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Invited Paper

Infrared photodetectors based on graphene metal nano clusters

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A B S T R A C T

Graphene is an outstanding photoconductive material for photodetection because of its wide range absorption spectrum and ultrafast response. It is well understood that by adding metal nanoparticle clusters on graphene layer enhances the absorption, also makes possible to focus on a particular region of the optical spectra via subwavelength plasmonic resonances between nanocluster and graphene substrate.

In this article, we have designed an improved structure for gold nonamer nanodisk arrays on graphene as a photodetector to enhance the light absorption for optical communication spectrum. Effects of different structural parameters on absorption spectrum have been investigated, numerically. We have shown that light absorption in graphene-based detectors can be manipulated by tuning cluster size, thickness, inter disks gap distance, graphene position, and the number of graphene layers. By changing the radius of central and peripheral disks, we have shown that the Au nonamer on top of graphene is able to support strong sub- and superradiant plasmon resonances because of its unique geometrical features and a second absorption peak is generated. This additionally generated absorption peak is more suitable for application in 1550 nm nanostructure photodetectors.

1. Introduction

Graphene is an appealing two-dimensional (2D) material which forms a honeycomb crystal lattice for photonic and electronic devices owing to its exceptional high carrier mobility, single-atom layer thickness, unique optical characteristics, and superb mechanical flexibility [1,2]. Abundance of free carriers as well as the linear dispersion of graphene, and the lack of a bandgap in the Dirac points, besides the unusual doping properties, make graphene as a material of inestimable potential for optoelectronic applications such as transparent electrodes [3], solar cells [4], phototransistors [5], and ultrafast photodetectors [6]. However, the intrinsically low absorption (%2.3) and low quantum efficiency are the main limits for using graphene in high-performance devices [7]. Due to the wavelength-independent absorption of graphene, it does not show spectral selectivity from 300 nm to 2500 nm [7].

Recently, there has been extensive interest in growing graphene detectors because of ultra-wideband absorption spectra from the UV to the far-infrared (FIR) and also, due to very short response time [8]. Ultrafast photodetectors based on graphene in the near infrared (NIR) region have been reported with a bandwidth over 40 GHz with low responsivity of ~5mA/W [6,9,10]. Some attempts have been done to enhance the optical absorption [11,12], photocarrier multiplication [13,14], and responsivity in graphene [15,16] while the low efficiency of collecting photocarriers originated from the short carrier lifetime, is the main limiting factor for graphene based detectors. A good method for improving the responsivity in these detectors is enhancement of carrier lifetime by employing carrier trapping mechanisms which in turn increases the detector response time to a few seconds or milliseconds [17].

Recent considerable studies on graphene plasmonics have been lead to appealing properties involving large mode confinement via graphene plasmonics [18]. Adjustment of Fermi level (which determines the optical response of graphene) relative to the Dirac point with chemical or electrostatical methods has been accomplished in less than a nanosecond [19]. It has been demonstrated that noble metal films and nanoparticles on top of graphene as a plasmonic configuration can modify properties of graphene based photodetectors [20,21]. Nanoclusters with plasmonic properties such as heptamers, nonamers, and more complex clusters, patterned directly on the graphene sheet are promising candidates for injecting hot carrier into graphene via light illumination [22–24]. As an example, closely spaced, coupled nanoparticles known as plasmonic oligomers, have been utilized as an effective antenna tool in the visible and near-infrared region which provide strong field enhancements in the gap regions of the coupled nanoparticles [24]. Manipulating geometrical and physical parameters

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of these plasmonic oligomers, unique spectral lineshapes known as Fano resonances (FR) are created that distinguished by a narrow spectral transparency window where scattering is suppressed and absorption is strongly enhanced [24]. Appearance of Fano resonance is due to the interference between a broad bright superradiant mode and a narrow dark subradiant mode which does not directly couple to the incident radiation [25]. The interference quality of the subradiant dark and superradiant bright modes results in the FR where the sharpness, depth, and position of plasmonic FR is strongly dependent on the shape and materials of which nanoparticle clusters are composed [26].

Nanostructures consisting of an arrangement of coupled (closely-spaced) nanoparticles, can be designed and engineered to show large absorption cross sections and strong field enhancements due to the gaps between the coupled nanoparticles. Also, plasmonic nanostructures show. This behavior originates from a weak coupling between a spectrally broad bright superradiant plasmon mode and a spectrally narrow dark subradiant mode that does not couple directly to incident radiation. By exciting the plasmonic nanostructure at the wavelength of the subradiant mode, light is coupled into the subradiant mode through the superradiant mode and can result in a strong indirect excitation of the subradiant mode. Since the subradiant mode is dark and does not directly couple to radiation, its dominant decay mechanism is electron-hole pair formation which leads to efficient production of hot electrons. Therefore, excitation of a plasmonic Fano resonance results in enhanced absorption and hot electron generation compared to excitation of standard bright plasmon resonances. Thus, this unique property of plasmonic Fano resonances can be exploited to enhance the absorption rate and the photocurrent in plasmon based photodetectors.

Graphene plasmonic nanostructures enhance the electric field intensity, absorption, and scattering. Although these structures have been considered in various detectors, an improved detector with optimized characteristics can be realized by proper structural engineering and modification of the structural parameters such as the gap distance, the nanoparticle thickness, and the size of nanoparticles.

