28th Summer School and International Symposium on the Physics of Ionized Gases

Aug. 29 - Sep. 2, 2016, 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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Serbian Academy
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Publisher:
University of Belgrade, Faculty of Physics,
Belgrade
Studentski trg 12, P. O. Box 44
11000 Belgrade, Serbia

Computer processing:
Tatjana Milovanov

Printed by
Skripta Internacional, Mike Alasa 54, Beograd

Number of copies
200

ISBN 978-86-84539-14-6

PREFACE

This publication of Faculty of Physics, University of Belgrade contains the Contributed papers and abstracts of Invited Lectures, Topical Invited Lectures, Progress Reports and associated Workshops' Lectures that will be presented at the 28th Summer School and International Symposium of the Physics of Ionized Gases – SPIG 2016. The symposium will be held at the Serbian Academy of Sciences and Arts in Belgrade, Serbia, from August 29th to September 2nd, 2016. The symposium is organized by the Faculty of Physics, University of Belgrade and Serbian Academy of Sciences and Arts, with the support of the Ministry of Education, Science and Technological Development, Republic of Serbia.

The SPIG conference covers a wide range of topics, bringing together leading scientists worldwide to present and discuss state of art research and the most recent applications, thus stimulating a modern approach of interdisciplinary science. The Invited lectures and Contributed papers are related to the following research fields: Atomic Collision Processes (Electron and Photon Interactions with Atomic Particles, Heavy Particle Collisions, Swarms and Transport Phenomena), Particle and Laser Beam Interactions with Solids (Atomic Collisions in Solids, Sputtering and Deposition, Laser and Plasma Interaction with Surfaces), Low Temperature Plasmas (Plasma Spectroscopy and other Diagnostic Methods, Gas Discharges, Plasma Applications and Devices) and General Plasmas (Fusion Plasmas, Astrophysical Plasmas and Collective Phenomena). The 28th SPIG includes two workshops that are closely related to the conference topics: the workshop on X-ray Interaction with Biomolecules in Gas Phase (XiBiGP) and the 4th International Workshop on Non-Equilibrium Processes (NonEqProc).

The Editors would like to thank the members of the Scientific and Advisory Committees of SPIG 2016 for their efforts in proposing the invited lectures and review of the contributed papers, as well as the chairmen of the associated workshops for their efforts and help in organizing the workshops and selection of invited talks. We particularly acknowledge the support of all members of the Local Organizing Committee for their help in the organization of the Conference. We are grateful to sponsors of the conference: RoentDek Handels GmbH and the European Physical Journal D.

Finally, we would like to thank all the invited speakers and participants for taking part in 28th SPIG and to wish them a pleasant stay in Belgrade, inspired and valuable moments and a very successful conference.

Editors: Dragana Marić, Aleksandar Milosavljević,
Bratislav Obradović and Goran Poparić

Belgrade, 2016.

ACKNOWLEDGEMENT

28th SUMMER SCHOOL AND INTERNATIONAL SYMPOSIUM ON THE PHYSICS OF IONIZED GASES

is organized by

University of Belgrade,
Faculty of Physics, Belgrade, Serbia

and

Serbian Academy of
Sciences and Arts

with the support of the

Ministry of Education, Science and Technological Development,
Republic of Serbia

with the technical support of the

PANACOMP - Zemlja Čuda d.o.o.

and sponsored by:

RoentDek Handels GmbH
The European Physical Journal D

SPIG 2016

SPIG 2016 CONFERENCE TOPICS

Section 1.

ATOMIC COLLISION PROCESSES

1.1. Electron and Photon Interactions with Atomic Particles
1.2. Heavy Particle Collisions
1.3. Swarms and Transport Phenomena

Section 2.

PARTICLE AND LASER BEAM INTERACTION WITH SOLIDS

2.1. Atomic Collisions in Solids
2.2. Sputtering and Deposition
2.3. Laser and Plasma Interaction with Surfaces

Section 3.

