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REGULAR ARTICLE

Thickness-Dependent Optical Response of Gold and Chromium Nanofilms: Insights into Plasmonic Sensing Efficiency

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The optical response of metallic nanofilms is a key factor in determining the performance of plasmonic sensors, which are widely employed in label-free biomedical detection and nanophotonic applications. This research investigates the thickness-dependent optical behavior of Gold (Au) and Chromium (Cr) nanofilms and their impact on plasmonic sensing efficiency. Thin films with varying thicknesses were fabricated and characterized using numerical simulations based on the Finite-Difference Time-Domain (FDTD) method. The analysis focused on critical parameters like reflectivity, Full-Width-At-Half-Maximum (FWHM), and sensitivity for detecting a 3% glucose solution. To optimize sensor performance, Response Surface Methodology (RSM) was employed to optimize the Kretschmann-based surface plasmon resonance (K-SPR) sensor, considering the incident optical wavelength, Au and Cr nanofilm thicknesses, and root-mean-square (RMS) surface roughness as control and noise factors. The results reveal that Au layer thickness and incident wavelength predominantly influence the plasmonic response, while Cr thickness and surface roughness have minimal effect. Optimal near-infrared configurations with 50 nm Au and 3 nm Cr achieved minimal reflectivity of 0.052 at 680 nm narrow FWHM, and high sensitivity, confirming precise nano-film control as critical for advanced applications. These findings provide insights between nanofilm thickness and optical properties, offering practical guidelines for designing plasmonic sensors.

Keywords: Solar panel, Current sensor, Arduino, Dust, Temperature, Photovoltaic.

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1. INTRODUCTION

Nanomaterials have become a prominent building block towards designing next-generation technologies primarily due to their unique characteristics with respect to physicochemical and optical properties. Nanostructured materials are spawning a new avenue in the design of efficient and scalable energy technologies given their intermediate surface area, modifiable morphology, and remarkable electron transport properties [1-2] Nanophotonic devices are developing into significant platforms for applications in biology requiring nanoscale precision in the control of light propagation and confinement, with the relevance emerging in drug delivery, biosensing, and diagnostic imaging [3]. Metallic nanoparticles and thin films are also used for many other applications associated with sensing, from antimicrobial coatings to medical imaging, cancer treatment, controlled delivery of drugs and wound healing [4]. Au nanofilms with various thicknesses are typically produced by electron beam evaporation (EBE) as a popular method to deposit thin metallic layers, including Au, Cr, Titanium (Ti), and Aluminum (Al), less than 100 nm [5]. Recent studies have shown that femtosecond laser excitation can probe the acoustic resonances of thin Cr films, enabling the determination of their elastic moduli through measurements of pulse-echo delays and breathing mode vibrations [6-7]. Among the different design parameters, the thickness of the metallic layer is the most significant parameter in controlling resonance linewidth, signal intensity, and sensing performance [8].

The performance of plasmonic sensors significantly depends on the optical behavior of metallic nano-films, still the influence of film thickness, particularly for Au and Cr, remains insufficiently determined. Thickness variations changed the reflectivity, resonance width, and sensitivity, which affect sensing performance.

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The research investigated the thickness-dependent optical response of Au and Cr nanofilms and the impact on plasmonic sensing efficiency. Using FDTD simulations and RSM, it aimed to optimize sensor parameters including wavelength, nano-film thickness, and surface roughness to achieve enhanced sensitivity, minimal reflectivity, and improved bio-sensing performance.

Organization of the research: Section 1 represents the introduction of the research, Section 2 describes the related works, Section 3 presents the materials and methods, Section 4 demonstrates the results and Section 5 presents the discussion, and Section 6 concludes the research.