In this article, we present a photodetector based on Au nonamer cluster on graphene substrate. The proposed structure consists of a central nanodisk surrounded by eight peripheral disks. The Effect of all structural parameters on the absorption spectrum are investigated. A design procedure to achieve the optimum nonamer plasmonic detector on graphene substrate is also proposed as well.

2. Nanocluster-graphene optical photodetector

Noble metals such as Au and Ag are widely utilized as the best available plasmonic materials, while plasmon ohmic losses in these metals are generally large in the visible and the NIR spectral range [27]. Due to coupling between photons in the infrared region with surface plasmons in graphene, surface plasmon-polaritons (SPPs) with long propagation length are formed [28].

It should be noted that for infrared detection applications, semiconductors such as HgCdTe, PbS, and GeInAs have been widely utilized which efficiently collect radiation across the infrared spectrum. However, for many optical filtration and biomedical applications, there is a requirement that the infrared material incorporated into another media should be nontoxic, or that the material should be small enough to pass through a specific pore size. On the other hand, the strong optical extinction of submicron metal particles such as gold nanoparticles provides an alternative method for accessing the infrared. The mentioned optical extinction of metal nanoparticles is due to plasmon resonances. The wavelength and magnitude of the extinction are determined by the electromagnetic boundary conditions at the metal/embedding medium interface [29]. Metal nanoparticles bridge the gap between the atomic level and the bulk, exhibiting mesoscopic properties unique to this size regime [30].

Due to the small group velocity of the propagating plasmons and the strong electromagnetic (EM) wave's confinement in the vicinity of the graphene layer, plasmon gain is very large in graphene [27]. In order to enhance the absorption ratio, design of plasmonic photodetectors can take benefit from the confined EM energy in a single graphene layer at desired resonance frequencies.

Based on the random-phase approximation (RPA), the complex conductivity of graphene consisting of the interband and the intraband terms can be derived according to the Kubo formula [28]:

$$\sigma_{total}(\omega) = \sigma_{\text{intra}}(\omega) + \sigma_{\text{inter}}(\omega) \tag{1}$$

$$\sigma_{\text{intra}}(\omega) = \frac{e^2 E_F}{\pi\hbar^2}\frac{i}{i\tau^{-1}+\omega} \tag{2}$$

$$\sigma_{\text{inter}}(\omega) = \frac{e^2}{4\hbar}\left[(\hbar\omega - 2E_F)\phi + \frac{i}{\pi}\log\left|\frac{\hbar\omega - 2E_F}{\hbar\omega + 2E_F}\right|\right] \tag{3}$$

The Fermi energy is defined through E_F and τ is the relaxation time defined by $\tau = \mu E_F/ev_f$, (here, v_f is the Fermi velocity (10^6 ms^{-1}), and μ is the electron mobility ($\approx 10^4$ cm^{2}V^{-1}s^{-1}). Eq. (2) represent the Drude model for highly-doped regions of a graphene layer for the frequency range below the Fermi energy. Using $E_F = \hbar v_f\sqrt{(\pi\,|n|)}$, one can change the Fermi energy through electrostatic doping of charge carriers with a density of n [31].

Generally, for lightly-doped graphene ($|\mu| < \hbar\omega/2$), the high-frequency dynamic conductivity which involves the telecommunication band and also the mid-IR region is dominated by the interband term. At the other hand, the intraband term is applicable in the terahertz range where $|\mu| > \hbar\omega/2$. This condition allows for plasmon momentum enhancement, and thus propagation of surface plasmon in graphene is possible [32,33].

Fig. 1 illustrates the schematic of the proposed graphene-based photodetector with a nonamer cluster array on top of it. As discussed in [34], changing the inner and outer nanodisk radii can be used as a design degree of freedom to reshape the scattering cross-section. Therefore, choosing a nonamer nanocluster can provide more design flexibility to modify the absorption spectra. This design flexibility allows the creation of a stronger secondary absorption peak which is due to much-intensed stimulation of quadra-pole modes. We will show that the secondary peak also shifts to longer wavelengths by increasing the dimensions of the cluster and provides an important design flexibility for a photodetector at telecommunication wavelengths.

The overall detector structure is composed of Si/ SiO_2/ graphene/ gold nanocluster regions of which the periodic nonamer cluster consists a gold central nanodisk with radius of r_1 surrounded by eight gold nanodisks with radii of r_2. Also, all of the nanoparticles are located with an identical gap distance from each other. Other geometrical and physical parameters of given structure are listed in Table 1.

The shape of nanostructures and their dimensions determine the

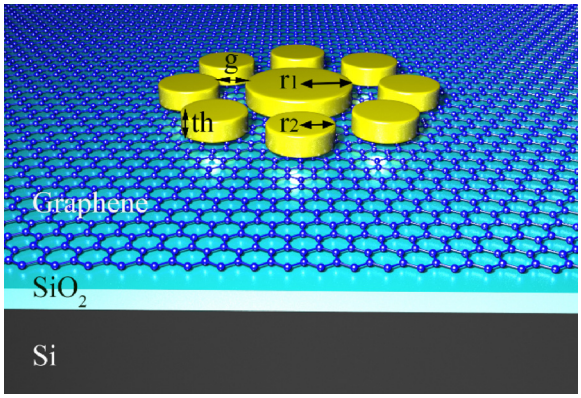

Fig. 1. Schematic illustration of the graphene-based photodetector with plasmonic nonamer clusters along with the geometrical parameter specifications based on Table 1.