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Energy Losses by the Interaction of Charged Particles with a Graphene Sheet

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Short Research Article

ABSTRACT

Using the fluid dynamics model, we studied the formation of graphene surface plasma when the charge is tilted to the graphene sheet for motion. We calculated the electron energy loss spectrum of electrons at different angles and proved that the resonance in the spectrum is related to the frequency of graphene surface plasma, as the electron velocity decreases, the dispersion shifts to higher energies. An increase in the tilt angle will also shift the dispersion energy in a higher range.

Keywords: Hydrodynamic; graphene; plasmonic; energy loss.

1. INTRODUCTION

The fluid dynamics model for plasmonic is a kind of macro approach to a micro problems [1-4]. It combines the Maxwell equation, Euler fluid dynamics equation, and continuity equation, with a supplementary term caused by the statistical pressure of the electron gas [5,6].

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Graphene plasmons have recently emerged as a new research branch in photonics that has attracted substantial research efforts [7-9]. The discuss of plasmons in graphene has been the subject of extensive experimental and theoretical work in the past few years, as graphene has significant properties that make it superior to other plasma materials such as precious metals. Researchers have explored its capabilities by taking advantage of its long plasma life, high space constraints and multi-functional tunability, as well as its two-dimensional (2D) geometry and large electro-optic response provided by its unique electronic structure [10]. Surface plasma is a collective oscillation of charge at the interface of metal and medium, which belong to the electromagnetic response of free electrons on the metal surface to the incident electric field. However, the metal surface plasmon has a limited tuning range and weak field constraint. The graphene surface plasmon makes up for these deficiencies.

When studying the electron energy loss (EEL) on planar surfaces, it is often discussed that when electrons are parallel to the graphene surface [11]. Previous studies [12] have calculated the production of plasmons and the EEL when charged particles incident in a direction perpendicular to graphene, and we extend this to the oblique incident case using similar methods. In this paper, we investigated the generation of surface plasmons when a moving charge slants onto a graphene sheet, the EEL spectrum is also discussed from different perspectives, we discuss the influence of electron velocity and tilt angle on dispersion.

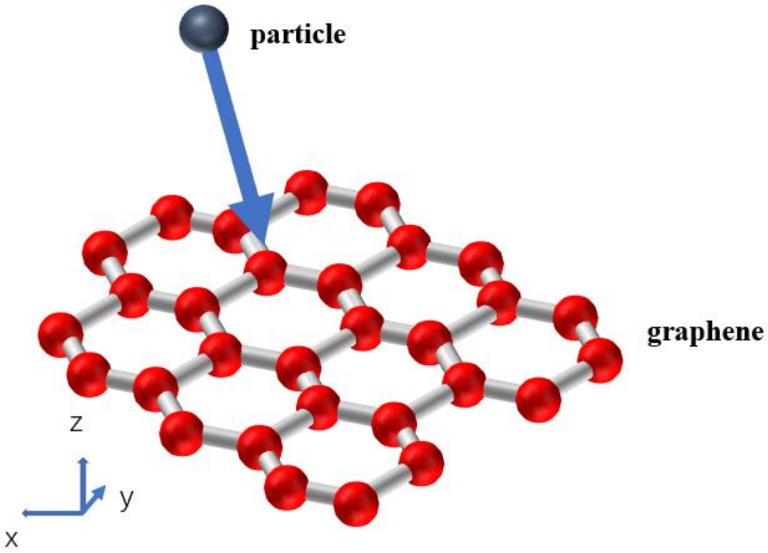


Fig. 1. The model studied in this article: The electrons are tilted with respect to graphene. The influence of charge electron gas interaction in graphene was studied using a fluid dynamics model, which established a nonlocal correction due to the statistical pressure of electron gas. Charge induced surface plasma in graphene can be detected through EEL spectroscopy

2. INDUCED ELECTRONSTATIC POTENTIAL GENERATED BY CHARGED PARTICLES

In this section, we will study the electrostatic potential $\varphi_{in}(\mathrm{r},z,t)$ generated when charged particles are obliquely incident on graphene sheets. Firstly, the equation for induced potential is:

$$\varphi_{in}(\mathrm{k},z,\omega)=\frac{n_0 e^3}{4\varepsilon_0 m_g}\frac{e^{-k|z|}}{\omega^2-\omega_{SPP}{}^2}\int dz' e^{-k|z'|}\rho_{ex}(\mathrm{k},z,\omega), \tag{1}$$

where n_0 is the 2D particle density. Next, we will perform a Fourier transform on the above equation,

$$\varphi_{in}(\mathrm{r},z,t)=\int dkd\omega e^{i(\mathrm{kr}-\omega t)}\varphi_{in}(\mathrm{k},z,\omega). \tag{2}$$

