Int. J. Nanoelectronics and Materials **10** (2017) 149-158

Surface plasmon resonance sensor sensitivity enhancement using gold-dielectric material

S. Fouad[1*], Naseer Sabri[2], Z. A. Z. Jamal[3,] P. Poopalan[4]

[1,3,4]*School of Microelectronic Engineering, Photonics Engineering, University Malaysia Perlis (UniMAP)*
[2] *School of Computer and Communication Engineering, University Malaysia Perlis (UniMAP)*

Received 17 May 2016; Revised 10 Jun 2016; Accepted 15 Jun 2016

Abstract

There has been increasing interest in the field of surface plasmon resonance sensing technology according to its advantages such as the small amount of sensing samples required, freedom of electromagnetic interference and greater sensitivity. This research investigates the using of a thin layer of dielectric material such as Barium Titanate ($BaTio_3$) over the Gold (Au) layer for enhancing the sensitivity of the surface plasmon resonance sensor based phase interrogation technique. $BaTio_3$ is adopted due to its excellent dielectric properties such as high dielectric constant and low dielectric loss. Numerical results have demonstrated that the surface plasmon resonance sensor with utilizing a thin layer of the BaTio3 layer (5nm) over a fixed Au layer thickness of (50nm) exhibited a high sensitivity of (250 degree/RIU) among other thickness values of $BaTio_3$. Contrarily, the comparison of the surface plasmon resonance sensor without utilizing $BaTio_3$ layer provides (160 degree/RIU) for fixed Au layer thickness (50nm). Hence, using of 5mm thin layer of BaTio3 over 50nm of Au layer within surface Plasmon layer yield higher sensitivity of 250 (degree/RIU).

Keywords: Surface plasmon resonance sensor, Au layer, $BaTio_3$ layer, Phase interrogation technique

1. Introduction

The surface Plasmon resonance (SPR) phenomenon is known as the resonance excitation of the surface Plasmon wave by exponentially decaying evanescent field of the incident p-polarized light. It takes place when the frequency of the incident light matches the frequency of the surface Plasmon wave; under this, the resonance condition is satisfied [1-4]. This phenomenon has been widely used in various fields such as sensor technology, nonlinear optics, spectroscopy, optical modulators and microscopy [5-6] [1]. During the last three decades, there has been an interest in the field surface Plasmon resonance sensing technology according to its advantages like high sensitivity, real time and high detection accuracy [7] [4]. One of the most important parameters that affects the performance of SPR sensor is the detection sensitivity because it will determine the ability of the sensor in

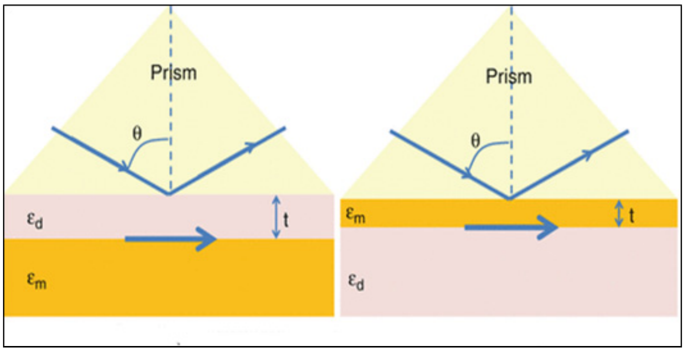
[*]) For Correspondence, Tel: 018-4010972, E-mail: huwaid96@yahoo.com.

detection the sample type and its concentration [8]. High sensitivity is attained by achieving a large shift of resonance angle (in phase interrogation) or resonance wavelength (in wavelength interrogation) with a small change of sample parameters like (refractive index, thickness and concentration) [9].

