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Hybrid graphene–molybdenum disulphide based ring resonator for label-free sensing

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ABSTRACT

In this paper, a novel graphene–MoS_2 hybrid structure based surface plasmon resonance sensor is presented for label-free analysis. The structure consists of a silicon nitride (Si_3N_4) dielectric layer vertically coupled to a thin layer of metallic strip made of silver (Ag) on top. A hybrid graphene–MoS_2 layer is added on top of the metallic strip to enhance the sensitivity and the quality factor of the sensor. The cladding layer is assumed to be porous alumina (p-Al_2O_3) increasing the interaction of the surface plasmon mode and the target molecules. Finite difference time domain analysis (FDTD) has been used to design and to analyze the performance of the sensor. It is shown that by addition of hybrid graphene–MoS_2 layer to the structure of a surface plasmon resonance based sensor, the refractive index sensitivity and the intrinsic quality factor of the sensor are enhanced simultaneously. It is also shown that addition of the hybrid graphene–MoS_2 layer leads to higher values of figure of merit (FOM) for the sensor, and consequently better performance of the sensor. Moreover, the effect of increasing the number of graphene and MoS_2 layers is investigated. The proposed sensor is very compact and can be used for lab-on-a-chip sensing applications.

1. Introduction

Label-free optical sensing has been a fascinating and fast-paced area in many fields such as medicine, biotechnology, and food quality control [1]. In this type of sensing, target molecules are not labeled, and are sensed in their natural forms through the change of refractive index of the interaction medium. This label-free scheme makes the sensing technique fast and simple due to eliminating the difficult preparation process for labeling the target molecules [2].

Various optical structures have been proposed for sensitive label-free detection, such as surface plasmon resonance based sensors [3,4], fiber based sensors [5,6], interferometer-based sensors [7], photonic traveling-wave resonator sensors [8,9] and photonic crystal based sensors [10]. Each of these techniques is proper for a special set of applications. Among them, surface plasmon resonance based sensors have been an attractive candidate for label-free biomolecule refractive index sensing [11]. A surface plasmon wave (SPW) is a charge density coherent oscillation that occurs at the interface between any two materials where the real part of the dielectric function changes sign across the interface, such as a metal (gold or silver) and a dielectric at optical frequencies [12]. These modes are very sensitive to the refractive index variation of the dielectric medium because of high confinement of the electromagnetic energy of a surface plasmon mode at the metal–dielectric interface [4].

Many materials have been used in the SPR based sensors. In recent decade, two dimensional (2D) nanomaterials have received a lot of attention because of their unique optical and electronic properties [13]. There are number of existing 2D nanomaterials such as transition metal dichalcogenide (TMDC) [14], transition metal oxides [15], topological insulators [16], silicene [17] and graphene [18]. Out of which, graphene has been one of the most extensively studied 2D nanomaterial since its first discovery in 2004 [19]. Recent studies have shown that by using graphene in the structure of a SPR based sensor, the sensitivity of the sensor can be enhanced [20,21]. In this case, the quality factor of the sensor however decreases due to high values of energy dissipation of graphene [22].

More recently, molybdenum disulphide (MoS_2), another 2D nanomaterial, that belongs to TMDC semiconductor group has attracted extensive attention due to its ultrathin direct bandgap semiconductor nature [23]. Although bulk MoS_2 has an indirect bandgap of 1.2 eV, monolayer MoS_2 has a direct bandgap of 1.8 eV because of quantum confinement effects making it suitable for electronic and optical applications [24,25]. It is shown that MoS_2 nanoresonators have considerably higher values of quality factors

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as compared to graphene nanoresonators because of lower values of energy dissipation [22].

In this paper, we first investigate the electromagnetic model of a graphene strip. We further design and analyze a hybrid graphene–molybdenum disulphide based ring resonator for label-free sensing. It is shown that by the addition of hybrid graphene–MoS_2 layer to the structure of a SPR based sensor, the sensitivity and the intrinsic quality factor of the sensor can be enhanced simultaneously which leads to the better performance of the sensor in terms of figure of merit (FOM). The effect of increasing the number of graphene and MoS_2 layers on the performance of the sensor is also investigated.

2. Electronic model of graphene

To investigate the electromagnetic properties of a single layer of graphene, we can model it as an extremely thin, local two-sided surface characterized by a two dimensional surface conductivity. The surface conductivity of the graphene strip σ_g can be expressed by the Kubo formula, which relates to the angular frequency ω, temperature T, chemical potential μ_c, and transport relaxation time τ [26]

$$\sigma_g = i\frac{e^2 K_B T}{\pi\hbar^2(\omega + i\tau^{-1})}\left[\frac{\mu_c}{K_B T} + 2\ln\left(\exp\left(-\frac{\mu_c}{K_B T}\right) + 1\right)\right] + i\frac{e^2}{4\pi\hbar^2}\ln\left[\frac{2|\mu_c| - \hbar(\omega + i\tau^{-1})}{2|\mu_c| + \hbar(\omega + i\tau^{-1})}\right] \quad (1)$$

where K_B is the Boltzman constant and $\hbar$ is the reduced Planck constant. The equivalent permitivity of the graphene strip is then expressed as [27]

$$\varepsilon_g = 1 + \frac{i\sigma_g\eta_0}{k_0\Delta} \quad (2)$$

where σ_g is the surface conductivity given in Eq. (1), η_0 is the characteristic impedance of air ($\simeq 377\ \Omega$), k_0 is the wavenumber of the incident light wave and Δ is the thickness of the graphene strip. In this work, we fix $T = 300$ K and $\tau = 0.5$ ps [28].

