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Modelling and performance analysis of a plasmonic biosensor comprising of silicon and chalcogenide materials for detecting refractive index variations of hemoglobin in near infrared

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ABSTRACT

A plasmonic biosensor comprising of prism as a light coupling material, gold (Au) as a plasmon supporting metal and oxygenated native hemoglobin (Hb) solution as a bio sample operating under attenuated total reflection (ATR) mode has been modelled using the admittance loci method for detecting wavelength and concentration dependent refractive index (RI) variations of oxygenated native Hb solution for 700 nm to 900 nm wavelength in near infrared (NIR). Silicon (Si) and chalcogenide (2S2G) as high refractive index light coupling prism materials have been used in order to investigate their plasmonic biosensing performance in near infrared. The performance issues of the concerned plasmonic biosensor have also been discussed in terms of sensing parameters such as dynamic range, sensitivity, Full Width Half Maximum (FWHM).

1. Introduction

Surface plasmon resonance (SPR) is a widely used plasmonic based optical sensing technique for identification of small variations in refractive indices of various types of chemical/biological samples. Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection was observed by Otto [1]. Radiative decay of non-radiative surface plasmons excited by light was reported in [2]. Plasmonic based gas detection and biosensing was first explored by Liedberg et al. [3]. A comparative theoretical analysis on sensitivity of prism and grating coupler based SPR sensors in angular as well as in wavelength interrogation modes was demonstrated in [4]. A work on performance analysis of surface plasmon resonance based fibre optic sensor with different bimetallic nanoparticle alloy combinations have been reported [5]. The variation of refractive index of water with temperature and wavelength has been reported in [6].

As a well established optical multilayer thin film structure modelling technique, admittance loci method [7] can also be used for modelling prism based plasmonic structures [8,9]. A high performance plasmonic sensor requires materials like chalcogenide and silicon as light coupling prism materials for improved sensing in infrared [10–13]. Tuning and sensitivity enhancement issues of a prism based plasmonic sensor have been discussed in [14]. Concentration dependent refractive index of native hemoglobin in the wavelength range of 250–1100 nm using model function was calculated [15] and refractive index data of human hemoglobin in the visible range was detailed in [16]. Plasmonic based detection of hemoglobin concentration in human blood was demonstrated in [17].

Chalcogenide glass (chemical composition: $Ge_{20}Ga_5Sb_{10}S_{65}$ known as 2S2G) and silicon are very useful for SPR sensing due to their wide spectral transparency and high refractive index in comparison to conventional silica based glasses. In present work, gold metal has been chosen as a plasmon supporting metal due to some of its favourable SPR sensing features like chemical durability, highly resistant to oxidation and high sensitivity in comparison with other conventional plasmon supporting metals.

In this work, the admittance loci method has been used to model and analyze a prism based plasmonic biosensor operating under angular interrogation mode. Here the main emphasis is given on the silicon (Si) and chalcogenide (2S2G) light coupling prism materials in order to investigate their influence on plasmonic biosensing for detection of wavelength and concentration dependent refractive index (RI) variations of oxygenated native Hb solution from 700 nm to 900 nm wavelength in near infrared (NIR) light. The Hb solution

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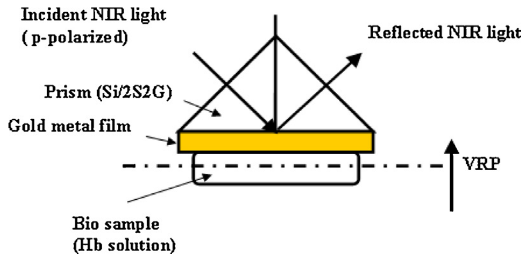

Fig. 1. An admittance loci based design structure of a plasmonic biosensor.

can be prepared from human erythrocytes including salts and other compounds as described in [15].

2. Theoretical Background

Admittance loci method is mainly used for designing multilayer thin film structures. Here we consider that a multilayer structure is already built up and a virtual reference plane (VRP) is moving continuously through the layers and the locus of admittance of the multilayer structure up to final destination is plotted. Such a plot is known as the admittance loci plot [7].

A plasmonic biosensor can be modelled using admittance loci method where the Virtual Reference Plane (VRP) moves from the sample and ends at the front surface (light coupling prism) of the plasmonic biosensor. Fig. 1 represents the structure of a plasmonic biosensor consisting of prism, gold metal film and bio sample with refractive indices represented by, byn_p, n_m and n_{sample} respectively.

The admittance of a three layer (prism-gold metal film-biosample) plasmonic biosensor is given by

$$Y = \frac{C}{B} = \frac{\eta_{sample}\cos\ \delta_m + i\eta_m \sin\ \delta_m}{\cos\ \delta_m + i(\eta_{sample}/\eta_m)\sin\ \delta_m} \quad (1)$$

The corresponding reflectance of a plasmonic biosensor can be written as

$$R = \left(\frac{\eta_p - Y}{\eta_p + Y}\right)\left(\frac{\eta_p - Y}{\eta_p + Y}\right)^* \quad (2)$$

where, η_p, η_m, η_{sample} are the admittances of prism, gold metal film and biosample respectively.