Many studies have been carried out to improve the sensitivity of SPR sensor by utilizing an additional layer of semiconductor, dielectric or metamaterial. Sharmila et al. (2015) worked on an analysis of silicon to enhance the SPR sensor performance. They used an additional silicon nano-layer to increase the stability and sensitivity, which enhances the evanescent field near the metal-sample interface in comparison with conventional SPR sensor [1]. Metamaterial has been exploited to enhance the detection accuracy of SPR sensor, this is done by Sarika et al. (2015), on the other hand, the sensitivity of SPR sensor based on metamaterial was still lower compared to the SPR sensor based on an additional dielectric layer [2]. Other researchers were focused on sensitivity enhancement of SPR sensor by using an additional layer of oxides based on interrogation technique, this work was reported by Sarika et al (2013). Besides the sensitivity enhancement, this oxide layeris also used as a protection layer for the metallic thin film from oxidation [3]. The semiconductor (Zno) thin layer was utilized as a protection layer, besides the performance of SPR sensor was also improved as presented in [4]. In this paper, we demonstrate that, by using thin film dielectric material Ba Tio_3, the SPR sensor can exhibit high sensitivity due to its excellent dielectric properties compared to conventional SPR sensor (without using this dielectric material) in which only Au layer is used.

2. Surface plasmon resonance sensor theory concepts

For SPR sensor, Attenuated Total Reflection (ATR) coupler method has been used for resonance excitation of surface Plasmon wave by exponentially decaying evanescent field of the incident P-polarized light. This method has two configurations as illustrated in Fig. 1. One is an Otto configuration in which the sensing medium whose dielectric constant ε_d is kept between the prism and the metallic layer with dielectric constant ε_m like Au or Ag for supporting the surface Plasmon wave. If the light beam is incident with an angle (Θ) larger than the critical angle, such that total internal reflection occurs at the prism/sensing medium interface. The evanescent fields of the total internal reflection wave tunnel through the sensing medium layer and excite propagating surface plasmon wave at the sensing medium/metal interface. The sensing medium slit should be only about 1 μm wide, and for this reason, the Otto geometry has not been widely explored in SPR sensing. The other type is Kretschmann type in which a thin metallic layer with dielectric constant ε_m is deposited directly on the base of high dielectric constant prism ε_0, the sensing medium (sample) whose dielectric constant ε_d is to be determined is kept in contact with the metallic layer. The light beam again illuminates the prism at an incident angle (Θ) larger than the critical angle, such that total internal reflection occurs at the prism/metal interface. The evanescent wave of the total internal reflection penetrates through the metal layer and excites propagating surface plasmon wave at the metal/sensing medium interface. This configuration is used in most practical applications because no need to control the sensing medium gap in comparison with Otto type [10-11].



(a) (b)

Fig. 1: Surface Plasmon Sensor Configuration (a) Otto type (b) Kretschmann Type

When the wave vector of P-polarized incident light matches the wave vector of the surface Plasmon wave, which propagates along the metal-sensing medium interface, the resonance condition is satisfied given by Eq. (1):

$$K = K_{sp} \tag{1}$$

where the incident wave light vector is a K and the surface Plasmon wave vector is K_{sp}

$$K = \frac{2\pi}{\lambda} n_p \times sin\left(\theta_{in}\right) \tag{2}$$

$$K_{sp} = \frac{2\pi}{\lambda} \times \sqrt{\frac{\varepsilon_1 \times \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \tag{3}$$

where λ is the wavelength of the incident light, n_p is the refractive index of the prism, θ_{in} is the incident angle of the laser beam at the prism-metal interface and ε_1, ε_2 are the dielectric constants of metal and sensing medium (dielectric) respectively [5].

There are many parameters that determine the resonance condition like wavelength of the incident light, incident angle, and the refractive index of both of the metal as well as the sensing medium (dielectric). Under this condition, the incident angle is known as resonance angle [4].

The P-polarized light is incident on the prism-metal interface at known incident angle and reflected according to the total internal reflection theory; the reflectivity of the light is measured by using optical detector. Based on Phase Interrogation mode, the reflected light is measured as a function of incident angle with fixed incident light's wavelength while depending on the Wavelength Interrogation mode, the reflected light is measured as a function of incident light 's wavelength with fixed incident angle. A sharp dip is observed at the resonance angle in the Phase Interrogation mode or resonance wavelength in Wavelength Interrogation mode. The refractive index of the sensing medium (sample) can be determined by knowing the resonance angle [10].

