J Nanostruct 15(4): 2430-2437, Autumn 2025

RESEARCH PAPER

Performance Improvement Approach for the Surface Plasmon Resonance of Gold NP Sensor Based on Optical Waveguide Configuration

Ali Sahib *, Ali M. Al-Jawdah, Nassar A. Al-Isawi

Department of Physics, Faculty of Science, University of Babylon, Iraq

ARTICLE INFO

Article History:
Received 01 June 2025
Accepted 19 September 2025
Published 01 October 2025

Keywords:
Biosensor
Nanomaterial
Opto-electronic
Sensor array
Surface plasmon resonance
Thin film

ABSTRACT

Detection of biomolecules is earning wide attention from sensing researchers because of demand in many critical fields. SPR technique is considered the most efficient method to study of biomolecular. In this work we present an idea to enhance efficiency and performance of SPR based biosensor system. SPR system response to presence of specific concentration of targeted molecules by absorbing a specific light wavelength from a wide light spectrum. The accuracy of the sensing depends on the accuracy of absorbed wavelength shift tracking. The resonance absorbation in the output light specrum observed as a dip in SPR reflection intensity. The tracking precision of the dip peak position on the wavelength axis determines sensitivity of the sensing. This work presents an idea that makes the dip peak more sharp, and decrease the full width at half maximum (FWHM) of the dip peak. consequently the whole performance will be improved in terms of sensitivity and consequently the whole performance will be improved in terms of sensitivity and low limit detection parameter.

How to cite this article
Sahib A., Al-Jawdah A., Al-Isawi N. Performance Improvement Approach for the Surface Plasmon Resonance of Gold NP Sensor Based on Optical Waveguide Configuration. J Nanostruct, 2025; 15(4):2430-2437. DOI: 10.22052/JNS.2025.04.079

INTRODUCTION

Biosensing, is a growing analytical technque to detect the biological molcules by use transducing systems [1]. Transduction mechanisms translates the bio variations into electrochemical, electrical, thermal or optical signals which are quantifiable and easy to readable [2]. Biosensing is plentifully employed to detect a various biological small biomolecules (e.g., glucose, uric acid) and biomacromolecules (e.g.,enzymes, proteins, nucleic acids bacteria, cells, and viruses) [3–7]. Biosensors with high sensitivity, good selectivity and fast response have high demand for a many fields such as (environmental studies, disease diagnosis, food inspection, agriculture and medical utilities). The most common of biosensors are the optical type. Optical biosensors are considered the best alternative to ordinary analytical techniques, due to their good performance particularly in terms of sensitivity, selectivity, and cost effectiveness [8,9]. In this type of biosensors the analyte is detected emlpying the reaction of the light field with the bio-recognition element, with either label free basedwhen the sensing signal is formed directly during interact the analysed sample with the transducer, or label based techniques When an additional element is used to generate the optical signal signal via (e.g.,luminescent, fluorescent

* Corresponding Author Email: sci866.ali.sahab@student.uobabylon.edu.iq

or colorimetric method). Development of optical biosensor device is a new step towards revolution in the bioelectronics technique.

Since first demonstration of SPR phenomenon in the early 1990s, it considered the most efficient method to obsorve the kinetic parameters of bio-molecules reaction [10].

The surface plasmon resonance phenomenon occur when specific wavelength p-polarized light strikes a conductive film at certian angle under TIR condition stited between two media (usually liquid and glass), a part of the light energy is coupled with the surface layer electrons of the metal thin film, which then oscillate due to excitation, these movement of electron is called plasmon. The oscillation of the plasmon generates an electric field extends approximately 300 nm from the interface of metal layer and the low reflative index medium which is usually a liquid medium Fig. 1 [11].

Practically, the resonance condition exhibits as a dip peak in the light reflected spectrum or in the angular distribution curve of certain wavelength reflected light intensity [13].

