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Performance analysis of semiconductor based surface plasmon resonance structures

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ABSTRACT

In the present work, we have explored the field of surface plasmon resonance by analyzing the evanescent field enhancement, shift of resonance position and phase-jump using high index semiconductor prism material for three different nano-plasmonic structures namely, germanium–metal–analyte (GMA), germanium–silicon–metal–analyte (GSMA), germanium–metal–silicon–analyte (GMSA) in both visible and infrared wavelength region employing angular and wavelength interrogation modes. Differential phase and differential reflectance with change of refractive index of the sensing medium have also been discussed. Enhanced sensitivity and adequate dynamic range are other inevitable advantages offered by such configurations. Performance of these structures has been analyzed in terms of figure of merit and detection accuracy.

1. Introduction

Surface plasmon polaritons are the transverse magnetic (TM) surface electromagnetic excitations that exist on the interface between a plasmon generating metallic film and a dielectric medium having real-part of dielectric permittivity of opposite signs [1–3]. Using attenuated total reflection (ATR) coupler method surface plasmon resonance (SPR) can occur provided phase-matching condition is satisfied at the interface. Otto [4] and Kretschmann and Raether [5] proposed two well known prism-based configurations for SPR-measurement. Though surface plasmon waves propagate parallel to the plasmon generating metallic surface, they also extend evanescently into the adjacent dielectric medium. Hence small change of refractive index (RI) of the adjacent dielectric medium to the nano-metric metal surface can be measured using SPR phenomena with a high precision. This phenomenon makes them suitable for sensing applications. Hence basic purpose of many early researchers was to explore the vast field of plasmonic resonance phenomenon in nanostructures and the related applications to sensor technology [6–10].

There are many traditional sensing techniques for extracting information from SPR. In this paper, a novel analysis based on simulation has been used to depict the evanescent field enhancement, reflectance dip and phase-jump associated with SPR for semiconductor-prism material based structures. From shift of resonance position, change of evanescent field enhancement and sharpness of phase jump analysis across resonance position for p-polarized light, the change of refractive index of the sensing medium can be extracted. The presence of SPR enhances the evanescent field, minimizes the reflected light intensity and enhances the phase change at the metal–dielectric interface. Phase sensitive SPR study is also an emerging research area due to its significant contribution in sensing applications [11–13]. Phase interrogation based SPR sensor has higher detection resolution than that of intensity interrogation counterpart [14].

Previously both theoretical and experimental works have been carried out in the field of SPR-sensor [15–18]. Presently performance of the SPR-sensor has been analyzed with high refractive index semiconductor prism material (Ge) for three different nano-plasmonic structures namely, germanium–metal–analyte (GMA), germanium–silicon–metal–analyte (GSMA) and germanium–metal–silicon–analyte (GMSA).

2. Mathematical formulation

For general N-layer model shown in Fig. 1 for SPR measurement [19,20] tangential field at the first boundary $z = z_1 = 0$ is related to that at the final boundary $z = z_{N-1}$ by the characteristic matrix

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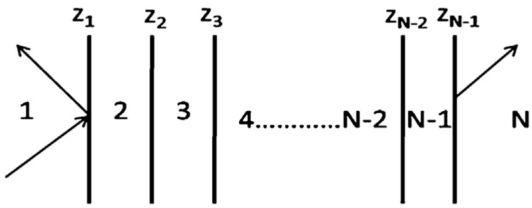

Fig. 1. N-layer model for SPR measurement.

$$M = \sum_{k=2}^{N-1} M_K = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{1}$$

$$\text{With} \quad M_K = \begin{bmatrix} \cos\beta_k & -i\sin\dfrac{\beta_k}{q_k} \\ -iq_k\sin\beta_k & \cos\beta_k \end{bmatrix} \tag{2}$$

where the phase factor is denoted by

$$\beta_k = \frac{2\pi d_k}{\lambda}\left(\varepsilon_k - n_1^2\sin^2\theta_1\right)^{1/2} \tag{3}$$

$$q_k = \frac{\left(\varepsilon_k - n_1^2\sin^2\theta_1\right)^{1/2}}{\varepsilon_k} \tag{4}$$

The reflection coefficient for TM wave is given by

$$r_p = \frac{(M_{11}+M_{12}q_N)q_1 - (M_{21}+M_{22}q_N)}{(M_{11}+M_{12}q_N)q_1 + (M_{21}+M_{22}q_N)} \tag{5}$$

And the reflectance is given by

$$R_p = \left|r_p\right|^2 \tag{6}$$

$$r_p = {R_p}^{1/2} e^{i\varphi_p} \tag{7}$$

When SPR occurs then reflectance at metal-dielectric interface acquires its minimum value which is always associated with a maximum of evanescent field. Transmission coefficient for magnetic field is

$$\left|t_H^p\right| = \frac{2q_1}{(M_{11}+M_{12}q_N)q_1 + (M_{21}+M_{22}q_N)} \tag{8}$$

As presented in Eq. (8), $\left|t_H^p\right|^2$ is the magnetic field enhancement factor of the evanescent wave. Transmission coefficient for the electric field is $t_E^p = (\mu_N/\mu_1)(n_1/n_N)t_H^p$ and with $\mu_N = \mu_1 = 1$, $t_E^p = (n_1/n_N)\,t_H^p$ and corresponding electric field enhancement factor is $\left|t_E^p\right|^2$.