3. The proposed surface plasmon resonance sensor

The proposed SPR sensor with utilizing dielectric material (BaTio3) is shown in Fig. 2. It consists of four layers; the first one is BK7 dielectric prism for achieving the resonance matching between the incident wave and SP wave that's its refractive index depends on the wavelength of the incident light due to dispersion relation.

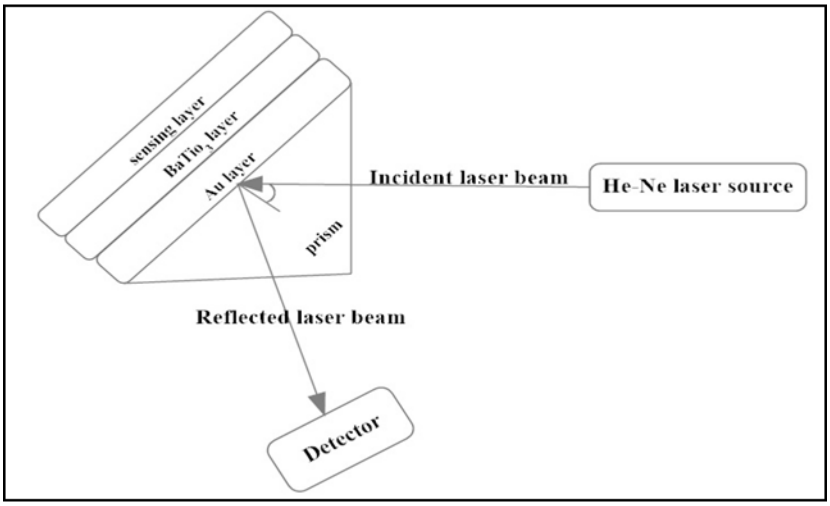


Fig.2: The proposed SPR sensor configuration.

It is followed by Au thin film metallic layer for supporting the surface plasmon wave at the metal-dielectric wave whose dielectric constant also depends on the wavelength according to Drude model. This metal layer is covered with a BA Tio3 dielectric layer to enhance the performance of SPR sensor. It is in contact with the sensing medium, which has a refractive index within range (1.338-1.348) RIU.

It is necessary to utilize the laser source for establishing the resonance condition, He Ne laser with wavelength 632.8 nm is proposed in this setup. Any small change within the dielectric constant of the sensing medium will cause a large shift with SPR curve (the reflectivity of the laser beam as a function of incident angle) this means large changing of the resonance angle thus increasing the sensitivity of the SPR sensor.

$$S = \frac{\Delta\theta_{res}}{\Delta n} = \frac{\theta_{res2} - \theta_{res1}}{n_2 - n_1} \tag{4}$$

where $\Delta\theta_{res}$ is the change in resonance angle based on phase interrogation and Δn is the change of refractive index. The detector is used to obtain the SPR curve from measuring the intensity of the reflected laser beam as a function of incident angle. The minimum reflectivity of SPR curve θ_{res} and λ_{res} based on the phase and wavelength interrogation respectively as illustrated in Fig. 3. The shift from λ_{res1} to λ_{res2}, or from θ_{res1} to θ_{res2} according to the change in refractive index of the sensing medium by using the phase and wavelength interrogation respectively. The summation of the two values CR and CL from the curve determine the full width at half maximum parameter of the sensor.

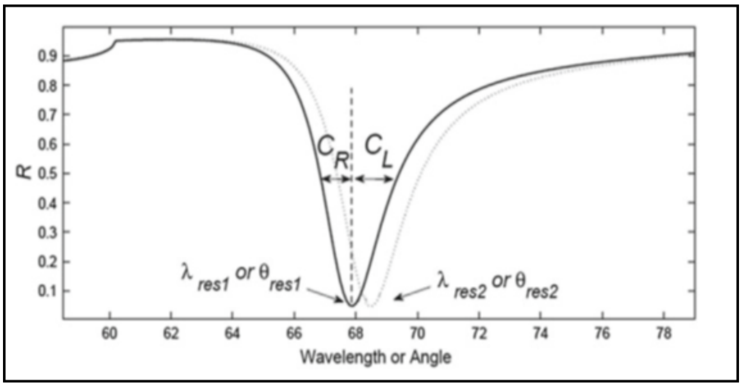


Fig. 3: Surface Plasmon resonance sensor curve [12].

