

Enhancement in Sensitivity of a Surface Plasmon Resonance Sensor with $\text{Al}_x\text{Ga}_{1-x}\text{As}$, 70% Al

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Abstract—The sensitivities of an aluminum gallium arsenide $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ -based surface plasmon resonance (SPR) sensor with gold (Au) and silver (Ag) layers are numerically analyzed and compared at 633 nm wavelength for different thicknesses of the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$. As the thickness of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ increases, the sensitivity of aluminum gallium arsenide $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ with a specific metal (Au or Ag) layer increases. Our calculations show that the sensitivities of the proposed sensors are 80.55% (Au film) and 34.74% (Ag film) higher than the conventional Au and Ag sensors successively. The aluminum gallium arsenide $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ -based SPR sensor has the advantages of high angular sensitivity, narrow resonance widths, and low minimum reflectance, making it a much better choice for biosensing applications.

1. INTRODUCTION

Surface plasmon resonance (SPR) is the resonant oscillation of conduction electrons at the interface between noble metal and dielectric stimulated by incident light [1, 2]. In 1980, the first demonstration of the surface plasmon resonance (SPR) as an optical sensor for the study of surface processes at metal surfaces for gas sensing occurred [3]. The potential of this technique is due to its very high sensitivity toward the change in refractive index of sensing medium.

In recent years, SPR sensors have been rapidly developed and applied in many fields such as fundamental biological studies [4–6], health science research [7, 8], drug discovery [9, 10], clinical diagnosis [11–13], environmental and food safety monitoring [14–18].

A commonly used structure for exciting SPR is based on the Kretschmann configuration based on attenuated total reflection (ATR): in which a thin metal film is coated on the base of a prism, and the other face of the metal touches the sensing medium [19, 20]. A gold transduction film is typically used to generate surface plasmon waves in SPR sensors due to its chemical stability and bio-affinity [21, 22]. However, silver displays superior optical properties over gold in the visible range and can provide a stronger enhancement of the evanescent field along the metal-dielectric interface [23, 24]. By using a silver sensing film, the sensitivity as well as signal-to-noise ratio of an SPR sensor can be enhanced. However, poor stability and bio-affinity of silver need to be ameliorated [25–27].

In this paper, a ternary semiconductor is introduced in an Au/Ag-based SPR biosensor. The aluminum gallium arsenide, $\text{Al}_x\text{Ga}_{1-x}\text{As}$, 70% Al, with large indirect band gap is often used in electronics and optoelectronics [28, 29]. In the experiments $\text{Al}_x\text{Ga}_{1-x}\text{As}$, 70% Al thin film was prepared by different methods onto several substrates: by pulsed laser deposition onto Si substrates [30] and by metal organic chemical vapor deposition [31].

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We believe that the proposed SPR biosensor is simple to realize and will open a new window for plasmonic sensors. The paper is organized as follows. Section 2 contains the necessary formula along with theoretical background of the proposed sensor. In Section 3, the obtained results are discussed and compared. A conclusion is drawn in Section 4.

2. THEORETICAL BACKGROUND

The schematic diagram of proposed sensor setup for the SPR is shown in Fig. 1. In the structure, we use BK7 glass as the coupling prism and a 47 nm of gold/51 nm of silver film as the noble metal for exciting SPP which is covered by a thin $\text{Al}_x\text{Ga}_{1-x}\text{As}$, 70% Al film (4 nm) and water as sensing medium. The working wavelength chosen in this paper is 633 nm He-Ne laser [32].

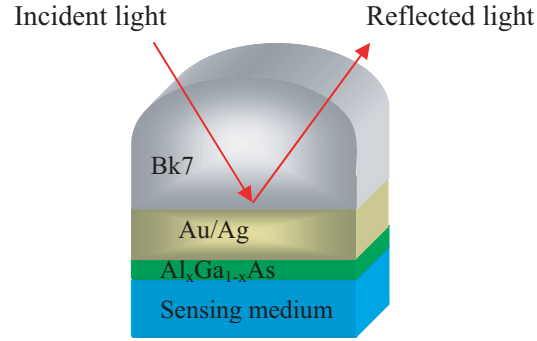


Figure 1. Schematic diagram of proposed sensors.

