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INTERACTIONS OF IONS WITH GRAPHENE-SAPPHIRE-GRAPHENE COMPOSITE SYSTEM: STOPPING FORCE AND IMAGE FORCE

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Abstract. We derive general expressions for the stopping and image forces on an external charged particle moving parallel to a sandwich-like structure consisting of two doped graphene sheets separated by a layer of Al_2O_3 (sapphire).

1. INTRODUCTION

In nanoscale devices graphene typically appears in stacks separated by insulating layers (Yan et al. 2012), which usually support strong Fuchs-Kliewer or optical surface phonon modes (Fischetti et al. 2001). Those phonon modes are active in the terahertz (THz) to mid-infrared (mid-IR) frequency range and can hybridize with the Dirac plasmon in doped graphene which operates in the same frequency range (Fei et al. 2011). As a prototype of layered heterostructures involving doped graphene sheets, in our previous publication (Despoja et al. 2017) we studied a graphene-sapphire-graphene composite system. We derived an expression for its effective dielectric function using two complementary methods for graphene's electronic response, based on the massless Dirac fermions method and the *ab initio* approach, and found that the structure supports a variety of interesting plasmon-phonon hybrid modes in the THz to mid-IR frequency range. In our recent publication (Despoja et al. 2019) we derived an expression for the total potential in the plane of the upper graphene sheet (the wake potential) and studied the impact of plasmon-phonon hybridization on the wake effect in the interaction of moving external charge with the graphene-Al_2O_3-graphene composite. In this work we derive general expressions for the stopping and image forces on an external charged particle moving parallel to the graphene-Al_2O_3-graphene composite system in order to study the effects of plasmon-phonon hybridization on those forces. Note that we use Gaussian electrostatic units, set $\hbar = 1$ and denote the charge of a proton by $e > 0$.

2. BASIC THEORY

We use a Cartesian coordinate system with coordinates $\{\vec{R}, z\}$, where $\vec{R} = \{x, y\}$ is a two-dimensional (2D) position vector in the xy-plane and z the distance from it, and assume that two graphene sheets are placed in the planes $z = a/2$ and $z = -a/2$, as shown in Fig. 1, with the space between them being a layer of Al_2O_3 (sapphire) of thickness a. The sapphire layer is approximated by a homogeneous dielectric slab described by local dielectric function $\varepsilon_s(\omega)$ (Ong et al. 2012), whereas graphene sheets are described by 2D response functions, $\chi_1(q, \omega)$ and $\chi_2(q, \omega)$, for their non-interacting electrons. Furthermore, we assume that an incident particle with charge Ze moves at the velocity v parallel to a graphene-Al_2O_3-graphene composite at distance b from the closest surface.

In our previous publication (Despoja et al. 2017) we derived an expression for the screened Coulomb interaction $W(\vec{q}, \omega, z, z')$ between the points in Fig. 1 with $z, z' \geq a/2$ as $W(\vec{q}, \omega, z, z') = (2\pi/q)e^{-q|z-z'|} + W_{ind}(\vec{q}, \omega, z, z')$, where

$$W_{ind}(\vec{q}, \omega, z, z') = \frac{2\pi}{q}\left[\frac{1}{\varepsilon(\vec{q},\omega)} - 1\right] e^{-q(z+z'-a)} \qquad (1)$$

is the induced Coulomb interaction with $\vec{q} = \{q_x, q_y\}$ being the momentum transfer vector parallel to the xy-plane and $q = \sqrt{q_x^2 + q_y^2}$, whereas the effective 2D dielectric function $\varepsilon(\vec{q}, \omega)$ may be written as:

$$\varepsilon(q, \omega) = \frac{1}{2}\left[1 + \varepsilon_s(\omega)\coth(qa) + \frac{4\pi e^2}{q}\chi_2\right] - \frac{1}{2}\frac{\varepsilon_s^2(\omega) cosech^2(qa)}{1 + \varepsilon_s(\omega)\coth(qa) + \frac{4\pi e^2}{q}\chi_1} \qquad (2)$$