3. Principle of operation and design of the proposed structure

3.1. Principle of operation

The schematic diagram of the proposed sensor is shown in Fig. 1(a). It consists of a hybrid plasmonic-photonic ring resonator and a photonic bus waveguide side coupled to the hybrid resonator. The cross section of the resonator with different dimensions specified is depicted in Fig. 1(b). The hybrid resonator is a multilayer traveling-wave ring resonator which consists of a dielectric layer (Si_3N_4) as a dielectric resonator and a surface plasmon ring resonator made of a thin silver film, separated by a buffer layer of SiO_2 and a hybrid graphene–MoS_2 layer on top of the metal layer. The cladding layer is assumed to be a porous layer of alumina acting as the sensing medium. The substrate is assumed to be silicon dioxide (SiO_2). As it is observed in Fig. 1(b), R is the radius of the resonator, t_d is the dielectric layer thickness, t_b is the buffer layer thickness, t_m is the metal layer thickness, t_{g-m} is the thickness of the hybrid graphene–MoS_2 layer and t_c is the cladding layer thickness.

The transmittance spectrum of the waveguide shows a dip at the resonance wavelength of the structure. When the target molecules are adsorbed to the walls of the cladding layer, the average refractive index of the layer is changed leading to a shift in the resonance wavelength of the structure. This wavelength shift can be used to sense the existence of the target molecules.

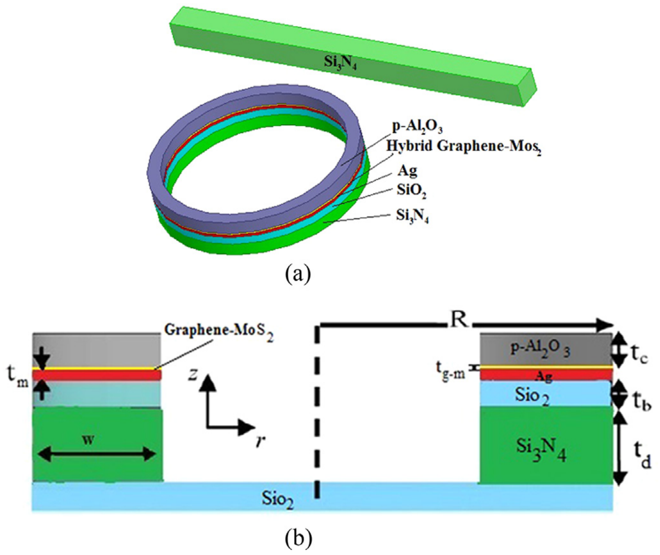

Fig. 1. (a) Schematic diagram of the proposed sensor consisting of a plasmonic-photonic ring resonator sensor and a photonic bus waveguide coupled to the hybrid resonator. The hybrid resonator consists of a traveling-wave resonator with the Si_3N_4 as the dielectric layer and a surface plasmon ring resonator made of a thin silver film, separated by a buffer layer of SiO_2 and a hybrid graphene–MoS_2 layer on top of the metal layer. The cladding is a porous layer of alumina. (b) Cross section of the hybrid resonator with the dimension specified on the figure, R is the radius of the resonator, t_d dielectric layer thickness, t_b is the buffer layer thickness, t_m is the metal layer thickness, t_{g-m} is the thickness of the hybrid graphene–MoS_2 layer and t_c is the cladding thickness.

3.2. Design of the proposed resonator

The hybrid ring resonator shown in Fig. 1 is a traveling-wave resonator. To design the resonator, we first investigate the equivalent hybrid ridge waveguide that has the same structure and the same cross-sectional dimensions as the ring resonator illustrated in Fig. 1(b). The hybrid waveguide supports TM-like confined modes, which is the mode type of interest in this paper. The design parameters for the waveguide structure are the dimensions, as shown in Fig. 1(b), and the material properties of different layers. The proposed hybrid resonator consists of seven layer. The first layer (substrate) is assumed to be (SiO_2), with the refractive index of $n = 1.44$ [4]. The second layer is the dielectric layer which is assumed to be Si_3N_4 with the refractive index of $n = 2$ [4]. The third layer is the buffer layer which is assumed to be (SiO_2), with the same refractive index as substrate. The fourth layer is the metal strip which is assumed to be Ag that supports surface plasmon waves at optical frequencies. Empirical material properties from [29] are used to model the Ag strip in our calculations. The fifth layer is MoS_2 layer which is added on top of the metal layer. The complex refractive index of monolayer MoS_2 is obtained from the experimental measurement data at [30]. The sixth layer of the structure is a graphene strip with the equivalent refractive index given in Eq. (2). The chemical potential of the graphene strip (μ_c) affects the surface conductivity of the graphene strip, and consequently affects the propagation constant of the surface plasmon mode. For larger values of μ_c, the surface conductivity of the graphene layer enhances leading to smaller values of the propagation constant of the surface plasmon mode [28]. The chemical potential of the graphene strip can be controlled by means of various methods such as chemical doping and applying an external electric filed or a bias voltage on the graphene strip [27]. To design the structure, we assume that the graphene layer