The angle or the wavelenght, at which SPR resonance occurs is dependent on the optical properties of the meduim near the metal surface. The resonance condition is quite sensitive to the refractive index nearby the metal film, as a result even littel varation changes the resonance condation.

Accordingly, change in the optical properties of the sensing medium (e.g., through bio-reaction), leads to shift in the angle or the wavelenght resonance.

The minimal detectable shift in the respnos parameter, in unit of degree or wavelength for at a fixed incidence angle or wavelength, respectively, may be used to describe the optical sensitivity of the system[14].

Convertting the flat metallic thin film to nano island in range of incedence light wavelenght show intense collective charge vibration with respect to the fixed ions, that provide opptiounty to develop a kind of plasmon named localized surface plasmon [15,16]. The idea of this kind of plasmon which called LSPR is a confine the plasmon field of plasmonic in the nanostructure or nanoparticles, whicg leads to depend the resonnance on the shape, size, aspect ratio, beside to the sourounding medium[17,18]. The LSPR extinction function of the field $E(\lambda)$ as an accumulation of light absorption and scattering is determined by [19,20]:

$$E(\lambda) = \frac{24\pi^2 N a^3 \varepsilon_D^{3/2}}{\lambda \ln(10)} \left[\frac{\varepsilon_i}{(\varepsilon_r + \zeta\varepsilon_D)^2 + \varepsilon_i^2}\right] \quad (1)$$

ε_i, ε_r are imaginary and real metal-dielectric constant, respectively, ε_D is the dielectric constant value of surrounding medium, ζ represent the form factor of nanoparticles.

Despite the rapid development, the reproduce of the sensing fabrication still challenging in local SPR because the particle size and aspect ratio are affecting the extinction field (Eq. 1), and there are many simulations and experimental studies confirm the correlation between geometric shape and dimensions of the nanoparticles and optical sensing performance

The characters of the LSPR are heavily affected by the particle size and aspect ratio, many studies confirm this dependence, and try fo find out the optimal geometric shape [21-24].

The association of change in the resonance wavelength with the change in a refractive index of sensing medium has been modeled by the Eq. 2 [25,26]

$$\Delta\lambda_{max} = m\,\Delta n \left(1 - e^{-\frac{2d}{l_d}}\right) \quad (2)$$

m is a bulk refractive index of nanopatricals, Δn ; vary in the refractive index, $\Delta\lambda$; the shift in the resonance wavelength, d; thickness of the absorbed layer, and l_d; electromagnetic field decay length.

Sensitivity is a one of essential parameter of the sensor which is identify as a plasmon resonance wavelength shift per a refractive index change in the sensing medium [25, 27]:

$$S = \frac{\Delta\lambda}{\Delta n} \left(\frac{nm}{RIU}\right) \quad (3)$$

The equation predicts a linear relationship between the postion of resonanc wavelenght and refractive index of the sensing medium, which is an encouraging sign to employ it in sensing function.

Drude mode has been used as another approach to find out the relationship between the sensing medium properties and the postion of plasmon resonance wavelength based on the plasma frequency of the metal film.

The mathematical model (Drude model) was studing the movment of the electrons cloud under effact of electrical restoring force from their equilibrium positions around the ionic positive. The result of this mathematical proceeding has been also shown that the association between refractive index of the sensing medium and the LSPR resonance wavelength (λ_{max}) is an approximately direct dependency, according to the Eq. 4 [25]:

$$\lambda_{\mathrm{max}} = \frac{\lambda_{\mathrm{p}}}{\sqrt{2n_{\mathrm{m}}^2 + 1}} \tag{4}$$

λ_p represents the light wavelength synchronized to the plasma frequency of the bulk metal. These linear feature makes this phenomenon suitable to employ it for sensing function.

The crucial point of plasmon sensing performance is an observed and tracking the shift in the absorption peak wavelength at the pasmon spectrum. Optimal performance requires the ability to observe the small change as possible observe as small changes as possible.