The BK7 glass refractive index can be calculated using the following equation [33]:

$$n^2(\lambda) = \frac{1.03961212\lambda^2}{\lambda^2 - 0.00600069867} + \frac{0.231792344\lambda^2}{\lambda^2 - 0.0200179144} + \frac{1.01046945}{\lambda^2 - 103.560653} + 1 \quad (1)$$

The complex dielectric function for Ag or Au can be expressed from the Drude model in the following form [34]:

$$\varepsilon(\lambda) = 1 - \frac{\lambda^2\lambda_c}{\lambda_p^2(\lambda_c + i\lambda)} \quad (2)$$

where λ_p is the plasma wavelength, and λ_c is the damping expressed as a wavelength. Their values are presented in Table 1.

Table 1. Parameters in Equation (2).

| λ_p (m) | λ_c (m) |
|----------------------------|-------------------------|
| Ag 1.4541×10^{-7} | 1.7614×10^{-5} |
| Au 1.6826×10^{-7} | 8.9342×10^{-6} |

The refractive index of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is given by [35]:

$$n^2(x, \lambda) = 10.906 - 2.92x + \frac{0.97501}{\lambda^2 - C} - 0.002467(1.41x + 1)\lambda^2 \quad (3)$$

where $C = (0.52886 - 0.735x)^2$ for $x \leq 0.36$, $C = (0.30386 - 0.105x)^2$ for $x \geq 0.36$.

The reflectance of the incident TM-polarized light of the proposed SPR sensor can be analyzed by the transfer matrix method (TMM) for an N-layer system [36]. The electric and magnetic field

amplitudes at the first boundary (E_1 and H_1) of this N-layer model are related to those at the last boundary (E_{N-1} and H_{N-1}) by:

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = M \begin{bmatrix} E_{N-1} \\ H_{N-1} \end{bmatrix} \quad (4)$$

where M is the total characteristic matrix and can be calculated by:

$$M_{ij} = \left(\prod_{k=2}^{N-1} M_k \right)_{ij}, \quad i, j = 1, 2 \quad (5)$$

$$M_k = \begin{bmatrix} \cos \beta_k & -i \sin \beta_k / q_k \\ -i q_k \sin \beta_k & \cos \beta_k \end{bmatrix} \quad (6)$$

where

$$q_k = \left(\frac{\mu_k}{\varepsilon_k} \right)^{1/2} \cos \theta_k = \frac{(\varepsilon_k - n_{pr}^2 \sin^2 \theta_1)^{1/2}}{\varepsilon_k} \quad (7)$$

And

$$\beta_k = d_k \frac{2\pi}{\lambda} (\varepsilon_k - n_{pr}^2 \sin^2 \theta_1)^{1/2} \quad (8)$$

where ε_k and d_k denote the dielectric constant and thickness of each layer in the N-layer structure; θ_k denotes the angle of light in each layer; and n_{pr} is the refractive index of prism.

The reflection coefficient can be expressed as

$$r_p = \frac{(M_{11} + M_{12}q_N)q_1 - (M_{21} + M_{22}q_N)}{(M_{11} + M_{12}q_N)q_1 + (M_{21} + M_{22}q_N)} \quad (9)$$

Therefore, the reflectance R_p is $R_p = |r_p|^2$.

The resonance angle θ_r is the incident angle corresponding to the minimum reflection. We shall evaluate the performance of the sensor in terms of three parameters:

- Angular sensitivity S_θ [37] is defined as the ratio of the resonance angle shift with respect to the variation of the refractive index in sensing medium:

$$S_\theta = \frac{\delta \theta_r}{\delta n} \quad (10)$$

- Detection accuracy (DA) is used to study the accuracy of the SPR sensor. For this the width and shape of the reflectance curve, particularly, in the vicinity of the minima of the curve need to be focused:

$$DA = \frac{1}{FWHM} \quad (11)$$

where $FWHM$ is the full width at half maximum of the reflectance dip ($\Delta\theta_{0.5}$).

