Absorption and Sensitivity Measurements of Noble Metals (Au, Ag, Cu) Thin Film Biosensor Based on SPR Simulation Characterizations

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Abstract

In this paper, we investigate the influence of varying the thickness of noble metals, namely gold (Au), silver (Ag), and copper (Cu), and the incident light wavelength on the surface plasmon resonance (SPR) properties for biosensor applications. Our analysis employs the Fresnel equations to examine the absorption characteristics of these metals. We explore metal layer thicknesses ranging from d = 30 to 70 nm and incident light wavelengths of λ = 500 and 600 nm, with incident angles (θ) ranging from 0° to 90°. Utilizing simulation analysis in MATLAB, we simulate the SPR responses of these metals when deposited on N_LASF9 and BK-7 glass prisms, with air as the surrounding medium. Our calculations reveal the absorption properties of Au, Ag, and Cu, as indicated by the angle of incidence (θ_{SPR}). Our findings demonstrate that the highest absorption occurs with copper (Cu) at A = 0.999 (a.u.) for λ = 500 nm and d = 30 nm. When λ is adjusted to 600 nm, gold (Au) exhibits the highest absorption at A = 0.997 (a.u.) with a thickness of d = 40 nm. Additionally, we calculate sensitivity values for all three metals, with copper (Cu) yielding the highest sensitivity of 101.6 Reflected Index Units (RIU^{-1}) for both λ = 500 and 600 nm. Furthermore, we compute the figure of merit (FOM), with silver (Ag) achieving the highest FOM of 443 at λ = 500 nm and 451 at λ = 600 nm. These findings provide valuable insights into the SPR properties of noble metals for biosensing applications and offer guidance for optimizing biosensor designs.

1. Introduction

The phenomenon known as surface plasmon resonance (SPR) arises from the collective oscillation of electrons at the interface between a metal and a dielectric medium when exposed to an incident electromagnetic wave [1]. When the wave vector of the incident field aligns with that of the surface plasmon, it results in a distinct reduction in reflected intensity, a phenomenon referred to as SPR. SPR has found widespread use in various chemical and biological sensing applications [2]. This effect occurs at the interface between materials with contrasting dielectric constants, typically a metal and a dielectric. Excitation of the surface plasmon wave leads to a dip in the reflected light intensity, a critical factor in determining the sensitivity of SPR sensing [3]. The concept of SPR for prism-based sensing was first proposed in 1968 by Kretschmann [4]. The Kretschmann configuration involves using p-polarized light directed onto a metal-coated coupling prism at a specific wavelength, making it a widely adopted approach in SPR sensors [5].

In recent research, Mahmoud H. Elshorbagy et al. (2017) utilized metallic nanostructures to scatter radiation onto thin metallic films, generating surface plasmon resonances when illuminated with normal incident light. They explored different geometric arrangements and material choices to optimize various performance parameters [6]. Keyi Li et al. (2020) introduced an innovative approach to enhance surface plasmon resonance biosensors by incorporating emerging two-dimensional materials such as blue phosphorus and graphene layers alongside a plasmonic gold film. This modification led to exceptionally high detection sensitivity, opening up promising avenues for diverse applications [7]. Liang Zhang et al. (2021) conducted a numerical simulation of an SPR chip based on an Ag-TiO-Au structure, investigating its sensitivity characteristics [8]. Hind Dhari Awad et al. (2021) undertook a comprehensive study on the optimization of SPR sensors. They explored different types of metal thin films, including gold and silver, as well as various thicknesses, light coupling techniques, and electromagnetic wave polarization modes [9].

This introduction provides an overview of the key concepts of SPR, its relevance to biosensors, recent advancements, and emphasizes the research gap in understanding the impact of noble metal film variations on SPR properties. In the subsequent sections of this paper, we delve into our own investigation of noble metal thin film biosensors and their SPR properties, contributing to the growing body of knowledge in this dynamic field.

