



OPEN On the sensing performance improvement in SPR biosensor using ZnO and TMDCs architecture for cancer detection

Elham Jalili Tazekande Janze¹, Sholeh Alaei^{1✉} & Bahar Meshginqalam²

In this study, we have unveiled an SPR biosensor for highly sensitive and rapid detection of cancerous cells employing 2D materials. The proposed sensor structure introduces a novel approach to cancer cell detection, offering a new perspective in biosensing technology. In other words, specifically, ZnO, Si₃N₄ and TMDCs based plasmonic sensor structures demonstrate great potential whenever high-accuracy detection of cancerous cells is required. We present four different configuration of SPR based sensor designed for the detection of different types of cancer cells. The designed conventional configuration consists of four functional layers namely Ag, ZnO, Si₃N₄ and sensing medium along with BK7 prism for coupling light at the interface of metal-dielectric. To illustrate performance improvement, enhancement of light absorption capacity and achieve higher sensitivity of sensor, we incorporated four different 2D materials, MoS₂, MoSe₂, WS₂ and WSe₂. Using the angular interrogation method, the proposed layered structure, BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium, demonstrated the highest overall sensitivity in terms of detecting three cancerous cells, blood cancer (Jurkat), cervical cancer (HeLa) and skin cancer (Basal) from healthy cells. Notably, the sensitivity which is achieved with the configuration BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium for blood cancer detection from healthy cells with the value of 342.14 deg/RIU and FOM equal to 124.86 RIU⁻¹, outperforms all other proposed configurations. Applying finite element method (FEM) simulations, the distribution of electric field across the interfaces of the SPR sensor configurations are analyzed. Overall, SPR biosensors offer a promising technology for the early and accurate cancerous cell detection. The high sensitivity, specificity, and ability to analyze complex biological samples make them valuable tools in the struggle against cancer. However, further research and development are demanded to optimize the performance and translation of these sensors into clinical and real-world applications.

Keywords SPR, Biosensor, Cancer detection, TMDCs, ZnO, Sensitivity

According to the declaration of the World Health Organization, one of the main causes of death around the world is cancer. Significant efforts have been made to develop early, accurate and cost-effective methods and treatments. The various types of cancer can be detected early using different methods and techniques such as peptide-based optical biosensors, electroactive material-based immunosensors, plasmonic fiber optic biosensors, fluorescence spectroscopy, surface plasmon resonance (SPR) biosensor, Colorimetric biosensors and etc^{1–5}. Notwithstanding notable advances in diagnosis of cancer, researchers intend to recognize accurate treatment methods and effective screening with a focus on the identification and application of disease biomarkers⁶.

The surface plasmon resonance (SPR) is a widely used technique for the on-the-spot detection of biomarkers in cancers since it can evaluate biomarkers with outstanding selectivity, rapid and reproducibility and can identify different types of cancers. Furthermore, SPR biosensors are used for studying molecular binding, molecular interactions and investigating the changes of conformation of biomolecules and ions for application in various fields such as environmental sciences, medicine, engineering and etc. The sensing mechanism of SPR biosensor is based on the change in the refractive index (RI) of the sensing medium for determination of molecule binding at a metal surface. By incorporating various layers and combinations, researchers have tried to improve the sensitivity of the SPR biosensors which paves the way for detecting subtle changes in the sensing layer for diseases diagnosis^{6–9}. Different designs and combinations of nanomaterials, thin films and

¹Department of Physics, Ur.C., Islamic Azad University, Urmia, Iran. ²Faculty of Physics, University of Tabriz, Tabriz, Iran. ✉email: sholeh.alaei@iau.ac.ir

two-dimensional (2D) materials such as carbon, gold and silver nanomaterials, graphene and transition-metal dichalcogenides (TMD or TMDCs) have been proposed for high-sensitivity plasmonic biosensors^{10,11}. Different configurations of SPR biosensor focus on the sensitivity enhancement and detection of small biomolecules and multiple analytes simultaneously. Moreover, SPR biosensor is usable for resolving the shortcomings of some old approaches and many studies have been done to improve sensitivity, detection limit and detection specificity of SPR technology in diagnosis of various cancers. In order to improve the SPR biosensor capabilities, some advances have been made. In a study¹², a dual-channel SPR sensor has been designed for simultaneous detection of free/total prostate antigen (PSA) ratio in serum through an asynchronous competitive inhibition immunoassay with fPSA@Au nanoparticles. The results exhibited significant increase in sensitivity of free PSA with a linear correlation from 0.010 to 0.40 ng/ml. The suggested method was effective and usable for recognizing prostate cancer from benign prostatic hyperplasia. Since PSA is recognized among primary biomarkers in order to monitor prostate cancer for clinical use, so when its level is above 4ng/ml, it may indicate the presence of prostate cancer. Furthermore, it has been suggested that for investigating the biospecific and analyte-ligand interactions, the SPR is one of the best choices^{13,14}. In a study, Mahani et al.¹⁵ employed molecular dynamics simulations to quantify low concentration of PSA protein in serum samples. They proposed an LSPR biosensor by conjugating Au nanoparticles with anti-PSA with a calibration sensitivity of 43.75 nm/(ng/mL) for the early-stage prostate cancer detection. Additionally, a numerical study of SPR sensor for early infectious illness diagnosis and pathogen detection using a multi-layered structure of silicon and selenium was conducted with a maximum sensitivity of 147.68 deg/RIU¹⁶. As well as, employing the same numerical analysis, for the rapid detection of SARS-COV-2 and Influenza-A virus, an SPR sensor of two different arrangement consisting of gold, PtSe₂, Graphene and gold, BaTiO₃ and Graphene have been designed. It has exhibited notable enhancement of selectivity and sensitivity for viral samples identification¹⁷. Considering the dependency of SPR performance on the configuration parameters, an SPR biosensor using PtSe₂ and BluePWS₂ was designed and simulated using COMSOL multiphysics software. The maximum sensitivity of 234 deg/RIU and detection accuracy of 7.8 deg⁻¹ illustrate its capability of the proposed to accurately and rapidly detect target analytes¹⁸.

The paramount importance of access to clean and safe drinking water is undeniable, otherwise, polluted and contaminated water may lead to many diseases, affect body tissues and produce public health concerns. Furthermore, SPR sensors, as a powerful analytical tool, have been used for detecting a wide range of biosamples including viruses, bacteria, hazardous ions, environmental pollutants, pathogens and others which have contributed to water pollution over the years. Besides, utilization of SPR biosensor for sensing of bio and chemical samples in drinking water have attracted great attention. In the 21st century, the detection of heavy metal ions in water and accessing to clean water has one of the most challenging global issue. Accordingly, SPR sensor demonstrated its strong capacity in water environmental monitoring and for improving the water treatment efficiency to reduce energy consumption, as well. Implementing nickel, Al₂O₃, blue phosphorous and WSe₂ in an optical surface plasmon resonance device (OSPRD) was developed to the common detector for chemical and biomedical applications with sensitivity equal to 298.55 deg/RIU¹⁹. Additional, revealing pathogens including *Escherichia coli*, *Shigella flexneri*, *Vibrio cholera*, and *Salmonella flagellin* in drinking water is important. M.G. Daher et al. employing layers of BiFeO₃ and black phosphorus in an SPR sensor proposed an effective sensing platform for detection of the mentioned pathogens with outstanding sensitivity²⁰. Recently an SPR bio-photonics sensor is developed for the quick detection of a hazardous bacteria named *Vibrio cholera* employing BaF₂ prism, Ag, Silicon and Graphene. The bio-photonics sensor showed specific sensitivity and selectivity compared with other studies, and had a sensitivity of 307.81 deg/RIU. The improved sensitivity was the result of increasing the thickness of Ag and Si layers²¹.

In the same manner detecting certain genetic alternations like mutations in the BRCA1 and BRCA2 genes, holds significant importance in proactive screening for breast and ovarian cancers²². In the hope of early breast cancer diagnosis, an SPR biosensor with high sensitivity and a detection limit below 50 nM for related mismatch sequence detection is proposed by Carrascosa et al.²³. A computational method was employed to develop a fiber optic SPR sensor for BRCA-1 and BRCA-2 genes mutations detection where the sensor surface was coated with graphene. The increment of sensitivity of the device confirmed the effectiveness of the proposed structure due to the absorption ability of graphene²⁴. In a study by Uniyal and colleagues, instead of graphene, a composite structure consisting of carbon nanotubes (CNTs), MXene and TiSi₂ was used in an SPR sensor for haemoglobin detection. They reported improved sensor performance, with sensitivity increasing to 300 degree/RIU²⁵. Employing silver and zinc selenide in a sensitive SPR sensor for the detection of the chikungunya virus in the blood sample, the geometry of each layer was optimized to enhance the overall performance. According to the simulation results, the proposed structure has significantly improved the sensor performance²⁶. For dengue virus detection through dengue-infected blood cells, a hybrid Au/BaTiO₃/WSe₂-based SPR biosensor was designed. The specific features of BaTiO₃ such as high dielectric and refractive index and also low dielectric loss makes it suitable material for improving the performance of sensor. Analysis of the output of the proposed structure showed that the sensitivity was higher than the conventional sensors²⁷.

