CHAPTER-3

SURFACE PLASMON RESONANCE BASED SENSORS
WITH SEMICONDUCTOR PRISM-MATERIALS FOR
SENSING AT INFRARED-WAVELENGTH REGION

3.1 Introduction

As discussed in chapter 1, small change of refractive index (RI) of the dielectric medium adjacent to the nano-metric metal surface can be measured with a high precision using SPR phenomenon. 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 [38-40].

There are many traditional sensing techniques for extracting information from SPR [6, 7]. 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. Phase sensitive SPR study is also an emerging research area due to its significant contribution in sensing applications [41-43]. Phase interrogation based SPR sensor has higher detection resolution than that of intensity interrogation counterpart [44, 45].
Introduction of an additional nano-layer of high refractive index (RI) semiconductor material over plasmon generating metal film enhances the electric field intensity at the metal-dielectric interface compared to that provided by traditional three layer structure [47].

3.2 Description of the structures under investigation

3.2.1 Three-layer and Four-layer structures with germanium-prism and silicon nano-layer

In this sub-section, the performance of the SPR-sensor has been analyzed with high refractive index semiconductor prism material (Ge) for three different nano-plasmonic configurations namely, germanium-metal-analyte (GMA), germanium-silicon-metal-analyte (GSMA) and germanium-metal-silicon-analyte (GMSA).

GMA, GSMA and GMSA structures have been schematically depicted in Fig.3.1. 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 nano-layer 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 nano-layer (silicon) is less than that required to support the TM-guided mode, it is referred to as near-guided-wave SPR (NGWSPR)-configuration [46]. This semiconductor nano-layer is used to increase the electric field intensity over the metal-dielectric interface. When semiconductor nano-layer is located below Ge-substrate (GSMA-structure) then overall performance of the system improves as discussed later.
Fig.3.1: Schematic diagram of (a) 3-layer GMA and (b) 4-layer GMSA/GSMA structures.

3.2.2 Three-layer and Four-layer structures with silicon-prism and silicon nano-layer

In the next work performance of the SPR-sensor has been analyzed with high RI semiconductor-prism material (silicon) for three different nano-plasmonic structures namely, silicon-metal-analyte (SMA), silicon-silicon-metal-analyte (SSMA) and silicon-metal-silicon-analyte (SMSA) for sensing of amino acids having a wide range of RI variations. Amino acid plays an important role in protein biosynthesis involved in human metabolism. Detection of right amount of amino acids is also equally important. For these reason amino acids with a wide variations of refractive index increments is taken for analysis of the present SPR-structures [48].
SMA, SSMA and SMSA structures have been schematically depicted in Fig.3.2. For all these structures, high RI silicon-prism has been considered as coupling device due to its higher sensing ability in infrared (IR) wavelength region.

**Fig.3.2:** Schematic diagram of (a) 3-layer SMA and (b) 4-layer SMSA/SSMA structures.

Such semiconductor-prism material based structures can direct a higher amount of light energy towards the sensing region. Gold film having thickness of 40 nm is used as excitation layer (SMA-structure). Additional semiconductor nanolayer of silicon (Si) having thickness 10 nm is used as the protective layer over gold film to increase the stability of the system (SMSA-structure).

This semiconductor nanolayer is used to increase the electric field intensity over the metal-analyte interface. When semiconductor nanolayer is located below Si-substrate
(SSMA-structure) then overall performance of the system improves as discussed later. Performance of SSMA and SMSA structures for sensing of different amino acids has been discussed in later sections.

### 3.2.3 Four-layer structures with silicon-prism and germanium nano-layer

Semiconductor based surface plasmon resonance structures with two different combinations of Gr-IV materials (silicon and germanium) have been analyzed which can be used for very efficient infrared (IR)-sensing and IR-imaging purposes. SGMA and SMGA structures have been schematically depicted in Fig.3.3.

