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Cavity-enhanced continuous graphene plasmonic resonator for infrared sensing

Wei Wei [a,b,c,d,*], Jinpeng Nong [a,b,c], Yong Zhu [b,**], Linlong Tang [c], Guiwen Zhang [b], Jun Yang [c], Yu Huang [c], Dapeng Wei [c,d]

[a] Key Laboratory of Optoelectronic Technology & Systems, Ministry of Education of China, Chongqing University, Chongqing 400044, China
[b] College of Optoelectronic Engineering, Chongqing University, Chongqing 400044, China
[c] Chongqing institute of green and intelligent technology, Chinese Academy of Sciences, Chongqing 401122, China
[d] Chongqing Engineering Research Center of Graphene Film Manufacturing, Chongqing 401329, China

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ABSTRACT

We propose a cavity-enhanced resonator based on graphene surface plasmonics for infrared sensing. In such a resonator, a continuous and non-patterned monolayer graphene serves as the sensing medium by exciting surface plasmons on its surface, which can preserve the excellent electronic property of graphene and avoid the interaction between biomolecules and dielectric substrate. To improve its sensing performance, an optical cavity is employed to enhance the coupling of the incident light with the resonator. Simulation results demonstrate that the reflection spectra of the resonator can be modified to be narrower and deeper to improve the figure of merit (FOM) of the device significantly by adjusting the structure parameters of the cavity and the Fermi energy level. The FOM can achieve a high value of up to 20.15 RIU^{-1}, which is about twice larger than that of the traditional structure without a cavity. Furthermore, the resonator can work in a wide angle range of the incident light. Such a plasmonic resonator with excellent features may provide a strategy to engineer graphene-based SPR sensor with high detection accuracy.

1. Introduction

Surface plasmon resonance (SPR) [1,2] is well known as one of the most outstanding optical sensing technology for allowing fast-speed, label-free and non-destructive detection with high sensitivity. Extensive efforts have been devoted to engineering metal-based SPR biosensors at visible and near-infrared frequencies [3–5]. However, the intrinsic shortcomings of traditional noble metals, such as the high surface inertness, the high intrinsic hydrophobicity and the large electronic density of states [6–8], become the major obstacles on the way of developing infrared SPR sensors. Graphene [9] that emerged as a revolutionary two-dimensional (2D) material, offers an unique opportunity to address this situation. It supports the propagation of surface plasmonics waves at infrared frequencies [10–12] with lower loss and higher confinement compared to the metals. And it can also adsorb the biomolecules efficiently attributed to its high surface-to-volume ratio and the π-stacking interactions between graphene and biomolecules. In addition, the frequency of surface plasmonics can be widely modulated within a wide range of infrared waveband via external gate voltage [13]. The combination of these distinctive features renders graphene a promising plasmonics material for infrared SPR sensing.

Recently, the excitations of localized surface plasmons in patterned graphene (nano-ribbons [14], nano-rings [15], nano-disks [16] and anti-dot arrays [17]) have been theoretically investigated for SPR sensing [7,18,19]. Though the performance of sensors are improved by optimizing the structure parameters and the properties of graphene layers, the preparation process of patterned graphene destroys its integrity. This severely decreases the contact area between graphene and biomolecules, and also dramatically reduces its electron mobility, which restricts the further improvement of the performance. Therefore, it is highly desirable to excite the surface plasmons in continuous graphene sheet. Apart from preserving the integrity and the high mobility of graphene, continuous graphene sheet can also provide brand-new advantages for sensing applications, including (1) excellent anti-fouling ability, (2) negligible interference from the interaction between biomolecules and dielectric substrate due to the high

* Corresponding author at: Key Laboratory of Optoelectronic Technology & Systems, Ministry of Education of China, Chongqing University, Chongqing 400044, China.
** Corresponding author at: College of Optoelectronic Engineering, Chongqing University, Chongqing 400044, China.
E-mail addresses: wwei@cqu.edu.cn (W. Wei), yongzhu@cqu.edu.cn (Y. Zhu).

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electron density of hexagonal rings that can be impermeable to the atoms and molecules, and more importantly, (3) offering a homogenous and complete 2D surface that is responsible for the highly uniform and effective surface loading of the biomolecules [20,21]. Recent studies theoretically and experimentally demonstrated the excitations of the surface plasmons in continuous graphene sheet with various sub-wavelength grating to compensate the mismatch of wavevector [22–25]. In such schemes, the rough sub-wavelength structures may degenerate the performance of the devices due to the deterioration of mobility caused by the increase of the interface scattering compared to the flat substrate. To resolve these problems, a hybrid grating structure is proposed by adding a low-permittivity buffer layer underneath the graphene sheet, which exhibits an improvement of 45.13% in sensitivity [26]. However, the improvement of the sensitivity of such transmission configuration is always accompanied with the dramatical red-shift of the resonance wavelength. This results in the increase of the real part of surface conductivity, and consequently the broadening of the spectral line, which decreases the figure of merit (FOM) of the devices. Though the FOM for a specific resonant wavelength can be theoretically improved by increasing the quality (carrier mobility) of graphene, it cannot be tuned in practice since the carrier mobility is the intrinsic property of graphene. Further improvement of the FOM remains challenge.