1.1 Theory

When the electric field vector lies in the incident plane, the light wave is called TM mode (transverse magnetic mode) or p-polarized light, and when the electric field vector is normal to the incident plane, it is called TE mode (transverse electric mode) or s-polarized light. For every electromagnetic field, it is essential to fulfill Maxwell's equations and adhere to electromagnetic boundary conditions. (TM, TE) perpendicular to the plane of incidence [10]: Fig. 1 illustrates the need to allow for two diverse probable states of polarization of the electromagnetic wave. [11].

2. The Simulation Method

The Fresnel reflection equations used for the SPR simulation are an extension of the example presented here. An expansion of the example given here is the Fresnel reflection equations used in the SPR simulation. The simulation analysis (in Matlab) uses two media, such as glass prism half sphere type N-LASF9, and a film of a noble metal (Au, Ag, or Cu) placed on it, as shown in Fig. 2, at different thicknesses from (30 to 70) nm step10nm with the finale medium (detecting medium), using different wavelengths of light beam from (500 to 700 nm).

The surface plasmon wave's wave vector is perturbed by a factor of k with respect to the wave vector k. Surface plasmon dispersion relation is [12] as follows

$$k = \frac{\omega}{\mathrm{c}}\sqrt{\frac{\phi 1 \phi 2}{\phi 1 + \phi 2}}$$

1

Where c is a light speed of, φ_1, and φ2 are the complex dielectric functions for mediums 1 and 2, respectively, and ω is the angular frequency of light.

Therefore, k is a property of two semi-infinite media and is expressed as [13]:

$$\mathrm{kr} = \mathrm{k} + \mathit{\Delta}\mathrm{k}$$

2

The presence of the prism and the limited thickness of the metal layer are associated with the imaginary component of k., while the real part of k causes a shift of the resonance site relative to Re (k). The intrinsic damping, which signifies the Joule loss in the metal, and the radiation damping, which represents the energy lost through back-coupled radiation, both contribute to the overall effects., can be used to approximate the new term k. There is an analytical approximation of the SPR curve that is given for metals that are typically employed in SPR studies, such as gold, aluminum, or silver. By [10]

R= $1-\frac{4\mathrm{l_m}(\kappa)\mathrm{l_m}}{\mathrm{n}^2\kappa_\mathrm{o}^2(\sin\theta-\sin\theta_{\mathrm{SPR}})+\mathrm{l_m}(\kappa_\mathrm{r})^2}$ (3)

SPR demands that the wave vector of the incident light in the surface plane is represented by (kx) and match the wave vector of the SP wave in metallic films, where lm is the imaginary portion and K_O the vacuum of wave victor (ksp) [13]

$$\kappa_{\mathrm{x=n_p}(2\pi\backslash\lambda)\sin\theta}$$

$$\kappa_{\mathrm{Sp}}=\frac{2\pi}{\lambda}\sqrt{\frac{\Psi_1\Psi_2}{\Psi_1+\Psi_2}}$$

4

$\Psi_1\Psi_2$ Represent the complex permittivity of dielectric material or metal. The refractive index of the prism is referred to as n_p. λ represents the wavelength, and the angle of the incident light is denoted by θ respectively. The appropriate relations for SPR are x = SP and:

$$\theta_{\mathrm{SPR}}=\sin-1\sqrt{\frac{\Psi_1\Psi_2}{\Psi_2(\Psi_1+\Psi_2)}}$$

5

Whereθ_{SPR} is the resonant angle [14].

Changing the angle of incidence, maximum absorption can happen. At definite incident angles, a surface plasmon is excited and resonated near the interface between the metal and dielectric. Phase matching gain occurs when the angle of incidence on the prism exceeds the critical angle [8]. In experiments involving maximum surface plasmon resonance (SPR), silver or gold is commonly employed as a thin layer (film) on the surface of the prism. Typically, the shape of the complete resonance curve is primarily determined by the thickness and optical characteristics of the metal layers.