2. RELATED WORK

The research evaluated nanomaterial-based biosensors for rapid Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) detection. It determined plasmonic, Field-Effect Transistor (FET)-based, electrochemical, and Reverse Transcription Loop-Mediated Isothermal Amplification (RT-LAMP) sensor designs. Findings showed that nanomaterials significantly enhanced detection sensitivity, speed, and accuracy compared to Real-Time Reverse-Transcriptase Polymerase Chain Reaction (RT-PCR). However, performance varied depending on sample type and sensor configuration and large-scale validation remained limited, restricting immediate clinical deployment [9]. Research on Localized Surface Plasmon Resonance (LSPR)-based gas sensors highlighted the use of sustainable fabrication methods for nanoparticle-embedded oxide thin films, coupled with electromagnetic simulations via discrete dipole approximation. Findings showed noble metal nanoparticles exhibit high sensitivity to dielectric changes, while factors like nanoparticle distribution, and fabrication reproducibility were noted as limitations affecting sensor performance [10]. The research introduced an improved method for calculating reflectance in Kretschmann-based Surface Plasmon Polariton (SPP) optical sensors, utilizing a stepwise analytical approach verified against experimental data from BK7–Au–air and BK7–Cr–Au–air structures, alongside simulations on SF10 configurations. Results indicated strong reflectance correlation and significant sensitivity to refractive index variations, though validation was restricted to particular material combinations and limited spectral ranges [11].

The ultra-highly sensitive SPR biosensor using graphene oxide layers were designed in the research. It employed transfer matrix and finite element methods to simulate six multilayer heterostructure configurations. The optimized design achieved 372 deg/RIU sensitivity and 88.11 RIU^{-1} quality factor, reaching 414 deg/RIU in tunable mode. However, experimental validation and large-scale fabrication feasibility remained unverified, limiting immediate practical deployment [12]. The research aimed to optimize Au nanoparticle (AuNP)-tungsten disulphide (WS_2) nanohybrid photodetectors for enhanced plasmonic performance. Limitations included slightly slower response time and potential scalability challenges [13]. The research determined to design a high-performance SPR sensor using a BlueP-MoS_2 heterostructure with a ZnO adhesive layer. The transfer matrix method was used to optimize layer thicknesses and evaluate sensitivity, FWHM, and quality factor. Results showed 260°/RIU sensitivity and 48.14 RIU^{-1} Quality Factor (QF), improving over conventional sensors. Limitations included narrow refractive index range and untested experimental fabrication [14]. The impact of a 5 nm amorphous zinc oxide (ZnO) layer on the stability of Au nano-layers and SPR measurements was assessed [15]. ZnO prevents Au oxidation and reduces microdeformation while maintaining surface roughness post-annealing at 773 K. A graphene-based multilayer SPR sensor designed for seawater pollutant detection achieved a peak sensitivity of 186 deg/RIU and an accuracy of 1.5 deg^{-1}. Limitations included fixed annealing parameters, scaled testing constraints, and reliance on simulations without experimental validation [16].

2.1 Research Gap

However, performance varied depending on sample type and sensor configuration, and large-scale validation remained limited, restricting immediate clinical deployment [9]. Sensor efficiency was limited by uncontrolled nanoparticle distribution, restricted surface accessibility, and issues with reproducibility in large-scale fabrication [10]. Existing investigations were often restricted to specific material combinations and narrow spectral operating ranges [11-13], reducing their adaptability to diverse sensing environments. The research intended to provide the impact on plasmonic sensing efficiency and the thickness-dependent optical behavior of Au and Cr nano-films.

3. MATERIALS AND METHODS

The research investigates the thickness-dependent optical response of Au and Cr nanofilms in a K-SPR sensor for glucose sensing. The K-SPR sensor comprised a Cr adhesion layer, borosilicate crown glass (BK7) prism, and Au plasmonic film, with a 3% glucose solution as analyte. FDTD simulations investigated the optical responses depending on thickness of Au/Cr layers, incident wavelength and surface roughness. The Response Surface Methodology (RSM) optimized sensor performance metrics such as reflectivity, full width at half maximum (FWHM), sensitivity and quality factor for enhanced performance in plasmonic glucose detection.

3.1 Fabrication of Nano-films

Au and Cr films of varying thickness were deposited on clean BK7 glass substrates via electron-beam (e-beam) evaporation in an ultra-high vacuum environment. Cr was deposited first as an adhesion layer followed by Au to obtain control over the thickness of the nanofilms. The thicknesses of the films were monitored in situ using a quartz crystal microbalance and later confirmed by atomic force microscopy (AFM).