Moreover, an innovative modified SPR biosensor incorporating gold and zinc oxide nanocomposite has been developed for the detection of Carbohydrate Antigen 15.3 (CA15-3), a tumor marker for breast cancer. The sensitivity has been improved and detection limit was 0.025 U/mL²⁸. In the hope of early diagnosis of malignant tumor, in 2015, a research team measured CA15-3 tumor marker and copper concentrations in breast cancer serum using an SPR sensor based on gold nanorods. The method yielded a high sensitivity which proved to be an effective tool for breast cancer detection²⁹. In addition to CA15-3, other biomarkers such as HER2 proteins can also be detected using SPR biosensors to enable earlier diagnosis of breast cancer. An optical fiber-based SPR optrodes coated with gold arranged in a sandwich configuration is utilized by Loyez et al. to increase the sensitivity to HER2 proteins³⁰. For the detection of colon cancer, Springer et al. proposed an SPR biosensor utilizing gold nanoparticles to quantify carcinoembryonic antigen (CEA) in human blood plasma whose

sensitivity has been improved for clinical applications³¹. Moreover, compared to other detection methods, SPR sensor can be used to determine organic combinations in urine of human bodies and also urea level in blood which are important for diagnosis of heart and kidney illnesses. A surface plasmon resonance-based biosensor (SPRBB) employing Ag and Si layers is suggested by³² with the sensitivity of 373 deg/RIU. It could directly determine and analyze the various levels of urea in blood.

Besides, some spectroscopy-based biosensors with high sensitivity have been designed for cancer-affected cells in various part of human body identification at early stage and in short time for better treatment. Examples of some cancerous cells are reported as blood cancer (Jurkat), skin cancer (basal), pheochromocytoma adrenal glands cancer (PC12), cervical cancer (HeLa), breast cancer-type 1 (MDA-MB-231), breast cancer-type 2 (MCF-7)^{33–36}. With several advantages, the SPR sensors can potentially be applied to detect cancerous cells at early stages and provides an analysis method which is real-time, label-free, rapid and sensitive. Uniyal et al.³⁷ put forward a novel SPR sensor for biomolecules and cancerous cells early detection with outstanding sensitivity of 263.57 deg/RIU and detection accuracy equal to 0.207 deg⁻¹ for Breast-II cancer. The structure was based on InP and Ti₃C₂T_x MXene materials.

Totally, for the detection of cancerous cells, the refractive index of both normal cell and cancerous cell is compared, thus the variation of some important optical parameters can be measured. In a different architecture, Sharma et al. suggested a two-dimensional photonic crystal sensor with a grating design which demonstrated enhanced sensitivity for detecting cervical, basal and breast cancer cells³⁸. Using finite element method, a novel bowl-shaped mono-core titanium coated SPR sensor was designed for the rapid detection of aforementioned cancerous cells. The sensor exhibits high wavelength sensitivity and birefringence with a resolution of the sensor varies between 1.5×10^{-2} and 9.33×10^{-3} RIU³⁹. Moreover, identification of a cancer cell using spectroscopic optical sensor was also studied by Parvin and his colleagues. They introduced a novel design based on compact cladding monomode PCF with silica as a dielectric material. The designed structure achieved enhanced sensitivity and low confinement loss, allowing for the effective detection of blood cancer, breast cancer, skin cancer, cervical cancer and adrenal cancer cells with high sensitivity under X-polarization mode⁴⁰. One of the significant improvements was shown in a SPR biosensor reported by Mostufa et al., who developed a multilayer-coated SPR sensor incorporating hybrid TiO₂/Au/graphene layers. This innovative sensing device exhibited significantly augmented angular sensitivity for six different types of cancer detection such as breast (MCF-7) cancer cells and others. Additionally, the detection accuracy (DA), figure of merits (FOM) and the distribution of the electric and magnetic field were evaluated⁴¹. Considering the working principle of SPR sensors, a simple, cost effective of Ag-based SPR biosensor incorporating a new semiconductor material- zinc selenide (ZnSe)- was proposed by⁴². This design aimed at improving sensitivity for biomedical applications. For identification of cancer cell from normal cell and also for glucose concentration detection, the biosensor revealed high sensitivity of 359 deg/RIU and 366.6 deg/RIU, respectively.

Karki et al. proposed a two-dimensional heterostructure composed of TiSi₂ and black phosphorus for the rapid detection of various cancerous cells. The results presented a relatively improved sensitivity compared to earlier designs⁴³. Considering the fact that normal and cancerous cells differ in their refractive indices, an SPR biosensor combining graphene oxide (GO) and Si₃N₄ was developed to detect different types of cancer cells. The biosensor presented better performance in comparison to previous studies with a maximum sensitivity of 245 deg/RIU for breast cancer type 1⁴⁴. Aiming at early cancer detection, Kumar and colleagues designed an SPR biosensor using titanium dioxide (TiO₂), and graphene layers. For the detection of adrenal gland (PC12) cells, the proposed sensor displayed high and enhanced sensitivity⁴⁵.

In the present study, using a nanomaterial-based SPR biosensor, we aim to detect various cancerous cells: skin cancer (basal), blood cancer (Jurkat) and cervical cancer (HeLa). The sensor features a multilayer structure consisting of BK7 glass prism coated with layers of ZnO, Ag, Si₃N₄, TMDCs and sensing medium. Numerical simulations demonstrate that the sensor achieves enhanced performance in terms of sensitivity, detection accuracy (DA), figure of merit (FoM) and signal-to-noise ratio (SNR) compared to other reported designs. These improvements are observed for both healthy and cancerous cells, suggesting that the proposed configuration could serve as a promising platform for early and highly sensitive cancer diagnosis.

Theoretical method

Description of sensor's constituent layers

In recent years, advances in nanocomposite-based biosensors have helped overcome some limitations in biosensing and the rapid detection of cancer cells. In that sense, surface plasmon resonance (SPR) method should not be ignored due to its nature strengthen level for nanosensing. Hence, we have introduced an SPR-based optical sensor aimed at investigation of three different types of cancer affected cells: blood cancer (Jurkat), cervical cancer (HeLa) and skin cancer (Basal). The approach relies on differences in the refractive index (RI) between healthy cells and cancerous cells- changes produced by the mutated genes- which provides a considerable basis for distinguishing between them. Thus, the designed structure will be a promising tool as a sensing device for identification of the chemical or ingredient modifications within the cells.

In general, achieving the desired sensitivity and specificity for biomolecule detection in SPR biosensors requires careful consideration and optimization of specific operational parameters. The first key factor lies in the selection of materials, such as the prism, metal thin film, and other layers, as well as the order of the layers and the optimization of their thickness. Additionally, effective functionalization of the surface, if needed, plays a crucial role. The material used in the biomolecular recognition layer is also of great importance, as it directly impacts the sensor's performance. Another critical parameter involves operational conditions, such as the angle and wavelength of the incident light. The refractive index (RI) of the prism, which couples light into the metal layer, and the refractive index of the sensing medium must be carefully considered to achieve optimal results. To ensure the best performance of the proposed sensor, advanced fabrication techniques should be employed

for the precise incorporation of layers and integration of nanomaterials. Proper optimization of all parameters and components will ultimately lead to label-free and real-time detection of biomolecules and cancerous cells.

The proposed structure shown in Fig. 1 is based on Kretschmann configuration consisting of a BK7 Prism-ZnO-Ag-Si₃N₄-TMDCs-sensing medium.

In that strategy, various prisms were evaluated and according to the best performance of the sensor, the BK7 prism was selected as the dielectric substrate. An electromagnetic light source with a wavelength of 633 nm was used in the setup. The semiconductor ZnO, a good adhesion layer material, provides significant enhancement in biosensor sensitivity due to its ability to efficiently gather light and making the larger shift in resonance angle. The interface between metal and ZnO layer operates as phonon interaction. Moreover the interaction at ZnO-metal interface eventuates to band flattening^{46,47}. Considering mentioned properties, ZnO is a promising candidate for integration into SPR biosensor structure. However, Silver (Ag) as a plasmonic material possesses excellent optical properties and relatively low oxidation resistance. These properties contribute to high detection accuracy and make Ag an appropriate choice for sensing applications. Moreover, Ag offers high electrical conductivity and also high reflectivity which are essential for supporting surface plasmon resonances and minimum energy loss during the excitation of surface plasmons^{48,49}. Besides, it supports both propagating and localized surface plasmon modes. In addition, its moderate biocompatibility and antimicrobial properties provide a suitable platform for biosensing applications⁵⁰. Nowadays, Silicon Nitride (Si₃N₄), as a dielectric material with a wide bandgap of ~5 eV has developed exceptional properties. Silicon Nitride (Si₃N₄), offers optical transparency in the visible to near-infrared range⁵¹ which facilitate an efficient light-matter interaction. In addition it has mechanical and chemical stability and resistance to corrosion which are important in biosensing and make it a suitable substrate material for sensors^{52,53}. In our proposed biosensor structure, the application of Si₃N₄ layer in combination with the Ag layer leads to fix the oxidation issue of this material, increasing the lifetime of the sensor, and enhancing sensor performance^{54–56}.

