

# High-sensitivity plasmonic biosensor based on a graphene-SiO<sub>2</sub> hybrid structure

XIANGDONG YI\*, TIANGUI HUANG, RENLONG ZHOU, JUNMING LAO

*School of Physics and Information Engineering, Guangdong University of Education, Guangzhou 510303, China*

This study presents the design and analysis of a highly sensitive surface plasmon resonance (SPR) biosensor based on a graphene-SiO<sub>2</sub> hybrid structure. Utilizing a prism-coupled configuration, the sensor incorporates a SiO<sub>2</sub> dielectric layer and a few-layer graphene film deposited on a gold film to substantially enhance the localized electromagnetic field and biomolecule capture efficiency at the sensing interface. The effects of key structural parameters—including the number of graphene layers, SiO<sub>2</sub> thickness, and gold film thickness—on sensor performance were systematically investigated. An optimized sensitivity of 220°/RIU was achieved with a five-layer graphene configuration at an analyte refractive index of 1.39, representing a 175% improvement over conventional SPR sensors. Electromagnetic field analysis revealed that localized field enhancement near the graphene edges is the primary mechanism driving this sensitivity improvement. The proposed sensor exhibits excellent responsiveness and stability across a broad refractive index range of 1.33–1.39, providing a high-performance platform for precise biochemical detection.

(Received April 19, 2026; accepted August 3, 2026)

**Keywords:** Surface Plasmon Resonance (SPR), Biosensor, Graphene, SiO<sub>2</sub>, Sensitivity

## 1. Introduction

Surface plasmon resonance (SPR) sensing technology has emerged as a vital tool for real-time, label-free detection of biomolecular interactions based on optical refractive index variations [1]. When incident light excites surface plasmon waves at a metal–dielectric interface, energy is strongly absorbed, resulting in a resonance absorption peak highly sensitive to minute refractive index variations at the interface [2]. Conventional SPR sensors typically employ a prism-coupled configuration with noble metal films (e.g., gold or silver) as plasmonic carriers. These sensors are widely applied in environmental monitoring, food safety, and clinical diagnostics; however, their sensitivity and detection limits are largely constrained by the intrinsic properties of metal films and their limited biomolecule capture efficiency. This limitation has motivated researchers to continuously explore novel materials and structures to further enhance performance [3].

To address these limitations, researchers have investigated various strategies. Incorporating dielectric interlayers (e.g., SiO<sub>2</sub> or TiO<sub>2</sub>) to modulate electromagnetic field distribution has proven effective in improving sensitivity [4]. Meanwhile, two-dimensional materials, with their atomic-scale thickness and unique optoelectronic properties, provide new opportunities for enhancing SPR sensor performance [5,6]. Graphene, in particular, exhibits high electron mobility, excellent mechanical strength, and remarkable adsorption capacity due to its sp<sup>2</sup>-hybridized carbon network, making it an ideal coating for SPR sensing interfaces [7,8]. Studies have shown that graphene layers enhance local electric

fields and improve analyte adsorption, which significantly boost sensor sensitivity [9,10].

However, critical challenges remain. The relationship between graphene layer count and SPR sensitivity is complex and nonlinear, with no consensus on the optimal number of layers and the underlying physical mechanisms [11,12]. Moreover, the synergistic effects of graphene and dielectric layers in composite structures—such as prism/metal/dielectric/graphene—require systematic parameter optimization and electromagnetic analysis to elucidate their contributions to localized surface plasmon resonance [13,14,15].

This study designs a prism/Au/SiO<sub>2</sub>/graphene hybrid sensor and evaluates its performance through comparative analysis with conventional Au-based and Au/SiO<sub>2</sub> sensors. We investigate the influence of graphene layer count (1–8 layers) on sensitivity, identify the optimal configuration, and analyze the effects of SiO<sub>2</sub> thickness, gold film thickness, and structure width on resonance angle and reflection spectra. Electromagnetic field simulations are employed to reveal the physical mechanisms driving sensitivity enhancement. The findings provide valuable insights for developing high-performance, reliable SPR biosensors.

## 2. Sensor structure and working principle

### 2.1. Sensor design and simulation parameters

As illustrated in Fig. 1, the proposed sensor employs prism-coupled configuration. The structure consists of a glass prism for p-polarized light input, a gold film for SPR excitation, a SiO<sub>2</sub> dielectric layer, and a few-layer

graphene film. The graphene surface serves as the functional interface for capturing target biochemical analytes. This composite design aims to synergistically enhance sensitivity through dielectric tuning and two-dimensional material enhancement.

