Effects of plasmons in electric biased graphene

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Dispersion properties and confinement in Graphene-SiO_2-Si structure have been investigated, and the properties of plasmons with an electric bias are mainly discussed. The results show that graphene plasmons have small loss which means plasmons can travel a long distance. It has a better confinement compared with metal, which can strongly confine energy at sub-wavelength scales. Plasmons in graphene also can be tuned and controlled via a gated voltage, thus providing an advantage for graphene over plasmons in metal-dielectric interface. The presented work is useful for the design of grapheme-based plasmons devices.

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1. Introduction

An electromagnetic(EM) wave propagating along the boundary of two dielectric mediums is called surface wave (SW). A surface plasmons (SP) is given in the interface of metal and dielectric medium, so SP is a kind of SW [1]. Surface plasmons represent electromagnetic excitations, which are coupled to surface collective oscillations of free electrons in a metal [2]. Surface plasmons has a maximum electric field in the interface and exponentially decays into neighboring media [3]. Permittivity plays an important role in SP, and the imaginary part of the permittivity is associated with loss of electromagnetic waves. How to reduce transmission losses to gain a longer transmission distance is the key to this technology. Plasmons devices based on metal have a good performance in the visible frequency, but have a bad confinement in the THz and infrared frequency [4], thus limiting the application of SP.

Two dimensional graphene has a honeycomb lattice structure. Graphene has a zero bandgap, whose conductivity can be tuned by electrostatic or magnetostatic bias [5]. Graphene has become a promising material for supporting surface plasmons, due to its excellent mechanical and electrical properties. Graphene-based plasmons devices can be used in the THz and infrared frequency range [6], in contrast with noble metals which can be only used in the visible range. Unlike conventional metal materials, graphene's electronic or optical properties can be changed via doping or electrostatic, leading to novel reconfiguration properties[7].

In this work, the dispersion properties and confinement of surface wave propagating along graphene are investigated, mainly considering the electrostatic affects the behavior of surface wave. The paper is organized as follows. Section II proposes the model of graphene-SiO_2-Si structure, and derives the conductivity model and the permittivity of graphene. Then, the dispersion relation, the confinement of surface wave and the effects of electrostatic bias are analyzed. Section III shows the compute results and corresponding analysis. Finally, a full summary and outlook are taken in section IV.

2. Surface plasmons guided by electrostatic biased graphene

Fig. 1 depicts the model sketch of graphene-SiO_2-Si multilayer structure. The SiO_2 layer is deposited on the Si substrate. The Si substrate can be used as a back gate, therefore it is easy to add bias voltage. A laterally graphene with a conductivity σ(s) lies in the X-Y plane at the interface between SiO_2 substrate and air. In the area of Z>0, permittivity and permeability of air are ε_1、μ_1, and in the area of Z<0, permittivity and permeability of SiO_2 are ε_2、μ_2. Electrostatic bias, although no magnetostatic bias, the conductivity of graphene is a scalar, which can be written as $\sigma(\omega, \mu_c, \Gamma, T)$, where ω is radian frequency, μ_c is chemical potential, Γ is phenomenological scattering rate and T is the temperature. For the conductivity the result of Kubo formula[8] has been used.

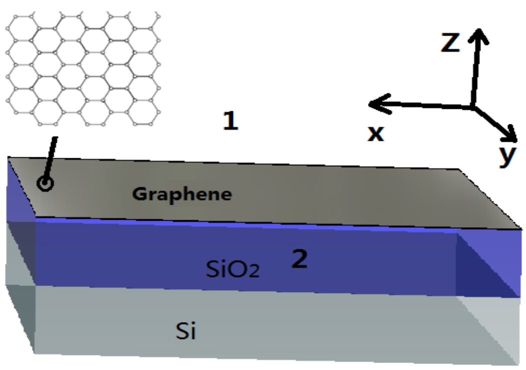

Fig. 1. The sketch of graphene-SiO_2-Si structure. The graphene is deposited on the SiO_2 substrate, and the SiO_2 layer is deposited on the Si substrate.

Here the TM and TE modes are considered in geometry depicted in Fig. 1. From top to bottom, there are four layers in this model, there are air, graphene, SiO_2 and Si. For definiteness we use ε_{r1}=3.9 corresponding to SiO_2 substrate with the thickness of 300nm, and ε_{r2}=1 for air on top of graphene.