In the design of proposed structure, different number and thickness of TMDCs (Molybdenum diselenide (MoSe₂), Molybdenum disulfide (MoS₂), Tungsten diselenide (WSe₂) and Tungsten disulfide (WS₂)) layers across multiple models were utilized to investigate their enhancement impact on the sensitivity of SPR biosensor. Because of the need for improved sensitivity and optimum performance of biosensor, we have considered alternative layers with various thicknesses. Thus, in order to determine the optimized thickness of Ag layer, thickness values ranging from 30 to 55 nm with the interval of 5 nm were evaluated. It was noticed that a 55 nm thick Ag layer provided the best performance with the lowest reflectance angle. As mentioned, the refractive index and thickness of each layer are among crucial parameters which affect the sensitivity and performance of SPR biosensor. Therefore, to achieve the best sensing performance of biosensor, the optimized thickness of each layer was calculated and are reported in Table 1.

The different thickness of other layers were tested and compared with different literatures for better results and more accurate data. In other words, using TMDCs is one of the engaged alternatives for increasing the adsorption rate of biomolecules of sensor surface, so the sensitivity improvement. The enhancement of sensitivity is due to the dielectric constant of TMDCs. Two parts of dielectric constant, the real and imaginary parts which are responsible for light absorption and electron energy loss, respectively, can be considered among important factors to affect sensitivity^{57–59}. To achieve the best sensing performance of biosensor, the optimized thickness of each layer was calculated and are reported in Table 1. Furthermore, the refractive index and the optimized thickness of other materials using various references is depicted in Table 1, as well.

Sensor theoretical modeling and optical performance parameters

For the proposed multilayer model of sensor, the reflectance calculations via transfer matrix method (TMM) and Fresnel's equations is used according to the model mentioned in our previous study⁸ and in the references^{42,44,60–63}.

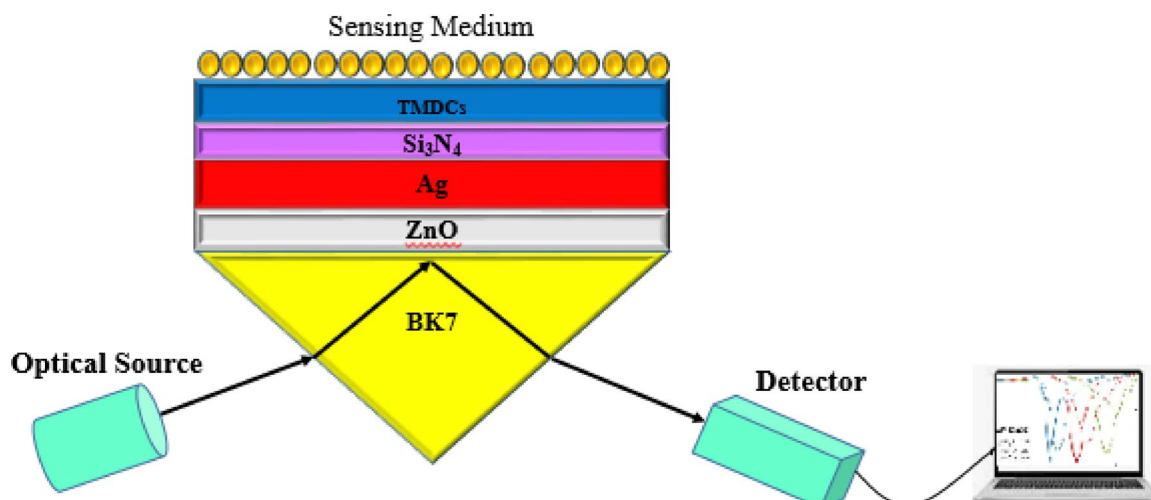


Fig.1. Schematic diagram of the SPR biosensor by using ZnO, Si₃N₄ and TMDCs for sensitivity enhancement.

Types of materials	Thickness of monolayer(nm)	Refractive index ($n + ik$)
Prism (BK7 glass)	-	1.5151
ZnO	5	1.952 + 0.02i
Silver (Ag)	55	0.056206 + 4.2776i
Si ₃ N ₄	5	2.0394
MoS ₂	0.65	5.08 + 1.1723i
MoSe ₂	0.7	4.62 + 1.0063i
WS ₂	0.8	4.9 + 0.3124i
WSe ₂	0.7	4.55 + 0.4332i

Table 1. Optimized values of thickness and refractive indices of various layers at $\lambda = 633$ nm.

The performance of sensor is evaluated by performance factors: sensitivity (S), quality factor (Q), detection accuracy (DA) and figure of merit (FoM) which are defined as following.

The parameter sensitivity is related to the capability of the sensor for detecting slight variations in the refractive index on the surface of sensor^{8,44}. Thus, it is described as the ratio of shift in resonance angle ($\Delta \theta$) and the variation of RI (Δn):

$$S = \frac{\Delta \theta}{\Delta n} \quad (1)$$

The sensitivity is evaluated in deg/RIU. Besides, the quality factor (Q) which is known as the parameter figure of merit (FOM) in RIU⁻¹ is defined as the ratio of reflectance sensitivity to the full-width half-maximum (FWHM) of the reflectance curve⁴⁴,

$$FOM = \frac{S}{FWHM} \quad (2)$$

where the FWHM describes the width of a peak related to the amplitude of a graph at half of its maximum value and FOM explains about the resolution of SPR sensor power.

The other performance parameter of biosensor is detection accuracy (DA). This parameter illustrates about the effectiveness and the quality of the sensor and can be defined as the following relation

$$DA = \frac{1}{FWHM} \quad (3)$$

From SPR characteristic curves, the parameter signal-to-noise ratio (SNR) of the real SPR sensing system can be written as given,

$$SNR = \frac{\Delta \theta_{SPR}}{FWHM} \quad (4)$$

This sensing parameter defines that using real instruments, how well the signals can be measured^{41,44,64}.

Practical fabrication process

In this paper, we theoretically investigated and proposed a hybrid structure BK7/ZnO/Ag/Si₃N₄/TMDCs/sensing medium-based biosensor using numerical modelling. Although, the design is currently theoretical, the proposed sensor layout could be practically fabricated. According to some researches and literature findings, various methods have been applied for synthesizing ZnO, Si₃N₄, TMDCs and fabrication of biosensors based on these materials. In General, two main approaches- top-down and bottom-up- are commonly used for synthesizing and fabrication. The top-down approach includes techniques such as liquid, mechanical, surface functionalization, lithography, chemical exfoliation techniques and the bottom-up approach consists of chemical vapor deposition (CVD), molecular layer deposition, chemical synthesis, sol-gel synthesis and solvothermal procedures⁶⁵. Zinc oxide (ZnO), a transparent semiconductor, has gained significant attention because of its unique electronic and optical properties. It also can be used as an effective adhesion layer. The ZnO layer can be deposited onto a BK7 prism using either atomic layer deposition (ALD) or thermal coating techniques, both used in thin film applications. This material can make larger shift in resonance angle so leads to sensitivity enhancement and increase in detection accuracy⁶⁶. In the next step, Ag layer can be deposited using high-frequency magnetron sputtering technique or Physical vapour deposition (PVD). According to⁵⁴ silicon nitride (Si₃N₄) and Si₃N₄ thin films have been successfully prepared by ion-assisted deposition (IAD) or ion assisted thermal evaporation, yielding favourable optical constants. The Si₃N₄ layer functions as an anti-reflection coating on Ag layer, overcome the oxidation problem of Ag. This makes silver layer highly resistive to the oxidation and environmental degradation^{54,55,67}. Each TMDCs layer, MoSe₂, MoS₂, WSe₂, and WS₂, can be deposited via the Chemical vapour deposition (CVD) technique, mechanical or chemical exfoliation, or hydrothermal/solvothermal processes^{68–71}. Elias and his colleagues using a controlled thermal reduction–sulfurization method synthesized heterogeneous systems of MoS₂ and WS₂ layers with thicknesses ranging from monolayers to a few layers⁷². However, considering the above mentioned methods, it is reasonable to suggest that the proposed sensor layout could be fabricated in practice. The possible fabrication process which contains some steps can

