Highly sensitive refractive index sensor by floating nano-particles in the solution for the detection of glucose/fructose concentration

Hamid Bahador1 · Hamid Heidarzadeh1

Received: 5 April 2021 / Accepted: 19 October 2021 / Published online: 13 November 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
In this research, an optimum design is proposed for better utilization of field resonance. More interaction of the field formed around nano-particles with a solution, which has refractive index variations, can substantially increase the sensitivity of the plasmonic biosensors. More interaction could be provided by floating nano-particles in the solution. The proposed structure, which has peak plasmonic resonance, has better light sensing features in comparison to similar non-floating structures. While without floating nano-particle, sensitivity is 265.8 nm/RIU with the realization of the full floating nano-particles, the sensitivity of the structure with elliptic disc and circular disc nano-particles are 574.2 nm/RIU and 425 nm/RIU, respectively. Full width at half maximum (FWHM) of the structure with elliptic disc and circular disc nano-particles are 57.4 nm and 49.4 nm, respectively. In presence of meshed SiO2 network and pseudo-floating form, sensitivity and FWHM of the structure are 504 nm/RIU and 58.4 nm for elliptic discs and 372 nm/RIU and 49.9 nm for circular discs, respectively.

Keywords Plasmonic · Nano-particles · Meshed SiO2 · Sensitivity · Refractive index sensor

1 Introduction

Plasmonic nanostructures able to control light in space smaller than the diffraction limit, have a widespread application in waveguides, detectors (Bahador and Heidarzadeh 2020; Heidarzadeh 2020), solar cells (Jangjoy et al. 2019, 2021; Mokari and Heidarzadeh 2019; Sobhani et al. 2020a, b; Heidarzadeh 2021), and lasers (Cubukcu et al. 2006). Based on the precise permeability function of metals, their optical properties are inherently dependent on the fluctuating behavior of electrons in the metal. The result of electron-photon interaction in a metal nanostructure is localized surface plasmons. These non-propagation excitations are produced from the scattering of the oscillating electromagnetic waves by
a small conductive nanoparticle in the sub-wavelength band. The realization of the oscillation condition depends on, shape, size, the material of metal nanoparticles, and the distance between them and the surrounding environment (Heidarzadeh and Bahador 2021; Ni et al. 2018; Sun et al. 2020; Tang 2020; Wang et al. 2020). In some works, a single crystalline or polycrystalline bulk or thin-film material has been used as a high sensitivity sensor (Zhou et al. 2020a; Jafari 2020). Their crystallite size is commonly determined by some methods such as X-ray diffraction (XRD) (Tan et al. 2021a, b). Titania nanoparticles have been prepared by solvothermal and sol–gel techniques in Dastan (2017), Dastan et al. (2017), Dastan (2015) and Dastan and Chaure (2014). The effect of annealing temperature on energy bandgap and transmittance of such structures have been studied (Dastan et al. 2014, 2016). In the past decades, a variety of biosensors have been developed that incorporate plasmonic nanoparticles (Belushkin et al. 2018; Vázquez-Guardado et al. 2018). The small-sized and bio-compatible sensing sensors are the critical elements to realize the best nano biosensors (Chang et al. 2018). Surface Plasmon Resonance (SPR) is a physical optical phenomenon that exists at the interface between metal and dielectric (Heidarzadeh et al. 2016; Zhou et al. 2020b). When light is incident on the interface between metal and dielectric, the evanescent wave when total internal reflection occurs causes free electrons in the metal to generate surface plasmon. After proper adjustment, when the light coupled into the metal film resonates with the surface