The sensitivity (S) of the device to variations in the refractive index of a critical substance in direct contact with the sensor surface is defined as follows: [15]

$$s = \frac{\Delta\theta}{\Delta n}$$

6

It can be demonstrated that for electromagnetic waves in the visible range and with noble metals like silver, gold, or copper, the ratio of the loss terms reaches 1 when the thickness varies. Moreover, it is feasible to establish a relationship indicating that the full-width half maximum (FWHM) of the absorption curve is proportional to the imaginary part of the wave vector of the plasma wave, which represents the losses in the system. [16].

3. Result and Discussion

In our study, we aimed to comprehensively evaluate a performance of a thin film based on surface plasmon resonance (SPR) sensing. We focused on key parameters such as sensitivity, full width at half maximum (FWHM), and figure of merit (FOM). The FOM, in particular, plays a crucial role in assessing the sensor's quality, as a higher FOM indicates better performance of the film.

Figure 3 illustrates the correlation between incident light absorption and the incidence angle on the metal surfaces for a wavelength of 500 nm. By analyzing the absorption data obtained from the simulations, we were able to determine the optimal metal thickness and refractive index change for achieving the highest sensitivity and FOM, thereby ensuring superior chip performance.

In Fig. 3, we observed that when the incident light beam loses all its energy, it is completely absorbed by the metal layers, resulting in the excitation of surface plasmons (SPs). The absorption curve depicted in the figure exhibits a gradual increase from low values until reaching a maximum at the resonance angle. Shifting the refractive index by $\Delta n = 0.03$ or 0.06 causes a change in the resonant angle (θ_{SPR}). This indicates that alterations in the layer structure lead to a different angle of absorption. For gold (Au), the optimal thickness for achieving maximum absorption is found to be d = 40 nm, resulting in absorption values of A = 0.988, 0.987, and 0.989 (a.u.) for $\Delta n = 0.00$, 0.03, and 0.06, respectively. The waves reflected from surfaces of the film interfere, leading to an enhanced electric field within the film. This increased electric field can lead to greater absorption of light in the case of silver (Ag), the best absorption occurs in layers with a thickness of d = 40 nm, resulting in absorption values of A = 0.9935 and 0.9933 (a.u.) for $\Delta n = 0.00$ and 0.03, respectively. However, at $\Delta n = 0.06$, the optimal absorption occurs at a thickness of d = 50 nm, with a value of A = 0.933 (a.u.). As for copper (Cu), the highest absorption occurs at a thickness of d = 30 nm, yielding absorption values of A = 0.999, 0.998, and 0.999 (a.u.) for $\Delta n = 0.00$, 0.03, and 0.06, respectively.

Based on the observations from Fig. 4, the optimal absorption for gold (Au) occurs at a thickness of d = 40 nm with an absorption value of A = 0.977 (a.u.) when $\Delta n = 0.00$. For silver (Ag), the best absorption is achieved at a thickness of d = 50 nm with an absorption value of A = 0.961 (a.u.) when $\Delta n = 0.00$. On the other hand, copper (Cu) exhibits the highest absorption at a thickness of d = 40 nm with an absorption value of A = 0.985 (a.u.) when $\Delta n = 0.06$. Thus, copper demonstrates the best absorption among the three metals. The optimal absorption values and thicknesses for these metals are a result of the interaction between incident light and the plasmonic oscillations of free electrons within the metal films. The specific values depend on the material properties and the surrounding medium's refractive index, which affect the plasmon resonance conditions. These findings have implications in various applications, including plasmonic devices, sensors, and optoelectronics.

Another important parameter is a full-width at half maximum (FWHM). At a wavelength of 500 nm, gold has an FWHM of 3.8 nm with a thickness of d = 40 nm and $\Delta n = 0.00$. This indicates that the plasmonic resonance in gold is not as sharp or narrow. The broader FWHM suggests that there is a wider range of wavelengths around 500 nm over which the plasmon resonance of gold is significant. This broader resonance could be due to the material's properties and the chosen thickness and refractive index conditions. Silver, on the other hand, has an FWHM of 0.2 nm with a thickness of d = 50 nm and $\Delta n = 0.00$. Silver exhibits an extremely narrow FWHM of 0.2 nm at 500 nm. This indicates an exceptionally sharp and focused plasmon resonance in the vicinity of 500 nm. The narrow FWHM suggests that silver's plasmonic response is highly specific to the chosen wavelength and the provided conditions. Silver's unique properties result in a very confined spectral range where the plasmon resonance is prominent.