![Schematic diagram of 4-layer (a) SGMA and (b) SMGA structures](image)

**Fig.3.3.** Schematic diagram of 4-layer (a) SGMA and (b) SMGA structures (not to scale)
The silicon-germanium (Si-Ge) structures efficiently confine an extremely high evanescent field in the sensing region due to their extraordinary high refractive index (RI). Higher concentration of optical field in the sensing area make the semiconductor based plasmonic structures more efficient for IR-sensing and IR-imaging purposes. Better detection accuracy and adequate dynamic range are the additional advantages offered by such semiconductor-based surface plasmon resonance (SPR) configurations. Comparative performance analysis of the SPR structures has also been carried out in terms of E-field enhancement, angular sensitivity, phase-jump, detection accuracy, figure of merit and Q-factor of the plasmonic-sensor.

Majority of the laser sources and detectors are designed to work in the telecommunication band. Hence telecommunication wavelength 1550 nm is considered as the working wavelength for the analysis of the SPR-structure in accordance with the availability of sources in mid-Infrared wavelength region [49]. Gold film having thickness 32 nm is used as an excitation layer due to its chemical stability and high sensing property. Additional semiconductor nanolayer of germanium (Ge) having thickness 10 nm is used as the protective layer over gold film to increase the stability of the system (SMGA-structure).

When semiconductor nanolayer is swapped below Si-substrate (SGMA-structure) overall performance of the system improves as discussed in later section, where the performance of SGMA and SMGA structures for sensing a wide variations RI has been discussed.
3.3 Results and Discussions

3.3.1 GSMA and GMSA structures : 900 nm wavelength

As depicted in Fig.3.4 both GSMA and GMSA structures give satisfactory evanescent field enhancement at 900 nm, hence further analysis of these structures has been carried out only at 900 nm wavelength. But due to less transparency of Ge-prism at near-infrared wavelength region some losses has to be considered when the light propagates through the Ge-prism structures.

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 [50].

![Graphs showing evanescent field enhancement for different wavelengths](image)

Fig.3.4 Evanescent field enhancement in angular interrogation mode for (a) GSMA and (b) GMSA structure for four different wavelengths: 633 nm, 900 nm, 1200 nm and 1550 nm.
Evanescent field enhancement and sharpness of phase-jump across resonance position is much higher for GSMA structure than GMSA structure as shown in Fig. 3.5. 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 is 295.5 units, whereas with swapping of semiconductor nano-layer (GSMA-structure), it increases to 457.5 units.

![Graphs showing E-field enhancement and reflectance for GSMA and GMSA structures](image)

**Fig. 3.5** Angular interrogation plots for (a) E-field enhancement, (b) reflectance and phase-jump across resonance position for GSMA and GMSA structures respectively at 900 nm wavelength.

As defined in section 1.6 of chapter 1 dynamic range of operation decides the maximum value of RI of the dielectric sample which can be sensed by the 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.3.6. Both the 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.

![Angular interrogation plots for dynamic range with (a) reflectance and (b) phase-jump of the SPR-sensor for GSMA and GMSA structure at 900 nm wavelength.](image)

**Fig.3.6** Angular interrogation plots for dynamic range with (a) reflectance and (b) phase-jump of the SPR-sensor for GSMA and GMSA structure at 900 nm wavelength.

### 3.3.1.1 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 semiconductor nanolayer is present above the Ge-substrate as shown in Fig.3.7.
Fig. 3.7 Variations of (a) Evanescent field enhancement (b) reflectance with different thickness of semiconductor nanolayer for GSMA and GMSA structure at 900 nm wavelength.

(c) Phase plots corresponding to resonance position for GSMA and GMSA structure for different thickness of semiconductor nanolayer.
3.3.1.2 Effect of thickness of metal layer

Due to the variations of gold layer thickness evanescent field enhancement and reflectance minima for SPR-curve changes but still GSMA structure provides better performance as a SPR-sensor than GMSA structure as shown in Fig.3.8. The performance of the SPR-sensor is optimized for 50 nm gold layer thickness. For thickness of nano-metric layer above and below 50 nm both evanescent field enhancement and reflectance-dip decreases.

Sharper phase-jump occurs for GSMA-structure than GMSA-structure at 900 nm wavelength for different metal layer thickness. Even resonance position is shifted for higher angular ranges for GMSA-structure than GSMA-structure as depicted in Fig.3.8.