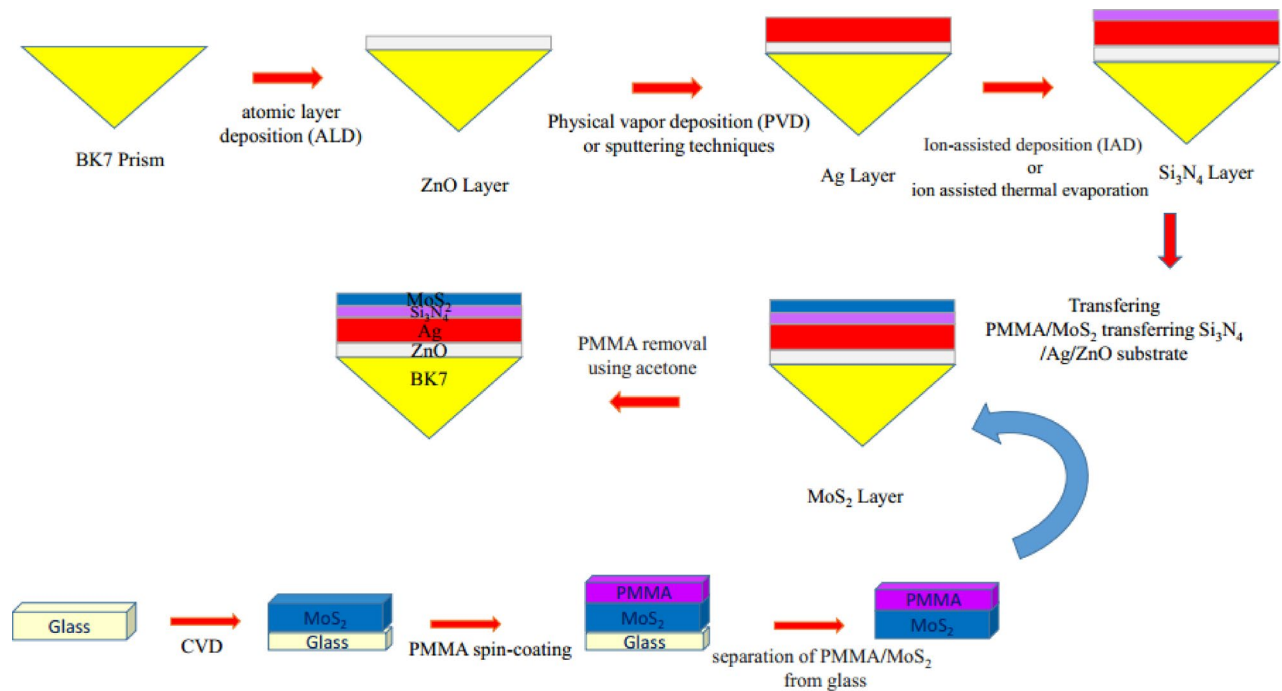


Fig. 2. The potential fabrication stages for the suggested design.

SPR sensor structure	Prism material	Sensitivity(deg/RIU)
Prism/ZnO/Ag/Si ₃ N ₄ /sensing medium	SF10	82.14
	SF11	67.14
	2S2G	35.71
	BK7	227.8
Prism/ZnO/Ag/Si ₃ N ₄ /WS ₂ /sensing medium (structure III)	SF10	83.57
	SF11	75.71
	2S2G	40
	BK7	342.14

Table 2. Analysis of Prism material effect on the sensitivity of the proposed conventional structure (Prism/ZnO/Ag/Si₃N₄/sensing medium) and Prism/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III) for Jurkat cell detection.

be explained with the help of Figs. 1 and 2 in the manuscript. At first, in order to conduct this experiment, a monochromatic light source operating a wavelength of 633 nm is typically employed. In the suggested setup, SPs are consequently excited by p-polarized light.

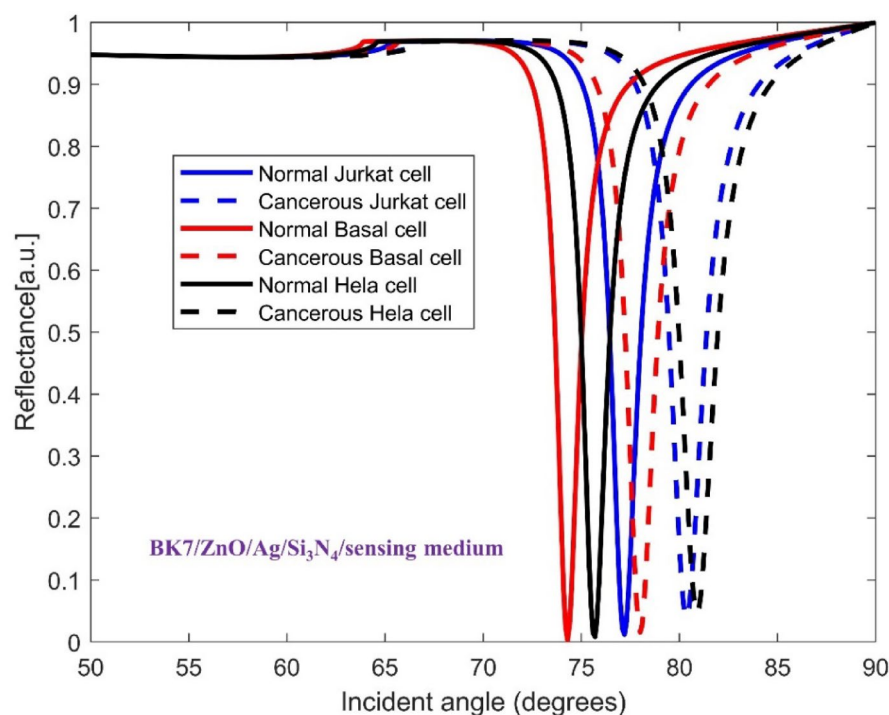
According to the ATR principle, the proposed setup consists of a prism through which incident light enters on one side and exits on the other. The output component usually consists of a detector and a software-loaded system that determines and calculates the results. The potential fabrication steps of the proposed biosensor can be explained as illustrated in Fig. 2.

Results and discussion

In the present study, four different prism-based designs of an SPR sensor, labeled structure I, structure II, structure III and structure IV, were simulated for the detection of different cancer cells. Spectral analysis was conducted for three specific cancer cells: blood cancer (Jurkat), cervical cancer (HeLa) and skin cancer (Basal). The first layers in our proposed sensor, in all designs are common and consisting of ZnO, Ag and Si₃N₄ with each layer optimized for thickness.

Considering the importance of selection of prism material and its effect on the performance of SPR sensor, we examined several prism materials and the related SPR responses were calculated. As a result, BK7 prism was selected due to its suitable resonance angle, FWHM and sensitivity. In Table 2, the result of our sensitivity calculations for some prism materials for comparison are presented. As it is obvious, the best prism material choice for our proposed configuration, is BK7 due to its appropriate refractive index in the working wavelength.

Structure	Silver (Ag) layer thickness (nm)	Sensitivity (deg/RIU)
BK7/ZnO/Ag/Si ₃ N ₄ /sensing medium	45	211.4
	50	214.2
	55	227.8
BK7/ZnO/Ag/Si ₃ N ₄ /WS ₂ /sensing medium (structure III)	45	312
	50	320
	55	342.14

Table 3. Optimization of Ag layer thickness.**Fig. 3.** Variation of reflectance as a function of incident light angle for normal and Jurkat cell, normal and cancerous Basal cell, normal and cancerous HeLa cell detection using conventional structure (BK7/ZnO/Ag/Si₃N₄/sensing medium). The solid and dashed reflectance curves correspond to the normal and cancerous cells, respectively.

In order to verify the influence of the thickness of silver layer on the performance of SPR sensor, the variation Ag layer thickness of 45 nm, 50 nm and 55 nm within the conventional structure (BK7/ZnO/Ag/Si₃N₄/sensing medium) and BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III), and their sensitivity for Jurkat cell detection are presented in Table 3. Considering the numerical analysis of these results, it can be concluded that the sensitivity of 55 nm Ag is higher for cancerous Jurkat cells, so the optimized thickness of 55 nm was chosen for implementation in proposed SPR sensor configuration. Besides the error tolerance of the proposed sensor can be evaluated considering Table 3.

The TMDCs materials were deposited on top of the mentioned base layers to improve the sensitivity in each configuration. Hence, the architecture of SPR sensor for detecting all three cancer cell types consists of a coupling prism BK7, ZnO, Ag metal, Si₃N₄, one of four distinct TMDC materials and sensing medium. This layered structure allows us to analyze how each material affects the sensitivity of sensor for recognizing the normal and cancer cells. In Figs. 3, 4, 5, 6 and 7, the variation of reflectance as a function of incident light angle for both normal cells and three selected cancer cells, Jurkat cell, Basal cell and HeLa cell using conventional setup as well as the four various structures are presented and compared.