In order to obtain an expression for radiate properties such as reflectance and transmittance of the multilayer, as in the Kretschmann configuration, there are three methods: the field tracing method, the resultant wave method and the transfer matrix method. Among these methods, the transfer matrix method is considered more accurate as it contains no approximations.

For each layer, the phase shift and the admittance should be found in order to compute the transfer matrix as follows:

$$\beta_j = \frac{2\pi}{\lambda} d_j \sqrt{n_j^2 - (n_p \sin(\theta_{in}))^2} \tag{5}$$

$$q_j = \frac{\sqrt{n_j^2 - (n_p \sin(\theta_{in}))^2}}{n_j^2} \tag{6}$$

where: q_j the admittance, β_j the phase shift, n_j refractive index and d_j the thickness of layer j respectively. The reflective index of the prism and the incident angle of the prism-metal interface are n_p and θ_{in} respectively [13].

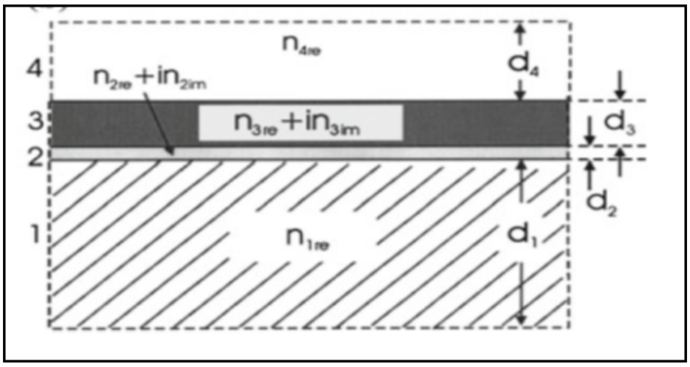


Fig.4: The proposed sensor layers architecture [12].

Fig. 4 illustrates the structure of the four layers surface plasmon sensor where several reflections resulting at the each interface of the layers according to the incident light at prism–first layer interface, the accumulation of those reflections must consider all for computing overall reflection/transmission computations. For a propagating wave through medium j towards medium j + 1 is described by the transfer matrix as shown in Eq. (7):

$$M_j = \begin{bmatrix} \cos(\beta_j) & -i\sin(\beta_j)/q_j \\ -iq_j\sin(\beta_j) & \cos(\beta_j) \end{bmatrix} \quad (7)$$

The overall transfer matrix of multilayer is calculated as a function of the transfer matrix M_j for each layer, described as:

$$M_{tot} = \prod_{j=2}^{m-1} \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (8)$$

For a multilayer architecture consists of m layers, the total reflection R and the transmission coefficients T are derived from:

$$R = \frac{(m_{11} + m_{12}q_m)q_1 - (m_{21} + m_{22}q_m)}{(m_{11} + m_{12}q_m)q_1 + (m_{21} + m_{22}q_m)} \quad (9)$$

