29th Summer School and International Symposium on the Physics of Ionized Gases

Aug. 28 - Sep. 1, 2018, Belgrade, Serbia

CONTRIBUTED PAPERS

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ABSTRACTS OF INVITED LECTURES, TOPICAL INVITED LECTURES, PROGRESS REPORTS AND WORKSHOP LECTURES

Editors:
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PREFACE

This publication contains the contributed papers and abstracts of Invited Lectures, Topical Invited Lectures, Progress Reports and Workshop Lectures that will be presented at the International Symposium on the Physics of Ionized Gases 2018. This is the 29th of a series of events which reflect the progress in this challenging field of science. The event is organized by the Vinča Institute of Nuclear Sciences in Belgrade and Serbian Academy of Sciences and Arts, with the support of the Ministry of Education, Science and Technological Development of the Republic of Serbia.

The aim of this book is to present new results in the fundamental and frontier theories and technology in the area of general plasma physics (including astrophysical and fusion plasmas), atomic collision processes and particle and laser beam interactions with solids. Also, the presented results and lectures of the 3rd Workshop on X-ray and VUV interaction with Biomolecules in Gas Phase - XiBiGP are also included.

Herein, the Editors would like to thank the authors and reviewers for their support of this event and to wish all participants a pleasant and productive stay in Belgrade. We are grateful to the Serbian Academy of Sciences and Arts for their long term commitment to support this event as well as the Serbian Ministry of Education, Science and Technological Development for their continuing help. We also acknowledge the support of the open access journal "Atom"

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SPIG 2018

SPIG 2018 CONFERENCE TOPICS

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PARTICLE AND LASER BEAM INTERACTION WITH SOLIDS

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The Workshop on X-ray Interaction with Biomolecules in Gas Phase (XiBiGP)

WAKE EFFECT DUE TO EXCITATION OF PLASMON-PHONON HYBRID MODES IN A GRAPHENE–SAPPHIRE–GRAPHENE STRUCTURE BY A MOVING CHARGE

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Abstract. We study the wake effect due to excitation of a plasmon-phonon hybrid mode in a sandwich-like structure consisting of two doped graphene sheets, separated by a layer of Al_2O_3 (sapphire), which is induced by an external charged particle moving parallel to the structure.

1. INTRODUCTION

Using doped graphene shows great promise for plasmonic applications in the range of frequencies from the terahertz (THz) to the infrared (IR) owing to long propagation distances and tunability of its Dirac (or sheet) plasmon [1]. Properties of that plasmon can be efficiently probed by inelastic scattering of low-energy electrons in the technique known as High-Resolution Electron Energy Loss Spectroscopy [2]. Both the energy and momentum transfers from the incident electron to graphene are significantly influenced by excitation of the Dirac plasmon, which can give rise to the wake effect in the induced potential, as shown in Refs. [3,4].

However, the dynamic response of graphene in the THz to IR frequency range is adversely affected by the presence of the transverse optical phonons in a nearby polar substrate, typically an oxide [2,5]. As a result, strong hybridization takes place between the Dirac plasmon and the resulting Fuchs-Kliewer, or surface optical phonon modes in the oxide, which can profoundly affect the damping of the collective modes in layered structures

involving graphene sheets [1,5]. Moreover, such hybridization also affects the energy loss of an incident electron [6], as well as the resulting wake effect [7]. For example, while in Ref. [3] it was shown that there exists a velocity threshold for the wake to be excited in a single, free graphene by an incident charged particle, given by the Fermi speed of graphene $v_{\rm F} \approx 10^6$ m/s, we have found in Ref. [7] that a hybrid mode between graphene and an SiO_2 substrate gives rise to a noticeable, phonon-dominated wake effect.

Since in nanoscale devices graphene typically appears in stacks separated by insulating layers [1], we have recently studied a sandwich-like structure with two graphene sheets, placed in the planes $z = a/2$ and $z = -a/2$ of a Cartesian coordinate system (x, y, z), as shown in Fig. 1, with the space between them being the air or a layer of Al_2O_3 (sapphire) of thickness a [8]. The dynamic response of each graphene was described by a two-dimensional (2D) independent-electron polarization function $\chi_1^0(\mathbf{q}, \omega)$ and $\chi_2^0(\mathbf{q}, \omega)$, with $\mathbf{q} = (q_x, q_y)$ being the 2D wavevector, whereas the response of the sapphire layer was described by a dielectric function $\varepsilon_{\rm S}(\omega)$ consisting of several Lorentzian terms [8]. For the microscopic model of χ_j^0 we used random phase approximation with two models: *ab initio* calculations with a full range of electronic bands in graphene [9], and analytical description of low-energy portions of graphene's π electronic bands in a massless Dirac fermion (MDF) approximation. While in Ref. [8] we analyzed the dispersion relations of the hybrid plasmon-phonon modes of this structure, we present here results on the wake effect due to the excitation of these modes by a charged particle moving parallel to the structure at the speed of v, a distance $b > 0$ from the top graphene sheet with the polarization χ_2^0. As in Ref. [8], we take $a = 5$ nm and assume that graphene sheets are equally doped, each having the same Fermi energy of $E_{\rm F} = 0.2$ eV.