Result analysis of SPR biosensor for Jurkat cells (blood cancer) detection

In this section, we analyze the performance and sensitivity of SPR biosensor designed for the detection of Jurkat cells which are considered as the principal candidate in blood cancer. Detecting variations in the refractive index of blood samples of patients is simpler and more feasible than measuring the physical dimensions of cancerous cells since they are typically on the nanometer scale. Thus, SPR biosensing emerges as an effective optical technology to detect life-threatening cancers accurately. The conventional sensor structure, composed of BK7/

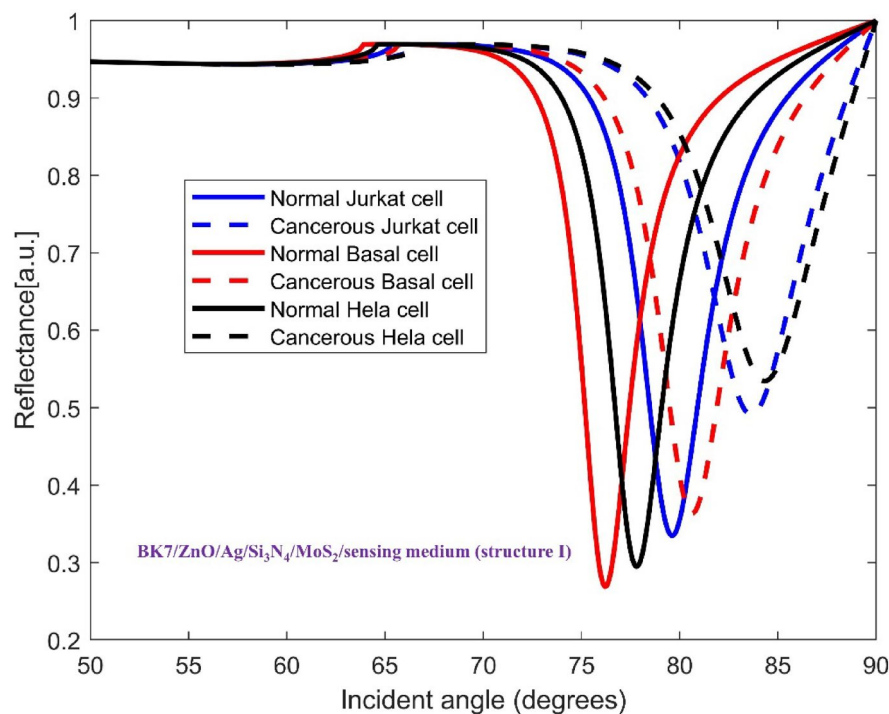


Fig. 4. Variation of reflectance as a function of incident light angle for normal and Jurkat cell, normal and cancerous Basal cell, normal and cancerous HeLa cell detection using conventional structure (BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium). The solid and dashed reflectance curves correspond to the normal and cancerous cells, respectively.

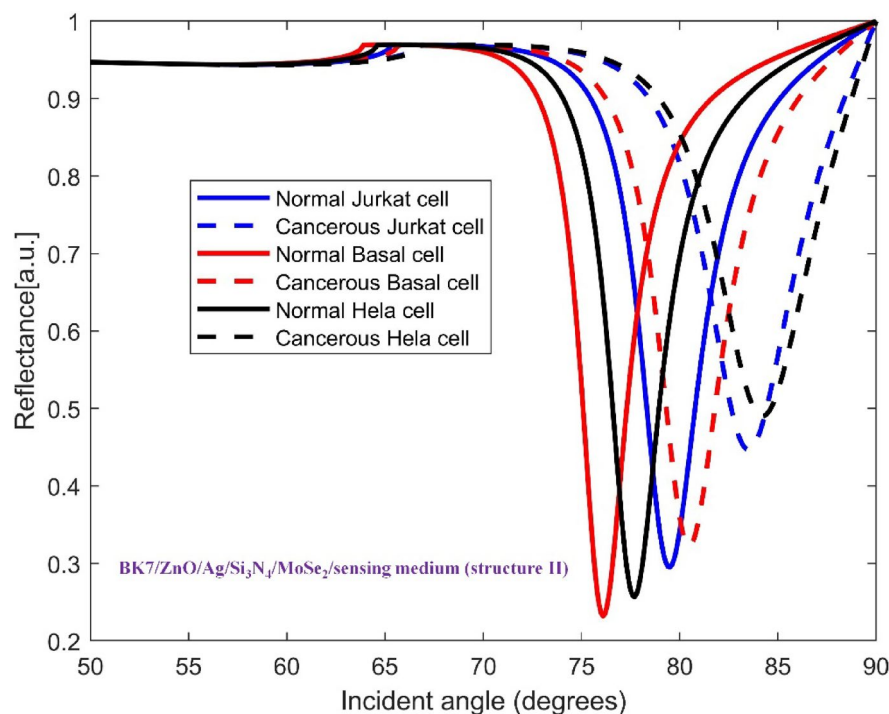


Fig. 5. Variation of reflectance as a function of incident light angle for normal and Jurkat cell, normal and cancerous Basal cell, normal and cancerous HeLa cell detection using conventional structure (BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium). The solid and dashed reflectance curves correspond to the normal and cancerous cells, respectively.

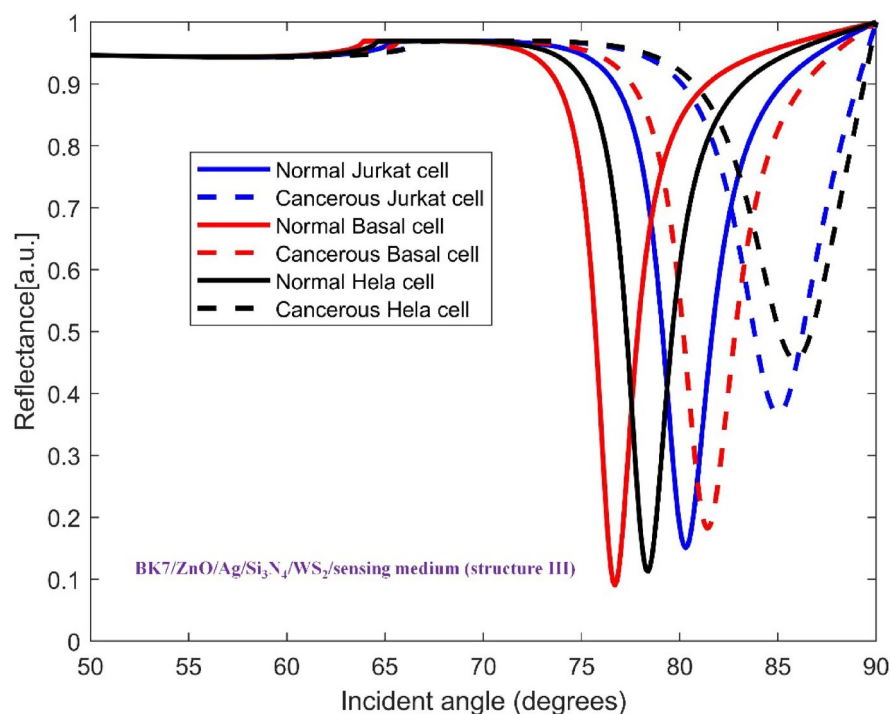


Fig.6. Variation of reflectance as a function of incident light angle for normal and Jurkat cell, normal and cancerous Basal cell, normal and cancerous HeLa cell detection using (BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III)). The solid and dashed reflectance curves correspond to the normal and cancerous cells, respectively.

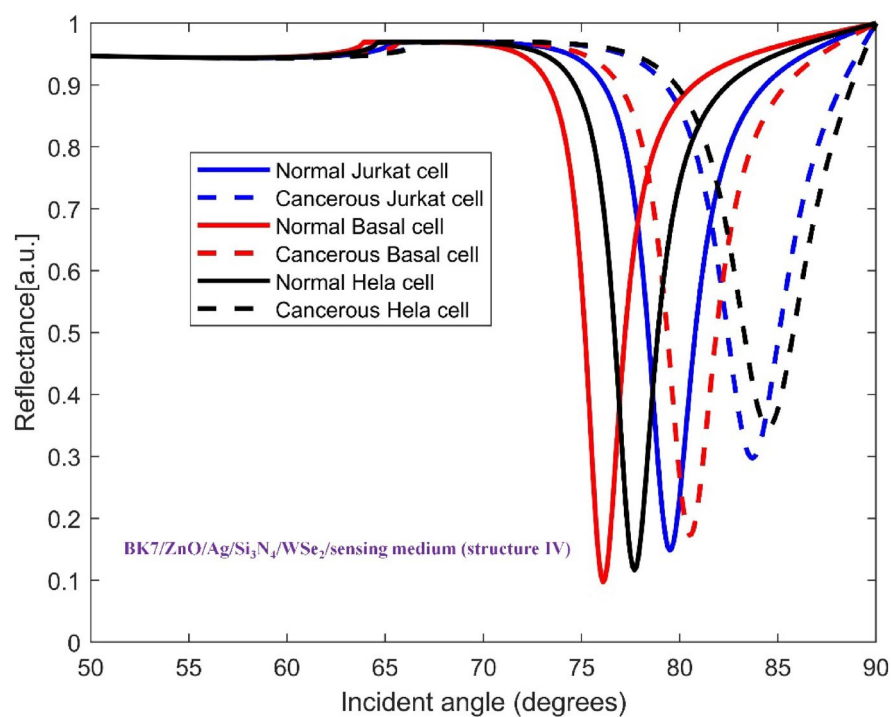


Fig.7. Variation of reflectance as a function of incident light angle for normal and Jurkat cell, normal and cancerous Basal cell, normal and cancerous HeLa cell detection using (BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV)). The solid and dashed reflectance curves correspond to the normal and cancerous cells, respectively.