The simulations utilize a monochromatic p-polarized light source with a wavelength ( $\lambda$ ) of 650 nm. The angle of incidence ( $\theta$ ) is scanned within the range of  $60^\circ$  to  $90^\circ$  to capture the full resonance dip. The frequency-dependent complex permittivity of the gold film is described by the Lorentz-Drude model [16], which accounts for both free electron contributions (Drude term) and interband transitions (Lorentz oscillators). The refractive index of the SiO<sub>2</sub> layer is set to 1.458, treated as a lossless dielectric in the visible spectrum. The graphene layers are modeled as anisotropic thin films with an effective thickness of 0.34 nm per layer. The surface conductivity is calculated using the Kubo formula, incorporating both intraband and interband transitions [4]. The initial structural parameters of this sensor are set as follows:  $w=550$  nm,  $h_{\text{Gl}}=550$  nm,  $h_{\text{Au}}=40$  nm,  $h_{\text{SiO}_2}=25$  nm,  $h_{\text{Gr}}=1.7$  nm,  $h_{\text{Sen}}=550$  nm.

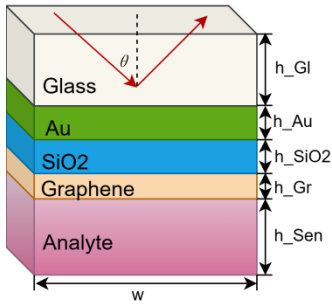


Fig. 1. Schematic diagram of the sensor structure (colour online)

## 2.2. Theoretical background of SPR

SPR is an optical phenomenon occurring when p-polarized light incident at an angle greater than the critical angle of total reflection generates an evanescent wave that penetrates the metal film. At the resonance angle ( $\theta_{\text{SPR}}$ ), the wave vector of the evanescent wave matches that of the surface plasmon polarization (SPP) at the metal-dielectric interface, leading to a sharp dip in reflectance.

The fundamental condition for resonance is that the in-plane component of the incident light's wavevector matches the surface plasmon polariton (SPP) wavevector. The corresponding dispersion relation is given by:

$$k_{\text{SP}} = k_0 n_p \sin \theta_{\text{SPR}} = k_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (1)$$

where  $k_0 = 2\pi / \lambda$  is the free-space wave number,  $\lambda$  is the wavelength,  $n_p$  is the prism refractive index, and  $\epsilon_m$ ,  $\epsilon_d$  are the permittivities of the metal and dielectric, respectively.

The dielectric constant of the gold film is a frequency-dependent complex number, and its properties can be precisely described by the Lorentz-Drude model, which takes into account the contributions of free electrons (the Drude term) and band-to-band transitions (the Lorentz term) [16]

$$\epsilon_m(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma_d \omega} + \sum_{j=1}^k \frac{f_j \omega_p^2}{(\omega_j^2 - \omega^2) - i\omega \gamma_j} \quad (2)$$

where  $\epsilon_\infty$ ,  $\omega_p$  and  $\gamma_d$  represent the high-frequency permittivity, plasma frequency, and damping coefficient, respectively.  $f_j$ ,  $\omega_j$  and  $\gamma_j$  denote the oscillation strength, resonant frequency, and damping coefficient of the  $j$ -th Lorentz oscillator, respectively.

For the four-layer structure designed in this paper, its optical response can be precisely calculated using the transfer matrix method [17]. Each layer is represented by a characteristic matrix, and the system matrix  $M$  of the entire structure is the product of the matrices of each layer:

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_{01}^{-1} \left( \prod_{j=1}^N D_j P_j D_j^{-1} \right) D_{N(N+1)} \quad (3)$$

Among them,  $D_j$  represents the dynamic matrix of the  $j$ -th layer, and  $P_j$  represents the propagation matrix. For p-polarized light, the reflection coefficient  $r_p$  and reflectance  $R$  can be derived as follows:

$$r_p = \frac{(M_{11} + M_{12}q_{N+1}) - (M_{21} + M_{22}q_{N+1})}{(M_{11} + M_{12}q_{N+1}) + (M_{21} + M_{22}q_{N+1})} \quad (4)$$

$$R = |r_p|^2 \quad (5)$$

Here,  $q_j = (2\pi / \lambda) \sqrt{\epsilon_j - n_p^2 \sin^2 \theta}$  represents the  $z$ -component of the wave vector in the  $j$ -th layer.