Copper exhibits an FWHM of 19.6 nm with a thickness of d = 30 nm and $\Delta n = 0.06$ this indicates a wider spectral range over which copper's plasmonic resonance is effective. The combination of a dielectric layer (as indicated by the refractive index difference) and the chosen thickness contributes to the broader resonance observed in copper.

When the wavelength is 600 nm, the gold layer shows an FWHM of 5.6 nm at d = 40 nm and $\Delta n = 0.00$. Silver demonstrates an FWHM of 0.2 nm with a thickness of d = 50 nm and $\Delta n = 0.00$. Copper, with $\Delta n = 0.06$, exhibits an FWHM of 17.5 nm. The FWHM measurements offer understanding regarding the range of wavelengths in which plasmonic resonance takes place for each metal at a 600 nm wavelength. These FWHM values are shaped by the properties of the materials, their thicknesses, and the differences in refractive indices. Together, these factors define the interaction between plasmonic resonance and incoming light. The differences in FWHM values signify distinctions in the resonance behaviors among gold, silver, and copper in the given settings.

Table 1presents the sensitivity of metal thin films (Au, Ag, and Cu) at wavelengths 500 nm and 600 nm, providing further details on their performance.

Table 1
sensitivity of (Au, Ag, Cu) metals layer at wavelengths (500,600) nm.

Metals	θΔ	nΔ	S RIU^{-1}	nmλ
Au	3	0.03	100	500
Ag	2.66	0.03	88.66	
Cu	3.05	0.03	101.6	
Au	2.95	0.03	98.33	600
Ag	2.7	0.03	90	
Cu	3.05	0.03	101.6	

Table 1illustrates the top sensitivity (S) readings acquired from copper (Cu), registering at 101.6 RIU^{-1} for both λ = 500 nm and 600 nm. Gold (Au) achieves the second-highest sensitivity value at λ = 500 nm, measuring S = 100 RIU^{-1}. These sensitivity findings align with the outcomes observed by N. Miguel et al, who utilized gold and silver, along with additional coatings, to enhance sensor sensitivity [17]. Furthermore, Farah Jawad Kadhum and associates employed gold-PVA as a biosensor [18]. Sensitivity holds significant importance in assessing sensor performance, serving as an indicator of the change in resonance angle for every unit change in refractive index.

To further assess the sensor performance, the figure of merit (FOM) can be calculated based on the sensitivity and full-width at half maximum (FWHM) values of the metal layers. Table 2displays the FOM values for gold (Au), silver (Ag), and copper (Cu) at wavelengths 500 nm and 600 nm.

Table 2
FOM for metal layers (Au, Ag, Cu) for λ = 500 and 600 nm

Thin film	S	FWHM	FOM	nmλ
Au	100	3.8	26.31	500
Ag	88.6	0.2	443	
Cu	101.6	19.6	5.18	
Au	98.33	5.6	17.55	600
Ag	90	0.2	451	
Cu	101.6	17.5	5.77	

From Table 2, we can observe the optimal figures of merit (FOM) for silver (Ag) with values of 443 at a wavelength of λ = 500 nm and 451 at λ = 600 nm. In the case of gold (Au), the FOM is 26.3 at λ = 500 nm and 17.55 at λ = 600 nm, while for copper (Cu), the FOM is 5.18 at λ = 500 nm and 5.77 at λ = 600 nm.