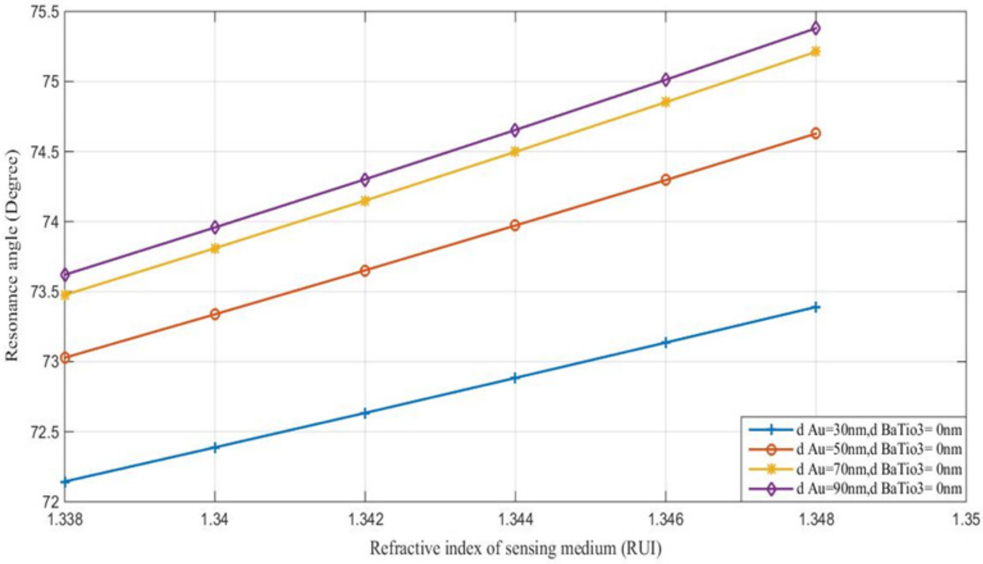
$$T = \frac{2q_m}{(m_{11} + m_{12}q_m)q_1 + (m_{21} + m_{22}q_m)} \quad (10)$$

4. Numerical results and discussion

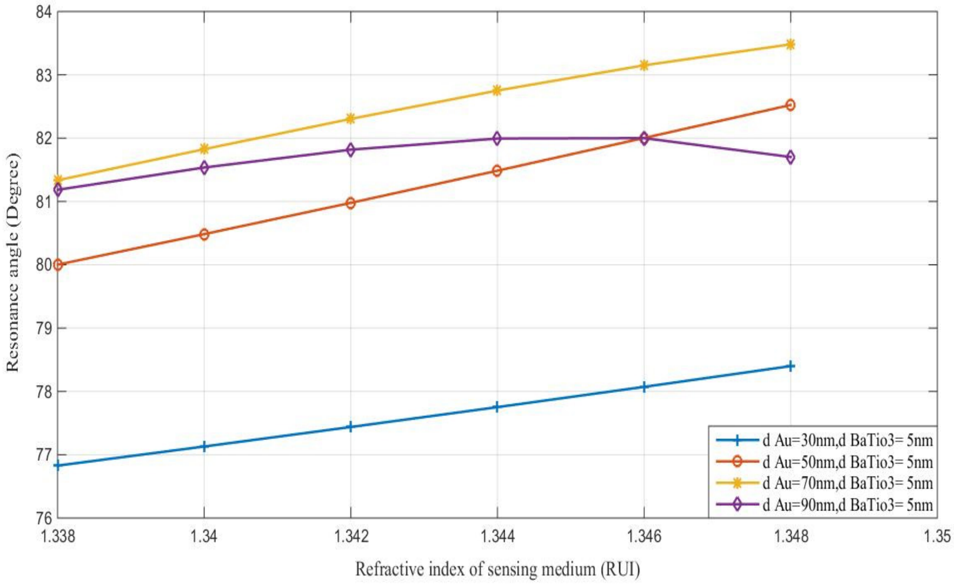
A transfer matrix method is used to study the performance of the SPR sensor without using $BaTio_3$ in compared with utilizing $BaTio_3$ layer based Mat lab software. The He-Ne laser with wavelength 633nm was chosen as an excitation source, the optical properties of the layers as shown in Table 1, where the refractive index and extinction coefficients are depend on the operating wavelength due to the dispersion relation while the thickness of the layers has been selected for optimum performance. For a sensing medium, the refractive index varies from 1.338 to 1.348 RIU (in steps 0.002).

Table 1: The optical properties of materials at 633 nm wavelength of light [14-15].

Material	Refractive index (n)	Extinction coefficient (k)	Thickness
BK 7 prism	1.515	0	25 mm
Au layer	0.183	3.431	30-90 nm
$BaTio_3$ layer	2.4043	0	5 nm
Sensing medium	1.338-1.348	0	∞



(a)



(b)

Fig. 5: SPR sensor's resonance angle disparities versus refractive index of sensing medium of various Au layer thickness (30nm,50nm,70nm and 90nm) of (a) 0nm and (b) 5nm thickness of $BaTio_3$ layers.

