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بهبود جذب نوری آشکارساز گرافنی ناشی از نانوذرات پلاسمونیکی هرمی شکل طلا در طیف مرئی

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چکیده – در این مقاله آشکارساز گرافنی مبتنی بر نانوذرات پلاسمونیکی طلا به شکل هرمی و قاعده مربعی شکل معرفی شده است. گرافن به عنوان ماده ای با خواص الکترونیکی مناسب برای آشکارسازی در طول موج مرئی مورد استفاده قرار گرفته است. یکی از محدودیت های اساسی گرافن تک لایه در افزاره های اپتوالکترونیکی، جذب نور کم(در حدود ۲/۳٪) در طول موج مرئی می‌باشد. لذا در مقاله ارائه شده سعی در بهبود مقدار جذب گرافن با استفاده از خواص پلاسمونیکی سطح مشترک نانوذرات هرمی¬شکل طلا و گرافن نموده ایم که محدودیت فوق را مرتفع می-سازد. در این صورت می‌توان با تغییر پارامتر های هندسه افزاره، مقدار جذب را بهبود بخشید. نتایج حاصل از شبیه سازی نشان می‌دهد که مقدار جذب به بیش از ۱۱ برابر نسبت به حالت عدم حضور نانوذرات افزایش یافته است که زمینه کاربرد گرافن تک لایه را در طول موج مرئی برای استفاده در افزاره ها تسهیل می‌کند.

کلید واژه- آشکارساز، پلاسمونیک، طول موج مرئی، گرافن، نانوهرم

Improvement of the optical absorption in graphene-based Photodetector using plasmonic pyramid-shaped gold nanoparticles at visible spectrum

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Abstract- In this paper, a graphene photodetector based on plasmonic gold nanoparticles in the form of the pyramid with square sides has been introduced. Graphene is used as a material with desired electronic properties for detection in the visible wavelengths. One of the major limitations of monolayer graphene is its low light absorption (about 2/3%) at visible spectrum. In the present work, we have improved the light absorption of a monolayer graphene employing plasmonic properties of the pyramid-shaped gold nanoparticles on top of graphene which enhances light absorption. In the our given structure, we have change the geometric parameters of the structure via optimization of light absorption. Simulation results demonstrate that the amount of light absorption is enhanced more than 11 times in comparison to the structure without nanoparticles. This would facilitate the application of monolayer graphene in optoelectronic devices at visible wavelengths.

Keywords: Photodetector, plasmonic, visible wavelengths, graphene, nanopyramid

1 Introduction

Graphene is a remarkable material for Photonics and optoelectronics because of its unique properties and wide applications from waveguides [1], biosensing, optical modulators [2], splitters [3] and high-speed lasers. In recent years, intrinsic characteristics of graphene caused to developing the Photodetectors. The Zero effective mass of Charge carriers and crystallinity lead to high mobility carriers in graphene. The Graphene band structure shows gapless properties that enable it as a promising material for light absorption and charge carrier generation over a wide energy spectrum. However, the absorption of monolayer graphene in the visible range is smaller than terahertz frequencies (2.3 % of incident light) that could decrease the photocurrent generation and photoresponsivity in photodetectors. This is one of the major limitations of its development in optoelectronic devices. At the present work, we focused our attention to enhance the light absorption of graphene from 400nm to 800nm by this fact that electromagnetic coupling between nanoparticles and plasmonic effect lead to more light confinement.

2 Modelling

Fig.1 shows the proposed graphene-nanopyramid structure consists of monolayer graphene decorated by pyramid-shaped gold nanoparticles (PsNP) with square sides on Si/SiO_2 substrate. The size and height of PsNP and pitch of simulated region is *a*, *h* and *P*, respectively.

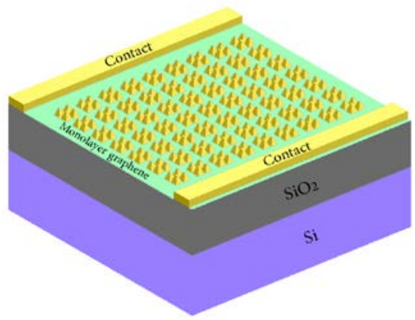

Figure 1: Schematic view of proposed Graphene-metal nanoparticle Photodetector

Relative permittivity of gold nanoparticles can be defined by Drude model:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + j\gamma\omega} \qquad (1)$$