- Figure of merit (FOM) is defined as the product of S_θ and DA [38]:

$$FOM = S_\theta \times DA$$

3. RESULTS AND DISCUSSION

In this work, we have theoretically investigated the sensitivity of the proposed SPR sensor with two different metal layers: gold and silver, by analyzing the optimized structure through reflection spectra. The sensing medium is water. The refractive index change $\delta n = 0.005$ RIU is assumed. The addition of $Al_xGa_{1-x}As$, 70% Al material between the metallic (Au or Ag) film and the sensing medium in the structure of sensors increases the angular sensitivities. There are several parameters of the SPR sensor that may affect the angular sensitivity; some important parameters are thickness and refractive index of different layers.

We have investigated the variation of reflectance with 4nm of aluminum gallium arsenide $Al_xGa_{1-x}As$, 70% Al. Due to the change in refractive index of the sensing medium, the SPR angle shifts toward higher angle of incidence as shown in Figs. 2(b) and (d).

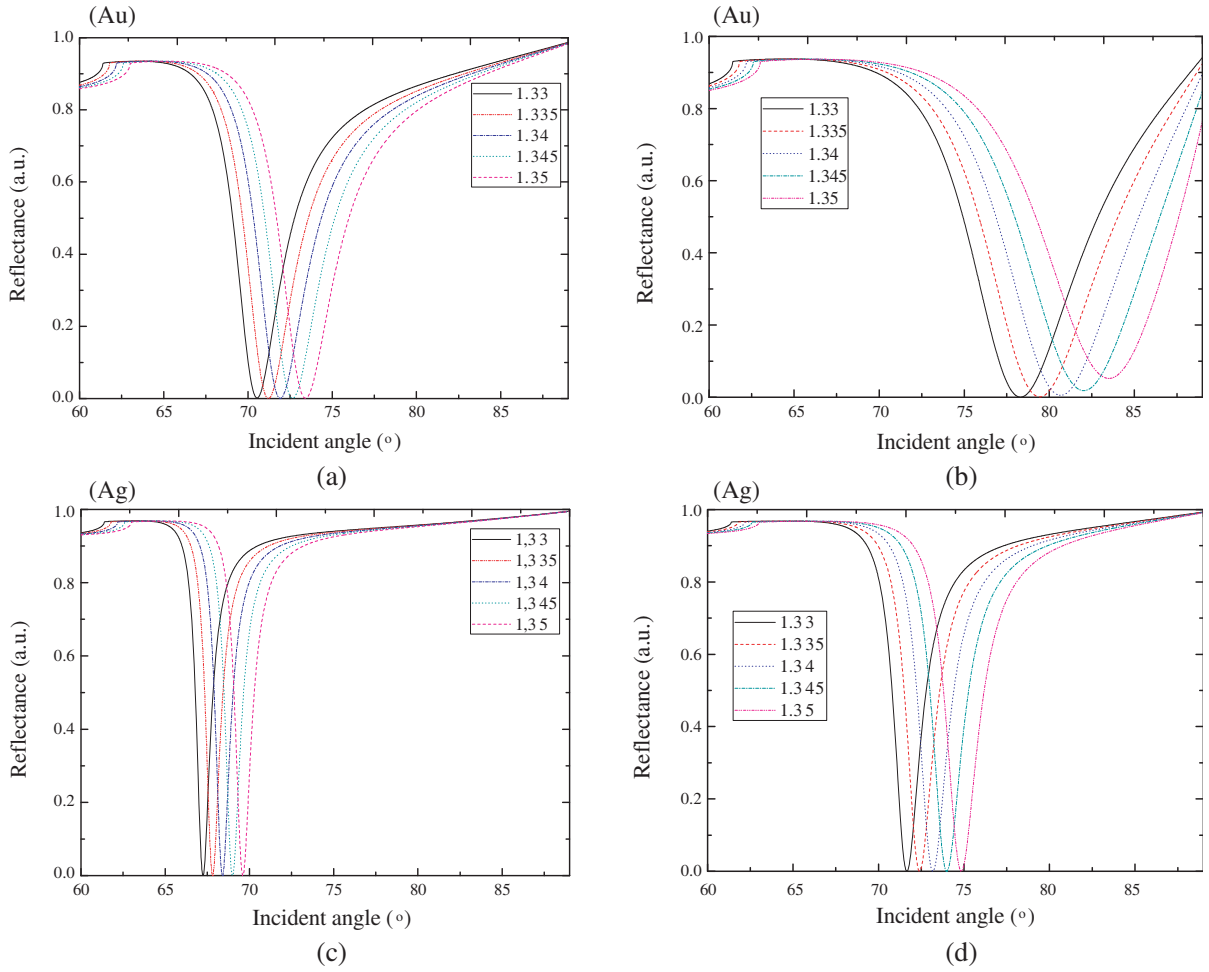


Figure 2. Variation of reflectivity with incident angles for (a), (c) the conventional sensor based on simplex Au or Ag film; and (b) (d) the proposed sensor with $\text{Al}_x\text{Ga}_{1-x}\text{As}$, 70% of Al on Au or Ag, respectively.