SPR sensor resolution is defined as the minimum change in the sample refractive index develops a observable change in the output signal of the sensor. The amount of sensor signal output change that can be detected depends on the level of disturbance of the sensor output signal - the output noise which can be recapitulated by standard deviation of the output signal. Therefore, refrective index mesurment resolution is defined as [28]:

$$\sigma_{\mathrm{RI}} = \frac{\sigma_{\mathrm{so}}}{\mathrm{S}} \tag{5}$$

Where σ_{so} is the std dev. of the sensor output, S is a RI sensitivity.

We note that the more sharp absorption peak leads to larger change in the sensor output signal, which means higher resolution. This work seeks to enhance accuracy and resolution by improving the shape of the signa.

The noise in the output signal originated mostly from two main sources, light intensity fluctuate , which affacts all detectoe elements (spectrometer pixels) equally and electronic noise that generate in the detector thermally and in its the electronic circuit which affact in each detector element independently.

Studies have been shown that the detectors independently behavior is a negligible compared with shot noise, which confirms the light source noise dominates the noise of the measured light intensity.

Data processing are used to minimize the light intensity noise effects, mostly two types of averaging; temporal averaging (signals average over time period for each detector element) and spatial averaging (average of N detector pixels signals on same sensing channel).

Mathematically, according to the resoluation of the sensor is determined by the value of standard deviation of standard deviation of the sensor output using Pearson correlation coefficient [28]:

$$\sigma_{\mathrm{so}}^{(\theta,\lambda)} = \mathrm{k}\frac{\mathrm{r_s}\sigma_{\mathrm{I}}^{\mathrm{th}}}{\mathrm{I_o}\sqrt{\mathrm{N}}}\,\frac{\mathrm{w}^{(\theta,\lambda)}}{\mathrm{d_r}} \tag{6}$$

Where σso(θ,λ) is the std dev of the sensor output (angular position or dip wavelength respectively), σIth is the noise level, d_r is a SPR dip depth, w(θ,λ) is the dip width of the wavelength or angular spectrum at the threshold.

All the above approaches are attempts to enhance accuracy and resolution by mathematically dealing or/and processing the signal in somehow. In this work we have trying to provide an experimental approach to enhance the resolution by producing a signal characterized by narrow w and deep d_r.

This work offers idea to boost the SPR spectrum signal shape by using a set up allows for repeat the plasmon excitation. where repeating the plasmonic reaction leads to more absorption of the resonance wavelength, as a result, a more sharp and narrow FWHM (Full-width-half-maximum) absorption peak which supports the sensitivity accuracy. According to the above equations. Improve optical performance os both SPR and LSPR systems in terms of refractive index sensitivity is reflected in their operation as chemical or biological sensors.

MATERIALS AND METHODS

The main part of this system is A piece of (10×40×3)mm slant angled ends glass strip was setted up as a optical waveguide core. The preparing of the glass waveguide core was initially begin by fixing the geometric dimensions, and carving the ends angles, then cleaning several times in with piranha solution (1:3, hydrogen peroxide and sulfuric acid) followed by rinse with deionized water, and drying by nitrogen blowing.

Establishing the plasmonic system was started with deposit a 2 nm of chrome on the top side of the glass strip serves as adhesion layer followed by 50 nm gold layer using thermal evaporation technique “Edwards 360 unit at the vacuum of 10^{-6}” Fig. 1.

The gold layer has been subjected to heat treatment extreme temperatures, using convection oven at 55 $^{\circ}$C for 10 h. to convert it to nano-spots (Fig. 2) . The surface morography of the gold layer was screened by use scan electron microscope (FEI Nova NanoSEM 450). and “ellipsometer spectroscopic (J.A.Woollam, M2000)”

The SEM images information shown that the size of the nano islands was in range of 90.9 ± 25.0 nm. While the information extracted from the ellipsometry have confirmed that the cross section consist of a 2nm of adhesion chromium layer, followed by a 50 nm of a gold.

Using (DH-2000-BAL, Ocean Optics) as source of wide range of wavelength (300-800nm) to apply light at the slant angle of glass bar, so the light propagates through the glass core by multi reflection.