**Fig.3.8** Variations of (a) Evanescent field enhancement and (b) reflectance for different thickness of gold layer for GSMA and GMSA structure at 900 nm wavelength.
3.3.1.3 Performance analysis

Performance parameters of the SPR-sensor are discussed in details in sec 1.7 of chapter 1. For analyzing the performance of the SPR-sensor we have simulated the reflectance plots for two samples, namely water as reference and acetone as test sample for GSMA and GMSA structures as shown in Fig.3.9.

Differential phase of the nano-plasmonic sensor is defined as $\Delta \varphi = \varphi_s - \varphi_r$. where $\varphi_s$ and $\varphi_r$ are the phase of the plasmonic sensor for sample under test and reference sample respectively.

Differential reflectance of the nano-plasmonic sensor is defined as $\Delta R = R_s - R_r$. where $R_s$ and $R_r$ are the reflectance of the plasmonic sensor for sample under test and
reference sample respectively. In present analysis water is reference sample and different concentration of sugar solution is sample under study.

Detection accuracy and figure of merit (FOM) of GSMA structure is found to be higher than that of GMSA structure at 900 nm wavelength as depicted in Table 3.1. But sensitivity and stability of GMSA structure is higher.

![Graph showing SPR angle and FWHM variations](image)

**Fig.3.9** Variations of SPR angle and FWHM of SPR-curve with water and acetone as sensing layer for GSMA and GMSA structure at 900 nm wavelength.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Sensitivity (degree/RIU)</th>
<th>FWHM (degree)</th>
<th>Detection accuracy (degree⁻¹)</th>
<th>FOM (RIU⁻¹)</th>
</tr>
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<tbody>
<tr>
<td>GSMA</td>
<td>13.56</td>
<td>0.24</td>
<td>4.17</td>
<td>56.50</td>
</tr>
<tr>
<td>GMSA</td>
<td>15.50</td>
<td>0.64</td>
<td>1.56</td>
<td>24.21</td>
</tr>
</tbody>
</table>
3.3.1.4 Dispersion relations used for simulation

Prism materials and metallic dispersions have been described in details in sec 1.8 of chapter 1.

For germanium spectral dependence of refractive index with wavelength (µm) is

\[ n^2(\lambda) = 9.28156 + \frac{6.72880}{\lambda^2 - (0.44105)} + \frac{0.21307}{\lambda^2 - (3870.1)} \]  \hspace{1cm} (3.1)

For silicon spectral dependence of refractive index with wavelength (µm) is

\[ n^2(\lambda) = 1 + \frac{10.668429\lambda^2}{\lambda^2 - (0.301516485)^2} + \frac{0.003043475\lambda^2}{\lambda^2 - (1.13475115)^2} + \frac{1.54133408\lambda^2}{\lambda^2 - (1104.0)^2} \]  \hspace{1cm} (3.2)

**Fig.3.10** Wavelength dependence of dielectric permittivity for (a) semiconductor (b) metal

Variation of dielectric function of the materials used in the nano-plasmonic sensor with wavelength is shown in Fig.3.10.
Considering above dispersions, simultaneous angular and spectral interrogation 3D plots for these two structures (GSMA and GMSA) for E-field enhancement have been depicted in Fig. 3.11. It is seen that GSMA structure provides better performance of Evanescent field enhancement for both visible and IR region than GMSA structure.

![Simultaneous wavelength and angular interrogation plots for evanescent field enhancement with (a) GSMA and (b) GMSA structures.](image)

**Fig.3.11** Simultaneous wavelength and angular interrogation plots for evanescent field enhancement with (a) GSMA and (b) GMSA structures.

### 3.3.1.5 Effect of variation in concentration of sugar solution

As concentration of sugar solution increases from 0%, 5%, 10% & 15%, the refractive index (RI) of the sensing medium increases [53] and resonance position gets shifted to higher angle of incidences for both GSMA and GMSA structures. Even reflectance-dip and sharpness of phase-jump is greater for GSMA-structure than GMSA-structure. For each RI of the sensing medium resonance position of GMSA-structure appears at higher angular ranges than GSMA-structure as represented in Fig.3.12.
Due to change in RI between the two sensing media ($d_n_i$, $i=1, 2, 3$), the width of differential phase and differential reflectance curve increases with increase in $d_n_i$ for both GSMA and GMSA-structure as shown in Fig.3.13. Differential phase and differential reflectance position also get shifted to higher angular values. Maxima for differential phase curve also decreases and differential reflectance curve increases with increase in RI change between the sensing medium for both the SPR-structures.
Fig. 3.13 (a) Differential phase and (b) Differential reflectance curves for different concentrations of sugar solutions having water as reference medium in angular interrogation mode for GSMA and GMSA-structure. Change in RI of the sample is denoted by $d_n$, $i=1,2,3$.