plasmon unit, part of the energy of the incident light will be converted into the energy of the surface plasmon unit, forming a surface plasmon resonance. When the refractive index of the substance adsorbed on the metal film surface is different, the resonance peak position will be different. So, the refractive index is an important physical quantity reflecting the interaction between light and medium. Based on the sensitive response of surface plasmons to changes in the refractive index of the surrounding environment. The working principle of most optical biosensors is to adsorb biological substances to the surface of the device and measure the change in the refractive index of the substance. Surface plasmon resonance has become the basis of existing biosensors, although the resulting detectors are usually too large and rely too much on moving parts to be incorporated into portable digital devices. As a result, scientists began to study plasmonic micro and nanosensors as a possible compact configuration for next-generation biosensors (Chen and Wang 2020). The plasmon-based nano-bio-sensors are becoming an ultra-sensitive chemical and biological analysis method (Liu et al. 2017). The overall quality factor or figure of merit (FoM) of the LSP-based nano-sensors sensing response is severely affected by the wide local plasmon resonance linewidth due to the large inherent absorption of general metals and the main radiation scattering contribution (Chen and Wang 2020; Špačková et al. 2016). To increase the total FoM, some efforts have been made to enhance the refractive index sensitivity of individual plasmonic nanoparticles by optimizing their size and shape (Zhu et al. 2016; Heidarzadeh 2020b; Amoosoltani et al. 2020). Recently, several new design principles have been proposed, including plasmonic hybridization (Liu et al. 2020), transformation optics (Fernández-Domínguez et al. 2012), and subgroup decomposition (Rahmani et al. 2012), which are used to modify the resonance line shape and enhance the spectral contrast of individual metal nanodimers and nanoclusters. However, the reduction of the LSP resonance linewidth based on the aforementioned strategy is very limited, and the quality factors of the hybrid resonances are still about an order of magnitude smaller than the quality factors of the propagating plasma. All of the above methods usually rely on strict design and precise control of the arrangement of individual components, such as the distance between particles and particle shape, which further causes experimental difficulties (especially in manufacturing) and cannot be applied to the following components. Sensitivity is one of the important
parameters to define the quality of an optical sensor. Optimized usage of field resonance around nanoparticles could increase the sensitivity of the detector. It is important to note that floating metal nanoparticles in solution could increase the interaction field produced around particle and solution. In this work, to have a theoretical model, floating of metal nanoparticle in solution (cover region), confinement region under nanoparticle, and substrate region form a three-layer planar waveguide. In the “Methodology and Structure” section, the effect of floating nanoparticles is investigated with this model. In the next section, simulation results are presented to achieve the optimum geometric dimensions and the appropriate distance of the floating nanoparticles from the substrate. In this section, the effect of the realization of a strong field in the confinement region and its intense interaction with a solution on detector performance improvement is discussed. A proper structure for a floating particle, which can be fabricated, has been proposed. A lattice of SiO₂ (or meshed-SiO₂) under the nanoparticles realizes the pseudo-floating design of the nanoparticles.