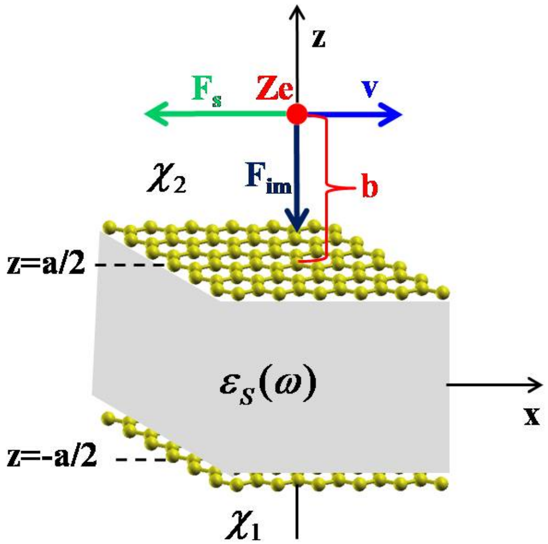

Figure 1: Diagram of the stopping force F_s and the image force F_{im} that act on the point charge Ze moving parallel to the x axis with constant speed v at a fixed distance b above the graphene-Al_2O_3-graphene composite system.

3. RESULTS FOR STOPPING AND IMAGE FORCES

For an external point charge Ze moving parallel to a graphene-Al_2O_3-graphene composite at a fixed distance b above the top graphene layer placed in the $z = a/2$ plane with a constant velocity $\vec{v}$, so that its charge density may be written as $\rho_{ext}(\vec{R}, z, t) = Ze\delta(\vec{R} - \vec{v}t)\delta[z - (a/2 + b)]$, the induced potential in the region above the upper graphene sheet, $z \geq a/2$, may be expressed as:

$$\Phi_{ind}(\vec{R}, z, t) = \frac{Ze}{(2\pi)^2} \int W_{ind}(\vec{q}, \vec{q} \cdot \vec{v}, z, a/2 + b)\, e^{i\vec{q}\cdot(\vec{R}-\vec{v}t)} d^2\vec{q} \tag{3}$$

Substituting Eq. (1) into Eq. (3) and assuming that a point charge moves along the x axis with the speed v, one obtains an expression for the induced potential as:

$$\Phi_{ind}(x, y, z, t) = \frac{Ze}{2\pi} \int \frac{e^{-q(z-a/2+b)}}{q} \left[\frac{1}{\varepsilon(q, q_x v)} - 1\right] e^{i[q_x(x-vt)+q_y y]} dq_x dq_y \tag{4}$$

The stopping and the image forces on the moving charge Ze are defined in terms of the induced potential $\Phi_{ind}(x, y, z, t)$, respectively, as follows (Marinković et al. 2015):

$$\mathrm{F}_s = -Ze \left. \frac{\partial \Phi_{ind}(x,y,z,t)}{\partial x} \right|_{x=vt, y=0, z=a/2+b} \tag{5}$$

$$\mathrm{F}_{im} = -Ze \left. \frac{\partial \Phi_{ind}(x,y,z,t)}{\partial z} \right|_{x=vt, y=0, z=a/2+b} \tag{6}$$

By using these definitions along with Eq. (4), it is easy to obtain:

$$\mathrm{F}_s = \frac{2(Ze)^2}{\pi} \int_0^\infty \int_0^\infty \frac{q_x e^{-2qb}}{q} Im \left[\frac{1}{\varepsilon(q, q_x v)} \right] dq_x dq_y \tag{7}$$

$$\mathrm{F}_{im} = \frac{2(Ze)^2}{\pi} \int_0^\infty \int_0^\infty e^{-2qb} Re \left[\frac{1}{\varepsilon(q, q_x v)} - 1 \right] dq_x dq_y \tag{8}$$

where we used the symmetry properties of the real and imaginary parts of the dielectric function $\varepsilon(q, \omega)$ from Eq. (2).

Note that the stopping force is the negative of the usual stopping power S, $\mathrm{F}_s = -S$, whereas the image force is related to the familiar image potential V_{im} via $F_{im} = -\, dV_{im}/db$.

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