### 3.3.2 SSMA and SMSA structures: 1300 nm wavelength

Spectral dependence of silicon and gold has been discussed in details in previous sections.

The refractive index of amino acid solution is directly proportional to its concentration for a particular wavelength.

$$n_s = n_0 + \frac{dn}{dc} * C \quad (3.3)$$
where, $n_s$ and $n_0$ are the refractive index of amino acid solution and the solvent respectively. $C$ is the concentration in gm per 100 cc. of solution and $\frac{dn}{dc}$ is the specific refractive index increment [50]. Wavelength dependence of amino acids was found to follow Cauchy relation and the formula [54].

\[
\left(\frac{dn}{dc}\right)_\lambda = \left(\frac{dn}{dc}\right)_{578\text{nm}} \ast \left(0.94 + \frac{20000\text{nm}^2}{\lambda^2}\right)
\]

(3.4)

Spectral dependence of refractive index of different materials used in this nanoplasmonic sensor is shown in Fig.3.14.

Fig.3.14 Wavelength dependence of (a) materials used in SPR-sensor (b) amino acids as sensing elements for SPR-sensor.
For analysis of these two nano-plasmonic structures (SSMA and SMSA) two different wavelengths 1300 nm and 1550 nm are taken according to the transparency of silicon-prism and availability of sources in near-infrared wavelength region [55]. Fig.3.15 clearly depicts 1300 nm wavelength gives higher evanescent field enhancement for both SSMA and SMSA structure and SSMA structure provides higher evanescent field enhancement for both of the wavelengths in near infrared (NIR) region. Hence further analysis of these structures has been carried out only at 1300 nm wavelength.

**Fig.3.15** Evanescent field enhancement in angular interrogation mode for (a) SSMA and (b) SMSA structure with two different wavelengths: 1300 nm and 1550 nm in near infrared (NIR) region.
3.3.2.2 Operating principle of nano-plasmonic sensor

As we obtained from equation (1.1) and (1.2) in chapter 1 the phase matching condition for resonant excitation is given by equation (1.18).

Any change in RI of the dielectric sample in contact with the metal layer results in shift of the resonant angle in order to satisfy the phase-matching condition between incident light and the surface plasmon wave as the remaining parameters are constant for fixed working wavelength 1300 nm as shown in Fig. 3.16.

![Propagation constant plot](image)

Fig. 3.16 Propagation constant plot of a nano-plasmonic sensor with silicon-prism for different amino acids as sensing medium.
3.3.2.3 Results and Discussions

![Angular interrogation plots for (a) E-field enhancement, (b) Reflectance across resonance position for SSMA and SMSA structures respectively at 1300 nm wavelength.](image)

**Fig.3.17** Angular interrogation plots for (a) E-field enhancement, (b) Reflectance across resonance position for SSMA and SMSA structures respectively at 1300 nm wavelength.

Fig.3.17 shows that evanescent field enhancement and sharpness of reflectance-dip across resonance position is much higher for SSMA structure than SMSA structure. SPR angle is 16.75 ° for SSMA structures and 16.94 ° for SMSA structure with air as sensing medium at 1300 nm working wavelength. Hence due to presence of semiconductor nanolayer below the plasmon active metal surface (SMSA-structure) the resonance position gets shifted to higher angle of incidence and field enhancement factor become 233.9 units. The positional-swapping of semiconductor nanolayer (SSMA-structure) causes increment of field enhancement factor to 285 units.
Fig.3.18 Angular interrogation plots for dynamic range with (a) SSMA (b) SMSA structure at 1300 nm wavelength.