2 Methodology and structure

2.1 Modeling methodology

Most of the optical sensing techniques are based on the existence of evanescent waves in the region where the analyte to be sensed is located. A confinement region in which the majority of the optical density exists can be a proper region to arise evanescent waves. The evanescent field in the confinement region and the two bounding regions called substrate and analyte is shown in Fig. 1.

The dielectric function of the structure may be written as:

$$\varepsilon = \begin{cases} n_w^2 & r \in V_w \\ n_{a,s}^2 & r \not\in V_w \end{cases}$$

(1)

where $n_w$, $n_a$, $n_s$ are the refractive indices in the confinement region, the analyte region, and the substrate region with $V_w$ being the space volume of the confinement region. Adding a nanoparticle to the analyte causes a variation in the dielectric function of the analyte. The wave equation analysis before and after the addition of the nanoparticle determines the shift of the guided wave vector. Using first-order perturbation theory, as mentioned in reference (Abdulhalim 2008), the shift in the wave vector, $\Delta k$, is proportional to the overlap integral, which in turn is proportional to the volume of the interaction, $V_{in}$.

Fig. 1 Schematic of evanescent wave sensor (Heidarzadeh et al. 2016)
where $E_i$ and $k_i$ are the electric fields and its wave vector before the change in the refractive index of the analyte, whereas, $E_f$ is the field after variation of refractive index and $\delta k$ is the corresponding shift at the wave vector due to the change in the analyte dielectric constant from $\varepsilon$ to $\varepsilon + \partial \varepsilon$. Because $\delta k$ expresses the change in wavelength, $\delta k/\partial \varepsilon$ represents the sensitivity of the sensor, which is proportional to the overlap integral in the numerator of Eq. (2) normalized to the total energy. Therefore, to maximize the sensitivity, it is necessary to maximize this integral, which can be achieved by increasing the volume of interaction in the analyte region.

It should be noted that the ratio $\delta k/k_i$ can be identified with the relative change in the mode effective index $\delta n_{\text{eff}}/n_{\text{eff}}$. The sensitivity of the evanescent wave sensors, in particular the guided wave ones, is defined by:

$$S = \frac{\delta n_{\text{eff}}}{\partial n_a}$$

(3)

The mode effective index is a function of many parameters:

$$n_{\text{eff}} = f(n_a, n_w, n_s, n_0, n_1, d_g, d_w, \gamma_1, \lambda, \Lambda, l, \rho)$$

(4)

where the additional parameters here are $n_0, n_1, d_g, d_w, \gamma_1, \lambda, \Lambda, l, \rho$ defined as: the refractive indices of the two regions forming the rectangular grating in case of grating coupling, the grating height, the waveguide thickness, the incidence angle, the grating period, the wavelength, the mode number, and mode type with $\rho = 0$ for TE and $\rho = 1$ for TM. The equations describing the sensitivity of planar waveguides were derived by Tiefenthaler and Lukosz (1989) for the three-layer waveguide and can be written as follows:

$$S = \frac{n_a \delta_a}{n_{\text{eff}} d_{\text{eff}}} \left[ \frac{n_w^2 - n_{\text{eff}}^2}{n_w^2 - n_s^2} \right] \left[ 2 \frac{n_{\text{eff}}^2}{n_a^2} - 1 \right]$$

(5)

where $d_{\text{eff}} = d_w + \delta_a + \delta_s$ an effective thickness with $\delta_{s,a}$ being the penetration depths in the substrate and analyte given by:

$$\delta_{s,a} = \frac{1}{k \sqrt{n_{\text{eff}}^2 - n_{s,a}^2}} \left( 1 - \rho + \rho \left[ \left( \frac{n_{\text{eff}}}{n_w} \right)^2 + \left( \frac{n_{\text{eff}}}{n_{s,a}} \right)^2 - 1 \right]^{-1} \right)$$

(6)

Based on Eq. 5 when $n_a \approx n_w$ the analyte is part of the waveguide (confinement region) and the sensitivity is high.

### 2.2 Proposed structure

Floating of the particle at a specific height (gap) produces an appropriate place under the particle for more mutual effect between the solution and result from the field. Increasing interaction between field and solution could improve the sensitivity of the system to the refractive index of the solution. It should be noted, however, it is difficult
to keep nanoparticles floating at a certain height in the solution. In this design, meshing a part of SiO$_2$ under the nanoparticles makes it possible for the solution to flow under the nanoparticles. Although meshed SiO$_2$ affects the sensitivity and FWHM of the sensor, it provides better gap control. Meshed SiO$_2$ creates a pseudo-floating structure for nanoparticles. In Fig. 2, the meshed SiO$_2$ structure for pseudo-floating and increasing interaction of field and solution is demonstrated. The sensor structure can be divided into several parts: SiO$_2$ part grown on Si, meshed SiO$_2$ and metal particles above that, and finally, solution enclosing particles and meshed part. For further investigation of the structure, elliptic disc, and circular disc particles, all silver is used. At first, by omitting the meshed region, the effect of the full floating of the particle on sensitivity is investigated. Then the effect of meshed SiO$_2$ area under particle is evaluated. By changing particle dimensions, a deeper understanding of the floating effect on structure, performance optimization could be achieved. For precise evaluation and comparison of system performance in different cases, the Maxwell equation is solved by finite difference time domain (FDTD), and the extinction spectra of the structure are calculated. The FDTD method is a volume-based method requiring dividing the space of the solution into a uniform mesh composed of cells (Yee cell) (Yee 1966). Over each cell, the E and H field components will be defined. In the FDTD method, no matrix solution is needed. Instead, the E and H fields are staggered in space, and the leapfrog in time method is employed. This allows a direct solution of the fields, in time. The special feature of the Yee cell is that the E and H field components are staggered one-half space-cell apart, which facilitates differencing schemes that are sufficiently accurate, as discussed in Kunz and Luebbers (1993). In addition, FDTD can also obtain the frequency solution by exploiting Fourier transforms, thus a full range of useful quantities can be calculated, such as the complex Poynting vector and the transmission/reflection of light.