Each up-side reflection will excite a plasmon, as a result of that the resonance wavelength will undergo to certain percentage of absorption. Therefore, as the reflections continue through the glass core, the resonant wavelength will be almost completely absorbed. Which leads to produce a plasmonic spectrum with a more sharpe absorption peak.

The output light from the glass strip collecte

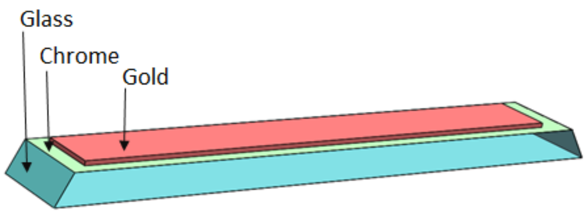

Fig. 1. Plasmon platform

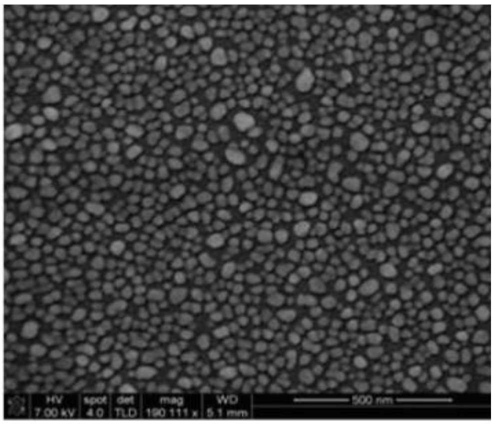

Fig. 2. SEM of Nanostructure of the gold layer

by a collimation package and passes areoss a polarizer to be analyzed spectroscopically by (FLAME-S-UV-VIS, Ocean Optics) spectrometer, As shown in the setup diagram Fig. 3.

The setup is shown in Fig. 3. this setting has been able to excite the plasmon resonance in the gold nanoparticle layer and yielded properly plasmonic spectrum. The plasmonic spectrum that has obtained from a single reflection was characterized by Full width at half maximum (FWHM) parameter 70nm (Fig. 4). Moreover, assessment the system's operation as a reflection index sensor require ability to control the medium adjacent to the nano gold film, This was achieved by using a nylon cell equipped with fluid inlet and outlet, to change the solution Fig. 3b.

The performance of the sensing is evaluated by using the concept of figure of merit (FOM), Which is the sensitivity divided by full-width at half-maximum (FWHM) of the resonance absorbation