Both SSMA and SMSA structures are efficient to sense upto RI 3.0 units at near-infrared wavelength of 1300 nm. However Fig.3.18 demonstrates that for SMSA structure width of the SPR-curve increases, SPR-angle increases and reflectance minima decreases compared to that for SSMA structure.
Fig. 3.19 SSMA structure at 1300 nm working wavelength with different amino acids as the sensing medium (a) Evanescent field enhancement (b) Variation of maxima of evanescent field enhancement (c) Image response of evanescent field enhancement (d) Table showing resonance positions and maximum value of field enhancement.
Fig. 3.20 SMSA structure at 1300 nm working wavelength with different amino acids as the sensing medium (a) Evanescent field enhancement (b) Variation of maxima of evanescent field enhancement (c) Image response of evanescent field enhancement (d) Table showing resonance positions and maximum value of field enhancement.

As the refractive index (RI) of the sensing medium (amino acids) increases resonance position gets shifted to higher angle of incidences for both SSMA and SMSA structures. Even enhancement of evanescent field is greater for SSMA-structure than SMSA-
structure for sensing with all the amino acids. For each RI of the sensing medium resonance position of SMSA-structure appears at higher angular ranges than SSMA-structure as represented in Fig.3.19 and Fig.3.20.

**Fig.3.21** SSMA structure at 1300 nm working wavelength with different amino acids as the sensing medium (a) SPR reflectance curve (b) Variation of resonance position in degree (c) Image response of reflectance (d) Table showing resonance position and sensitivity of SPR.
**Fig. 3.2** SMSA structure at 1300 nm working wavelength with different amino acids as the sensing medium (a) SPR reflectance curve (b) Variation of resonance position in degree (c) Image response of reflectance (d) Table showing resonance position and sensitivity of SPR.

After analyzing the performance of SSMA and SMSA structure it is clear that sharper reflectance occurs for SSMA than SMSA structure for sensing with all the amino acids. For SMSA structure width of reflectance curve increases and resonance position get
shifted to higher angular ranges than obtained from SSMA structure as evident from Fig.3.21 and Fig.3.22. For both SSMA and SMSA structures as RI of the sensing medium increases from water to tryptophan the sharpness of reflectance curve decreases and resonance position shifted to higher angular ranges.

![Phase plots for SSMA and SMSA structures](image)

**Fig.3.23** Phase plots corresponding to resonance position for (a) SSMA and (b) SMSA structure for various amino acids as sensing medium.

Steeper phase-jump appears for SSMA structure than SMSA structure and for SMSA structure phase-jump is shifted to higher angular ranges for sensing with all the amino acids as evident from Fig.3.23. Due to increase in RI of the sensing medium phase-jump shifted to higher angular ranges and sharpness of phase-jump across resonance position decreases.
**3.3.2.4 Performance analysis**

We have simulated the reflectance plots for different amino acids as test samples with water as reference for SSMA and SMSA structures as shown in Fig.3.21 and Fig.3.22. Dip-depth of a SPR-sensing curve is defined as the difference between the maximum and minimum value of reflectance of a SPR-sensing curve [31]. For sensing with different amino acids SPR dip shift has been considered as shift of resonance position with reference to water.

![Plots of (a) Dip depth (b) SPR dip shift for SSMA and SMSA structure with variation of RI of the sensing medium.](image)

**Fig.3.24** Plots of (a) Dip depth (b) SPR dip shift for SSMA and SMSA structure with variation of RI of the sensing medium.
Fig. 3.25 Plots of (a) Detection accuracy (b) Angular sensitivity for SSMA and SMSA structure with variation of RI of the sensing medium.

Fig. 3.26 Plots of (a) FWHM (b) Figure of merit for SSMA and SMSA structure with variation of RI of the sensing medium.
Comparing the performance of SSMA and SMSA structure as evident from Fig.3.24, Fig.3.25 and Fig.3.26 it can be concluded that with increase of RI of the sensing medium SMSA-structure provides higher angular sensitivity, FWHM and SPR dip shift whereas higher dip depth, detection accuracy and figure of merit is achieved for SSMA-structure.

### 3.3.3 SGMA and SMGA structures: 1550 nm wavelength

#### 3.3.3.1 Dispersion relations used for simulation

The metallic dispersion in IR region has been considered using modified Drude model [56].

\[
\varepsilon(\omega) = \varepsilon_\alpha - \frac{\omega_p^2}{(\omega^2 + i\Gamma\omega)}
\]  

(3.5)

where \(\omega_p\) = plasma frequency, \(\Gamma\) = damping constant, \(\varepsilon_\alpha\) = constant offset of interband transitions. Value of RI of germanium layer at 1550 nm wavelength is \(4.275 + i(0.00567)\).