These results indicate that silver exhibits superior sensor performance compared to gold and copper. Silver's superior sensor performance can be attributed to its enhanced sensitivity, narrow resonance peaks, strong field enhancement, versatility, and applications in various fields. These properties make silver a preferred choice for plasmonic-based sensors that require high sensitivity, selectivity, and accuracy in detecting molecular interactions and changes in the surrounding environment.

4. Conclusion

In conclusion, the investigation of noble metal layers (Au, Ag, Cu) in biosensor applications, considering their thickness and the wavelengths of incident light, has provided valuable insights into optimizing sensor performance. Copper (Cu) demonstrated the highest light absorption, with notable values at $d = 30$ nm and $\lambda = 500$ nm for various refractive index changes ($\Delta n = 0.00, 0.03, 0.06$). Similarly, at $\lambda = 600$ nm, copper exhibited optimal absorption at $d = 40$ nm and $\Delta n = 0.06$. Sensitivity analysis revealed that copper (Cu) exhibited the highest sensitivity, reaching 101.6 RIU-1, at both $\lambda = 500$ nm and $\lambda = 600$ nm. This highlights the potential of copper as a promising material for Biosensing applications. Moreover, the figure of merit (FOM) and the full-width half maximum (FWHM) were evaluated as essential performance metrics. Silver (Ag) demonstrated superior FOM values, with a peak FOM of 443 at $\lambda = 500$ nm and a FOM of 451 at $\lambda = 600$ nm, accompanied by a narrow FWHM of 0.2. These results indicate the excellent performance of silver as a biosensor material.

Overall, this study underscores the importance of carefully selecting noble metal layers and optimizing their thickness in biosensor designs. The findings can contribute to the advancement of Biosensing technologies by enhancing sensitivity, FOM, and absorption characteristics, thus enabling improved detection capabilities and potential applications in various fields such as medical diagnostics and environmental monitoring.

Declarations

Conflict of Interest

We have conducted this research independently without any specific grant, sponsorship, or financial assistance from external sources. All expenses related to data collection, analysis, and publication have been covered by our institution or ourselves.

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A inform you that there is no external funding or financial support associated with the research presented in our paper titled “Absorption and Sensitivity Measurements of Noble Metals (Au, Ag, Cu) Thin Film Biosensor Based on SPR Simulation Characterizations” which is currently under consideration for publication in [Plasmonics].

Availability of data and materials

My manuscript titled” Absorption and Sensitivity Measurements of Noble Metals (Au, Ag, Cu) Thin Film Biosensor Based on SPR Simulation Characterizations” did not rely on any external data sources or datasets.

Ethics declarations:

