Gain enhancement of terahertz surface plasmon in electrically pumped multilayer graphene*

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We propose a surface plasmon (SP) structure in electrically pumped multiple graphene-layer (MGL), and calculate the functions of dynamic conductivity and absorption coefficient. Meanwhile, the dependences of absorption coefficient on different factors are simulated. SP can get gain when absorption coefficient is negative, and the SP gain can be enhanced by lowering temperature, applying high bias voltage and choosing the graphene with proper layer number and long momentum relaxation time. The study on SP gain is hopeful to be used in amplifiers and graphene-based plasmon devices.

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Graphene is a kind of special material with a single layer of carbon atoms tightly packed into the two-dimensional honeycomb crystal structure. It has drawn wide attention due to its unique photoelectric properties and potential applications[1-3]. The interband population inversion occurs in optically or electrically pumped single-graphene layer (SGL) and multiple-graphene layer (MGL), which can lead to the negative conductivity in terahertz (THz) range[4-7]. The effect can be used in photoelectric devices and THz laser[8,9].

Recently, not only the electric mode, but also the surface plasmon (SP) is stimulated in optically or electrically pumped SGL and MGL[10,11]. A. A. Dubinov et al[10] have primarily researched SP in optically pumped SGL theoretically, and the propagation index and SP absorption coefficient are also studied. V. Ryzhii et al[12-16] have studied the plasmon extensively, while there is no work about the amplification of SP in electrically pumped MGL. In this paper, we study the SP absorption coefficient in electrically pumped MGL theoretically. We demonstrate that the amplification of SP is larger when it is with high bias voltage, long momentum relaxation time and low effective temperature. Such properties can be used in amplifiers and plasmon devices.

The SP structure in electrically pumped MGL is shown in Fig.1. The structure has two split gates, and the gate voltages are assumed to be $V_n=V_g/2$ and $V_p=-V_g/2$, respectively. Each graphene layer (GL) contacts the side edge. The n and p regions can be formed when the bias voltage V is applied. If the distance $2L$ between the two split gates is much lager than the thickness of the gate W_g, i region will exist in each GL. Thus the p-i-n junction is formed[5,7,17,18].

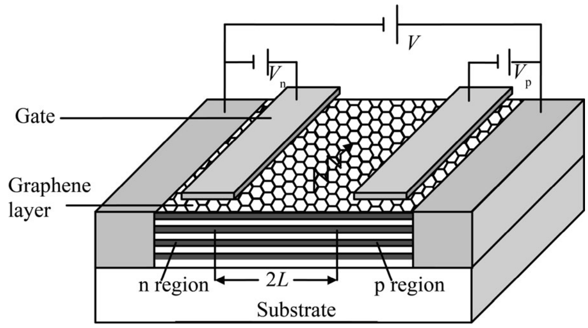

Fig.1 Schematic diagram of SP structure based on electrically pumped multilayer graphene

Introducing the dimensionless potential of $\Psi_k=2\varphi_k/V_g$ in the kth GL, where φ_k is the potential of the kth GL, it

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can be obtained by solving one-dimensional Poisson equation[7,18] as follows

$$\frac{d}{W_{\mathrm{g}}}\left(2-\psi_{1}\right)-\psi_{1}+\psi_{2}=\frac{d}{W_{\mathrm{g}}}\ell\phi\left(\psi_{1}\right), \tag{1}$$

$$\psi_{k-1}-2\psi_{k}+\psi_{k+1}=\frac{d}{W_{\mathrm{g}}}\ell\phi\left(\psi_{k}\right),\ \left(2\le k\le K-1\right), \tag{2}$$

$$\psi_{K-1}-\psi_{K}=\frac{d}{W_{\mathrm{g}}}\ell\phi\left(\psi_{K}\right), \tag{3}$$

$$\phi\left(\psi\right)=\frac{12}{\pi^{2}}\int_{0}^{\infty}\frac{\xi\mathrm{d}\xi}{1+\exp\left(\xi-U_{\mathrm{g}}\psi\right)}-\int_{0}^{\infty}\frac{\xi\mathrm{d}\xi}{1+\exp\left(\xi+U_{\mathrm{g}}\psi\right)}, \tag{4}$$

where $\ell=(8\pi/\alpha)(eW_{\mathrm{g}}\sum_{T}/V_{\mathrm{g}})\propto T^{2}/V_{\mathrm{g}}$, $U_{\mathrm{g}}=eV_{\mathrm{g}}/2k_{\mathrm{B}}T$, $\sum_{T}=(\pi/6)(k_{\mathrm{B}}T/\hbar v_{F})$ is the electron density in the intrinsic graphene, $\xi=v_{F}p/k_{\mathrm{B}}T$, d is the thickness of each GL, α is the dielectric constant, e is the electron charge, k_{B} is the Boltzmann constant, $\hbar$ is the induced Plank constant, $v_{F}=10^{8}$ cm/s is the characteristic of electrons, p is the momentum of electrons or holes, T is the temperature, and K is the total graphene layer number. In this paper, we neglect the thermal effect.