Assuming the TM mode SP propagating in X direction, the electric field components of TM mode can be expressed as:

$$\left.\begin{aligned} E_x &= E_{1a}e^{jk_\rho x - q_1 z}, \\ E_y &= 0, \\ E_z &= E_{1b}e^{jk_\rho x - q_1 z} \end{aligned}\right\} \quad Z>0 \tag{1a}$$

$$\left.\begin{aligned} E_x &= E_{2a}e^{jk_\rho x + q_2 z}, \\ E_y &= 0, \\ E_z &= E_{2b}e^{jk_\rho x + q_2 z} \end{aligned}\right\} \quad Z<0 \tag{1b}$$

Where E_{na}、 E_{nb} mean the amplitudes of electric field in air or SiO_2, and the subscripts 1 and 2 stand for in the air and SiO_2, respectively. $k_\rho$is the wavenumber propagation along the graphene sheet, $q_n^2 = k_\rho^2 - \varepsilon_n^r k_0^2$. In this case $\mu_1=\mu_2=\mu_0$, $k_0^2=\omega^2\mu_0\varepsilon_0$ is the wavenumber in free space.

Considering the boundary conditions at graphene interface (Z=0), the equation can be written as:

$$H_y^1 - H_y^2 = \sigma E_x \tag{2a}$$

$$E_x^1 = E_x^2 \tag{2b}$$

By the boundary condition and the Maxwell equations, finally we can obtain the dispersion relationship for TM mode:

$$\varepsilon_2\sqrt{k_\rho^2 - k_1^2} + \varepsilon_1\sqrt{k_\rho^2 - k_2^2} + \frac{\sigma\sqrt{k_\rho^2 - k_1^2}\sqrt{k_\rho^2 - k_2^2}}{j\omega} = 0 \tag{3}$$

By the same method, the dispersion relationship for TE mode also can be obtained:

$$\sqrt{k_\rho^2 - k_1^2} + \sqrt{k_\rho^2 - k_2^2} + j\sigma\omega = 0 \tag{4}$$

Attenuation length ζ can be used to gauge the degree of confinement of the SP to the graphene sheet, which means the wave decay to 1/e of the value in the graphene surface. The relationship between attenuation length and wavenumber is ζ^{-1}=Real(q_n). After some calculation and derivation, the expression for TE mode and TM mode can be written as: $\frac{\zeta^{TE}}{\lambda} = \frac{1}{\pi\eta\sigma''}$ and $\frac{\zeta^{TM}}{\lambda} = \frac{\eta|\sigma|^2}{4\pi\sigma''}$. With the expression above we can see a large imaginary part of conductivity of graphene means a good confinement, which enable strongly confine of electromagnetic energy at sub-wavelength scales.

From the dispersion equation(3)(4), we can see that characteristics of SP is directly related to the conductivity. As we discussed above the conductivity also can be changed by the electrostatic bias. In particular, the numerical relationship between the electrostatic bias and chemical potential μ_c is given by[9]:

$$\frac{\varepsilon_0\pi\hbar^2 v_F^2}{e}E_0 = \int_0^\infty \varepsilon\left[fd(\varepsilon) - fd(\varepsilon + 2\mu_c)\right]d\varepsilon \tag{5}$$

Where $v_F \approx 10^6$m/s is the Fermi velocity of graphene. The chemical potential μ_c can be treated as a function of electrostatic bias, whose relationship is shown in Fig. 3.

3. Numerical results

In this section, the surface wave's property is investigated under different conditions. All the results will be presented at room temperature T=300K for Γ=1.32meV(τ=0.5ps), which corresponding to a mean free path of several hundred nanometers.

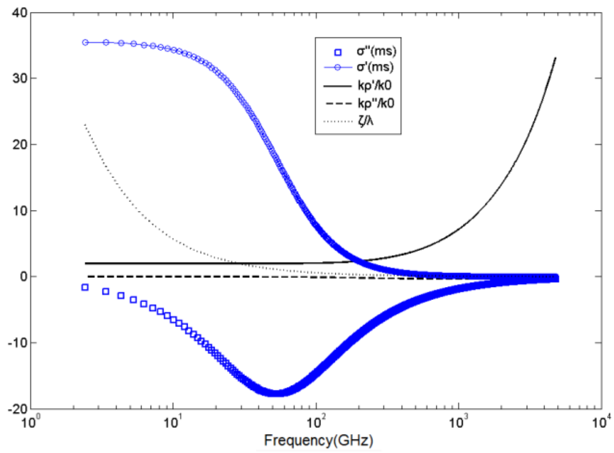

Fig. 2. The conductivity of graphene(bule line), TM mode wavenumber and confinement property at T=300k and μc=0.1eV.