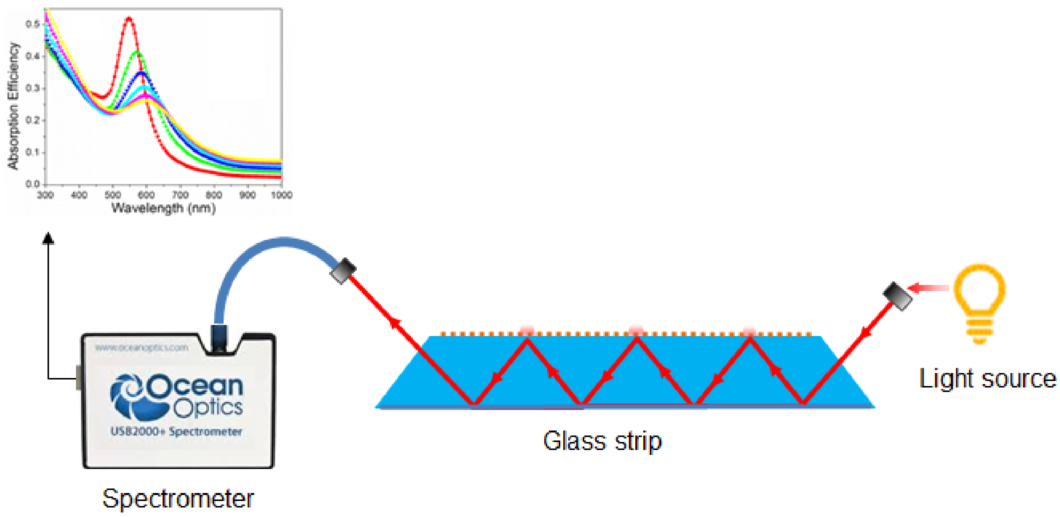

Fig. 3. Experiment setup

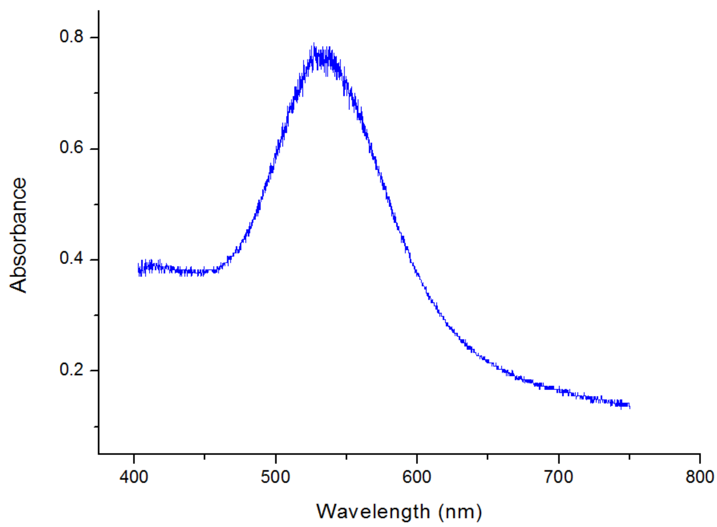

Fig.4. Plasmon spectrum produced by single reflaction

peak; [29].

$$\mathrm{FOM} = \frac{\Delta\lambda}{\Delta \mathrm{n}\ \times (\mathrm{FWHM})} \quad (7)$$

Therefore FOM has become an significant indicator to evaluate the SPR sensing performance This work is concerned to present an idea improves the FORM factor for the plasmon resonance spectrum via provide mechanism based on optical waveguide system allowed to repeat the plasmon excitation.

The resonance wavelength (637nm) was applied at the glass stripe (waveguide core) to test the effect of the of reflections repeat on the resonance absorption, the outcome shown that the resonance wavelength absorption doublesis and almost completely absorbed after nearly five