We shall consider the calculation of the induced electric field in graphene, $E_{\mathrm{in}}(\mathrm{k},z,\omega)=-\nabla\varphi_{in}(\mathrm{k},z,\omega)$ .A particle with a charge of Ze slants into a graphene sheet at velocity v, so we consider this calculation model

$$\rho_{\mathrm{ex}}(\mathrm{r},z,t)=\mathrm{Z}\delta(\mathrm{y})\delta(\mathrm{x}-\mathrm{v}_x\mathrm{t})\delta(\mathrm{z}-\mathrm{v}_z\mathrm{t}). \tag{3}$$

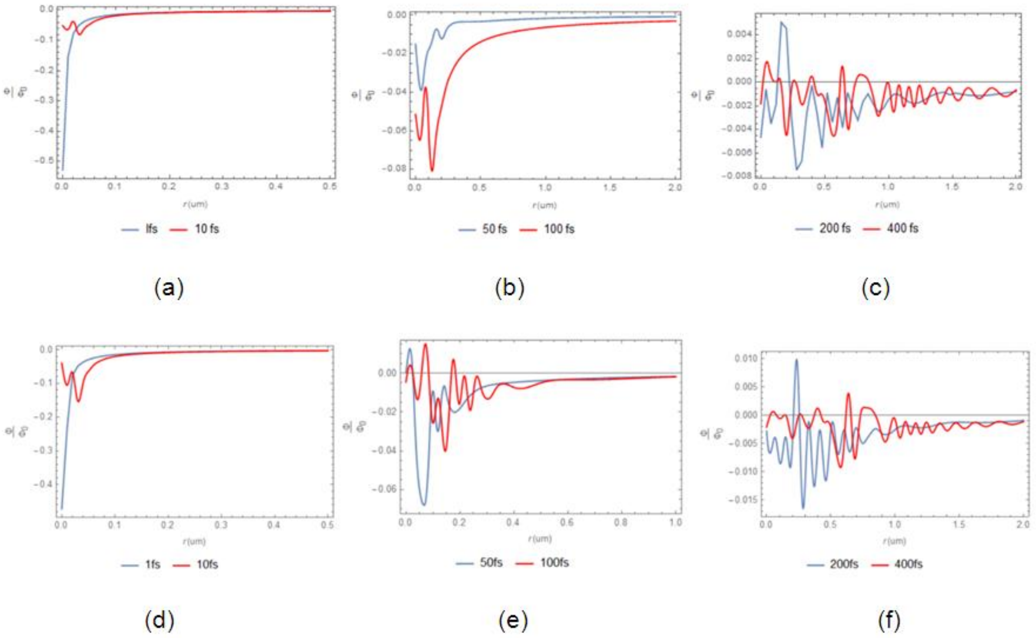
This equation represents the motion of a mobile charge tilted towards the graphene plane. For the sake of our later calculations, we now introduce a common prefactor $\varphi_0=n_0e^3/4\varepsilon_0 m_g$ that will make many formulas dimensionless. The unit of φ_0 is electric potential. Since $k_F=2\pi/\lambda_F$, where λ_F is the Fermi wavelength, φ_0 can be interpreted as the average Coulomb energy between particles in electron gas. Substitute equation (3) into equation (1) and we get

$$\varphi_{in}(\mathrm{r},z,t)=\frac{\varphi_0 Z}{4\pi}\int dr'dz'dt'dk\rho_{ex}(\mathrm{r}+\mathrm{r}',z',t')kJ_0(kr')e^{-k(|z|-|z'|)}\frac{\sin\omega_{spp}|t-t'|}{\omega_{spp}}. \tag{4}$$

By integrating equation (4), it can be obtained that

$$\varphi_{in}(\mathrm{r},z,t)=\frac{\varphi_0 Z}{4\pi}\int dt'dkkJ_0(k\sqrt{y^2+(x-v_x(t+t')^2})e^{-k(|z|-v_z|t+t'|)}\frac{\sin\omega_{spp}|t'|}{\omega_{spp}}, \tag{5}$$

where $v_x=v\cos\theta, v_z=v\sin\theta$,and set angles to $\pi/6$ and $\pi/3$.