Ethics Approval

Not applicable

Consent of participate

All the authors agreed to be involved in this research work

Consent for publication

All the authors have been permitted to publish the results

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Figures

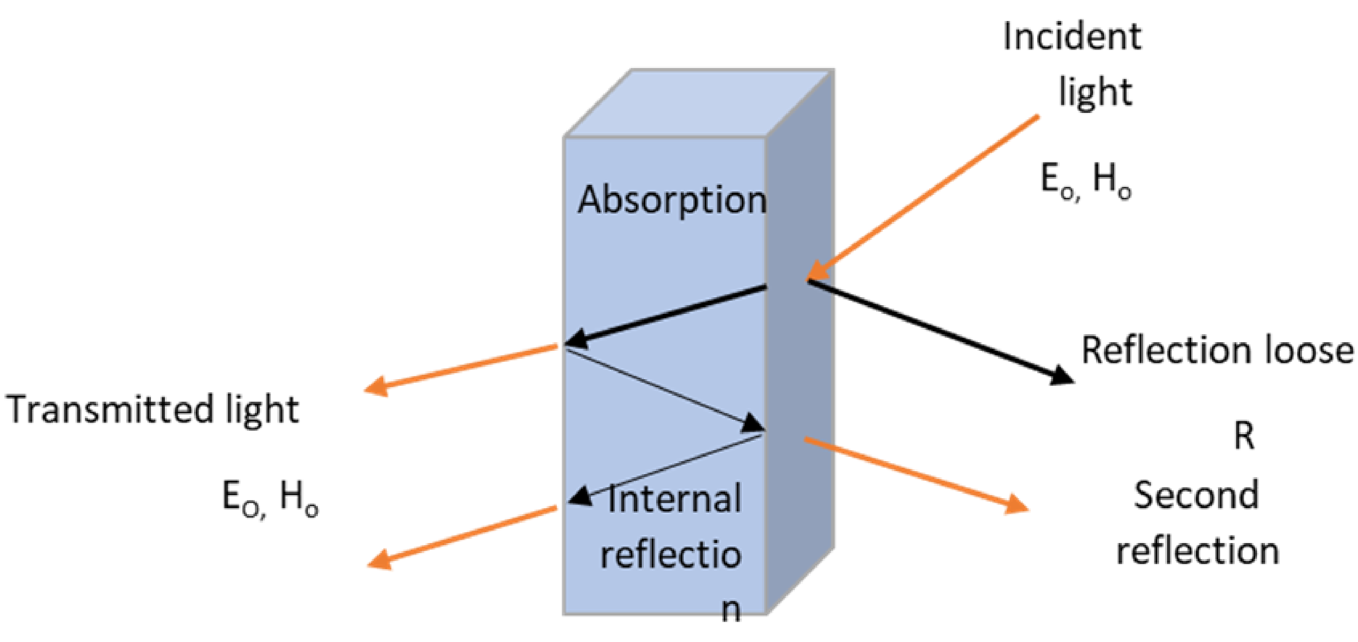

Figure 1

Incident wave on interface of tow media