Graphene can be regarded as an extremely thin surface layer, and its optical properties are usually described by the surface conductivity  $\sigma_g$ , which is composed of the contributions from intraband (Drude) and interband transitions [4]. In calculations, it is often equivalent to a thin layer with a specific dielectric constant:

$$\epsilon_g = 1 + i \frac{\sigma_g}{\epsilon_0 \omega \Delta_g} \quad (6)$$

where  $\Delta_g = 0.34$  nm is the effective thickness of monolayer graphene, and  $\epsilon_0$  represents the vacuum dielectric constant.

### 2.3. Sensitivity definition and analysis

The sensitivity  $S$  of the SPR biochemical sensor is the core performance indicator of it, defined as the ratio of the resonance angle shift to the change in the refractive index of the measured object:

$$S = \frac{\Delta\theta_{SPR}}{\Delta n_s} (^\circ / RIU) \quad (7)$$

Since the SiO<sub>2</sub> dielectric layer can more effectively extend the electromagnetic field to the sensing area, and graphene, with its large specific surface area and abundant  $\pi$  bonds, can efficiently adsorb biological molecules, it can significantly increase the local refractive index change at the sensing interface. At the same time, the introduction of graphene can also generate a local field enhancement effect, further amplifying the SPR signal [7,21]. Therefore, this composite structure achieves a significant improvement in sensitivity through the synergistic effect of physical field regulation and chemical adsorption enhancement.

## 3. Experimental results and discussion

### 3.1. Performance comparison and enhancement mechanism

To quantitatively evaluate the superiority of the hybrid structure proposed in this study, the angle modulation spectra of three different structures of SPR sensors were first simulated when the refractive index ( $n_s$ ) of the analyte changed from 1.35 to 1.36. The traditional Au-film sensor (Fig. 2(a)) exhibited a sensitivity of 80 °/RIU. Adding a 20 nm SiO<sub>2</sub> layer (Fig. 2(b)) increased sensitivity to 110 °/RIU. The graphene-SiO<sub>2</sub> hybrid structure (Fig. 2(c)) achieved a sensitivity of 150 °/RIU, an 87.5% improvement over the conventional design.

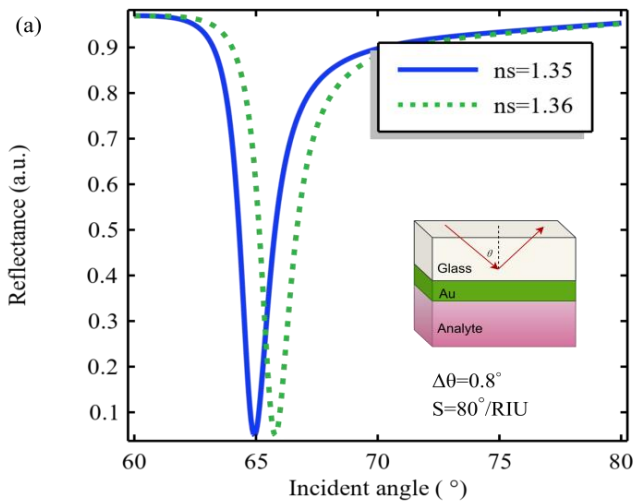


Fig. 2(a). Structures and sensitivity analysis of the Au-structured SPR sensor (colour online)

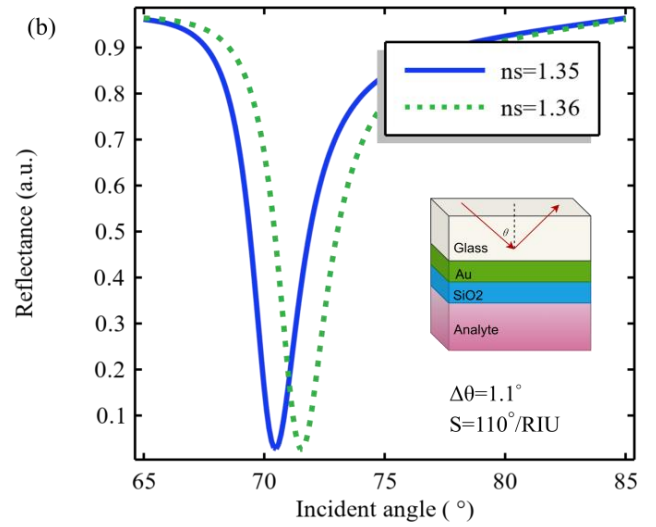


Fig. 2(b). Structures and sensitivity analysis of the Au/SiO<sub>2</sub>-structured SPR sensor (colour online)