3.2 Characterization and Optical Simulation

The optical response of the nanofilms was studied using numerical simulations based on the FDTD method. Key parameters including reflectivity, FWHM, and sensitivity were evaluated for glucose detection. Surface roughness of the films was measured using AFM to determine its effect on plasmonic performance.

$$\mu \frac{\partial H}{\partial t} = -\nabla * F - N \tag{1}$$

Eq.1, μ is the magnetic permeability, H is the magnetic field vector, $\frac{\partial H}{\partial t}$ is its time derivative, $\nabla * F$ is the curl of the electric field F, and N represents magnetic current sources or losses.

$$\varepsilon \frac{\partial F}{\partial t} = \nabla * I - J_s - \sigma F \tag{2}$$

Here, ε is the electric permittivity, F is the electric field vector, $\frac{\partial F}{\partial t}$ is its time derivative, $\nabla * I$ is the curl of magnetic intensity I, J_s is the electric current source density, and σF represents the conduction current due to conductivity σ. In FDTD, Eq. 2 updates electric fields over time, accounting for currents, sources, and material conductivity.

3.3 Sensor Optimization

A Kretschmann-based SPR sensor model was implemented. RSM was employed to optimize the sensor performance by varying the optical wavelength, Au and Cr nanofilm thicknesses, and RMS surface roughness as control and noise factors. The simulation aimed to identify configurations that achieve minimal reflectivity, narrow FWHM, high sensitivity, and high-quality factor for glucose sensing. The simplest model which can be used in RSM is based on a linear function.

$$x = \alpha_0 \sum_{i=1}^{k} \alpha_i y_i + \varepsilon \tag{3}$$

In Eq. 3, x represents the response variable, α_0 denote the intercept, α_i denote the regression coefficients, y_i represent the input factors, $\sum$ denotes the sum of the following terms for all i from 1, k is the total number of predictor variables, and ε is the error term. The linear RSM model expresses response x as intercept, weighted sum of input factors, plus error, capturing variable influences concisely.

$$x = \alpha_0 \sum_{i}^{k} \alpha_i y_i + \sum_{1 \le i \le j}^{k} \alpha_{ij} y_i y_j + \varepsilon \tag{4}$$

In Eq. 4, x represents the predicted response, α_0 is the intercept, α_i are linear coefficients for input variables y_j, α_{ij} are interaction coefficients between variables y_i and y_j, k is the total number of factors, and ε denotes the random error term.

3.4 Optical Properties

The research provided certain optical response, including reflectivity, resonance wavelength, and FWHM was analyzed for varying Au and Cr thicknesses. Surface Plasmon confinement, sensitivity, and quality factor was evaluated to optimize near-infrared glucose sensing performance.

4. RESULT AND DISCUSSION

The research investigated the thickness-dependent optical behavior of Au and Cr nanofilms to optimize plasmonic sensing efficiency using FDTD and RSM approaches. Au thickness and incident wavelength significantly influenced reflectivity, FWHM, and sensing sensitivity, whereas Cr and surface roughness showed minor effects.

4.1 Reflectivity Response as a Function of Gold and Chromium Thickness

The simulated reflectivity revealed a strong dependence on Au thickness, while Cr served primarily as an adhesion layer with minimal impact on resonance strength. Thinner Au layers (20-30 nm) yielded shallower dips due to higher absorption losses, while intermediate thicknesses (40-50 nm) produced Surface Plasmon Resonance (SPR) minima with minimal reflectivity. Increasing Au thickness beyond 60 nm resulted in broader resonance curves, indicating reduced field captivity.

Table 1 – Minimum Reflectivity at Resonance for Different Au/Cr Thickness Combinations

Experiment number	Optical Wavelength (nm)	Au Thickness (nm)	Cr Thickness (nm)	R_{min}
1	650	20	1	0.145
2	670	40	2	0.067
3	680	50	3	0.052
4	690	60	2	0.061
5	690	60	5	0.065

Table 1 shows the minimum reflectivity (R_{min}) for different Au and Cr thickness combinations at specific optical wavelengths, highlighting their influence on plasmonic resonance. The 50 nm Au with 3 nm Cr at 680 nm achieves the lowest reflectivity (0.052), indicating optimal surface Plasmon confinement. Thinner Au layers or excessive Cr slightly increase R_{min}, while moderate Cr ensures film grip without significantly affecting resonance demonstrates the critical role of layer thickness and wavelength in K-SPR sensor performance. Fig. 1 represents the minimum reflectivity of different wavelength and Au/Cr thickness.