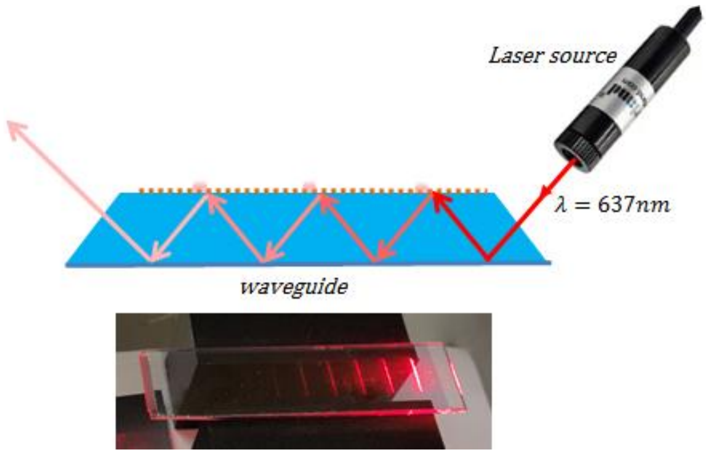

Fig. 5. Resonant wavelength absorption test

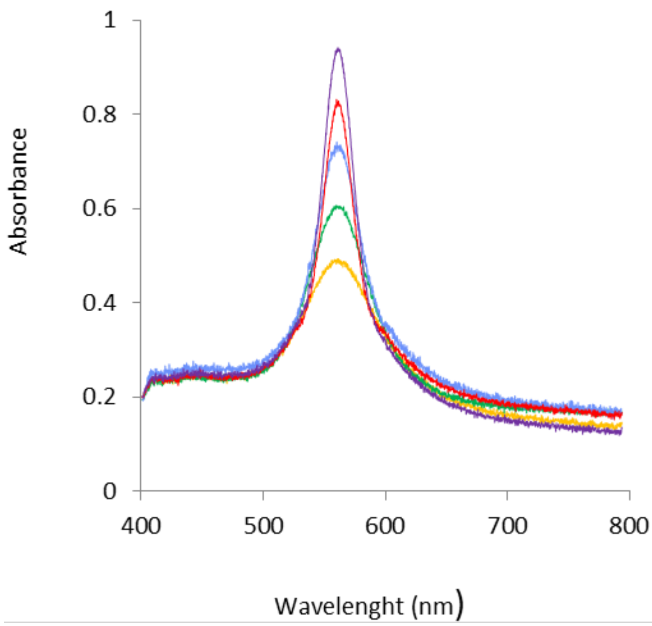

Fig. 6. Plasmon spectra for each number of reflections

reflections in this setup (Fig. 5).

RESULTS AND DISCUSSION

Experimentally, the full-width at half-maximum (FWHM) of the absorption peak of plasmonic spectrum was recorded for each plasmon states distinguished by the number of reflections. The results using this setup shown (Fig. 6) that repete of the plasmonic excitation interaction causes 30% reducing the FWHM for each time.

The value of FWHM for each number of reflections case are shown in the Fig. 7. the results show the semi-exponential decrease of the H value, as well as an increase the resonant wavelength absorption. Therefore, this procedure seems to have succeeded in improving the signal consequently improve the sensing performance in terms of accuracy.

The outcome of this work can be summarized as repeating the reflections five times led to an improvement in the signal by 40 percent.

To test the accuracy and estimate the refractive index sensitivity of the setup, the refractive index of the medium in sensing area was changed five times by using standr RI soluations.

To test the accuracy and estimate the refractive index sensitivity of the setup, the refractive index of the medium in sensing area was changed