The surface plasmon resonance condition can be expressed as

$$Kn_p \sin\theta_{SPR} = K\sqrt{\frac{\varepsilon_{mr} n_{sample}^2}{\varepsilon_{mr} + n_{sample}^2}} \quad (3)$$

where, n_p is the refractive index of prism material, n_{sample} is the refractive index of the sample and ε_{mr} is the real part of dielectric constant of the metal. θ_{SPR} is the angle at corresponding to SPR dip position and K is the free space wave number.

In Eq. (3), the right hand side term is the real part of the SPW propagation constant and the term on the left hand side is the propagation constant of the p-polarized light incident at SPR angle through the light coupling prism. The matching of the propagation constants indicates the optical excitation of SPR.

The sensitivity of a plasmonic biosensor is given by [4]

$$S = \frac{d\theta_{SPR}}{dn_{sample}} = \frac{\left(\frac{\varepsilon_{mr}}{\varepsilon_{mr}+n_{sample}^2}\right)^{3/2}}{\sqrt{n_p^2 - \frac{\varepsilon_{mr} n_{sample}^2}{\varepsilon_{mr}+n_{sample}^2}}} \quad (4)$$

where, $d\theta_{SPR}$ is the small change in SPR angle corresponding to small change in bio sample refractive index, dn_{Sample}.

3. Results and discussion

3.1. Admittance loci based design simulations based on change in Hb concentration

Fig. 2(a) shows the admittance loci plot of a 3-layer plasmonic biosensor comprising of silicon (Si) prism-gold metal film-bio sample (Hb: Hb concentration of 5 g/dL and 30 g/dL) at 700 nm wavelength. For simulations, the refractive index dispersions of chalcogenide (2S2G), silicon prism materials were used from [13] and expression of complex dielectric constant of gold metal was used from literature [5]. The biosample considered in this work is Hb solution having wavelength dependent refractive index values calculated using model function as mentioned in [15].

From Fig. 2(a) it can be explained that for Hb concentration of 5 g/dL, the starting admittance for the gold film is on the imaginary axis; the locus point moves from 3.501i on imaginary axis corresponding to gold film thickness of 0 nm and ends at 3.684 (which is close to refractive index of Si, which is 3.6881 at 700 nm wavelength) on real axis corresponding to gold film thickness of 49.8 nm for an angle of incidence of 22.51°. It also corresponds to near-zero reflectance for that particular angle of incidence and gold metal film thickness. If this locus would have intercepted the real axis of the admittance diagram exactly at the refractive index of the prism material, the excitation of surface plasmons would have been achieved with maximum efficiency.

Similarly, Fig. 2(b) shows the admittance loci plots for 2S2G prism material with Hb concentrations of 5 g/dL and 30 g/dL at 700 nm wavelength. The calculated values of refractive index, admittances, angle of incidence, optimized gold metal film thickness for Si and 2S2G prism materials with Hb concentrations of 5 g/dL and 30 g/dL at 700 nm wavelength are tabulated in Table 1. In all these cases, the gold metal film thickness has been optimized for each prism material and each Hb concentration values in order to ensure that the respective admittance loci end with real admittance value close to the value of refractive index of the prism material, which indicates the most efficient excitation of SPR.

3.2. Admittance loci based design simulations based on wavelength variation

Fig. 3(a) and (b) shows the admittance loci plots for Si and 2S2G prism material with Hb concentrations of 15 g/dL at 700 nm and 900 nm wavelength. The calculated values of refractive index, admittances, angle of incidence, optimized gold metal film thickness for Si and 2S2G prism materials with Hb concentrations of 15 g/dL at 700 nm and 900 nm wavelength are tabulated in Table 2. In all these cases, the gold metal film thickness has been optimized for each prism material and each wavelength in order to ensure the most efficient excitation of SPR.

3.3. Angular interrogation SPR sensing curves based on change in Hb concentration

Fig. 4(a) shows the SPR sensing curves for Si and 2S2G prism materials with optimized gold metal film thicknesses (as tabulated in Table 1) at 700 nm wavelength. From this plot it can be concluded that Si displays narrower SPR sensing curves than 2S2G and SPR occurs at lower incident angle with increase in prism material refractive index. Also as the Hb concentration increases from 5 g/dL to 30 g/dL, SPR dips shift towards higher value of incident angle for both prism materials considered.

Fig. 4(b) shows SPR dip position vs. Hb concentration plot for Si and 2S2G prism materials with fixed gold metal film thickness of 50 nm at 700 nm wavelength. It is seen that SPR dip position values are higher for 2S2G and lower for Si and also SPR dip position values