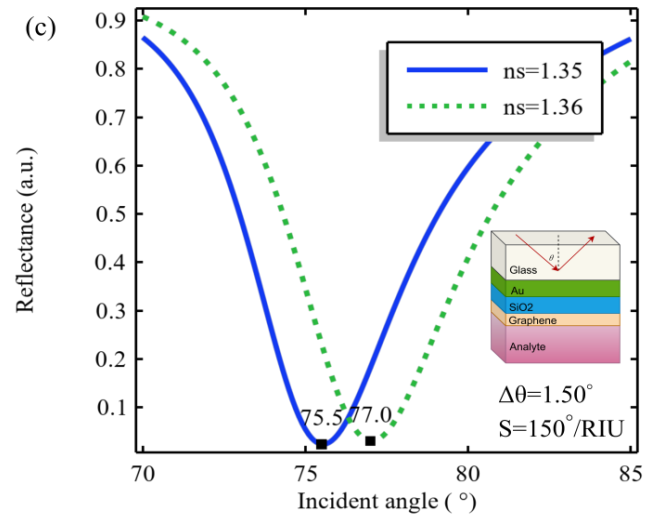


Fig. 2(c). Structures and sensitivity analysis of the Au/SiO<sub>2</sub>/graphene mixed-structured SPR sensor (colour online)

Electromagnetic field distributions (Fig. 3) confirm strong field localization at the graphene edges and SiO<sub>2</sub> layer, attributed to coupling between localized and propagating surface plasmons. The enhanced local electric field greatly amplifies the signal disturbance caused by the minute changes in refractive index at the sensing interface, directly leading to a significant improvement in sensitivity.

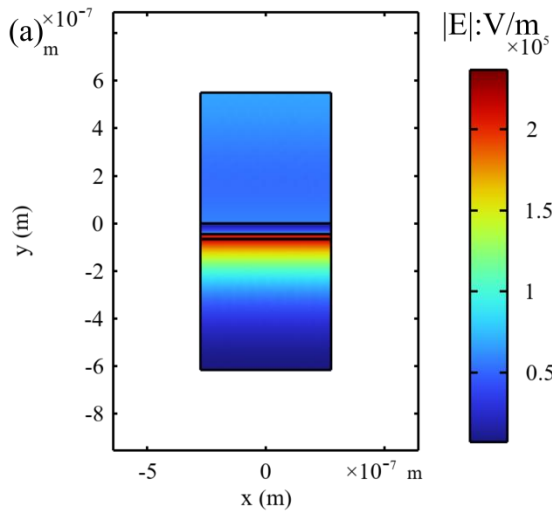


Fig. 3(a). The Electric field distribution of the SPR sensor (colour online)

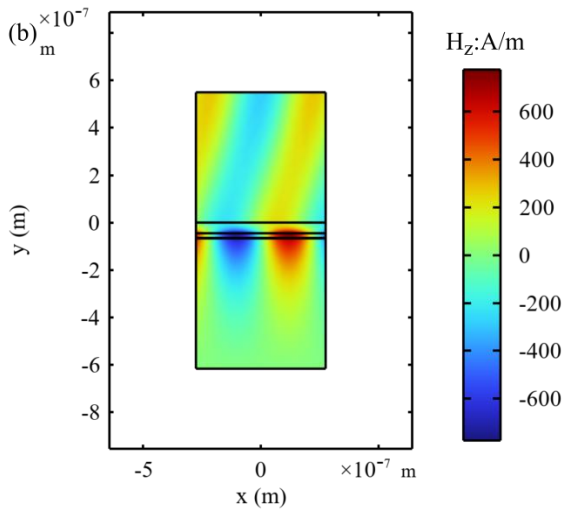


Fig. 3(b). Magnetic field distribution of the SPR sensor (colour online)

### 3.2. Sensing performance and graphene layer optimization

This paper evaluates the performance of the hybrid structure SPR sensor within a wider refractive index range (1.33 to 1.39 RIU). As shown in Fig. 4(a), as the refractive index of the analyte ( $n_s$ ) increases, the resonance angle ( $\Delta\theta$ ) gradually increases, moving from  $72.9^\circ$  ( $n_s = 1.33$ ) to  $82.7^\circ$  ( $n_s = 1.39$ ), indicating that this sensor has efficient SPR excitation capability within this wide range. As shown in Fig. 4(b), the sensor's sensitivity increases with the increase in the refractive index of the analyte, from  $120^\circ/\text{RIU}$  ( $n_s = 1.33$ ) to  $220^\circ/\text{RIU}$  ( $n_s = 1.39$ ), which reflects that the plasmonic wave is more sensitive to interface changes in high refractive index media.

