, a quality factor of 269.44 RIU^{-1}, and an exceptionally low detection limit of 5.1×10^{-6} RIU.

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➢ *Author Contribution:*

Original draft writing, methodology, and conceptualization, Avantika Bharti. Software and Supervision: Ramesh Mishra, Vipin Sharma. Validation, Reviewing, and Editing: Lalit K. Dwivedi, Sandeep Kumar Nigam.

➢ *Declarations:*

- **Competing interests**: The authors declare no competing interests.
- **Ethics Approval**: This theoretical study does not require ethical approval.
- **Conflict of Interest**: The authors declare no competing interests.

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