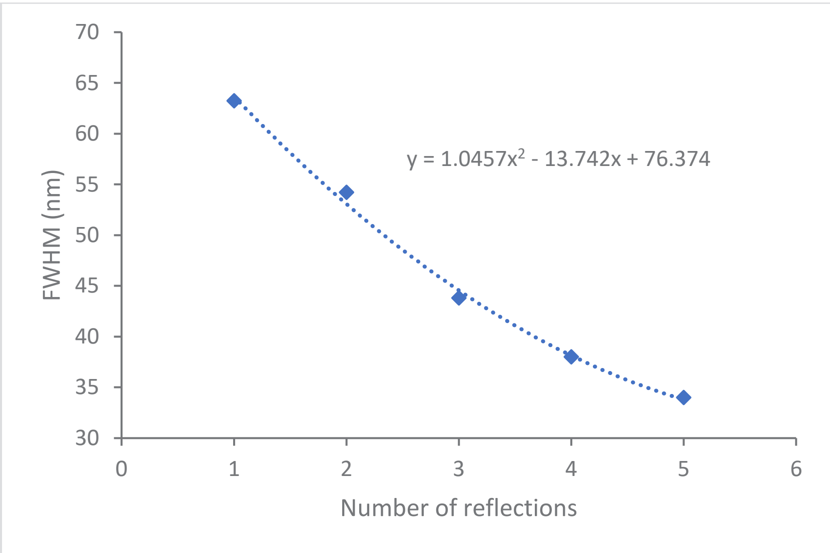

Fig. 7. FWHM of the absorption peak vs number of reflection

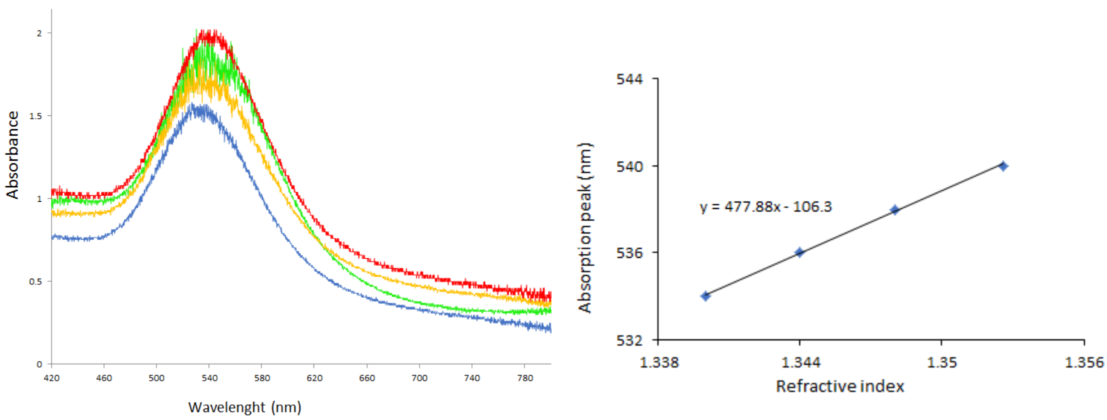

Fig. 8. Refractive index sensitivity

five times by using standr RI soluations, with monitering the resonance absorption peak postion for each RI value. The optical sensitivity that estimated from this was approximately 477 nm/RIU Fig. 8.

CONCLUSION

The approach of a repeating the plasmon excitation using optical waveguide configuration has success in improving the absorption spectrum signal in terms of FOM parameter. Utilizing the glass strip as waveguide core was proper configuration to establish multi plasmon excitation system. Computationally, there was exponential decrease in the value of the H with number of reflaction, five times reflaction had achieved nearly total absorption of the resonance wavelength and reduced the FWHM value by 30%. As the figure of merit parameter rising nearly six times, the resolution become more accurcy apprroximitly five time. This approach opened up new a trend to improve the sensing performance that based on plasmon excitation repation, by try out and employ an another repetition mechanisms.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