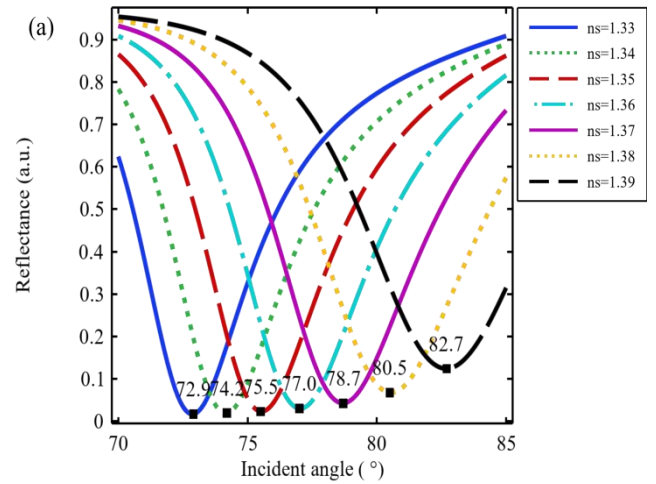


Fig. 4(a). The incident resonance angle varies with the refractive index  $n_s$  (colour online)

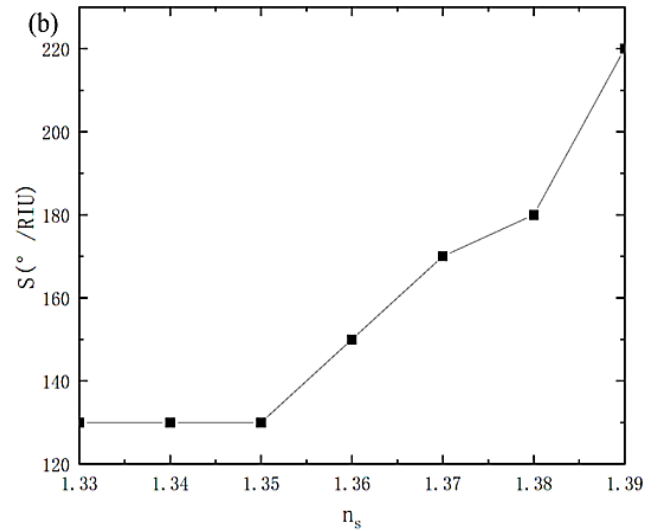


Fig. 4(b). The sensitivity varies with the refractive index  $n_s$  (colour online)

The number of graphene layers ( $L$ ) is a key parameter affecting the performance of the sensor. This paper investigates the influence of  $L$  increasing from 1 layer to 8 layers. As shown in the experimental data in Table 1, when  $n_s \leq 1.38$ , the sensitivity steadily increases with the increase of graphene layers, which is due to more graphene layers providing a larger specific surface area to enhance molecular adsorption and field enhancement effects. However, when  $n_s = 1.39$ , the sensitivity reaches a peak of  $220^\circ/\text{RIU}$  at  $L = 5$ , and then begins to decline. This is because overly thick graphene layers will cause excessive light absorption loss, weakening the SPR effect, indicating that there is an optimal balance point between adsorption capacity and light loss. Therefore, a five-layer graphene structure is determined to be the best configuration for this sensor.

Table 1. The influence of graphene layer number on the sensitivity of SPR sensor

| Layers | Parameter           | $n_s=1.33$ | $n_s=1.34$ | $n_s=1.35$ | $n_s=1.36$ | $n_s=1.37$ | $n_s=1.38$ | $n_s=1.39$ |
|--------|---------------------|------------|------------|------------|------------|------------|------------|------------|
| L=1    | Incident angle (°)  | 71.4       | 72.6       | 73.9       | 75.3       | 76.8       | 78.5       | 80.3       |
|        | Sensitivity (°/RIU) | 120        | 120        | 130        | 140        | 150        | 170        | 170        |
| L=2    | Incident angle (°)  | 71.8       | 73.0       | 74.3       | 75.7       | 77.2       | 79.0       | 80.9       |
|        | Sensitivity (°/RIU) | 120        | 120        | 130        | 140        | 150        | 180        | 190        |
| L=3    | Incident angle (°)  | 72.1       | 73.4       | 74.7       | 76.1       | 77.7       | 79.5       | 81.5       |
|        | Sensitivity (°/RIU) | 130        | 130        | 130        | 140        | 160        | 180        | 200        |
| L=4    | Incident angle (°)  | 72.5       | 73.8       | 75.1       | 76.6       | 78.2       | 80.0       | 82.1       |
|        | Sensitivity (°/RIU) | 130        | 130        | 130        | 150        | 160        | 180        | 210        |
| L=5    | Incident angle (°)  | 72.9       | 74.2       | 75.5       | 77.0       | 78.7       | 80.5       | 82.7       |
|        | Sensitivity (°/RIU) | 130        | 130        | 130        | 150        | 170        | 180        | 220        |
| L=6    | Incident angle (°)  | 73.3       | 74.6       | 76.0       | 77.5       | 79.2       | 81.1       | 83.2       |
|        | Sensitivity (°/RIU) | 130        | 130        | 140        | 150        | 170        | 190        | 210        |
| L=7    | Incident angle (°)  | 73.7       | 75.0       | 76.4       | 78.0       | 79.7       | 81.6       | 83.6       |
|        | Sensitivity (°/RIU) | 130        | 130        | 140        | 160        | 170        | 190        | 200        |
| L=8    | Incident angle (°)  | 74.1       | 75.4       | 76.9       | 78.5       | 80.2       | 82.1       | 84.0       |
|        | Sensitivity (°/RIU) | 130        | 130        | 150        | 160        | 170        | 190        | 190        |