The Femi energy μ_{k} in the kth GL can be expressed as $\mu_{k}=eV_{\mathrm{g}}\Psi_{k}/2$, and it can be obtained numerically by solving Eqs.(1)–(4).

The conductivity σ_{ω} consists of the contribution of both interband transition (electron emission) and intra-band transition (Drude absorption). It can be presented as[5,19-22]

$$\sigma_{\omega}=\sum_{k=1}^{K}\left(\sigma_{\omega}^{\mathrm{inter}}+\sigma_{\omega}^{\mathrm{intra}}\right)=$$
$$\sum_{k=1}^{K}\left[\frac{e^{2}}{2\hbar}\exp\left(\frac{eV-2\mu_{k}}{2k_{\mathrm{B}}T}\right)\sinh\left(\frac{\hbar\omega-eV}{2k_{\mathrm{B}}T}\right)-\right.$$
$$\left.\frac{4\hbar\omega}{\mathrm{i}\pi}\int_{0}^{\infty}\frac{G\left(\varepsilon\right)-G\left(\hbar\omega/2\right)}{\left(\hbar\omega\right)^{2}-4\varepsilon^{2}}\mathrm{d}\varepsilon+\frac{e^{2}}{2\pi\hbar}\left(\frac{\mu_{k}}{\hbar}\right)\frac{\tau}{1-\mathrm{i}\omega\tau}\right], \tag{5}$$

where ω is the plasmon frequency, and τ is the momentum relaxation time, and

$$G\left(\varepsilon\right)=\frac{\sinh\left(\frac{\varepsilon-eV/2}{k_{\mathrm{B}}T}\right)}{\cosh\left(\frac{\varepsilon-eV/2}{k_{\mathrm{B}}T}\right)+\cosh\left(\frac{\mu_{k}-eV/2}{k_{\mathrm{B}}T}\right)}. \tag{6}$$

The propagation index ρ can be got by solving Maxwell equation, which can be expressed as[13]

$$\rho=\varepsilon\omega\sqrt{\frac{1}{c^{2}}-\frac{1}{4\pi^{2}\sigma_{\omega}^{2}}}, \tag{7}$$

where ε is the structure parameter, and c is the speed of light in vacuum. The SP absorption coefficient is equal to $2\mathrm{Im}(q)$, where $q=\rho\omega/c$ is SP wavenumber. The SP can be amplified when the absorption coefficient is negative. In the following simulations, it is assumed that $V_{\mathrm{g}}=2$ V, $W_{\mathrm{g}}=10$ nm, $d=0.35$ nm, $\varepsilon=5$ and $\alpha=4$.

Fig.2 shows the SP absorption coefficient dependence on the frequency with different graphene layer numbers and temperatures at $V=40$ meV and $\tau=10$ ps. The absolute value of negative absorption coefficient can be large with big graphene layer number and high temperature. Therefore, the largest SP gain can be obtained by increasing temperature and choosing proper graphene layer number.

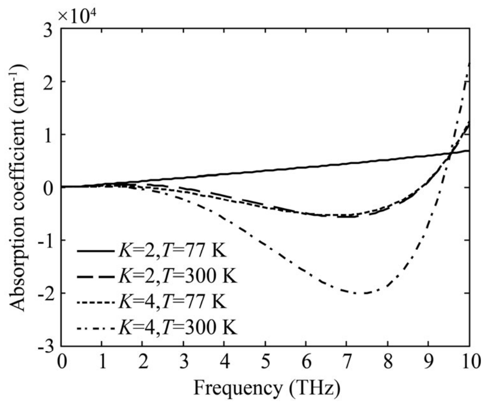

Fig.2 SP absorption coefficient dependence on frequency with different graphene layer numbers and temperatures at *V*=40 meV and *τ*=10 ps

Fig.3 shows the SP absorption coefficient dependence on the frequency with different graphene layer numbers and temperatures at $V=80$ meV and $\tau=10$ ps. Compared with Fig.2, the absolute value of negative absorption coefficient at $V=80$ meV is one order of magnitude larger than that at $V=40$ meV. As a result, the largest SP gain can be got effectively by increasing bias voltage appropriately.