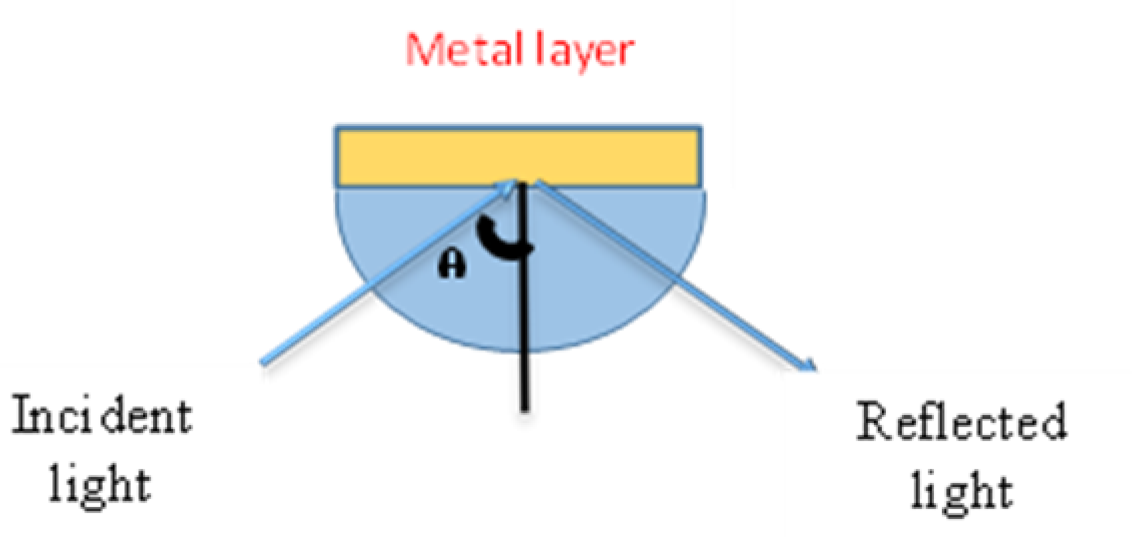

Figure 2

A metal layer deposited on a glass half sphere prism

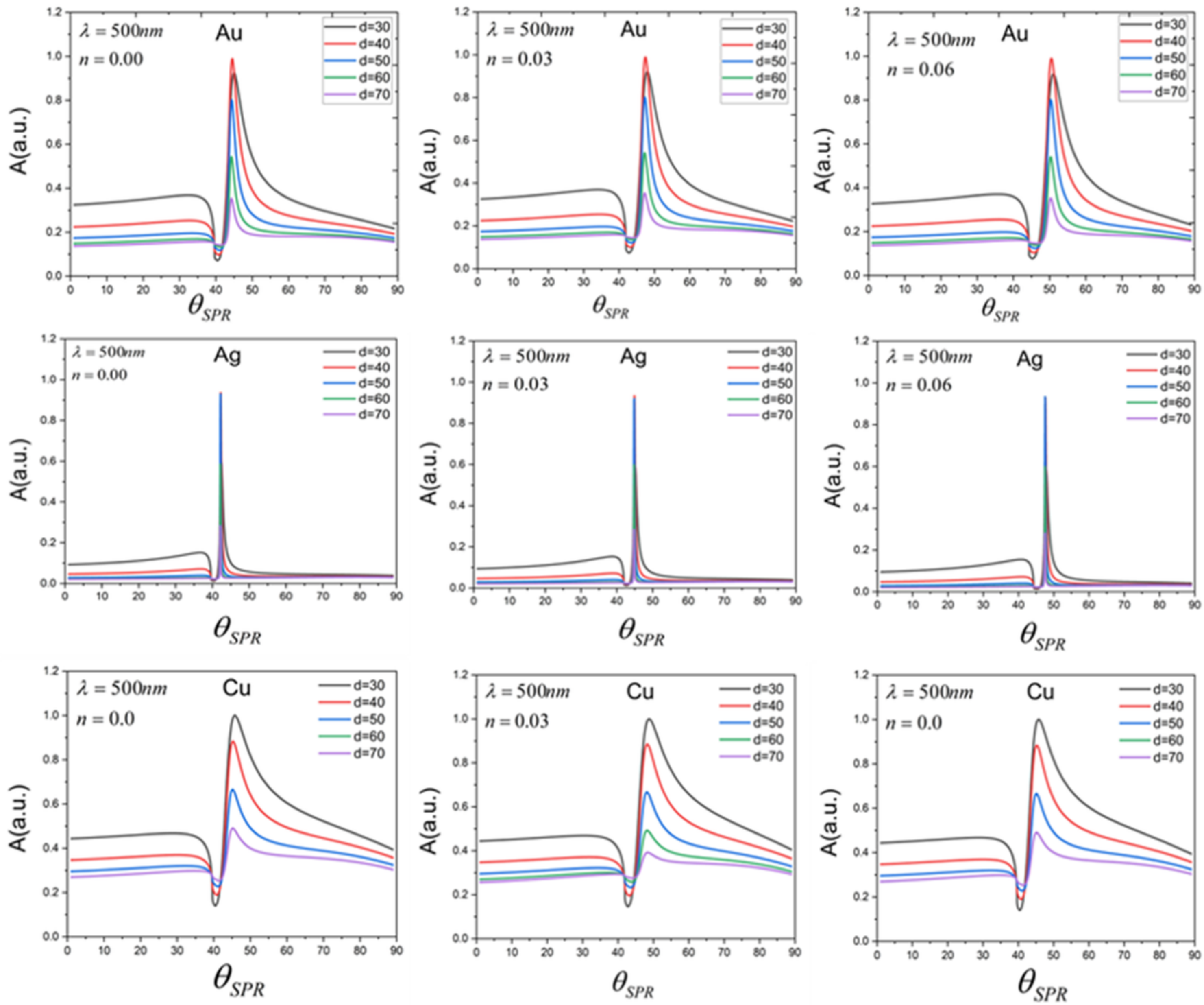

Figure 3

Absorption of gold (Au), silver (Ag), and cooper (cu) for light in wavelength (500 nm), Δn=0.0, 0.03, 0.06 with θSPR, the thickness of layers (30, 40, 50.60.70 nm)