### 3.3. Tolerance analysis of structural parameters

The actual fabrication of the sensor inevitably involves parameter deviations. Therefore, we analyzed the effects of the thickness of the SiO<sub>2</sub> layer ( $h_{\text{SiO}_2}$ ), the thickness of the gold film ( $h_{\text{Au}}$ ), and the width of the waveguide ( $w$ ) on the performance. The study found that when using a single-layer graphene structure, an increase in  $h_{\text{SiO}_2}$  would cause a linear drift in the resonance angle ( $\Delta\theta$ ), as shown in Fig. 5(a) and Fig. 5(b). However, the calculated sensitivity values remained unchanged. This indicates that the thickness of the SiO<sub>2</sub> layer mainly affects the resonance angle of the sensor, without changing its sensitivity to refractive index changes. This provides guidance for sensor packaging and calibration.

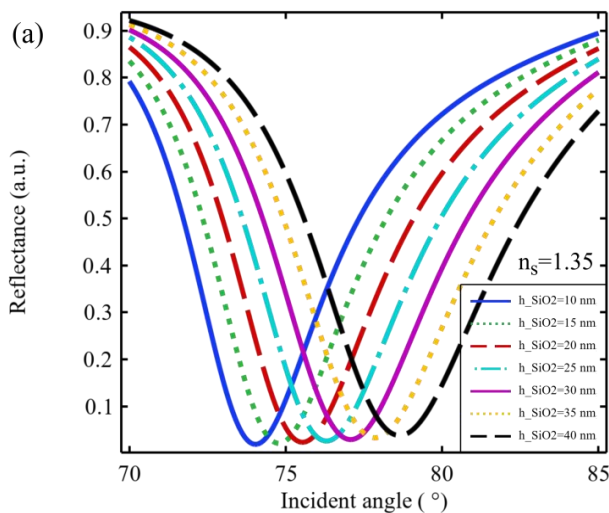


Fig. 5(a). The incident resonance angle varies with the thickness of the SiO<sub>2</sub> layer when  $n_s = 1.35$  (colour online)

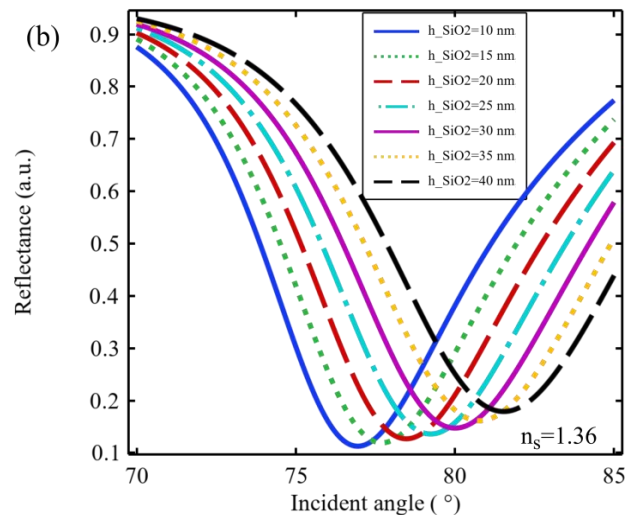


Fig. 5(b). The incident resonance angle varies with the thickness of the SiO<sub>2</sub> layer when  $n_s = 1.36$  (colour online)

Furthermore, as shown in Fig. 6(a), the thickness of the gold film has a significant impact on the performance of the sensor. Only when  $h_{\text{Au}}$  is within the range of 40–45 nm can a sharp resonance peak with a reflectivity close to zero be obtained. While when the sensor width ( $w$ ) varies within the range of 400 nm to 700 nm, the resonance angle and the line shape do not undergo any significant changes (Fig. 6(b)), indicating that this design has good tolerance for width parameters and is conducive to the realization of the actual process.