Phase change associated with resonance is $\phi_p = \arg(r_p)$. To excite surface plasmons the wave vector of the incident light in the prism K_x^{PR} must phase-match with the wave vector of the surface plasmons at metal-dielectric interface K_x^{SP}. Hence resonance condition of the light in the prism with the surface plasmons at metal-dielectric interface is $K_x^{\mathrm{PR}} = K_x^{\mathrm{SP}}$.where,

$$K_x^{\mathrm{PR}} = \left(\frac{2\pi}{\lambda}\right)\sqrt{\varepsilon_1}\sin\theta_{\mathrm{res}} \tag{9}$$

and

$$K_x^{\mathrm{SP}} = \left(\frac{2\pi}{\lambda}\right)\left(\sqrt{\frac{\varepsilon_2\varepsilon_3}{\varepsilon_2+\varepsilon_3}}\right) \tag{10}$$

$\varepsilon_1, \varepsilon_2$ and ε_3 represent permittivity of coupling device, metal and dielectric sample respectively. θ_{res} is the resonance angle and λ is the wavelength of light used for surface plasmon excitation. From Fresnel's equation the reflection coefficient for p-polarized light is expressed as $r_p = \left|r_p\right| e^{i\varphi_p}$, and ϕ_p denotes phase for p-polarized light. When SPR occurs, phase angle changes very sharply across the resonance point. Small variation of refractive index of dielectric sample gives a remarkable change of amplitude reflection coefficient and phase factor for p-polarization only. As refractive index variation leads to change in SPR characteristics, this can be used to measure refractive index change.

3. Three-layer and four-layer structures under investigation

GMA, GSMA and GMSA structures have been schematically depicted in Fig. 2. For all these structures, high RI germanium prism has been considered as coupling device due to its higher sensing ability in Infrared (IR) wavelength region. Gold film having thickness 50 nm is used as excitation layer (GMA-structure). Additional semiconductor nanolayer of Silicon having thickness 10 nm is used as the protective layer over gold film to increase the stability of the system (GMSA-structure). As the thickness of semiconductor nanolayer (silicon) is less than that required to support the TM-guided mode, it is referred to as near-guided-wave SPR (NGWSPR)-configuration [21]. This semiconductor nanolayer is used to increase the electric field intensity over the metal-dielectric interface. When semiconductor nanolayer is located below Ge substrate (GSMA-structure) then overall performance of the system improves as discussed later.

As both GSMA and GMSA structures give satisfactory evanescent field enhancement at 900 nm as depicted in Fig. 3, further analysis of these structures has been carried out only at 900 nm wavelength.

4. Results and discussions

At resonance position of the SPR-sensor, a dip in reflectance or an enhancement of the evanescent field is always associated with a phase-jump. This phenomenon is potentially important because steep phase-jump across resonance position leads to improved detection sensitivity of the SPR-sensor [22].

Evanescent field enhancement and sharpness of phase-jump across resonance position is much higher for GSMA structure than GMSA structure as shown in Fig. 4. SPR angle is 11.99° for GSMA structures and 12.36° for GMSA structure with air as sensing medium. Hence due to presence of semiconductor nanolayer below the plasmon active metal surface (GMSA-structure) the resonance position gets shifted to higher angle of incidence and field enhancement factor become 295.5 units. Even when semiconductor nanolayer is swapped (GSMA-structure), the field enhancement factor increased to 457.5 units.

Another important performance criterion of a nano-plasmonic sensor is its dynamic range of operation which decides the maximum value of RI of the dielectric sample can be sensed by the SPR-sensor. In this nano-plasmonic structure high RI of the germanium substrate and additional silicon nano-layer is capable of sensing a much wider range of RI of the dielectric samples as evident from Fig. 5. GSMA structure can sense up to RI = 3.0 unit of the sensing layer but for GMSA structure reflectance dip, sharpness of phase-jump across resonance position decreases and full width at half maximum (FWHM) of the SPR curve increases for such high RI of the sensing layer.

4.1. *Effect of thickness of semiconductor nanolayer*

If we further investigate the effect of thickness of the semiconductor nanolayer, we find that as the thickness of semiconductor nanolayer increases the enhancement of evanescent field decreases and resonance position is shifted to higher angle of incidence for GMSA structure but for GSMA structure both resonance position and evanescent field enhancement remains almost same as