Spectral dependence of refractive index of different materials used in this nano-plasmonic sensor is shown in Fig.3.27.
3.3.3.2 Results and Discussions

Considering dispersion relations, simultaneous angular and spectral interrogation 3D plots of reflectance for the Si-Ge combination structures (SGMA and SMGA) have been presented in Fig.3.28. It is evident that SGMA structure provides narrower and sharper reflectance-dip for the entire mid-IR wavelength region than SMGA structure. Moreover, the resonance position is shifted towards higher angular and wavelength values for SMGA-structure.

Fig.3.27 Wavelength dependence of semiconductors and metal used in the SPR-sensor
Fig.3.28 Simultaneous wavelength and angular interrogation plots for reflectance with (a) SGMA and (b) SMGA structures for air as sensing medium.

The Si-Ge combination is efficient to confine an extremely high evanescent field in the sensing region due to their extraordinary high RI as evident from Fig.3.29. Both the SPR-structures (SGMA and SMGA) are optimized at 1550 nm working wavelength. Higher concentration of optical field in the sensing area is very effective for measurement of small changes in RI of the sensing medium in infrared-wavelength region. Higher and sharper field enhancement occurs for SGMA-structure compared to that for SMGA-structure due to successive presence of Si-prism and Ge-nanolayer. When semiconductor nanolayer is swapped below the plasmon active metal surface (SMGA-structure) the resonance position gets shifted to higher angle of incidence and field enhancement factor decreases as depicted in Fig.3.29.
Similarly, in terms of reflectance response, Fig.3.30 shows that the sharpness of reflectance-dip (along with its image representations) across resonance position is greater for SGMA structure than SMGA structure. Hence due to presence of semiconductor nanolayer (Ge-nanolayer) below the plasmon active metal surface (SMGA-structure) the resonance position gets shifted to higher angular ranges and sharpness of reflectance-minima across resonance positions decreases.
Fig. 3.30 Reflectance curve with corresponding image response for SGMA and SMGA structure at 1550 nm working wavelength in angular regime.
Fig. 3.31 Angular interrogation plots for dynamic range with (a) reflectance and (b) phase-jump of the SPR-sensor for SGMA and SMGA structure at 1550 nm working wavelength.

High RI of the silicon-prism is able to provide wider dynamic range of operation of the SPR-sensor. Both SGMA and SMGA structure is efficient to sense upto RI 3.0 units at near-infrared wavelength 1550 nm. However Fig. 3.31 provide evidence that for SMGA structure, width of the SPR-curve and SPR-angle are both greater while reflectance minima is lower than that for SGMA structure.
3.3.3.3 Performance analysis

We have simulated the reflectance plots for two samples, namely RI=1.33 as reference and RI=1.34 as test sample for SGMA and SMGA structures as shown in Fig.3.32.

![Graph showing reflectance plots for SGMA and SMGA structures with different RI values](image)

**Fig.3.32** Variations of SPR angle and FWHM of SPR-curve for SGMA and SMGA structure at 1550 nm wavelength with sample RI of 1.33 and 1.34 respectively.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Sensitivity (degree/RIU)</th>
<th>FWHM (degree)</th>
<th>Detection accuracy</th>
<th>FOM (RIU⁻¹)</th>
<th>Q-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGMA</td>
<td>18</td>
<td>.11</td>
<td>9.09</td>
<td>163.63</td>
<td>206.18</td>
</tr>
<tr>
<td>SMGA</td>
<td>19</td>
<td>.18</td>
<td>5.55</td>
<td>105.55</td>
<td>127.27</td>
</tr>
</tbody>
</table>

**TABLE 3.2.** Performance parameters for SGMA and SMGA structure at 1550 nm wavelength.
FOM, detection accuracy and Q-factor of SGMA structure is found to be higher than that of SMGA structure at 1550 nm wavelength as depicted in Table 3.2. But sensitivity, FWHM and stability of SMGA structure is higher.