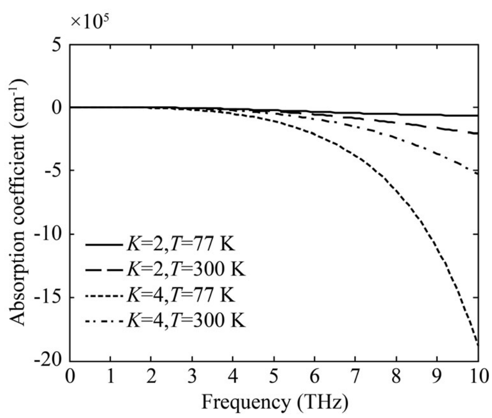

Fig.3 SP absorption coefficient dependence on frequency with different graphene layer numbers and temperatures at *V*=80 meV and *τ*=10 ps

Comparing Fig.2 with Fig.3, the absolute values of negative absorption coefficients dependence on temperature are different in different bias voltages. So the absolute value of negative absorption coefficient dependence on temperature should be studied systematically.

Fig.4 shows the absorption coefficient dependence on the bias voltage V with different temperatures at K=3, $\omega/2\pi$=7 THz and τ=10 ps. The absolute value of negative absorption coefficient increases first and then decreases with the increase of bias voltage. The maximum value can be obtained at about V=100 meV. The maximum value of the absolute value is big at low temperature, and the bias voltage corresponding to the maximum is small. Hence, the largest SP gain can be got with low temperature at about V=100 meV.

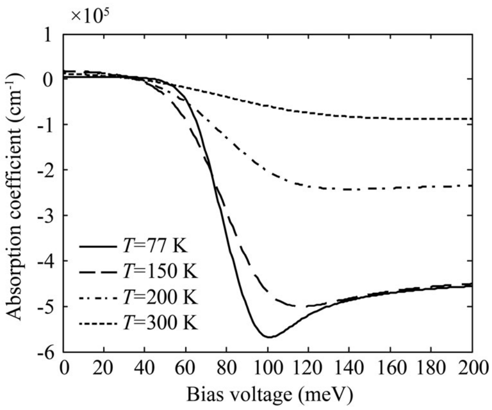

Fig.4 SP absorption coefficient dependence on bias voltage with different temperatures at *K*=3, *ω*/2π=7 THz and *τ*=10 ps

Fig.5 shows the absorption coefficient dependence on the electron (hole) momentum relaxation time with different bias voltages at K=3, $\omega/2\pi$=7 THz and T=77 K.

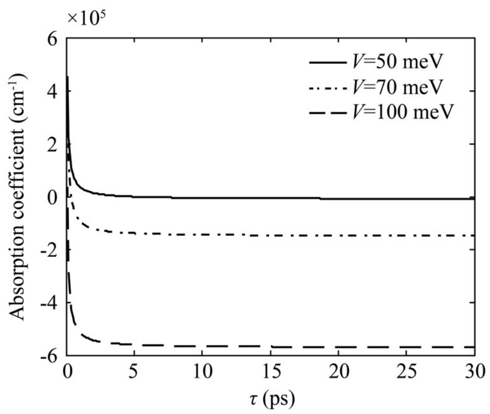

Fig.5 SP absorption coefficient dependence on electron (hole) momentum relaxation time with different bias voltages at *K*=3, *ω*/2π=7 THz and *T*=77 K

The absolute value of negative absorption coefficient increases with the increase of electron (hole) momentum relaxation time, and it is almost unchanged when the electron (hole) momentum relaxation time is larger than 10 ps. The maximum of the absolute value of negative absorption coefficient increases with the increase of bias voltage. Therefore, the large SP gain can be achieved by choosing the graphene with momentum relaxation time of τ=10 ps and applying bias voltage of $V\approx$100 meV.

In summary, we propose an SP structure in electrically pumped MGL, calculate its conductivity and simulated absorption coefficient numerically. SP can get gain when absorption coefficient is negative. The bigger the absolute value of absorption coefficient is, the larger the SP gain is. The SP gain can be enhanced by lowering temperature, applying bias voltage of $V\approx$100 meV, and choosing graphene with proper layer number and long momentum relaxation time of $\tau\approx$10 ps. The study on SP gain in electrically pumped MGL is potentially useful in the design of amplifiers and graphene-based plasmon devices.

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