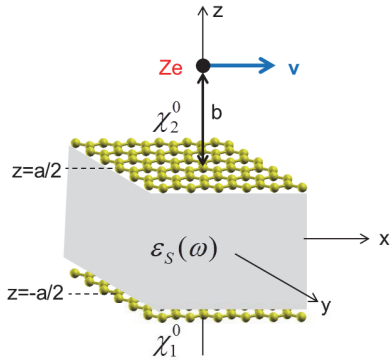

Figure 1. Diagram of a sandwich-like structure with point charge Ze moving at the speed v, a distance b above the top graphene with χ_2^0.

2. RESULTS AND DISCUSSION

In Ref. [8] we used a Feynman diagram technique, as well as analytical solution of Dyson-Schwinger equation, to express the screened Coulomb interaction $W(\mathbf{q}, \omega, z, z')$ between the points in Fig. 1 with $z, z' \geq a/2$ as

$$W(\mathbf{q}, \omega, z, z') = V_q \left\{ {\rm e}^{-q|z-z'|} + \left[\frac{1}{\varepsilon(\mathbf{q}, \omega)} - 1 \right] {\rm e}^{-q(z+z'-a)} \right\}, \qquad (1)$$

where $q = \|\mathbf{q}\| = \sqrt{q_x^2 + q_y^2}$ and $V_q = 2\pi/q$ is the Fourier transform of the bare Coulomb potential between unit point charges in 2D, whereas the effective 2D dielectric function $\varepsilon(\mathbf{q}, \omega)$ is defined as

$$\varepsilon(\mathbf{q},\omega) = \frac{1}{2}\left\{\left[1 + \varepsilon_{\rm S}\coth(qa) - 2V_q\chi_2^0\right] - \frac{\varepsilon_{\rm S}^2\,\mathrm{cosech}^2(qa)}{1 + \varepsilon_{\rm S}\coth(qa) - 2V_q\chi_1^0}\right\}. \quad (2)$$

For a point charge Ze moving parallel to the x axis with constant speed v, the 2D translational invariance of the structure in Fig. 1 renders the induced electrostatic potential stationary in the moving frame of reference attached to that particle, so that the total potential at a point (x, y, z) with $z \geq a/2$ may be written as

$$\Phi_{\rm tot}(x - vt, y, z) = Ze \iint \frac{dq_x\, dq_y}{(2\pi)^2}\, W(\mathbf{q}, q_x v, z, \tfrac{a}{2} + b)\, \mathrm{e}^{iq_x(x-vt)+iq_y y}. \quad (3)$$

In Fig. 2 we show the cross section of this potential with $y = 0$, in the plane of the upper graphene sheet, $z = a/2$, normalized by $\Phi_0 = Ze/b$ with $b = 0.5$ nm, for a particle moving at the sub-threshold speed of $v = v_{\rm F}/2$.

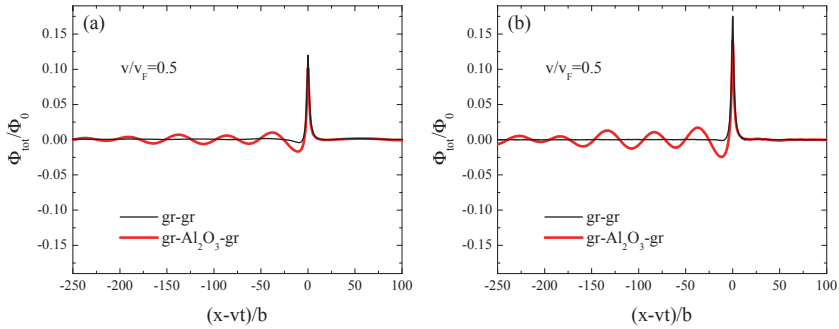

Figure 2. The total potential, normalized by $\Phi_0 = Ze/b$ with $b = 0.5$ nm, shown as a function of the normalized distance $(x - vt)/b$, when the space of thickness $a = 5$ nm between graphene sheets is filled by air (thin black lines) or Al_2O_3 (thick red lines). The polarization functions of graphene sheets are obtained from (a) *ab initio* calculations and (b) MDF approximation [8].

One notices that, when the space between graphene sheets is air, there is only a sharp, somewhat asymmetric peak in the potential at the position of the particle. This is due to the fact that the condition of kinematic resonance for exciting a collective mode, $v > \omega/q$ [3,7], is not fulfilled because the phase velocities of the two hybridized Dirac plasmon modes are $> v_{\rm F}$ in this case. On the other hand, when the space is filled with sapphire, there is a prominent wake pattern in the potential behind the particle, $x - vt < 0$, resulting from a low-frequency plasmon-phonon mode, $\omega_{\rm low}$ [8], which does not disperse as q increases, thereby enabling the kinematic resonance for a sufficiently large wavenumber, $q > \omega_{\rm low}/v_{\rm F}$ [7].

At the same time, it is remarkable in Fig. 2 that the analytical MDF model reproduces the overall shape and the period of quasi-oscillations in the wake potential obtained from the *ab initio* calculations. The main quantitative difference is seen to be in the magnitude of the main peak and in the amplitudes of quasi-oscillations, which appear larger in the MDF model than in the *ab initio* case. For example, the ratio of the MDF to *ab initio* data is ≈ 1.4 for the main peak and it increases from about 1.5 to about 2 for the amplitudes as the distance from the charged particle increases. Since the wake in Fig. 2 arises due to excitation of a low-frequency mode $\omega_{\rm low}$, it is possible that the observed difference arises due to the fact that the MDF model underestimates the static limit of the graphene polarization function, $\chi_j^0(q, \omega \to 0)$, in comparison to the *ab initio* calculations [10].

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