ZnO/Ag/Si₃N₄/sensing medium, was evaluated alongside four modified designs of sensor with the presence of TMDCs for investigating the most efficient design. These structures are comprising BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium (structure I), BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium (structure II), BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III), BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV). Inasmuch the refractive index of normal cells increases when they become cancerous, this change can be utilized to recognize between normal and cancerous cells effectively. Figures 3, 4, 5, 6 and 7 presents the characteristic curves for the conventional and the four modified SPR sensor configurations to detect normal and Jurkat cells. Specifically, in Fig. 3 the reflectance variation as a function of incident light angle for normal and Jurkat cell recognition for conventional configuration is displayed.

It is comprehended that the resonance dip for normal cells occurs at 77.18° whereas for Jurkat cells occurs at 80.37°. Therefore, the SPR angle shift ($\Delta \theta_{spr}$) equals to 3.19°, and considering the difference in RI between normal and cancerous Jurkat cells, the performance of this configuration in cancerous cells detection is described by its angular shift sensitivity which is 227.8 deg/RIU. Furthermore, other sensing parameters including Figure of Merit (FOM), detection accuracy (DA) and SNR are found to be 152.88 RIU⁻¹, 0.671 deg⁻¹ and 2.14, respectively. For the sake of clarifying the improvement of the performance of the proposed sensor, the incorporation of the mentioned TMDCs into the conventional sensor structure have been done. As it is obvious in Fig. 4, in the presence of MoS₂, i.e. forming the configuration BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium (structure I), the SPR angle shift increases eventuating in sensitivity improvement in the detection of Jurkat cells which are calculated as 4.08° and 291.4 deg/RIU, respectively. In the Fig. 5, the simulation result for both normal and cancerous Jurkat cells is presented for the configuration BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium (structure II). It is evident from the graph that the sensitivity of detection of Jurkat cancer cells increases to 292.14 deg/RIU. Subsequently, to investigate the methods for improving sensitivity in cancer cells detection, WS₂ and WSe₂ layers were added to the sensor structure.

To explore further enhancement in sensitivity, for the structures BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III) and BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV), the reflectance vs. incident angle curves are shown in Figs. 6 and 7, respectively. Considering the unique optical and electronic properties along with strong plasmonic effects of these materials, the sensitivity of sensor increases to 342.14 deg/RIU and 303.57 deg/RIU. Moreover, the corresponding values for Figure of Merit (FOM), detection accuracy (DA) and SNR for these modified structures are presented in Table 4. The comparison between the calculated results demonstrates that the inclusion of WS₂, i.e. BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium layered structure yields the highest sensitivity for detection of cancerous Jurkat cells from normal cells among other configurations tested..

Result analysis of SPR biosensor for Basal cells (skin cancer) detection

We now turn our attention to the optimization of the sensitivity for detection of cancerous Basal cells with particular emphasis on the effect of TMDCs materials. Figure 3 displays the reflectance curves for the conventional configuration of the proposed SPR sensors for both normal and cancerous basal cells detection. Basal cells are considered one of the primary biomarkers in the skin cancer, as they originate in the outermost layer of the skin⁶⁸. The RI of biomolecule solutions for healthy and cancerous Basal cells of the skin cancer are 1.36 and 1.38, respectively. As shown in Fig. 3, for conventional structure, the resonance angle shift induced by the presence of cancerous Basal cells is clearly observed. The sensitivity, Figure of Merit (FOM), detection accuracy (DA) and SNR are found to be 185.5 deg/RIU, 146.06 RIU⁻¹, 0.787 deg⁻¹ and 3.92, respectively.

We now turn our attention to the enhancement the sensitivity of SPR biosensor for cancerous Basal cells detection with respect to the incorporating 2D materials onto the conventional configuration. The obtained

Structures	Cancer cells	Sensitivity (deg/RIU)	FOM, (RIU ⁻¹)	DA, deg ⁻¹	SNR
BK7/ZnO/Ag/Si ₃ N ₄ /sensing medium	Jurkat	227.8	152.88	0.671	2.14
	Basal	185.5	146.06	0.787	2.291
	HeLa	222.08	163.29	0.735	3.919
BK7/ZnO/Ag/Si ₃ N ₄ /MoS ₂ /sensing medium (structure I)	Jurkat	291.4	77.70	0.266	1.088
	Basal	222	76.02	0.342	2.098
	HeLa	276.25	87.69	0.317	2.104
BK7/ZnO/Ag/Si ₃ N ₄ /MoSe ₂ /sensing medium (structure II),	Jurkat	292.14	77.08	0.263	1.079
	Basal	215.5	79.22	0.367	1.584
	HeLa	276.6	95.37	0.344	2.289
BK7/ZnO/Ag/Si ₃ N ₄ /WS ₂ /sensing medium (structure III),	Jurkat	342.14	124.86	0.364	1.748
	Basal	236	115.12	0.487	2.302
	HeLa	315.83	129.97	0.411	3.119
BK7/ZnO/Ag/Si ₃ N ₄ /WSe ₂ /sensing medium (structure IV)	Jurkat	303.57	120.46	0.396	1.686
	Basal	222	111.55	0.502	2.231
	HeLa	285	129.54	0.454	3.109

Table 4. The performance characteristics of the various proposed SPR biosensor for Jurkat, Basal and HeLa cancerous cells concerning the normal cells.

results for all structures: BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium (structure I), BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium (structure II), BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III), BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV) for both normal and cancerous Basal cells detection are summarized in Table 4. Furthermore, the Figs. 4, 5, 6 and 7 show the variation of reflectance as a function of the incident angle for the four proposed configurations with TMDCs in the detection of cancerous Basal cells. Comparing these figures, it is concluded that the influence of the presence of WS₂ layer in sensing chip on the improvement of performance of the sensor is more considerable. The SPR angle shift ($\Delta\theta_{SPR}$) equals to 4.72°, resulting in an improved sensitivity of 236 deg/RIU for the BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV). As well as, the sensor performance of the four proposed structures with TMDCs for detection of healthy and cancerous Basal cells are evaluated by the measurement of sensitivity, FOM, DA and SNR for each case. As a result, for BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV), FOM is 115.12 RIU⁻¹, DA is 0.487 deg⁻¹, and SNR is 2.30. In summary, Table 4 provides a comprehensive comparison of the performance parameters of the proposed structures. Based on these results, the proposed biosensor shows a high capability to detect a subtle refractive index change between normal and cancerous Basal cells with significant sensitivity.

Results analysis of SPR biosensor for HeLa cells (cervical cancer) detection

Nowadays, cervical cancer is one of the most commonly diagnosed cancer among women, making early and more precise detection essential for improving patient life quality. However, remarkable diagnosis methods rely on subjective assessments by physicians, highlighting the need for more standardized measuring and detection techniques of cancerous cells to support clinical decisions-making and treatments. The SPR biosensor as one of optical biosensing technologies offer a promising solution to meet these requirements. Considering the mechanism of SPR sensors which depend primarily on the changes of refractive index which result in a measurable shift in the SPR inclination, this kind of optical device is used for detection of HeLa cells, a key biomarker in cervical cancer. Normal HeLa cells become cancerous following infection with human papillomavirus 18 (HPV18). In this study, the RI of normal and cancerous HeLa cells are measured as 1.368 and 1.392, respectively and tested using the proposed biosensor configuration in the present study^{67,73}.

The configuration of sensor for cancerous HeLa cells detection is composed of the materials and layers structure described previously. In Figs. 3, 4, 5, 6 and 7, the reflectance plots as a function of incident angle for both normal and cancerous HeLa cells using the conventional structure as well as modified configurations incorporating TMDCs are presented. The shifts in the SPR angle are influenced by the variation in the refractive index between normal cells and cancerous cells. The calculated performance parameters namely sensitivity (S), Figure of Merit (FOM), detection accuracy (DA) and SNR have been presented in Table 4. For the detection of normal and cancerous HeLa cells, the evaluated sensitivity for the proposed conventional structure and four configurations: BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium (structure I), BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium (structure II), BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III), BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV) are 222.08 deg/RIU, 276.25 deg/RIU, 276.6 deg/RIU, 315.83 deg/RIU, 285 deg/RIU, respectively. The superiority of the proposed BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III) sensor for cancerous HeLa cells with the highest sensitivity of 315.83 deg/RIU, Figure of Merit (FOM) of 129.97 RIU⁻¹, detection accuracy (DA) of 0.411 deg⁻¹ and SNR of 3.11 is evident. Furthermore, a comparative analysis of all proposed configurations is illustrated in Table 4.