In this work, to evaluate the proposed structures, the Maxwell equations using the finite difference time domain (FDTD) method are solved employing the commercially available Lumerical Software Package. In all simulation profiles, mesh size around nanoparticles is $dx = dy = dz = 0.1$ nm, and the Johnson Christy dielectric constant of metal is used (Johnson and Christy 1972). For upper and lower sides, perfectly matched layer boundary conditions, and for other sides, periodic boundary conditions are used. The geometrical and physical parameters of the optical detector structure are presented in Table 1.

![Sensor structure](image)

**Fig. 2** Sensor structure: a SiO$_2$ part grown on Si, meshed SiO$_2$ and metal particles above it, solution enclosing particles and meshed part. b Floating nano-particles in the solution to design a highly sensitive detector. In figure (a), there is meshed SiO$_2$ under the nanoparticles (in the gap)
3 Results and discussion

Variation of the refractive index of solution around metal nanoparticles could be considered as a shift of resonance wavelength location. Figure 3 shows simulation results for variation of extinction spectrum of nanostructure for the case that metal particle is on the substrate and when there is a gap between the particle and substrate. This examination is for the Ag elliptic disc with 116 nm large radii, 58 nm small radius, and 25 nm thickness, and a solution with 1.333 refractive indexes. Sensitivity and FWHM of the structure have been reported in three cases for Δn = 0.05, the variation of the refractive index of the solution, in Table 2. Results show that making the proper distance between a metal nanoparticle and the substrate increases system FOM from 4.7 to 10. As stated in this Table, with meshed SiO₂ region, to realize pseudo-floating of the particle, the figure of merit and sensitivity of system with 13% reduction are 8.6 and 504.5 nm/RIU, respectively. These features show that this design improves detector sensitivity at least twice. Figure 4 shows the electrical field profile, which is formed under particles. In this figure, the amplitude of the electric field oscillation at four different times is depicted. Selecting the appropriate gap between

| Geometrical parameter                        | Values   |
|----------------------------------------------|----------|
| The large radius of the elliptic disk (ro₁)   | 116 nm   |
| The small radius of the elliptic disk (ro₂)   | 58 nm    |
| The thickness of elliptic disk (th)           | 25 nm    |
| the gap between the elliptic disk and host (gap) | 70 nm    |
| Host thickness (SiO₂)                         | 325 nm   |
| SiO₂ refractive index                         | 1.55     |
| Si refractive index                           | 3.42     |

### Table 2

| Gap size (nm) | sensitivity (nm/RIU) | FWHM (nm) | FOM (S/FWHM) | Peak intensity normalized |
|---------------|----------------------|-----------|--------------|--------------------------|
| 0             | 265.8                | 56.3      | 4.7          | 0.59                     |
| 70            | 574.2                | 57.4      | 10           | 0.6                      |
| 70 and mesh-SiO₂ | 504.5                | 58.4      | 8.6          | 0.66                     |
the nanoparticle and the substrate causes the full interaction of the field and the solution at the maximum field amplitude. The existence of this strong field and oscillation in the region in which a solution exists improves the sensitivity of the detector to the refractive index of the solution, considerably.