Herein, we propose a cavity-enhanced infrared SPR sensor based on surface plasmons in continuous graphene sheet to improve the FOM of the sensor while maintaining the quality of graphene. A thick gold film is introduced to form a resonance cavity to enhance the interaction between the graphene and the incident wave. Thus the spectral lines can be reshaped (to be narrower and deeper) without changing the resonance wavelength to achieve the maximum FOM. The temporal coupled mode theory is employed to reveal the reshaping of the spectral line with varying F–P cavity length. Finally, we further investigate the actively tuning of FOM by adjusting the Fermi energy level and the dependence of the performance on the incident angle. Understanding of these mechanisms will greatly facilitate the design of graphene-based SPR sensors with high detection accuracy.

2. Structure and method

A schematic view of the considering cavity-enhanced continuous graphene plasmonic resonator is illustrated in Fig. 1(a). A continuous doped graphene sheet is resting on an insulator-covered sub-wavelength silicon grating (ICSWSG). The graphene

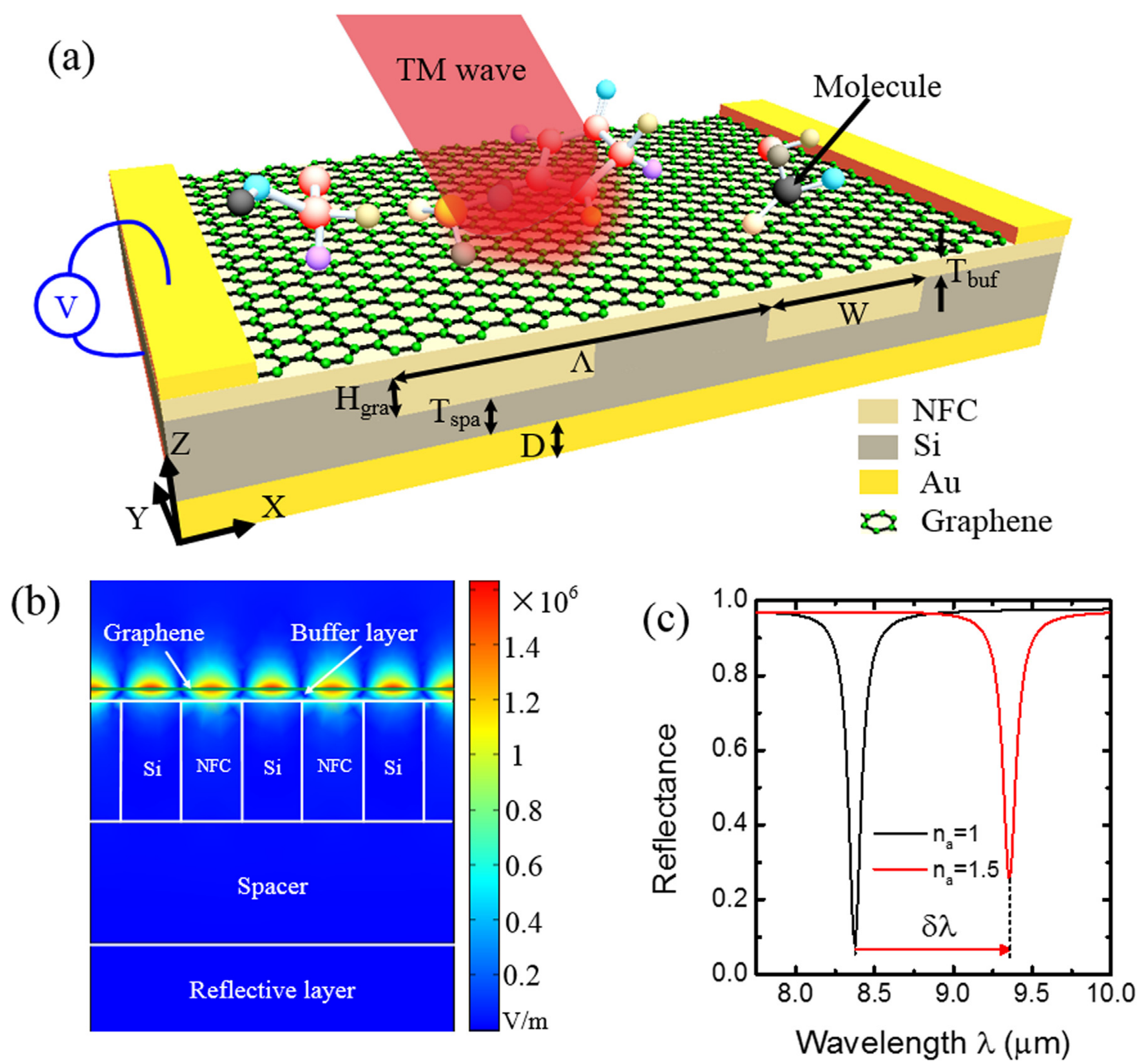

Fig. 1. (a) Schematic of the ICSWSG resonator with deposited reflective layer. (b) Calculated GSP mode pattern when T_{buf}=10 nm, Λ=200 nm, W=100 nm, H_{gra}=200 nm, T_{spa}=200 nm and D=100 nm. The while lines in (b) depict the profile of the ICSWSG. (c) The evolution of the reflection spectra with increasing refractive index of the sensing medium.

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