It is comprehended that the resonance dip for normal cells occurs at 77.18°, while for Jurkat cells it is detected at 80.37°. Therefore, the SPR angle shift ($\Delta\theta_{SPR}$) equals to 3.19°. Based on the refractive index difference between normal and cancerous Jurkat cells, the sensing performance of this configuration in cancerous cells detection is characterized by its angular sensitivity which is calculated to be 227.8 deg/RIU. Furthermore, other key sensing parameters including Figure of Merit (FOM), detection accuracy (DA) and SNR are found to be 152.88 RIU⁻¹, 0.671 deg⁻¹ and 2.14. To further clarify the improvement of the performance of the proposed sensor, the conventional sensor was modified by incorporation of the mentioned TMDCs materials into the sensing layer. As it is obvious in Fig. 4, in the presence of MoS₂, i.e. with the configuration BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium (structure I), the SPR angular shift and the sensitivity of the detection of Jurkat cells are calculated as 4.08° and 291.4 deg/RIU, respectively. Similarly, in the Fig. 5, the simulation results for normal and cancerous Jurkat cells for the configuration BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium (structure II) are presented. It is evident from the plot that the sensitivity for the Jurkat cancer cells detection increases to 292.14 deg/RIU. Subsequently, to investigate the potential methods for improving sensitivity in cancer cells detection, WS₂ and WSe₂ layers were also introduced into the sensor design. Thus, for the structures BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III) and BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV), the reflectance vs. incident angle graph are shown in Figs. 6 and 7. Considering the unique optical and electronic properties as well as strong plasmonic effects of these materials, the sensitivity of sensor increases to 342.14 deg/RIU for structure III and 303.57 deg/RIU for structure IV. Moreover, the other key sensing parameters Figure of Merit (FOM), detection accuracy (DA) and SNR for these structures are presented in Table 4. The comparison between the calculated results demonstrates that the incorporation of WS₂ into the proposed configuration, i.e. BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium layered structure exhibited the highest sensitivity for detection of cancerous Jurkat cells from normal cells.

Impact due to the sensor configuration on characteristics of biosensor

In this part, the precise performance metrics and parameters for the conventional SPR structure and the four modified configurations incorporating TMDCs are compared and depicted in Fig. 8. Advancing the analysis, in Fig. 8a the variation in sensitivity across different sensor structures for the detection of cancerous HeLa, Basal and Jurkat cells is displayed. As it is obvious in this graph for detection of cancerous cells, the combination of WS₂ in structure III (BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium) achieves the highest sensitivity among

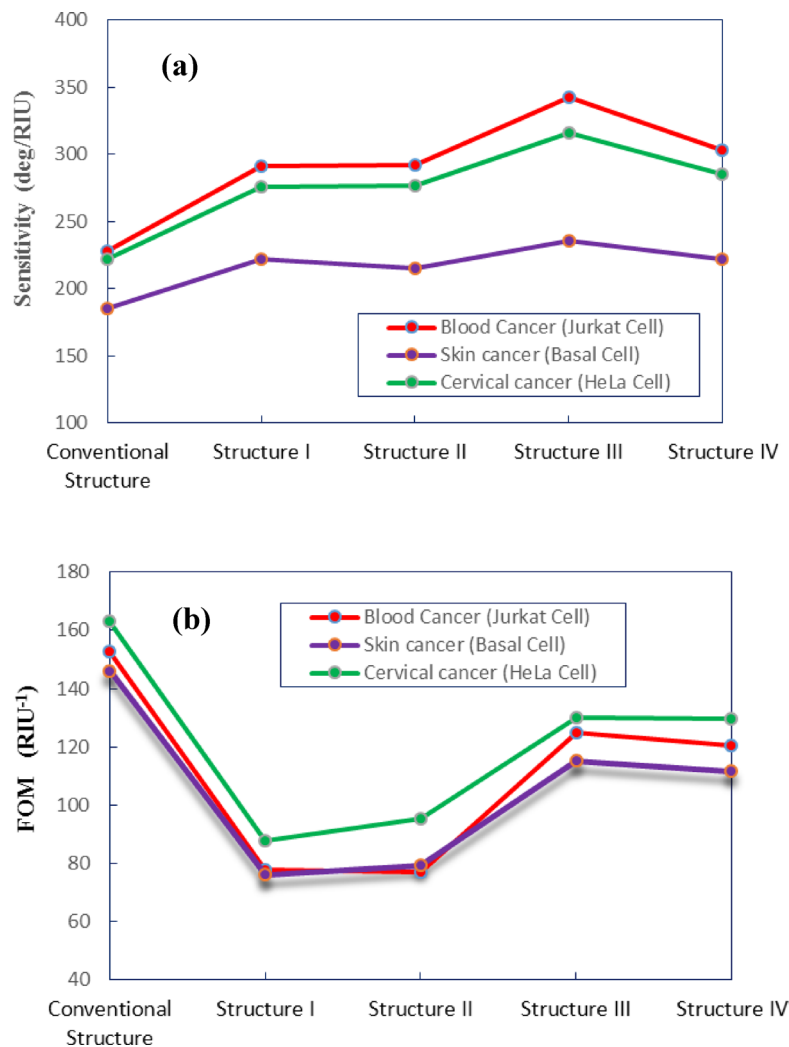


Fig. 8. Performance parameters for conventional (BK7/ZnO/Ag/Si₃N₄/sensing medium) and BK7/ZnO/Ag/Si₃N₄/MoS₂/sensing medium (structure I), BK7/ZnO/Ag/Si₃N₄/MoSe₂/sensing medium (structure II), BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III), BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium (structure IV) (a) Sensitivity (b) FOM.

all configurations which is 342.14 deg/RIU, 236 deg/RIU and 315.83 deg/RIU for cancerous Jurkat, Basal and HeLa cells, respectively. In contrast, the conventional structure exhibits the lowest sensitivity. Comparing to other configurations, the structure IV (BK7/ZnO/Ag/Si₃N₄/WSe₂/sensing medium) ranks second in terms of sensitivity for cancer cells detection.

It is evident that the presence of WS₂ and WSe₂ layers in the SPR sensor configuration, enhances the sensitivity comparing to others. Thus, due to specific optical properties such as high refractive indices, strong plasmonic properties, stability and biocompatibility, the presence of these materials can improve the performance of the sensor. Figure 8b depicts the variation in Figure of Merit (FOM) across all sensor configurations. It is comprehended that the FOM of the characteristic curve decreases from conventional structure (163.29 RIU⁻¹) for HeLa cell detection when MoS₂ and MoSe₂ are introduced. Although all four structures exhibit lower FOM values than the conventional one, structures III and IV with the WS₂ and WSe₂ layers present better FOM in comparison to structures I and II. It can be said that the sensitivity increasing inevitably brings a decrease in quality factor and detection accuracy. The optimum sensitivity of value 342.14 deg/RIU for Jurkat cell detection and FOM equal to 124.86 RIU⁻¹ are proposed for detection of cancerous cells using SPR sensors. Furthermore, considering other structures, the WS₂ layer due to relatively small imaginary part of dielectric constant, exhibits lower energy loss compared to other TMDCs, thereby offering better improvement effect on the performance of SPR biosensor for detection of biomolecules and biochemical substances.

Furthermore, Table 5 presents a comparative analysis of the performance of some various recently reported 2D materials-based SPR biosensors and the proposed sensor. It is obvious that the proposed structure successfully achieves the goal of improved sensing performance.

SPR sensor design	Type of cancer (cancerous cell)	Sensitivity (deg/RIU)	DA (deg ⁻¹)	Ref.
Prism/Ag/Si ₃ N ₄ /GO/sensing medium	Breast Cancer	259	1.19	44
Prism/TiO ₂ /Au/graphene/sensing medium	cancerous cells in the Adrenal Gland (PC12)	282.86	-	45
Prism/TiO ₂ /Au/graphene/sensing medium	Breast MDA-MB-231 Cancer Detection	292.85	0.263	41
Prism/Ag/Bi ₂ Te ₃ /MXene/sensing medium	cancerous (skin, cervical and blood) cells	319.46	0.30	74
Prism/Ag/ZnSe/sensing medium	MDA-MB-231 cells Cancerous HeLa cells	359 247	0.22 0.26	42
CaF ₂ /Ag/Al ₂ O ₃ /Ag/graphene/analyte	Blood cancer	427.43	-	46
Prism/Ag/BaTiO ₃ /Ag1/(MoSe ₂ /WS ₂)	breast (MM-231) cancer cells Skin cancer, Basal cells	309.28 253.5	0.829	75
Prism/Au/Gr/Ag/black P	Jurkat cancer cell	329.1		76
Prism/Ag/InP/MXene/WS ₂ /sensing medium	MCF-7 (Breast-II cancer cell)	263.57		37
Prism/ZnO/Ag/Si ₃ N ₄ /WS ₂ /sensing medium	Blood cancer (Jurkat cell) Cervical cancer (HeLa cell)	342.14 315.83	0.364 0.411	Present Work

Table 5. Comparison of sensitivity of proposed and recently investigated SPR biosensors for cancer detection.