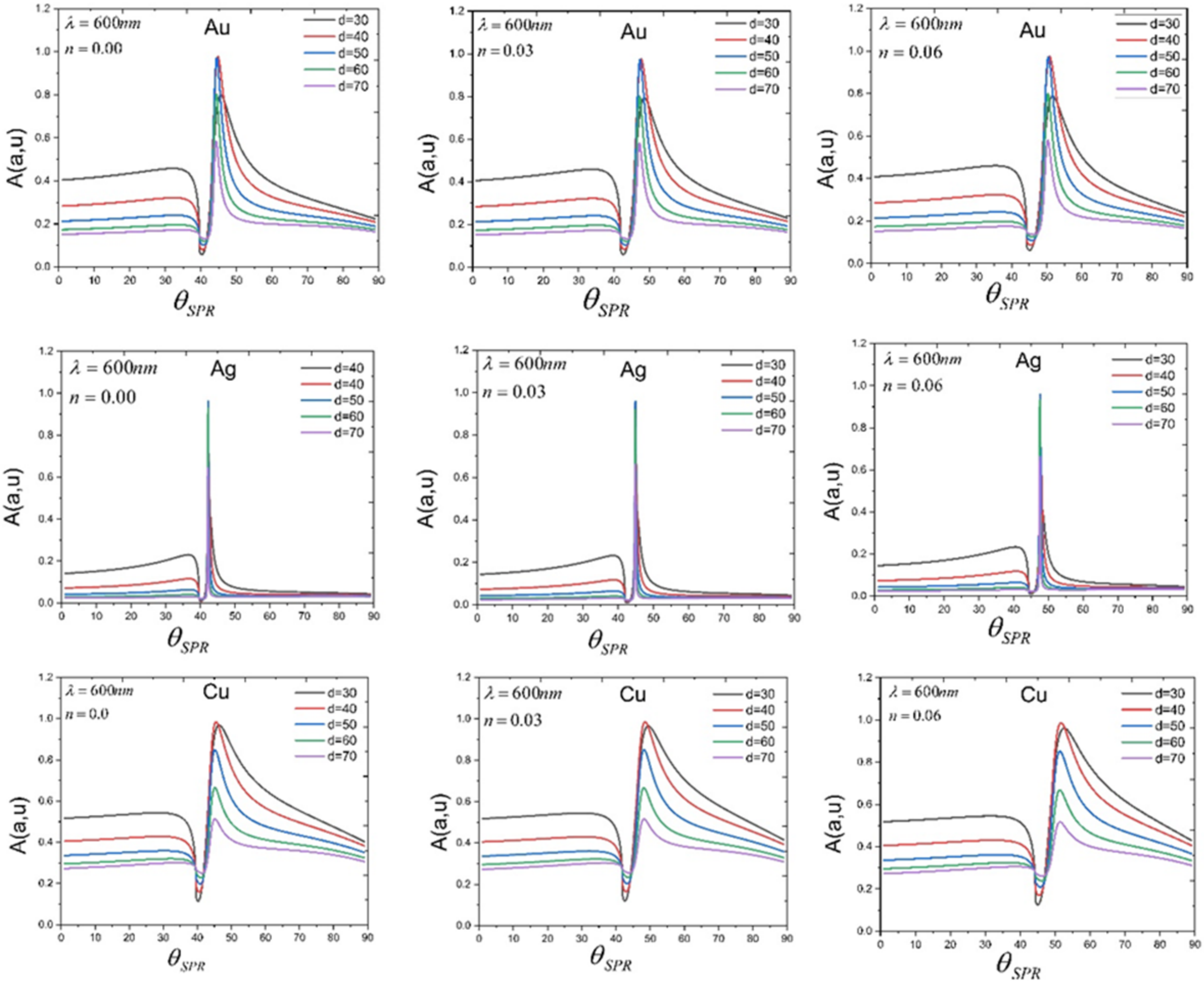

Figure 4

Absorption angel of (Au, Ag, Cu) for energy of light beam incident with wave length 600nm and Δn=0.0,0.03,0.06 for thickness d=30-70 nm