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Mid-infrared plasmonic tuning via nanogap control in periodic multilayer graphene nanoribbons

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ABSTRACT

Plasmonic tuning at mid-infrared wavelength by regulating the nanogap between the adjacent multilayer graphene nanoribbons (GNs) is investigated with Finite-Difference Time-Domain (FDTD) method. The 100-nm-wide multilayer GNs formed on a SiO_2/p-Si show that plasmon resonance moves to longer wavelength by decreasing the nanogap from 100 nm to 5 nm, due to the inter-nanoribbon attractive interaction. Also, the resonance wavelength shifts are 7.0, 4.8 and 3.9–3.3 μm in this nanogap range for 1-, 2-, 3- and 4-layer GNs, respectively, at Fermi energy (E_F) of 0.2 eV, implying enhanced confinement in plasmonic oscillation as the number of graphene layer increases. Meanwhile, by shifting the E_F from 0.2 eV to 0.4 eV, the resonance peaks for each multilayer GN move to shorter wavelengths, and the peak shifts in the same nanogap range are further decreased resulting from the increased charge carriers involved in the localized plasmonic oscillation. These observed results can provide an insight in designing mid-infrared plasmonic devices for advanced nano-photonic systems.

1. Introduction

Graphene has attracted widespread interest due to its extremely high mobility and light absorption over a broad wavelength, producing great promise for the development of advanced nano-electronics and nano-photonics [1–4]. The low density of states of carriers near Dirac point resulting from its linear energy dispersion can be changed significantly with low electrical energy [5]. An excess of electrons or holes in doped graphene can produce collective plasmonic oscillations [6–8]. These graphene-based plasmonic modes can be tuned via chemical or electrostatic doping, and expected to be future platforms for highly integrated plasmonic devices operating at the infrared and THz frequencies [9–12]. To develop broadly tunable graphene-based plasmonic circuits, it is essential to enhance and manipulate light absorption in the graphene. Thus, periodic diffractive grating structures was used to achieve highly confined plasmonic waves in a continuous monolayer graphene [13]. Also, a graphene optical absorber inspired by metal-dielectric-metal meta-material was adopted for perfect absorption of electromagnetic waves [14]. Moreover, plasmonic oscillations bounded by the graphene nanoribbon (GN) were used to induce the plasmonic resonance in mono- and few-layer doped graphene ribbon arrays [15]. The study on the propagation of plasmons guided along individual and interacting monolayer GNs suggests the additional control of these excitations by the surrounding dielectric layer and the relative arrangement of the interacting waveguides [16]. Most of the researches on the plasmonic tuning have been performed with varying the width, the number of layer and the Fermi level (E_F) of GNs. However, there have not been enough studies on the plasmon resonance tuning by varying the nanogap between the multilayer GNs, especially for the narrower gap size compared to the width.

Therefore, in this paper, we systematically investigate the mid-infrared plasmonic tuning with decreasing the nanogap from 100 nm to 5 nm between the adjacent 100-nm-wide GNs formed on a SiO_2/p-type Si using three-dimensional Finite-Difference Time-Domain (FDTD) simulation. The observed resonance peaks are redshifted with decreasing the nanogap, and the resonance wavelength shifts in this nanogap range are reduced with increasing the number of graphene layer. Also, the resonance wavelengths and their shifts decrease with increasing E_F of GNs. The observed resonance wavelength shift and minimum transmittance variation of the multilayer GNs as a function of the nanogap are explained taking into account the inter-nanoribbon attractive interaction, as well as the localized plasmonic oscillation in the GNs for different number of graphene layer.

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2. Numerical calculation

The schematic illustration of the periodic mono- and multilayer-GN for use in our numerical calculation is shown in Fig. 1. Here, the width of the GN is fixed at 100 nm, and the nanogap between the adjacent GNs is varied from 5 nm to 100 nm. The mono- and multilayer-GNs are formed on the top of SiO_2 layer deposited on p-type Si substrate, and the Au electrode is patterned on these periodic GNs. Thus, the E_F of graphene can be easily tuned by the electrostatic doping when a bias voltage is applied to the p-Si substrate with respect to the grounded Au electrode.

A normally incident light polarized perpendicular to the nanoribbons restricts the motion of the free carriers exciting the localized plasmonic resonance [4,17]. To analyze the plasmon resonance of periodic multilayer GN in comparison with the monolayer one, we performed full electromagnetic wave simulation using a three-dimensional FDTD solution package (Lumerical solutions). Here, the GNs are oriented along the y-direction, so periodic boundary conditions are used along the x- and y-directions, while perfectly matched layer condition along the z-direction. The plane wave source is impinged along the z-axis towards the GNs with a wavelength range of 5–25 μm to estimate the transmittance after passing through the device structure. The monitor is placed at the SiO_2 layer underneath the graphene pattern because the p-Si substrate with a resistivity of 5–6 Ω-cm has a transmittance less than 50% at these mid-infrared wavelengths.

The surface conductivity [S] of monolayer graphene is given by [18]

$$\sigma(\omega,\Gamma,E_F,T)=\sigma_{intra}(\omega,\Gamma,E_F,T)+\sigma_{inter}(\omega,\Gamma,E_F,T) \quad (1)$$

where ω is the angular frequency, Γ is the scattering rate, E_F is the Fermi energy and T is the temperature. The two conductivity terms in Eq. (1) come from the intraband and interband terms, respectively. The E_Fs considered here are 0.2 eV and 0.4 eV, and the scattering rate corresponds to 0.001 eV at the temperature of 300 K. Thus, the values obtained by means of Eq. (1) are used to carry out the FDTD simulation for the GNs. We also considered GNs that have one-, two-, three- or four-layer graphene, where the conductivity for N-layer graphene is $N\sigma$ by scaling the surface conductivity with the number of layers [19].