REFERENCES

1. Guo Z, Liu H, Dai W, Lei Y. Responsive principles and applications of smart materials in biosensing. Smart Materials in Medicine. 2020;1:54-65.
2. Polat EO, Cetin MM, Tabak AF, Bilget Güven E, Uysal BÖ, Arsan T, et al. Transducer Technologies for Biosensors and Their Wearable Applications. Biosensors. 2022;12(6):385.
3. Javanpour AA, Liu CC. Evolving Small-Molecule Biosensors with Improved Performance and Reprogrammed Ligand Preference Using OrthoRep. ACS Synthetic Biology. 2021;10(10):2705-2714.
4. Sargazi S, Fatima I, Hassan Kiani M, Mohammadzadeh V, Arshad R, Bilal M, et al. Fluorescent-based nanosensors for selective detection of a wide range of biological macromolecules: A comprehensive review. Int J Biol Macromol. 2022;206:115-147.
5. Castillo-Henríquez L, Brenes-Acuña M, Castro-Rojas A, Cordero-Salmerón R, Lopretti-Correa M, Vega-Baudrit JR. Biosensors for the Detection of Bacterial and Viral Clinical Pathogens. Sensors. 2020;20(23):6926.
6. Song K, Hwang S-J, Jeon Y, Yoon Y. The Biomedical Applications of Biomolecule Integrated Biosensors for Cell Monitoring. Int J Mol Sci. 2024;25(12):6336.
7. Wahid Anwar A, Anwar Z, Dildar I, Ali N, Uzba, Ahsan K. Biosensing Basics. Biomedical Engineering: IntechOpen; 2024.
8. Abdulhalim I, Zourob M, Lakhtakia A. Overview of Optical Biosensing Techniques. Handbook of Biosensors and Biochips: Wiley; 2007.
9. Duque T, Chaves Ribeiro AC, de Camargo HS, Costa Filho PAd, Mesquita Cavalcante HP, Lopes D. New Insights on Optical Biosensors: Techniques, Construction and Application. State of the Art in Biosensors - General Aspects: InTech; 2013.
10. Rothenhäusler B, Knoll W. Surface–plasmon microscopy. Nature. 1988;332(6165):615-617.
11. Kooyman RPH. Physics of Surface Plasmon Resonance. Handbook of Surface Plasmon Resonance: The Royal Society of Chemistry; 2008. p. 15-34.
12. Howe CL, Webb KF, Abayzeed SA, Anderson DJ, Denning C, Russell NA. Surface plasmon resonance imaging of excitable cells. J Phys D: Appl Phys. 2019;52(10):104001.
13. Mondal B, Zeng S. Recent Advances in Surface Plasmon Resonance for Biosensing Applications and Future Prospects. Nanophotonics in Biomedical Engineering: Springer Singapore; 2020. p. 21-48.
14. Azuelos P, Girault P, Lorrain N, Poffo L, Guendouz M, Thual M, et al. High sensitivity optical biosensor based on polymer materials and using the Vernier effect. Opt Express. 2017;25(24):30799.
15. Hutter E, Fendler JH. Exploitation of Localized Surface Plasmon Resonance. Adv Mater. 2004;16(19):1685-1706.
16. Chen Y, Ming H. Review of surface plasmon resonance and localized surface plasmon resonance sensor. Photonic Sensors. 2012;2(1):37-49.
17. Willets KA, Van Duyne RP. Localized Surface Plasmon Resonance Spectroscopy and Sensing. Annu Rev Phys Chem. 2007;58(1):267-297.
18. Maier SA. Localized Surface Plasmons. Plasmonics: Fundamentals and Applications: Springer US; 2007. p. 65-88.
19. Willets KA, Hall WP, Sherry LJ, Zhang X, Zhao J, Van Duyne RP. Nanoscale Localized Surface Plasmon Resonance Biosensors. Nanobiotechnology II: Wiley; 2007. p. 159-173.
20. Anker JN, Hall WP, Lyandres O, Shah NC, Zhao J, Van Duyne RP. Biosensing with plasmonic nanosensors. Nature Materials. 2008;7(6):442-453.
21. Dengler S, Muller O, Ritt G, Eberle B. Influence of the geometric shape of silver nanoparticles on optical limiting. SPIE Proceedings; 2012/11/08: SPIE; 2012. p. 854503.
22. Firoozi A, Khordad R, Rastegar Sedehi HR. Effects of geometry and size of noble metal nanoparticles on enhanced refractive index sensitivity. Appl Phys A. 2022;128(12).
23. Sherka GT, Berry HD. Insight into impact of size and shape on optoelectronic properties of InX (X = As, Sb, and P) semiconductor nanoparticles: a theoretical study. Frontiers in Physics. 2024;12.
24. Naithani S, Heena, Sharma P, Layek S, Thetiot F, Goswami T, et al. Nanoparticles and quantum dots as emerging optical sensing platforms for Ni(II) detection: Recent approaches and perspectives. Coord Chem Rev. 2025;524:216331.
25. McOyi MP, Mpofu KT, Sekhwama M, Mthunzi-Kufa P. Developments in Localized Surface Plasmon Resonance. Plasmonics. 2024;20(7):5481-5520.
26. Bingham JM, Willets KA, Shah NC, Andrews DQ, Van Duyne RP. Localized Surface Plasmon Resonance Imaging: Simultaneous Single Nanoparticle Spectroscopy and Diffusional Dynamics. The Journal of Physical Chemistry C. 2009;113(39):16839-16842.
27. Homola J, Piliarik M. Surface Plasmon Resonance (SPR) Sensors. Springer Series on Chemical Sensors and Biosensors: Springer Berlin Heidelberg; 2006. p. 45-67.
28. Piliarik M, Homola J. Surface plasmon resonance (SPR) sensors: approaching their limits? Opt Express. 2009;17(19):16505.