The effect of the gap between a metal nanoparticle and substrate to form a strong field that has good interaction with the solution has been illustrated in Fig. 5. The effect of gap change for the Ag elliptic disc on the extinction spectrum is shown in Fig. 5a. Sensitivity variation and normalized amplitude of the extinction spectrum peak are also shown in Fig. 5b. This elliptic nanoparticle has a large radius of 116 nm, a small radius of 58 nm, and a thickness of 25 nm.

Figure 5c shows the variation trend of the extinction spectrum of the Ag circular disc with the variation of the gap between particle and substrate. This disc has a radius of 116 nm and a thickness of 30 nm. Also, Fig. 5d shows the sensitivity and amplitude of the extinction spectrum as a function of the gap. Sensitivity and FWHM of the structure for Ag circular disks have been reported in Table 3. To have both good sensitivity and proper amplitude of the extinction spectrum, a 70 nm gap for the elliptic disc and 40 nm for the circular disc has been used.

Increasing the radius from 96 to 126 nm reduces system sensitivity from 425.3 to 372.1 nm/RIU. Also, the FWHM of the structure increases from 44.6 to 51.6 nm. While in these radius ranges, the normalized peak amplitude of the extinction spectrum is increased from 0.32 to 0.77. It seems that 116 nm for the 40 nm gap and 30 nm thickness is a proper choice.

Increasing the radius of the Ag elliptic disc, from a large radius of 96 nm and a small radius of 48 nm to a large radius of 126 nm and a small radius of 63 nm produces a similar result to that of a circular disc. In this range, sensitivity and FWHM of structure change from 548 nm/RIU and 50.05 nm to 531 nm/RIU and 60.6, respectively. Variation of the normalized peak amplitude of the extinction spectrum by increasing radius, from 0.24 to 0.8 shows that a particle with a large radius of 116 nm, a small radius of 58 nm has a peak amplitude of the extinction spectrum, which could be considered an optimum size. Investigation of the relationship between changing particle radius and detector parameters has been done for a particle with a 70 nm gap and 25 nm thickness.
Fig. 5  

(a) The effect of gap variation for the Ag elliptic disc, and Δn=0.05, on extinction spectrum and sensitivity variation and normalized amplitude of extinction spectrum peak;  

(b) The effect of gap change for the Ag circular disc, and Δn=0.05, on extinction spectrum and sensitivity variation and normalized amplitude of extinction spectrum peak.

Table 3  
Sensitivity and FWHM of the structure for circular disks for three cases: gap=0, gap=40 without meshed SiO₂, and gap=40 with meshed SiO₂

| Gap size (nm) | Sensitivity (nm/RIU) | FWHM (nm) | FOM (S/FWHM) | Peak intensity normalized |
|---------------|---------------------|-----------|---------------|--------------------------|
| 0             | 265.8               | 48.9      | 5.4           | 0.9                      |
| 40            | 425.3               | 49.4      | 8.6           | 0.6                      |
| 40 and mesh-SiO₂ | 372                | 49.9      | 7.45          | 0.66                     |

Table 4  
The effect of thickness variation in silver elliptic disk

| Thickness (nm) | Sensitivity (nm/RIU) | FWHM (nm) | FOM (S/FWHM) | Peak intensity normalized |
|---------------|----------------------|-----------|---------------|--------------------------|
| 20            | 585                  | 61.13     | 9.57          | 0.7                      |
| 25            | 585                  | 57.414    | 10.189        | 0.602                    |
| 30            | 532                  | 54.218    | 9.81          | 0.509                    |
| 35            | 531                  | 53.161    | 9.9885        | 0.431                    |
| 40            | 584.9                | 52.096    | 11.22         | 0.36                     |
Simulation results to choose a good thickness for particle show that changing the thickness of Ag circular disc does not have a considerable effect on detector parameters and 30 nm thickness has a good normalized peak amplitude of the extinction spectrum. Table 4, shows simulation results for thickness variation in silver elliptic disc. From Table data, it could be seen that 25 nm thickness is a good choice for this particle.