Fig.5a shows that the resonance angles for each Au layer thickness of rose proportionally with a value of refractive index sensing medium. This can be explained by Eq. (1): by increasing the refractive index of sensing medium for different thick Au layers, the real part of wave vector of the surface plasmon wave (K_{sp}) also increases, which in turn the resonance angle at which the resonance condition is satisfied. On the other hand, the thickness of the Au layer also contributes to establishing the resonance condition at which the resonance angle is happening, because changing its thickness from 30 nm to 90 nm (in step 20nm) leads to changes in dielectric constant of this layer. Fig.5b: illustrates the variation of the resonance angle with refractive index of the sensing medium for 30nm, 50nm, 70nm and 90nm Au layers with preset 5nm thick $BaTio_3$ layer.

As well as, for each thickness of Au and $BaTio_3$ the resonance angle increases with the increasing in refractive index of sensing medium. Where the BaTio3 layer with thickness 5nm comes in contact with the Au layer, which leads to changes in the surface Plasmon wave propagation real part constant of the wave vector and thus increases the resonance angle of the proposed SPR sensor. Fig.6. shows the variations of sensitivity of SPR sensor with a thickness of the metallic layer Au for fixed 0nm and 5nm thick $BaTio_3$ layer. It is clear from this figure,in the fixed gold layer range from 30nm to 70nm, the sensitivity of sensor with $BaTio_3$ layer is higher compared to the sensitivity of sensor without $BaTio_3$ layer . This isdue to the large shift of resonance angle within a small change of refractive index of sensing medium, which causes high sensitivity of the sensor,where the thickness of this layer is selected for achieving higher performance of SPR sensor. It can be viewed from Table 2 that, for Au layer with 50nm thickness, the sensitivity of SPR sensor (without $BaTio_3$ layer) increases from 160 (degree/RIU), to 250 (degree/RIU) when $BaTio_3$ layer of 5nm thickness is applied to the Plasmon resonesensor.

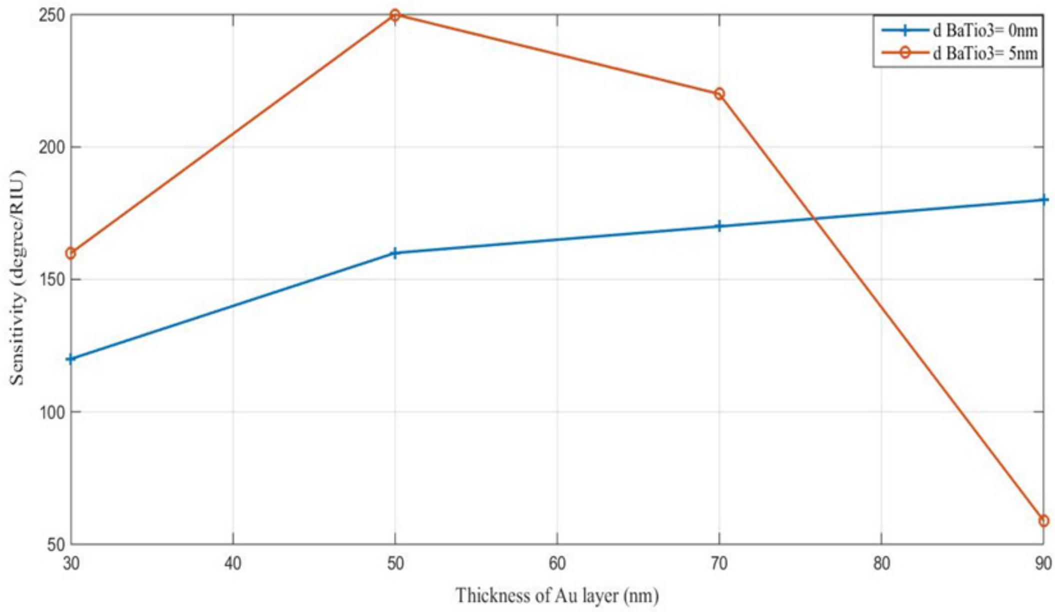


Fig. 6: SPR sensor sensitivity variation against metallic layer Au thickness in $BaTio_3$ thickness values (0n and 5nm).