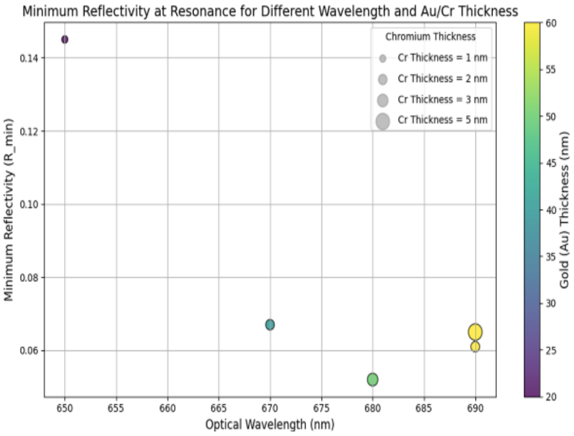

Fig. 1 – Minimum reflectivity at resonance for varying Au/Cr thickness across optical wavelengths

4.2 Sensitivity Analysis for Glucose Detection

The sensitivity analysis of Au/Cr nano-films for 3 % glucose detection shows that the optical wavelength and Au thickness significantly influence R_{min}, FWHM, and sensor sensitivity, while Cr thickness has minimal impact on plasmonic performance.

Table 2 – Effect of Optical Wavelength and Au/Cr Thickness with R_{min}, FWHM, and Glucose Sensitivity

Ex.no	Control Factor	Level	FE, $\boldsymbol{R_{min}}$ (%)	Level	FE, FWHM (%)	Level	FE, Sensitivity (%)
1	Optical Wavelength (nm)	3	12	2	55	3	88
2	Au Thickness (nm)	2	70	3	40	2	12
3	Cr Thickness (nm)	1	5	1	3	1	2

Note: FE – Factor Effect

Table 2 determines the sensitivity analysis of Au/Cr nano-films for detecting 3% glucose, highlighting the effect of key control factors like optical wavelength, Au thickness, and Cr thickness on plasmonic sensor performance. The optical wavelength exhibits the strongest influence on sensitivity, achieving 88 %, and moderately affects R_{min} and FWHM that indicasting its significant role in tuning resonance. Au thickness significantly impacts R_{min} (70 %) and FWHM (40 %), while moderating the influencing sensitivity of 12 % is determined. In comparison, Cr thickness shows minimal factor effects across all parameters, validating its primary function on adhesion layer. These results emphasize the dominant roles of wavelength and Au thickness in optimizing K-SPR sensor efficiency. Fig. 2 represent the comparison of control variables.

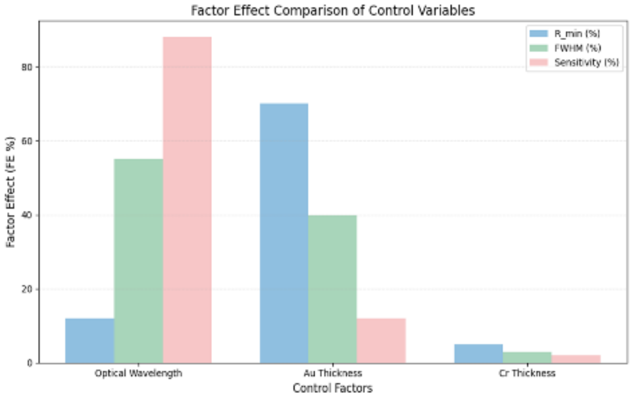

Fig. 2 – Factor effect comparison of control variables

4.3 Effect of Surface Roughness on Plasmonic Confinement

Surface roughness at the metal dielectric interface influences plasmonic confinement by scattering surface Plasmon, which broaden the resonance and slightly reduce sensitivity. In the research, the effect of RMS surface roughness was analyzed while keeping Au and Cr thicknesses and incident wavelength constant. Simulations show that increasing RMS roughness leads to higher minimum reflectivity and wider FWHM, resulting in a gradual decrease in sensitivity and quality factor. The overall impact was less compared to the dominant influence of Au thickness and incident wavelength, validating that precise control of Au thickness is more significant than surface roughness for optimizing sensor performance in Fig. 3.