Fig. 2 shows the conductivity of graphene, TM mode SP wavenumber and confinement property versus frequency at a chemical potential μ_c=0.1eV. Graphene conductivity has a large real part at low frequency. But the SP is poorly confinement(ζ_{TM}/λ>>1), and propagation characteristics is the same as the one in free space($k_\rho/k_0\approx$1). As the frequency increases, SP becomes tightly confined to the graphene which means a strong confinement of electromagnetic energy at sub-wavelength scales. And the wavenumber becomes very large, which shows the characteristics of slow wave. The Fig. 2 shows that the wavenumber and attenuation of plasmons are bound with the surface conductivity of graphene, so in the following an analysis of the effects of electrostatic bias has been made.

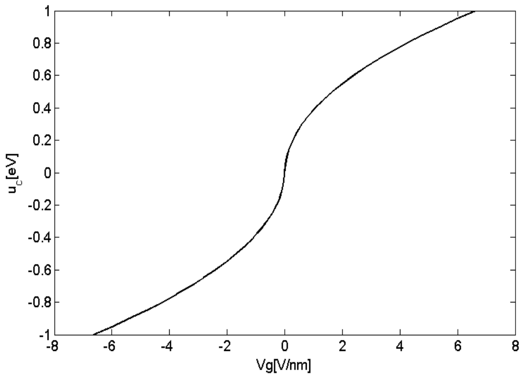

Fig. 3. The relationship between the chemical potential and the electrostatic bias.

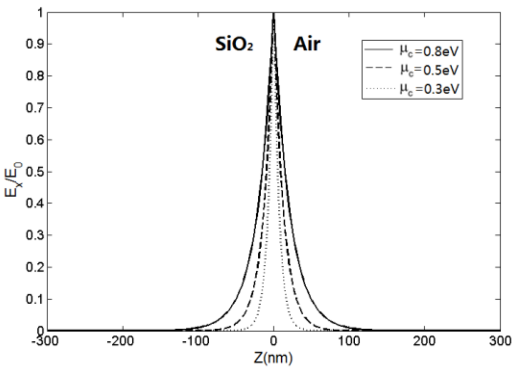

Fig. 4. Shows Normalized E_x field component for the TM mode in graphene-SiO_2-Si structure. The frequency is 50THz, with different chemical potentials 0.3 eV，0.5 eV and 0.8 eV.

Using silicon substrate as an electrode, the relationship between chemical potential and electrostatic bias is shown in Fig. 3. It can be noted that with an appropriate electric bias the chemical potential can be any value between -1ev to 1ev. The normalized E_x field component for TM mode in graphene structure can be found in Fig. 4, at 50THz with different chemical potential (0.3eV， 0.5eV and 0.8eV which can be achieved by adding electric bias). The E_x component decays exponentially in the air and SiO_2 substrate. Either in the air or SiO_2 substrate they have almost the same attenuation depth, the permittivity of SiO_2 has little effect on attenuation at 50THz because $k_\rho >> k_0$. Compared the wave wavelength in free space λ_0=6μm, the E_x field components penetrate nearly 100nm into the air or SiO_2 substrate, it shows a good confinement. The attenuation length which is governed by electric bias can be varied by adjusting the chemical potential. With the increasing of chemical potential the attenuation length becomes large, because the conductivity increases with increasing of chemical potential. The coupling of surface plasmons propagating along the grapheme-air interface and graphene-SiO_2 interface is not considered, because in this case graphene has good isolation properties.