3. Results and discussion

Fig. 2 shows the transmittance as a function of wavelength for two nanogaps of 10 nm and 20 nm between the adjacent GNs at the E_F of 0.2 eV depending on the number of graphene layers (N = 1, 2, 3, 4). Here, ΔT and Δλ represent the differences in the minimum transmittance and the resonance wavelength, respectively, as the nanogap varies for each GN. The transmittance value of off-resonance region for the GNs is ~0.97 in this mid-IR wavelength. As the number of graphene layer increases from 1 to 4 with a nanogap of 20 nm, the resonance wavelengths are observed at 17.5, 12.6, 10.4 and 9.2 μm, while the transmittances at each resonance wavelength are 0.307, 0.177, 0.128 and 0.107, accordingly. By reducing the nanogap to 10 nm, the resonance peaks are redshifted to 19.3, 13.9, 11.5 and 10.1 μm with the corresponding minimum transmittance of 0.271, 0.147, 0.100 and 0.079, respectively. At the plasmon resonance in the GN, the condition $Width \sim m\lambda_{GP}/2$ is approximately satisfied [20], where $\lambda_{GP} = 2\pi/\mathrm{Re}(k_{GP})$ is the wavelength of plasmon resonance and m is the number of the half of wavelengths that fit inside the width of GN at a mode. In the considered mid-infrared range, $\mathrm{Re}(k_{GP})$ can be represented by $\hbar\omega^2/(2\alpha_0\mu c)$, where α_0 is the fine structure constant. Thus, the resonance wavelength is related to the excitation of the longest wavelength in each GN by the following equation [20]

$$\lambda_p \sim \sqrt{2\pi c\hbar/(n\alpha_0 E_F)} \sim \sqrt{Width/E_F} \quad (2)$$

Then, the observed results in Fig. 2 imply that the plasmon coupling strength near the edge of GNs gets stronger as the nanogap decreases.

To quantify the plasmon coupling enhancement in the periodic GNs by inter-nanoribbon attractive interaction, we analyze the electric field distribution of this structure at each resonance wavelength for the nanogap of 10 nm and 20 nm as illustrated in Fig. 3. Electromagnetic coupling of both optical fields at the air/GNs and SiO_2/GNs interfaces shows that the electric field surrounding the corners of GNs is concentrated and enhanced such that the maximum amplitude of electric field becomes 120 (88), 111 (82), 102 (76) and 94 (70) for 1-, 2-, 3- and 4-layer GNs with the nanogap of 10 (20) nm, respectively. Here, the values of electric fields are relative amplitudes normalized to the amplitude of the impinging plane wave. Thus, the strengths of plasmonic coupling for the GNs with a nanogap of 10 nm are increased by a factor of 36.4%, 35.4%, 34.2% and 34.3% with respect to the cases with a 20 nm nanogap. These enhanced optical fields penetrating GNs dissipate in the lossy dielectric materials.

We then further consider the variation of resonance wavelength shift and minimum transmittance at each resonance peak by

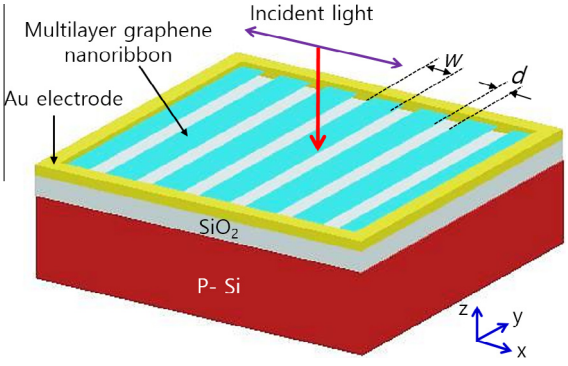

Fig. 1. Schematic of periodic multilayer GNs with width W and separation d, formed on SiO_2/p-Si substrate. These GNs are placed between two dielectric half spaces with dielectric constant ε_1 (air) and ε_2 (SiO_2). Incident light with polarization perpendicular to the GNs is impinged on the top of the structure.

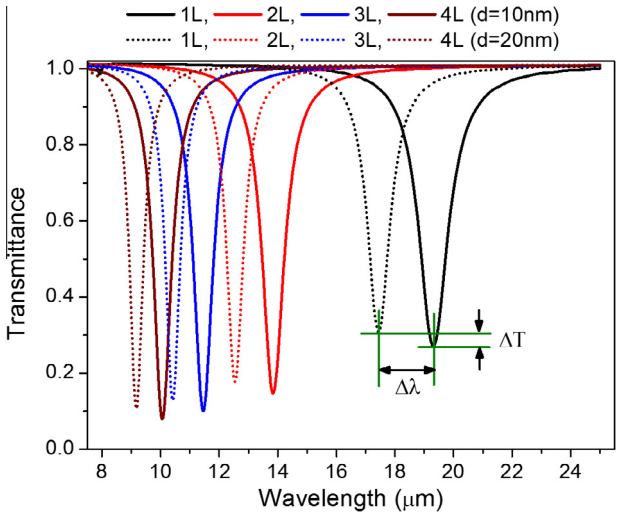

Fig. 2. Spectral transmittance of periodic 2-, 3- and 4-layer GNs as a function of wavelength for the two different nanogaps of 10 and 20 nm in comparison with periodic mono-layer GNs.