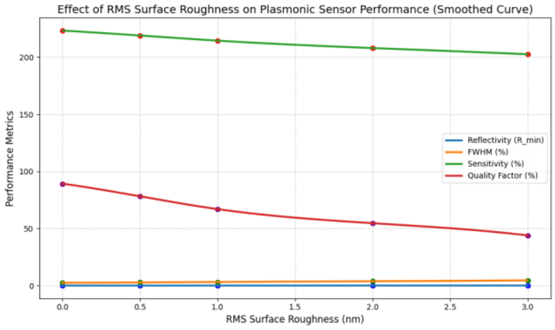

Fig. 3 – Influence of RMS surface roughness on reflectivity, FWHM, sensitivity, and quality factor

5. DISCUSSION

The research investigates the way Au and Cr nano-film thickness and wavelength affect reflectivity, FWHM, and sensitivity to optimize plasmonic sensing. Previous plasmonic sensing research demonstrated results and experienced several critical limitations. Limited control over emission direction, stability, and reproducibility hinders practical implementation of random lasers in precise biomedical applications [17-18]. The research examined the optical behaviors of gold and chromium nanofilms of different thicknesses through simulation and optimization methods. Utilizing FDTD and RSM across a wide wavelength range, the study improved K-SPR configurations, leading to increased sensitivity, reduced reflectivity, and thinner FWHM in near-infrared conditions. The Au/Cr nano-film architect is optimally configured for high-sensitivity plasmonic sensors, useful in glucose sensing for biomedical diagnostics, environmental sensing, and scalable integration into cost-effective lab-on-chip and wearable platforms.

6. CONCLUSIONS

The research investigated the thickness-dependent optical response of Au and Cr nano-films and its impact on plasmonic sensing efficiency with a specific focus on glucose detection. The thin Au/Cr films were fabricated using electron-beam evaporation and characterized through FDTD simulations was provided. Key optical parameters including reflectivity, FWHM, and sensitivity were analyzed, while RSM was employed to optimize sensor configurations by varying nano-film thicknesses, incident wavelength, and surface roughness. The research demonstrated that Au thickness and incident wavelength predominantly manage plasmonic sensor efficiency, while Cr mainly acts as an adhesion layer. Optimal near-infrared configurations with 50 nm Au and 3 nm Cr achieved minimal reflectivity (0.052) at 680 nm, narrow FWHM, and high sensitivity, confirming precise nano-film control as critical for advanced bio-sensing applications. While Au thickness and wavelength were optimized to improve plasmonic sensing, the research limited with the reliance on simulations, a lack of significant influence of Cr, and few experimental validations. Future research can include optimized Au/Cr nanofilm thickness validation experimentally, utilize a variety of analytics, incorporate complex nanostructure designs, and develop scalable, affordable sensors in a plasmonic sensing context related to real time biomedical diagnostics and environmental monitoring.

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Оптична реакція наноплівок золота та хрому, що залежить від товщини: дослідження ефективності плазмонного зондування

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Оптична чутливість металевих наноплівок є ключовим фактором у визначенні продуктивності плазмонних сенсорів, які широко використовуються в біомедичному детектуванні без міток та нанофотонних застосуваннях. Це дослідження досліджує залежну від товщини оптичну поведінку наноплівок золота (Au) та хрому (Cr) та їхній вплив на ефективність плазмонного зондування. Тонкі плівки різної товщини були виготовлені та охарактеризовані за допомогою числового моделювання на основі методу кінцевих різниць у часовій області (FDTD). Аналіз зосереджений на критичних параметрах, таких як відбивна здатність, чутливість до повної ширини на половині максимуму (FWHM) та чутливість для детектування 3 % розчину глюкози. Для оптимізації продуктивності сенсора було використано методологію поверхні відгуку (RSM) для оптимізації сенсора поверхневого плазмонного резонансу (K-SPR) на основі Кречмана, враховуючи довжину хвилі падаючого оптичного випромінювання, товщину наноплівок Au та Cr, а також середньоквадратичну шорсткість поверхні (RMS) як контрольні та шумові фактори. Результати показують, що товщина шару Au та довжина хвилі падаючого випромінювання переважно впливають на плазмонну реакцію, тоді як товщина Cr та шорсткість поверхні мають мінімальний вплив. Оптимальні конфігурації в ближньому інфрачервоному діапазоні з 50 нм Au та 3 нм Cr досягли мінімальної відбивної здатності 0,052 при вузькій ширині хвилі на півширині 680 нм та високої чутливості, що підтверджує критичну важливість точного контролю наноплівки для передових застосувань. Ці результати дають уявлення про взаємозв'язок між товщиною наноплівки та оптичними властивостями, пропонуючи практичні рекомендації для проектування плазмонних сенсорів.

Ключові слова: Сонячна панель, Датчик струму, Arduino, Пил, Температура, Фотоелектричні елементи.