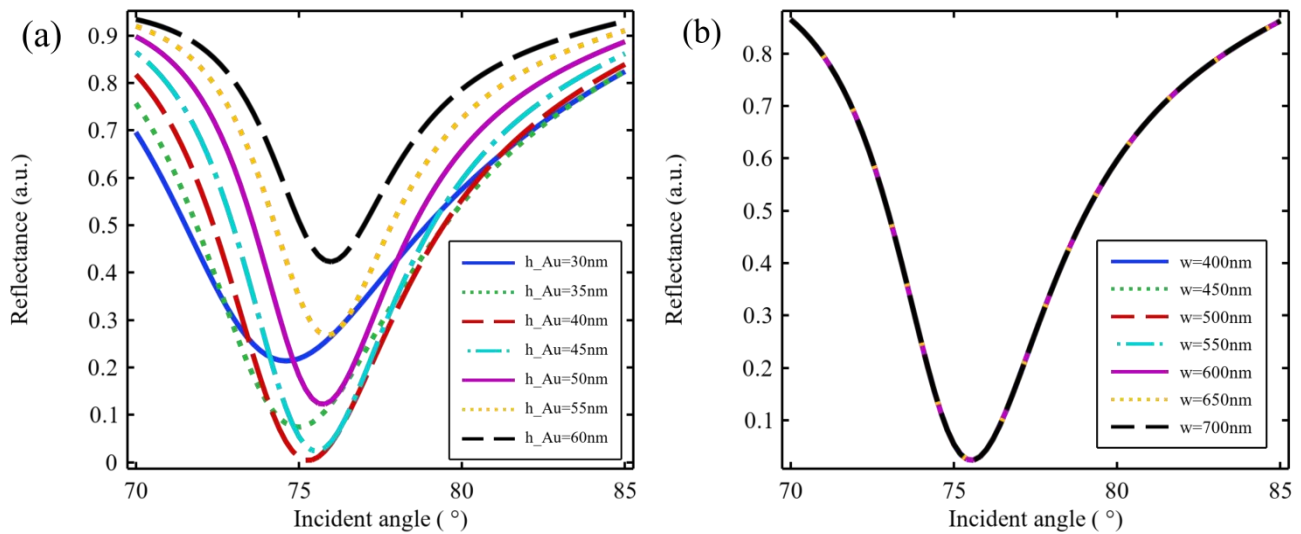


Fig. 6. (a) The variation of the incident resonance angle with the thickness of the gold film (colour online).  
(b) The variation of the incident resonance angle with the width (colour online)

### 3.4. Performance comparison

To objectively evaluate the performance of the SPR sensor in this study, it is compared with other sensors reported in the literature (see Table 2). The comparison shows that the highest sensitivity achieved in this study (220°/RIU) is superior to that of traditional SPR sensors and single two-dimensional material-modified sensors, and is comparable to the performance of more complex composite structures. This sensor exhibits stable responses within a wide refractive index range of 1.33 to 1.39 RIU, covering the refractive index ranges of most biochemical

analytes (such as proteins, DNA, viruses), indicating its good versatility. This design achieves high sensitivity while maintaining a relatively simple structure, and is insensitive to changes in the thickness of the  $\text{SiO}_2$  layer and the width of the waveguide. These features demonstrate excellent robustness and highlight its potential for practical applications in high-performance, reliable biosensor development. As shown in Table 2, the proposed sensor achieves competitive sensitivity and a broad detection range, outperforming conventional and single-enhanced designs while maintaining structural simplicity and robustness.

Table 2. Performance comparison of different surface plasmon resonance sensors

| Sensing Structure                               | Operating Wavelength (nm) | Sensitivity (°/RIU) | Refractive Index Range (RIU) |
|-------------------------------------------------|---------------------------|---------------------|------------------------------|
| Prism/Au Film (Conventional) [10]               | 633                       | 80                  | 1.33–1.37                    |
| Prism/Au Film/Graphene (Monolayer) [6]          | 633                       | 150                 | 1.33–1.38                    |
| Prism/Au Film/ $\text{MoS}_2$ (Multilayer) [18] | 1550                      | 178                 | 1.33–1.39                    |
| Prism/Au Film/ $\text{ZnO/TMDC}$ Composite [19] | 633                       | 206                 | 1.33–1.39                    |
| Prism/Au Film/Ag NPs/Graphene [20]              | 633                       | 223                 | 1.34–1.38                    |
| This work: Prism/Au/ $\text{SiO}_2$ /Graphene   | 650                       | 220                 | 1.33–1.39                    |