Where ε, ω and γ are the dielectric constant at infinite frequency, bulk plasmon frequency and the distinctive collision frequency, respectively[4]. The refractive index of SiO_2 can be set as 1.46. Surface conductivity of monolayer graphene is characterized by Kubo formula [5]. Complete surface conductivity of graphene can be defined as a sum of intraband electron-photon scattering and interband transition:

$$\sigma_{total} = \sigma_{inter} + \sigma_{intra} \qquad (2)$$

$$\sigma_{inter} = i\frac{e^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - \hbar(\omega + i\tau^{-1})}{2|\mu_c| + \hbar(\omega + i\tau^{-1})}\right) \qquad (3)$$

$$\sigma_{intra} = \frac{e^2}{\pi\hbar^2}\frac{2k_BT}{\tau^{-1} - i\omega}\ln\left(2\cosh(\frac{E_f}{2k_BT})\right) \qquad (4)$$

Here e, μ_c, k_B, $\hbar$ and T are the electron charge, chemical potential, Boltzmann's constant, reduced Planck's constant and temperature, respectively. Interband transition is the dominant term at visible frequencies. We considered it as the total graphene surface conductivity for simulation process. Permittivity of graphene can be expressed as:

$$\varepsilon_g = 2.5 + i\frac{\sigma}{\varepsilon_0\omega d} \qquad (5)$$

We used finite difference time domain (FDTD) method with periodic boundary conditions for one unit cell in x-y plane to simulate the proposed structure. Lumerical FDTD is employed as commercial software for the simulation process that could solves Maxwell's equations. The physical parameters of the graphene can be set as μc=0.28 eV, T=295 K, τ=0.6 ps, thickness d=0.34nm, respectively. When the chemical potential is above the interband transition energy of ħω/2(i.e. 0.77eV at a wavelength of 800 nm), electrons occupy all of the possible states that photoexcited electrons can transition to, and the absorption of photons is decreased[2].

3 Result and discussion

We investigated the dependence of the light absorption on some parameters of the system. First, we considered silica substrate and monolayer graphene without nanoparticles. Simulation result shows the maximum absorption of 3.1% at 584 nm. As depicted in fig.2, by placing one PsNP on the top of the monolayer graphene, its light absorption is increased by 4.7 times more than before and reached to 14.5% at 680 nm. This is because of plasmonic effect between graphene and PsNP interface. However, absorption enhancement is influenced by two facts: hot electron (HE) injection of nanoparticles and plasmonic resonant effect which increases the optical near field in the monolayer graphene. Here, we simulated the second term as an important effect. We plotted the electric field distribution of PsNP at the highest absorption peak in Fig.4. However, to ensure the absorption mechanism by plasmonic effect at the interface between graphene and gold nanoparticle, we repeated our simulation of the structure without the presence of monolayer graphene. We found that gold metallic nanopyramid possesses 51% of light absorption without graphene layer, but the absorption decreases to 33.1% with graphene layer at the wavelength of 613 nm. This is in agreement with the result in fig.4.

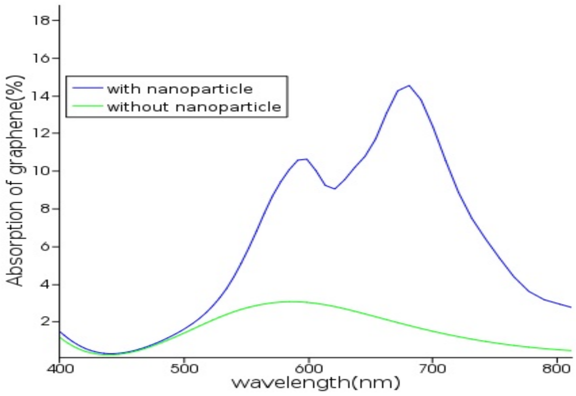

Figure 2: Light absorption of graphene with and without a gold nanoparticle (a=50 nm, h=30nm, p=100nm).

The geometry of the nanoparticle is symmetric, therefore, it does not matter to change the polarization of incident light in x or y direction. Different polarizations have the same results. We found that by increasing the size of the PsNP, resonant peak moves to longer wavelengths, as shown in fig. 3. If we set the pitch of the simulation region as a constant number, by adjusting the size of PsNP, we would able to provide a good pathway for the light confinement. For example, when the size of PsNP is so small, coupling between adjacent PsNP is not so enough and the light confinement is reduced. So, photocurrent generation will be low.

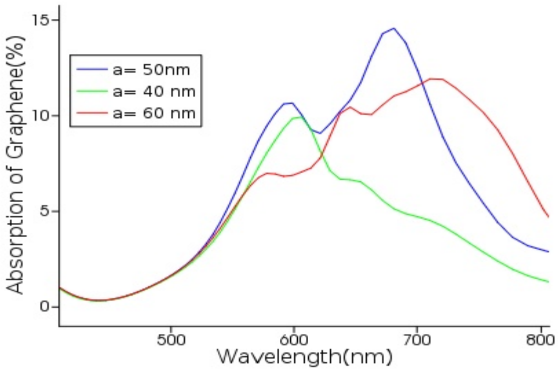

Figure 3: Plasmonic resonant peak position when h=30 nm.