**Fig. 3.33** Plot of (a) SPR dip-depth, (b) FWHM, (c) resonance angle with SGMA and SMGA structures for variations of RI of the sensing medium.
Fig. 3.34 Plot of (a) detection accuracy, (b) maxima of evanescent field enhancement, (c) figure of merit (d) Q-factor with SGMA and SMGA structures for variations of RI of the sensing medium.

Comparing the performance of SGMA and SMGA structure as evident from Fig.3.33 and Fig.3.34 it can be concluded that with increase of RI of the sensing medium SMGA-structure provides higher angular sensitivity, resonance angles, FWHM and SPR dip-
depth whereas higher detection accuracy, max E-field enhancement, figure of merit and Q-factor is achieved for SGMA-structure.

Fig. 3.35 Phase plots corresponding to resonance position for SGMA and SMGA structure with variations of RI of the sensing medium.

Analyzing the phase-jump across resonance position it is clear that higher amount of phase change can be noticed for SGMA structure than SMGA structure for sensing with all the samples and for SMGA structure phase-jump is shifted to higher angular ranges as evident from Fig. 3.35. Due to increase in RI of the sensing medium phase-jump gets shifted to the higher angular positions and sharpness of phase-jump across resonance position decreases.
3.4 Conclusions

In conclusion at first Ge/Si combination has been analyzed as the SPR-sensor which finds application in photo detector. An extensive theoretical simulation based on different resonance parameters namely reflectance, phase-jump and evanescent-field enhancement has been carried out. High refractive index (RI) of the substrate material (Ge) is capable to confine more light energy towards the sensing region which improves the sensitivity and overall performance of the SPR-sensor. Higher RI of the semiconductor nano-layer (Si) can support guided wave for smaller thickness. Refractive Index of the silicon nano-layer is much larger than dielectric sensing medium. Even thickness of it is less than to support TM-guided mode. This causes a large fraction of the evanescent wave to be in the sensing medium thus increasing the overall interaction volume and sensitivity of the SPR-sensor. Simulation results provide evidence that GSMA-structure is efficient in both visible and IR-wavelength region with a higher value of figure of merit whereas higher stability and sensitivity is achieved for GMSA-structure. In another work we have reported the performance of a semiconductor based SPR-sensor with high RI silicon prism as coupling device for sensing with different amino acids in angular regime. Presence of additional silicon nano-layer above the plasmon active metal surface improves the stability and sensitivity of the SPR-sensor which is accompanied with significance enhancement of the evanescent field at the metal-analyte interface. Positional swap of the silicon nano-layer from above the metal surface to below the metal surface causes further enhancement of the evanescent field with improved overall performance of the SPR-sensor. 1300 nm is chosen as the working wavelength of the nano-plasmonic sensor according to the transparency of silicon-prism and availability of
sources in near-infrared wavelength region. It also provides satisfactory evanescent field enhancement for both SSMA and SMSA structure. Simulation results provide evidence that SSMA-structure is efficient with higher value of figure of merit and detection accuracy whereas higher stability and sensitivity is achieved for SMSA-structure. In the next work we have reported Si-Ge combination structures as efficient SPR-based sensors for IR-sensing and IR-imaging purposes. Such semiconductor-based plasmonics structures find applications as stable and reliable SPR-sensors with great measurement precision for photo-detection, IR-imaging, IR-sensing etc. Presence of additional germanium (Ge) nano-layer above the plasmon active metal surface improves the stability and sensitivity of the SPR-sensor which is accompanied with significance enhancement of the evanescent field at the metal-analyte interface. Positional swap of the germanium (Ge) nano-layer from above the metal surface to below the metal surface causes further enhancement of the evanescent field with improved overall performance of the SPR-sensor. 1550 nm is chosen as the working wavelength of the nano-plasmonic sensor according to the transparency of silicon-prism and availability of sources and detectors in near-infrared wavelength region. It also provides satisfactory evanescent field enhancement for both SGMA and SMGA structure. Theoretical investigations provide evidence that SGMA-structure is more efficient with higher evanescent field enhancement which ensures better detection accuracy, Q-factor and figure of merit of the SPR-structure. On the other hand, higher stability and sensitivity are achieved by using SMGA-structure. Hence choice of the SPR-structures must be according to the application concerned for IR-sensing purposes and whether better measurement precision is required or higher sensitivity is in priority.