Fig. 5 shows the power attenuation along the transmission direction (dB/μm) for μ_c=0.3eV, 0.5eV and 0.8eV. The power attenuation increases with the increasing of frequency. It also can be seen that in THz and low infrared regime the SP shows a good confinement and moderately loss. It is reported that at 40 THz frequency, the SP guided by gold has a normalized wave number 1-j8.4 $\times 10^{-5}$, such SP has a very low power attenuation 2.4$\times 10^{-4}$dB/μm and the confinement property is ζ_{gold}/λ=7.22. For Graphene the normalized wave number is 23.32-j0.2, with the attenuation 0.3dB/μm and good confinement ζ_{grap}/λ=0.017 for μ_c=0.8eV. It can be noticed that the loss is lower in gold, but confinement is much worse in gold. In a lower frequency the loss in graphene decreases very fast, and has a good confinement property. SP supported by graphene will be very useful in these frequencies.

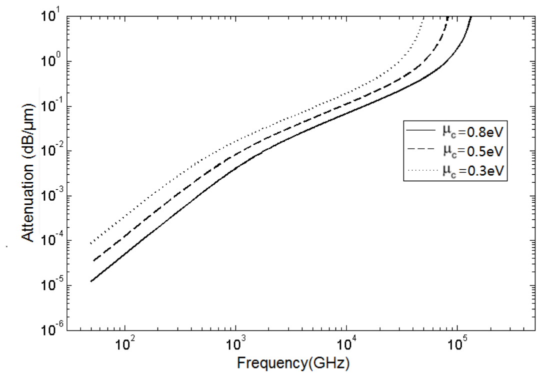

Fig. 5. Power attenuation(dB/μm) along the graphene sheet with different chemical potentials 0.3eV，0.5eV and 0.8eV.

At infrared frequency changes in chemical potential can change the conductivity of graphene, as is shown in Fig. 6a. It not only changes the value of conductivity but also changes the sign of imaginary part at 300THz, which will directly change the transmission mode supported by graphene. From the conductivity equation, we can know that the abrupt change happens when $2|\mu_c|=\hbar\omega$, in this case $|\mu_c|$= 0.1eV. In this condition for $|\mu_c|$ less than 0.1eV the sign of imaginary part of conductivity is positive, and outside of this range, its imaginary part is negative. The wavenumber and confinement property are shown in Fig. 6b, where it can be seen that TM mode has a good confinement, and the real part of wavenumber is large. The dispersion of TE waves is very close to the light line($k'_\rho \approx k_0$) which leads to their very small field confinement. Through these Figures we can conclude that the tunability can be achieved by changing the value of electric bias.

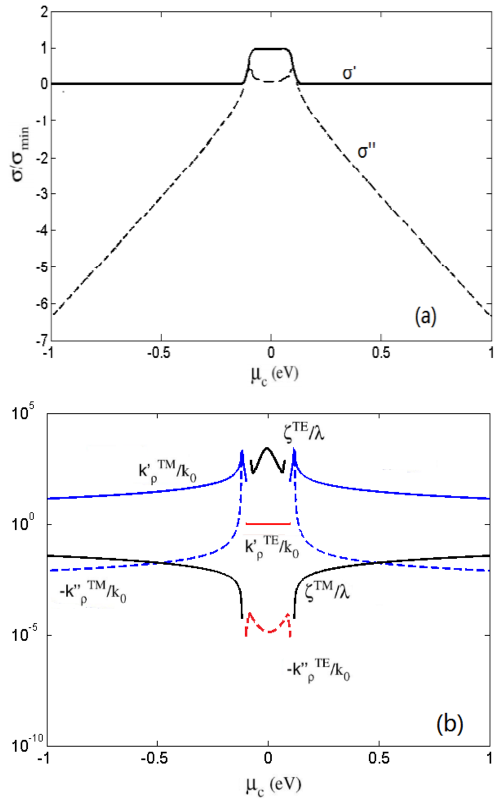

Fig. 6.(a) Shows the conductivity of graphene as a function of chemical potential. (b) shows the confinement property and wavenumber (for TM mode blue one, for TE mode red one) as a function of chemical potential.

4. Conclusion and outlook

Surface plasmons wave supported by graphene shows a great confinement of the electromagnetic energy and a relatively low loss. Compared to conventional metal materials, graphene has some advantages: first of all is its tunability; second it shows a stronger confinement, which is good for miniaturization and integration; third it can be used in THz and infrared frequencies, in which it shows a poor performance for metal. Due to these excellent characteristics graphene has become the star material for supporting SP. With the improving of manufacturing process, more and more graphene based SP devices will be developed, and this will be a hot spot of research.

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