In addition to nanoprymid, PsNP height variations also can be used to increase the plasmonic resonant effect and optimize the light absorption. Fig.4 shows absorption changes versus wavelength for different height of simulated PsNP. Maximum absorption of 17.8% at 613 nm is obtained.

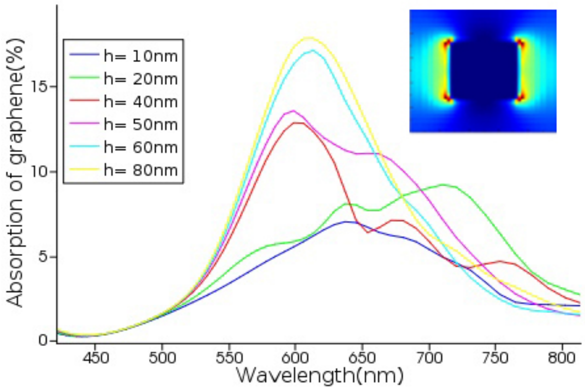

Figure 4: Light absorption of graphene for different nanprymid height. Inset shows $|E|^2$ for nanoprymid with a=50 nm , h= 80 nm and p= 100 nm.

Increasing of the PsNP height eventuate an increase in the amount of the absorption. Inset illustrates the electric field distribution of the simulated structure. As can be seen, light concentrates in the corners of square sides. However, there are some losses due to light scattering in the corners and Pyramid-shaped section that we did not consider it in our simulation.

As described before, the array pitch *p* is another parameter to determine the light absorption of the graphene. We also considered this effect. Choosing efficient size of array pitch would provide good electromagnetic coupling associated with the PsNP plasmonic effect and results strong light confinement.

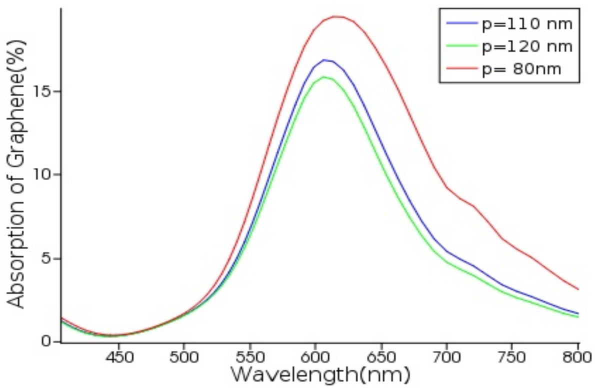

Figure 5: Light absorption of graphene for different pitches.

Another way to optimize the light absorption of graphene is utilizing nanoantennas with different geometries and sizes. Recently, some practical works have been done to improve the performance of Photodetectors using nanoantennas[6]. Here, we also investigated four pyramidal nanoantennas with a six nanometer-gap between them. Local field around the nanoantennas could excite the surface plasmons at the interface between graphene and nanoantenna and increase the output photocurrent. According to the Fermi's golden rule generation of carriers is proportional to the intensity of the local field ($|E|^2$).

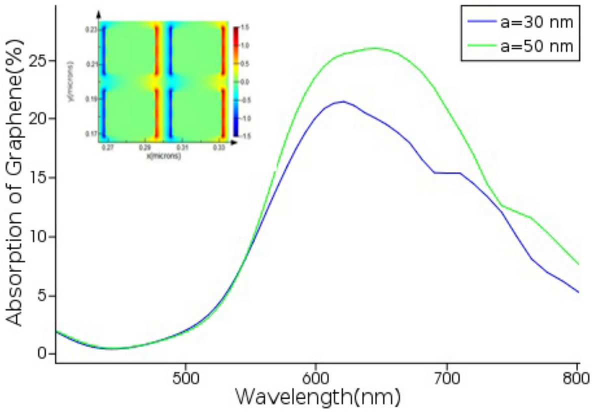

Figure 6: Optical absorption of graphene for four pyramids and two different sizes of square sides. Inset shows the hybrid plasmons at the interface between graphene and nanoantennas.

4 conclusions

In summary, we propose using of nanopyramids on the graphene that the electromagnetic coupling of the nanoparticles enhance the light absorption of graphen in two ways: first, direct excitation of plasmons in graphene by plasmonic effect at the interface of graphene and nanoparticles, and second, hot electrons that due to a gapless property of graphene, they could inter conduction band of graphene. We utilized FDTD method to simulate the photodetector. Simulation results demonstrate that by plasmonic effect of graphene-gold nanopyramid, we were able to improve the light absorption of monolayer graphene from 2.3% to 26% at 645nm.

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