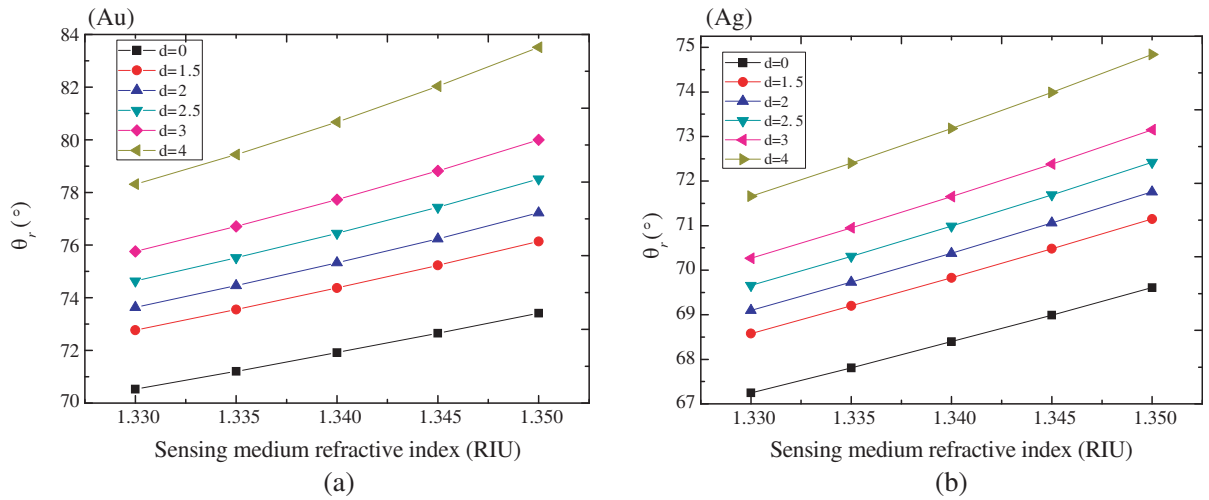


Figure 3. Resonance angle as a function of sensing medium refractive index for different $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer thicknesses on (a) Au and (b) Ag.

Figure 3 shows the variation of resonance angle versus the sensing medium refractive index for different $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer thicknesses on (a) Au and (b) Ag.

The changes of angular sensitivity for $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ on Au or Ag with different $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer thicknesses are plotted in Fig. 4. From the investigation, the sensitivity increases with thickness of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$, and it is obvious that the proposed structure leads to $260^\circ/\text{RIU}$ and $159^\circ/\text{RIU}$ for 4 nm thickness of the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer with gold and silver, respectively, which means an increase in sensitivity of 34.74% for structure with silver and 80.55% for structure with gold with only 4 nm of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$, clearly visible in Fig. 4.