4 Application for glucose/fructose monitoring

In the beverage industry, the refractive index and its variations are used to detect and measure the main components existing in aqueous solutions like ethanol, glycerol, and glucose/fructose. Because of its good resolution, a plasmonic sensor can be used to measure glucose/fructose density in a liquid. In Shehadeh et al. (2020), the value of the refractive index of a model aqueous solution containing glucose/fructose has been measure and recorded. In this reference, by the regression analysis of experimental data, the equation below has been proposed to obtain the refractive index of the liquid solution including glucose/fructose:

\[ n = 1.3329 + 0.000135 \times (\text{glucose/fructose}) \text{ (g/L)} \]

With the aid of this equation, Table 5 shows the variation of the refractive index of a model aqueous solution containing glucose/fructose. To measure the quantity of glucose/fructose,

Table 5  Peak wavelength as a function of densities of glucose/fructose

| Glucose/Fructose (g/100 mL) | 0   | 4   | 8   | 12  | 16  |
|-----------------------------|-----|-----|-----|-----|-----|
| Refractive index (n)        | 1.3330 | 1.3383 | 1.3437 | 1.3491 | 1.3545 |
| Peak wavelength             | 1046.5 | 1049.2 | 1051.9 | 1054.5 | 1057.2 |

Fig. 6  Extinction spectrums for different densities of glucose/fructose
the model aqueous solution is replaced in the structure of the sensor. The Ag elliptic disc with 116 nm large radius, 58 nm small radius, 30 nm thickness, and 70 nm meshed-SiO₂ under nanoparticles are the parameters used for this evaluation. Figure 6 shows the relocation of extinction spectrums by different densities of glucose/fructose. The peak wavelength of the extinction spectrum for different densities of glucose/fructose of 0, 4, 8, 12, and 16 mg in every 100 mL are 1046.5, 1049.2, 1051.9, 1054.5, and 1057.2 nm which are spaced around 2.65 nm from each other. Calculating output results from Fig. 6 shows that FOM and sensitivity are 8.25 and 495 nm/RIU, respectively.

5 Conclusion

In this work, the floating of nano-particles in a solution with varying refractive index has been investigated for the first time. Floating nano-particles at a specific height above the substrate improves the sensitivity of the refractive index sensor. Parameters to evaluate the sensor, such as extinction spectrums and electric field distribution, are calculated by the FDTD method. Without the floating of nano-particle, the sensitivity is calculated as 265.8 nm/RIU. Floating elliptic disc and circular disc nano-particles increases the sensitivity to values higher than 10 and 8.6. Also, the effect of nano-particles distance from substrate and their dimensions to achieve the best sensitivity are evaluated and simulated. Finally, for the realization of floating nano-particles, a meshed structure of SiO₂ is added underneath the nanoparticles and its effect evaluated as a pseudo-floating case. Based on the proposed structure and completed simulations, it is reasonable to conclude that floating metal nanoparticles in solution can be used as a novel method in sensory applications for the production of very sensitive plasmonic biosensors.

References

Abdulhalim, I.: Biosensing configurations using guided wave resonant structures. In: Optical Waveguide Sensing and Imaging, pp. 211–228. Springer (2008)
Amoosoltani, N., Yasrebi, N., Farmani, A., Zarifkar, A.J.: A plasmonic nano-biosensor based on two consecutive disk resonators and unidirectional reflectionless propagation effect. IEEE Sens. J. 20, 9097–9104 (2020)
Bahador, H., Heidarzadeh, H.: Analysis and simulation of a novel localized surface plasmonic highly sensitive refractive index sensor. Plasmonics 15(5), 1273–1279 (2020)
Belushkin, A., Yesilkoy, F., Altug, H.: Nanoparticle-enhanced plasmonic biosensor for digital biomarker detection in a microarray. ACS Nano 12(5), 4453–4461 (2018)
Chang, C.-Y., et al.: Flexible localized surface plasmon resonance sensor with metal–insulator–metal nanodisks on PDMS substrate. Sci. Rep. 8(1), 1–8 (2018)
Chen, C., Wang, J.: Optical biosensors: an exhaustive and comprehensive review. Analyst 145(5), 1605–1628 (2020)
Cubukcu, E., Kort, E.A., Crozier, K.B., Capasso, F.: Plasmonic laser antenna. Appl. Phys. Lett. 89(9), 093120 (2006)
Dastan, D.: Nanostructured anatase titania thin films prepared by sol-gel dip coating technique. J. At. Mol. Condens. Mater. Nano Phys. 2(2), 109–114 (2015)
Dastan, D.: Effect of preparation methods on the properties of titania nanoparticles: solvothermal versus sol–gel. Appl. Phys. A 123(11), 1–13 (2017)
Dastan, D., Chaure, N.B.: Influence of surfactants on TiO₂ nanoparticles grown by sol-gel technique. Int. J. Mater. Mech. Manuf. 2(1), 21–24 (2014)
Dastan, D., Londhe, P.U., Chaure, N.B.: Characterization of TiO₂ nanoparticles prepared using different surfactants by sol–gel method. J. Mater. Sci. Mater. Electron. 25(8), 3473–3479 (2014)
Highly sensitive refractive index sensor by floating…