### 4. Conclusion

This paper studies a graphene- $\text{SiO}_2$  hybrid structure SPR sensor. By comparing it with traditional SPR sensors and single-modified sensors, the significant advantages of this hybrid structure in improving sensitivity are verified. Parameter scanning studies determine that the graphene layer number ( $L = 5$ ) was the optimal configuration. At this point, the sensor achieves the highest sensitivity of 220°/RIU when the analyte refractive index is 1.39. The

electromagnetic field distribution indicates that the introduction of graphene and  $\text{SiO}_2$  achieves significant field enhancement through the localized surface plasmon resonance effect, which is the key to performance improvement. Additionally, the study shows that the sensor has good robustness to changes in  $\text{SiO}_2$  layer thickness and waveguide width, which is conducive to practical fabrication. This research provides valuable theoretical guidance and design ideas for the development of high-performance and reliable SPR biochemical sensors.

Future work will focus on specific functionalization modification of the graphene surface to enhance the selectivity for specific biomarkers and promote laboratory verification and practical application.

### Acknowledgements

This work was supported by the Scientific Research Capability Enhancement Project for Guangdong Provincial Key Disciplines (2024ZDJS052), The Scientific Key Research Fund of Guangdong Provincial Education Department (2025ZDZX1020, 2025ZDZX1021), Guangdong Engineering Research Center for Silicon Carbide Smart Sensor Technology (202504221065).

### References

- [1] J. Homola, *Chemical Reviews* **108**(2), 462 (2008).
- [2] M. Piliarik, J. Homola, *Optics Express* **17**(19), 16505 (2009).
- [3] S. Szunerits, J. Spadavecchia, R. Boukherroub, *Reviews in Analytical Chemistry* **34**(1-2), 1 (2015).
- [4] C. Woo, H. Li, Q. Zhao, P. Lai, *Optics Express* **29**(12), 18420 (2021).
- [5] F. H. L. Koppens, D. E. Chang, F. J. García de Abajo, *Nano Letters* **11**(8), 3370 (2011).
- [6] L. Wu, H. S. Chu, W. S. Koh, E. P. Li, *Optics Express* **18**(14), 14395 (2010).
- [7] Y. Zhao, J. J. Hu, X. L. Bai, H. P. Liu, X. W. Qi, X. Liao, *Analytical and Bioanalytical Chemistry* **414**(6), 2265 (2022).
- [8] J. B. Maurya, Y. K. Prajapati, V. Singh, J. P. Saini, *Applied Physics A* **121**(2), 525 (2015).
- [9] S. Zeng, J. Chen, C. Qi, Y. Shang, Y. Yang, J. Chen, *Sensors and Actuators B: Chemical* **420**(000), 9 (2024).
- [10] J. Homola, S. S. Yee, G. Gauglitz, *Sensors and Actuators B: Chemical* **54**(1-2), 3 (1999).
- [11] R. B. M. Schasfoort, *Handbook of Surface Plasmon Resonance*, 2<sup>nd</sup> edition, London: Royal Society of Chemistry, 2017.
- [12] A. G. Brolo, *Nature Photonics* **6**(11), 709 (2012).
- [13] S. Unser, I. Bruzas, J. He, L. Sagle, *Sensors* **15**(7), 15684 (2015).
- [14] Y. Wang, W. Knoll, J. Dostalek, *Analytical Chemistry* **84**(19), 8345 (2012).
- [15] S. Deng, P. Wang, X. Yu, *Sensors* **17**(12), 2819 (2017).
- [16] P. B. Johnson, R. W. Christy, *Physical Review B* **6**(12), 4370 (1972).
- [17] W. W. Hansen, *Physical Review* **47**(2), 139 (1935).
- [18] L. Wu, J. Yue, L. Jiang, J. Guo, D. Fan, *Journal of Lightwave Technology* **35**(99), 1 (2017).
- [19] A. Shalabney, I. Abdulhalim, *Laser Photonics Rev.* **5** (4), 571 (2011).
- [20] L. Wu, J. Guo, Q. Wang, S. Lu, X. Dai, Y. Xiang, D. Fan, *Sensors and Actuators B: Chemical* **249**, 542 (2017).
- [21] J. Li, Y. Liu, Z. Liu, H. Tian, Y. Sun, D. W. Zhang, *IEEE Electron Device Letters* **46**(10), 1917 (2025).

\*Corresponding author: yixiangdong@gdei.edu.cn