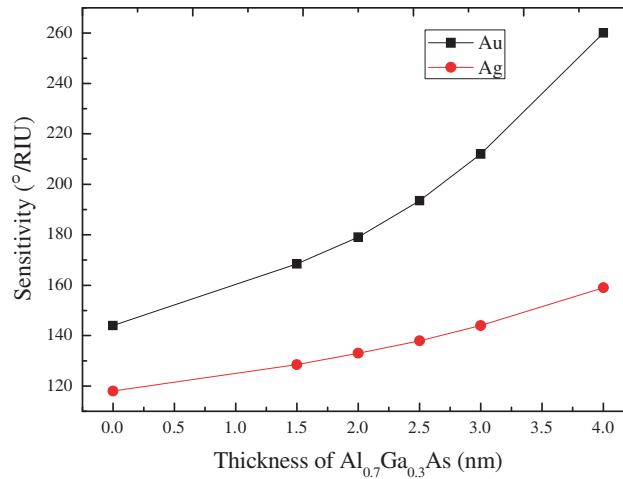


Figure 4. The sensitivity curve of proposed sensor for different thicknesses of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$.

Table 2 presents the change in thickness of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$, resonance angle (θ_r), minimum of angular reflectivity (R_r), angular sensitivity (S_θ), full width at half-maximum (FWHM), detection accuracy (DA), and figure of merit (FOM).

We are aware that an increase in angle sensitivity SPR sensor is accompanied by a reduction in

Table 2. The performance parameters of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ SPR sensor with Au and Ag.

| Metal | Thickness of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ (nm) | θ_r (°) | R_r (a.u.) | S_θ (°/RIU) | FWHM (degree) | DA (degree ⁻¹) | FOM (RIU ⁻¹) |
|-------|---|----------------|------------------------|--------------------|---------------|----------------------------|--------------------------|
| Au | 0 | 70.53 | 3.299×10^{-6} | 144 | 3.42 | 0.2923 | 42.09 |
| | 1.5 | 72.77 | 0.0003609 | 168.5 | 4.32 | 0.2314 | 38.99 |
| | 2 | 73.64 | 0.0001279 | 179 | 4.94 | 0.2024 | 36.22 |
| | 2.5 | 74.64 | 4.323×10^{-6} | 193.5 | 5.47 | 0.1828 | 35.37 |
| | 3 | 75.76 | 0.0004052 | 212 | 5.91 | 0.1692 | 35.87 |
| | 4 | 78.31 | 4.66×10^{-5} | 260 | 7.42 | 0.1347 | 35.04 |
| Ag | 0 | 67.25 | 5.799×10^{-5} | 118 | 0.95 | 1.0526 | 124.21 |
| | 1.5 | 68.58 | 1.654×10^{-5} | 128.5 | 1.32 | 0.7575 | 97.34 |
| | 2 | 69.1 | 3.268×10^{-5} | 133 | 1.41 | 0.7092 | 94.32 |
| | 2.5 | 69.66 | 2.743×10^{-5} | 138 | 1.58 | 0.6329 | 87.34 |
| | 3 | 70.27 | 3.477×10^{-5} | 144 | 1.67 | 0.5988 | 86.22 |
| | 4 | 71.66 | 9.493×10^{-6} | 159 | 1.87 | 0.5347 | 85.02 |

the figure of merit (FOM), but in $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ sensor with a gold layer, angle sensitivity increases by 80.55%. However, figure of merit (FOM) decreases only by 16.75%.

4. CONCLUSION

We have theoretically investigated the sensitivity of the proposed structure with two different metal layers, gold and silver, for different thicknesses of the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$. 4 nm thickness of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ between gold and sensing medium (water) leads to better result: the sensitivity increases by 80.55% with only 4 nm of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$, and the figure of merit (FOM) decreases only by 16.75%; Ag film covered by $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ enhances sensitivity of sensor by 34.74%.

We hope that these kinds of sensors will open a new window for several sensing applications: biochemical detection, environmental and medical diagnostic.

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