Dastan, D., Panahi, S.L., Chaure, N.B.: Characterization of titania thin films grown by dip-coating technique. J. Mater. Sci. Mater. Electron. 27(12), 12291–12296 (2016)

Dastan, D., Chaure, N., Kartha, M.: Surfactants assisted solvothermal derived titania nanoparticles: synthesis and simulation. J. Mater. Sci. Mater. Electron. 28(11), 7784–7796 (2017)

Fernández-Domínguez, A., Wiener, A., García-Vidal, F., Maier, S., Pendry, J.: Transformation-optics description of nonlocal effects in plasmonic nanostructures. Phys. Rev. Lett. 108(10), 106802 (2012)

Heidarzadeh, H.: Analysis and simulation of a plasmonic biosensor for hemoglobin concentration detection using noble metal nano-particles resonances. Opt. Commun. 459, 124940 (2020)

Heidarzadeh, H.: Effect of parasitic absorption of the plasmonic cubic nanoparticles on the performance of a plasmonic assisted halide thin-film perovskite solar cell. Sol. Energy 223, 293–301 (2021)

Heidarzadeh, H., Bahador, H.: Photocurrent improvement of an ultra-thin silicon solar cell using cascaded cylindrical shape plasmonic nanoparticles. Phys. Scr. 96(5), 055501 (2021)

Heidarzadeh, H., Rostami, A., Dolatyari, M., Rostami, G.: Plasmon-enhanced performance of an ultrathin silicon solar cell using metal-semiconductor core-shell hemispherical nanoparticles and metallic back grating. Appl. Opt. 55(7), 1779–1785 (2016)

Jafari, A., et al.: Ion implantation of copper oxide thin films; statistical and experimental results. Surf. Interfaces 18, 100463 (2020)

Jangjoy, A., Bahador, H., Heidarzadeh, H.: Design of an ultra-thin silicon solar cell using localized surface plasmonic effects of embedded paired nanoparticles. Opt. Commun. 450, 216–221 (2019)

Jangjoy, A., Bahador, H., Heidarzadeh, H.: A comparative study of a novel anti-reflective layer to improve the performance of a thin-film GaAs solar cell by embedding plasmonic nanoparticles. Plasmonics 16(2), 395–401 (2021)

Johnson, P.B., Christy, R.-W.: Optical constants of the noble metals. Phys. Rev. B 6(12), 4370 (1972)

Kunz, K.S., Luebbers, R.J.: The Finite Difference Time Domain Method for Electromagnetics. CRC Press, Boca Raton (1993)

Liu, X., et al.: Ultra-sensitive graphene based mid-infrared plasmonic bio-chemical sensing using dielectric beads as a medium. Carbon 122, 404–410 (2017)

Liu, Y., Nie, Y., Wang, M., Zhang, Q., Ma, Q.: Distance-dependent plasmon-enhanced electrochemiluminescence biosensor based on MoS2 nanosheets. Biosens. Bioelectron. 148, 111823 (2020)