(a) (b) (c)

(d) (e) (f)

Fig. 2. (a) The potential at$\pi/6$ for t = 1, 10 fs，(b) The potential at$\pi/6$ for t = 50, 100 fs , (c) The potential at$\pi/6$ for t = 200, 400 fs , (d) The potential at$\pi/3$ for t = 1, 10 fs ,(e) The potential at$\pi/3$ for t = 50, 100 fs , (f)The potential at$\pi/3$ for t = 200, 400 fs

In Fig. 2 we plot the potential at two different incident angles and six different times. We can observe the formation of surface plasmons in a relatively short period of time. The surface plasmon wave has already propagated a certain distance over a longer period of time. Fig.2.(c) and Fig.2.(f) showed that the charge modulation-related induced potential oscillates in the graphene sheet over time. This is the EEL spectrum we will calculate in the next section.

3. THE EEL SPECTRUM

Next we need to calculate the electron energy loss when charged particles incident on graphene, the calculation formula for the electron energy loss is [12].

$$\Gamma(\omega)=\frac{Ze}{\pi\hbar\omega}\int dt\Re\{e^{i\omega t}\vec{v}\cdot\vec{E}(\mathrm{r},v_z t,\omega)\}, \tag{6}$$

where $\vec{v}=(v_x,0,v_z)$ and Z = 1 , and the symbol $\Re$ represents the real part. Applying Fourier transform to equation (3) can obtain $\rho_{ex}(\mathrm{k},z,\omega)=\frac{Z}{v_z}Exp\{i(\omega-k_x v_x)\frac{z}{v_z}\}$. So it can be concluded that the induced potential is

$$\varphi_{in}(\mathrm{k},z,\omega)=\varphi_0\frac{e^{-k|z|}}{\omega^2-\omega_{spp}{}^2}\frac{2kzv_z}{(kv_z)^2+(\omega-k_x v_x)^2}. \tag{7}$$

We can obtain the following equation by performing Fourier transform on the above equation

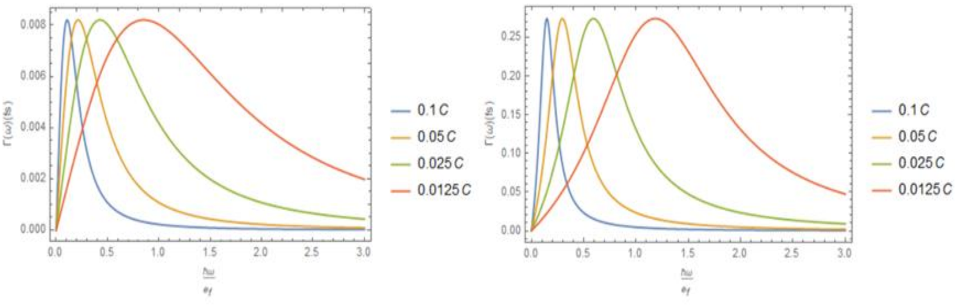
$$\varphi_{in}(\mathrm{r},z,\omega)=\varphi_0\int_0^\infty\frac{dk_x dk_y}{4\pi^2}\frac{e^{-k|z|}e^{ik_x X}}{\omega^2-\omega_{spp}{}^2}\frac{2kzv_z}{(kv_z)^2+(\omega-k_x v_x)^2}. \tag{8}$$

Where $\omega_{spp}=\sqrt{ak}$, the parameter a is

$$a=\frac{2\alpha E_F c}{h}. \tag{9}$$

We can determine the final formula for electron energy loss is

$$\Gamma(\omega)=\frac{Ze}{\pi\hbar\omega}\varphi_0(v\sin\theta-v\cos\theta)\int 2k\frac{dk_x dk_y}{4\pi^2}\frac{\omega+k\sin\theta v\sin\theta}{(\omega+k\sin\theta v\sin\theta)^2-(\cos\theta kv)^2}\frac{2k}{(kv\cos\theta)^2+(\omega-k\sin\theta v\sin\theta)^2}, \tag{10}$$



(a) (b)

Fig. 3. Electron energy loss spectrum at four different velocities at $\pi/6$and $\pi/3$. Different electron velocities result in different peaks. The long tail as a frequency function indicates that the continuum of surface plasma is excited by moving charges

We plot Γ(ω) in Fig. 3. From Fig. 3, we can see that the loss spectrum shifts from higher energy to lower energy as the velocity decreases. An increase in the tilt angle will also shift the dispersion energy in a higher range.

4. CONCLUSION

We considered the interaction between charged particles and the surface of graphene. We described the case of electron oblique incident on graphene using a hydromechanical model and calculated the potential at different angles and at different times. In a relatively short period of time, we can see the formation of surface plasmons. As time increases, the induced potential oscillates. We calculated the EEL spectrum at different angles, as we can see, as $\vec{v}$ decreases and increase of tilt angle, the frequency maximum shifts to a higher frequency. This provides a new way for us to explore the energy loss of graphene.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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