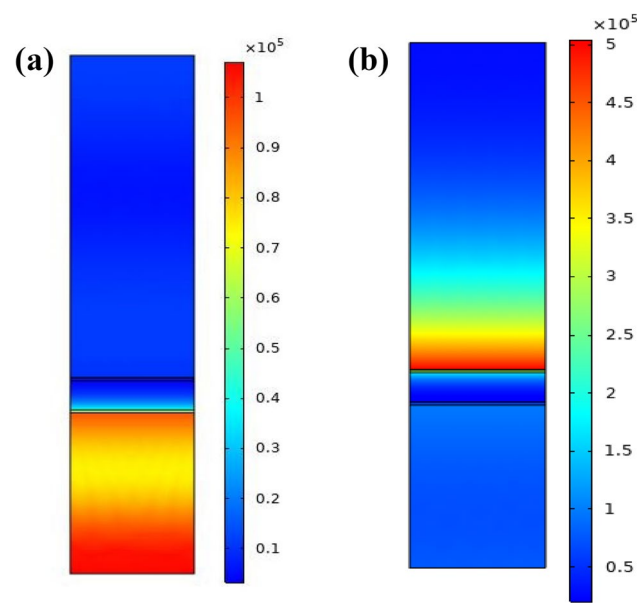


Fig.9. Electric field distribution (a) at a non-resonance angle (b) at a resonance angle for BK7/ZnO/Ag/Si3N4/WS2/sensing medium (structure III) SPR biosensor.

Distribution of electrical field in the proposed SPR biosensor

The SPR phenomenon occurs at the interface between the TMDCs and the sensing medium or analyte layer due to the matching of the momentum of the incident light and the surface plasmon waves. This equality, in the metal layer, will lead to the collective oscillation of the free electrons. The electric field of the waves of surface plasmon and the electric field of incident light are coupled so intensity of the electric field at the metal-dielectric interface will increase. As a result, the reflectance or transmission spectrum of the structure changes which is due to the interaction between the surface plasmon waves and the analyte layer. Using COMSOL multiphysics software the distribution of the electric field is simulated. As shown in Fig. 9, the interpretation of the performance parameters of the designed SPR biosensor with better sensitivity can be prospected by the distribution of electric field intensity from the prism boundary. To compare the proposed structure in SPR and non-SPR conditions, the electric field intensity propagation at the resonance and non-resonance angle is presented in Fig. 9a,b. In the non-resonance condition, no electric field intensity on the plasmonic layer is observed, while in the resonance condition, significant increase in the electric field intensity is observed at the sensing surface due to the maximum excitation of surface plasmons and the strong localization in the plasmonic layer.

Considering Fig. 9 the intensity of the electric field, at the interface between the TMDCs and the sensing medium is high due to the strongest excitation of surface plasmons which happen at the interface. In other words, since the interface between the TMDCs material and the sensing medium is conductive for detection of the refractive index variation of the sensing medium, so it can be seen that the electromagnetic wave energy is concentrated on this interface.

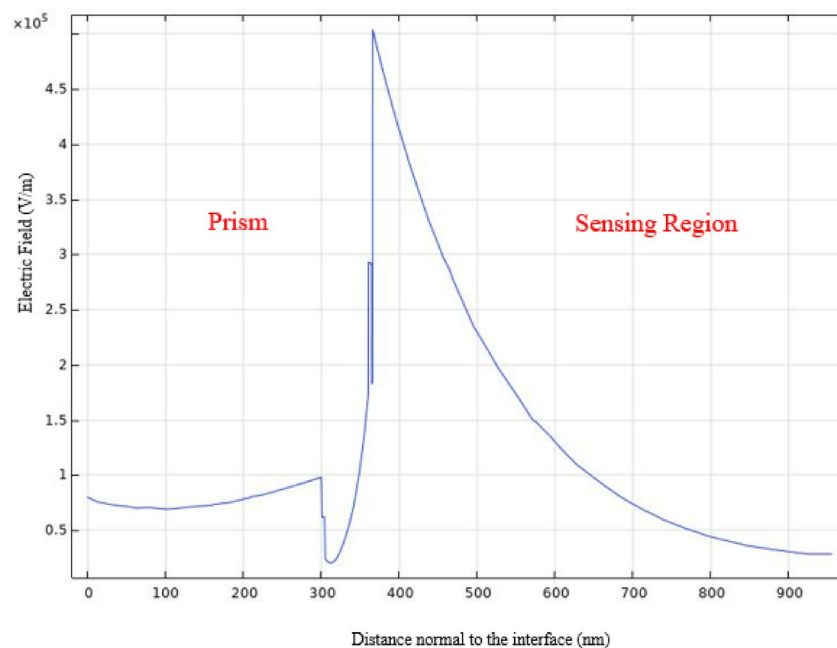


Fig.10. Cross-section plot of the electric field distribution along the direction perpendicular to the prism base at the resonance angle presenting an obvious evanescent field at the sensing interface.

To further confirm the strong SPR excitation of the proposed BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium (structure III), we employed the electric field distribution of the structure at the resonance angle condition. Thus, in Fig. 10, the electric field propagation versus distance normal to interface at the resonance angle is shown. As it is comprehended, an electric field enhancement is produced on the plasmonic Ag layer, and the intensity of the electric field exponentially falls to the sensing medium, which contains the biomolecules, so presents highly sensitivity to biomolecules interactions. It indicates the intensified field strength under these conditions, as it is common in resonance phenomena. The trend of EF is also consistent with the trend of the reflectance variation and sensitivity of the structure III.

Conclusion

In this study, we presented and theoretically analyzed the performance of a heterostructure composed of Ag-ZnO-Si₃N₄-TMDCs as an SPR sensor layers for detection of three different types of cancer cells, Jurkat, Basal and HeLa. Each material, ZnO, Si₃N₄ and TMDCs, was selected based on their specific and unique properties that contribute to enhancing the performance of the biosensor. Zinc Oxide (ZnO), a semiconductor, offers several key features beneficial for SPR biosensing including biocompatibility, a high refractive index, capability of light gathering plasmonic effect enhancement, surface functionalization capability and cost-effectiveness, making it a suitable choice for integration into SPR biosensor structure^{47,48}. Likewise, dielectric Si₃N₄ was incorporated due to its specific advantages such as large RI which can improve light interaction in SPR sensor, chemical and thermal stability and some other properties which are essential for improvement of performance of the optical biosensor^{54–56}. Moreover, Transition Metal Dichalcogenides (TMDCs) were chosen as the sensing layer owing to their favorable properties such as their adsorption ability, a large real part of dielectric constant and also their ability to support enhanced surface plasmon excitations, all of which significantly improve sensor performance. The average sensitivity for the structure BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium of 342.14 deg/RIU for Jurkat cell detection which causes blood cancer, the value of 236 deg/RIU and 315.83 deg/RIU for Basal and HeLa cancerous cells, respectively, can be achieved from our design. These values demonstrate the high effectiveness of the design in detecting various types of cancerous cells. In addition, other performance parameters Figure of Merit (FOM), Detection Accuracy (DA) and Signal-to-Noise Ratio (SNR) of proposed structure are found to be superior in comparison with other configurations. It is concluded that WS₂, in comparison to MoS₂, MoSe₂ and WSe₂ gives rise to a greater shift in the resonance angle, resulting in the sensitivity enhancement for cancer cells detection. Besides, using finite element method (FEM) simulations, the electric field distribution at various layer interfaces is analyzed for BK7/ZnO/Ag/Si₃N₄/WS₂/sensing medium configuration of proposed SPR sensor. The findings of this study provide valuable insights for designing of photonic and plasmonic biosensors, particularly for applications in cancer diagnostics. Totally, optical and plasmonic sensors can provide a promising opportunity for early and accurate cancer detection, offering a powerful tool in the fight against the cancer. Meanwhile, further research is still needed to optimize and improve the performance of optical sensors for broader use in medical and clinical applications.

Data availability

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

E.J and S. A. developed the theory and presented idea. E.J and B.M. and S.A. performed the computational framework, simulations, calculations and modeling. All authors discussed the results and analyzed the data. S.A wrote the manuscript in consultation with B.M and S.A.supervised the project.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to S.A.

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