Mokari, G., Heidarzadeh, H.: Efficiency enhancement of an ultra-thin silicon solar cell using plasmonic coupled core-shell nanoparticles. Plasmonics 14(5), 1041–1049 (2019)

Ni, Y., Kan, C., Xu, J., Liu, Y.: The synthesis of high yield Au nanoplate and optimized optical properties. Superlattices Microstruct. 114, 124–142 (2018)

Rahmani, M., et al.: Subgroup decomposition of plasmonic resonances in hybrid oligomers: modeling the resonance lineshape. Nano Lett. 12(4), 2101–2106 (2012)

Shehadeh, A., Evangelou, A., Kechagia, D., Tataridis, P., Chatzilazarou, A., Shehadeh, F.: Effect of ethanol, glycerol, glucose/fructose and tartaric acid on the refractive index of model aqueous solutions and wine samples. Food Chem. 329, 127085 (2020)

Sobhani, F., Heidarzadeh, H., Bahador, H.: Photocurrent improvement of an ultra-thin silicon solar cell using the localized surface plasmonic effect of clustering nanoparticles. Chin. Phys. B 29(6), 068401 (2020a)

Sobhani, F., Heidarzadeh, H., Bahador, H.: Efficiency enhancement of an ultra-thin film silicon solar cell using conical-shaped nanoparticles: similar to superposition (top, middle, and bottom). Opt. Quantum Electron. 52(9), 1–13 (2020b)

Špačková, B., Wrobel, P., Bocková, M., Homola, J.: Optical biosensors based on plasmonic nanostructures: a review. Proc. IEEE 104(12), 2380–2408 (2016)

Sun, J., Lu, Y., He, L., Pang, J., Yang, F., Liu, Y.: Colorimetric sensor array based on gold nanoparticles: design principles and recent advances. TrAC Trends Anal. Chem. 122, 115754 (2020)

Tan, G.-L., et al.: Structures, morphological control, and antibacterial performance of tungsten oxide thin films. Ceram. Int. 47(12), 17153–17160 (2021a)

Tan, G.-L., Tang, D., Dastan, D., Jafari, A., Silva, J.P., Yin, X.-T.: Effect of heat treatment on electrical and surface properties of tungsten oxide thin films grown by HFCVD technique. Mater. Sci. Semicond. Process. 122, 105506 (2021b)

Tang, H., et al.: Plasmonic hot electrons for sensing, photodetection, and solar energy applications: a perspective. J. Chem. Phys. 152(22), 220901 (2020)

Tiefenthaler, K., Lukosz, W.: Sensitivity of gratings couplers as integrated-optical chemical sensors. JOSA B 6(2), 209–220 (1989)

Vázquez-Guardado, A., et al.: Enzyme-free plasmonic biosensor for direct detection of neurotransmitter dopamine from whole blood. Nano Lett. 19(1), 449–454 (2018)
Wang, L., Hasanzadeh Kafshgari, M., Meunier, M.: Optical properties and applications of plasmonic-metal nanoparticles. Adv. Funct. Mater. 30(51), 2005400 (2020)
Yee, K.: Numerical solution of initial boundary value problems involving Maxwell’s equations in isotropic media. IEEE Trans. Antennas Propag. 14(3), 302–307 (1966)
Zhou, W.-D., Dastan, D., Li, J., Yin, X.-T., Wang, Q.: Discriminable sensing response behavior to homogeneous gases based on n-ZnO/p-NiO composites. Nanomaterials 10(4), 785 (2020a)
Zhou, X.L., Yang, Y., Wang, S., Liu, X.W.: Surface plasmon resonance microscopy: From single-molecule sensing to single-cell imaging. Angew. Chem. Int. Ed. 59(5), 1776–1785 (2020b)
Zhu, S., Li, H., Yang, M., Pang, S.W.: High sensitivity plasmonic biosensor based on nanoimprinted quasi 3D nanosquares for cell detection. Nanotechnology 27(29), 295101 (2016)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.