Table 2: The sensitivity of SPR sensor comparison for various thickness of Au layer for fixed $BaTio_3$ layer thickness

Thickness of BaTio3 layer (nm)	**Sensitivity (degree/RIU)**			
	Thickness of Au layer (nm)			
	30	**50**	**70**	**90**
0 (without layer)	120	160	170	180
5	160	250	220	59

5. Conclusion

In this paper, a thin layer of dielectric material $BaTio_3$ is utilized. This layer is added over the Au layer of the Plasmon resonance sensor. The numerical results have demonstrated that a 5 nm thickness of this dielectric material is able to enhance the sensitivity of the SPR sensor without $BaTio_3$ from 160 (degree/RIU) to 250 (degree/RIU) when $BaTio_3$ layer with 5nm thickness is applied over the fixed Au layer of 50nm thickness. The theoretical analysis is based on the phase interrogation technique. $BaTio_3$ is used due to its high dielectric constant, which provide large shift in resonance angle of the SPR curve within a small change in the refractive index sample, thus high sensitivity can be investigated.

References

[1] Sharmila Ghosh and Mina Ray. "Analysis of silicon based surface Plasmon Resonance Sensors with different amino acids", Silicon. **7** (2015) 313-322

[2] Sarika PAL, Y.K.Prajapati, J.P.Saini, and V.Singh. "Resolution enhancement of optical surface Plasmon resonance sensor using metamaterial", photonic sensors. **5** (2015) 330-338

[3] Sarika Singh, Satyendra K. Mishra and Banshi D. Gupta. "Sensitivity enhancement of a surface plasmon resonance based fibre optic refractive index sensor utilizing an additional layer of oxides", Sensors and Actuators A. **193** (2013) 136– 140

[4] Sarika Shukla, Navneet K. Sharma and Vivek Sajal. "Sensitivity enhancement of a surface plasmon resonance based fiber optic sensor using ZnO thin film: a theoretical study", Sensors and Actuators B. **206** (2015) 463–470

[5] Trianjita Srivastava, Ritwick Das and Rajan Jha. "Highly accurate and sensitive surface Plasmon resonance sensor based on channel photonic crystal waveguides", Sensors and Actuators B. **157** (2011) 246–252

[6] W.M.Robertson and M.S.May. "Surface electromagnetic wave excitation on one-dimensional photonic band-gap arrays",Applied physics letters. **74** (1999) 1800-1802

[7] Wei Su, Gaige Zheng and Xiangyin Li. "A resonance wavelength easy tunable photonic crystal biosensor using surface Plasmon resonance effect", optic. **124** (2013) 5161-5163

[8] Fang Wang et al. "Sensitive surface Plasmon resonance biosensor based on a photonic crystal and bimetallic configuration", IEEE conference. (2014) 117-118

[9] Jir'ı´ Homola , Sinclair S. Yee and Gu¨ nter Gauglitz. "Surface plasmon resonance sensors: review", Sensors and Actuators B. **54** (1999) 3–15

[10] Pradeep Kumar Maharana, Rajan Jha and Srikanta Palei. "Sensitivity enhancement by air mediated graphene multilayer based surface plasmon resonance biosensor for near infrared", Sensors and Actuators B **190** (2014) 494– 501

[11] Masahiro Yamamoto. "Surface Plasmon Resonance (SPR) Theory: Tutorial", Kyoto-Daigaku-Katsura, Nishikyo-ku (2008) 615-8510

[12] Leiva Casemiro Oliveira, et al. "Surface Plasmon Resonance Sensors A Materials Guide to Design and Optimization",Springer. (2014)

[13] Jose Luis and Faramarz Farahi. "Handbook of optical sensors" (2014)

[14] Internet source. "Refractive index.info=refractive index data base"

[15] Alwan M. Alwan1, Narges Z. Abdulzahra, N. M. Ahmed and N. H. A. Halim. "Influence of rapid thermal oxidation process on the optoelectronic characteristics of PSI devices" Int. J. Nanoelectronics and Materials **8** (2015) 61-68