LOW TEMPERATURE PLASMAS

3.1. Plasma Spectroscopy and Other Diagnostics Methods
3.2. Gas Discharges
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The Workshop on X-ray Interaction with Biomolecules in Gas Phase (XiBiGP)

The 4th International Workshop on Non-Equilibrium Processes (NonEqProc)

PLASMON-PHONON HYBRIDIZATION IN LAYERED STRUCTURES INCLUDING GRAPHENE

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Abstract. We present a method to introduce several graphene sheets into the non-retarded Green's function for a layered structure containing polar insulators, which support transverse optical phonon modes. Dispersion relations are derived to illustrate hybridization of Dirac plasmons in two graphene sheets with phonon modes in an oxide spacer layer between them.

1. INTRODUCTION

Recent developments in the area of Nano-Plasmonics are concerned with integrating graphene sheets and other two-dimensional (2D) materials with various dielectric materials in order to design novel devices that operate in the Terahertz to mid-infrared range of frequencies [1,2]. Particulary interesting is the possibility to control the doping density of charge carriers in graphene via chemical or electrical means, which enables the tunability of the dispersion relation of graphene's Dirac plasmon [2]. However, insulating spacer layers between graphene sheets in such nanoscale devices are typically composed of strongly polar materials, such as SiO_2, Al_2O_3 and other oxides, which support pronounced transverse optical (TO) phonon modes in the above mentioned frequency range [3]. Those phonon modes can provide efficient means for damping of Dirac plasmons and they may undergo strong hybridization with the Dirac plasmons in the nearby graphene sheets, thereby modifying the dispersion of the collective modes in layered structures that involve graphene sheets [4].

This plasmon-phonon hybridization (PPH) may be explored by moving charged particles, e.g. in a high-resolution electron energy loss spectroscopy (HREELS). We have recently shown that the wake effect in the dynamically screened potential induced by a slow charge moving parallel to a graphene sheet on a SiO_2 substrate can be used as a sensitive probe for the PPH [5]. In Ref. [5] we have used a classical dielectric formalism in the non-retarded limit to solve the Poisson equation with suitable boundary conditions. However, in the case of complex layered structures of dielectrics, it is preferable to use the available electrostatic Green's functions (GFs) for those structures [6] as a starting point. Then, owing to the 2D nature of the polarization function of graphene, it is possible to solve analytically the Dyson-Schwinger (DS) equation for the GF describing a layered structure that contains any number of graphene sheets. Using this GF allows one to develop closed-form expressions for the induced potential and the related polarization forces of interest in HREELS [5,6].

In this work, we illustrate the process of solving the DS equation for a "sandwich" structure consisting of two graphene sheets with an oxide layer between them.

2. GREEN'S FUNCTION FORMALISM

We assume that the layered structure is translationally invariant in the directions of the position vector $\mathbf{r} = \{x, y\}$ in a system of Cartesian coordinates $\{x, y, z\}$, allowing us to perform a 2D spatial ($\mathbf{r} \to \mathbf{q}$) and a temporal ($t \to \omega$) Fourier transform (FT) of all relevant quantities. Then the DS equation for the FT of the full GF, $\widetilde{G}(\mathbf{q}; z, z'; \omega)$, is

$$\widetilde{G}(z, z') = \widetilde{G}_0(z, z') + \frac{1}{4\pi} \int_{-\infty}^{\infty} \widetilde{G}_0(z, z'')\, \check{\mathcal{V}}(z'')\, \widetilde{G}(z'', z')\, dz'', \qquad (1)$$

where we have dropped $\mathbf{q}$ and ω to simplify the notation. Here, $\widetilde{G}_0(z, z') \equiv \widetilde{G}_0(\mathbf{q}; z, z'; \omega)$ denotes the GF for the structure *without* graphene, e.g., as given in Ref. [6]. One can include N graphene sheets placed in the planes $z = z_n$ by defining the interaction potential $\check{\mathcal{V}}(z) \equiv \check{\mathcal{V}}(\mathbf{q}; z; \omega)$ in Eq. (1) as

$$\check{\mathcal{V}}(z) = -4\pi e^2 \sum_{n=1}^{N} \chi_n \delta(z - z_n), \qquad (2)$$

where $\chi_n \equiv \chi_n(\mathbf{q}, \omega)$ is the polarization function of the nth graphene sheet. Notice that different graphene sheets may be doped with different densities of charge carriers, and hence they may have different Fermi energies E_F.

We limit our interest to a sandwich structure with $N = 2$ graphene sheets placed at $z_1 = 0$ and $z_2 = h$. Hence, from Eqs. (1) and (2),

$$\widetilde{G}(z, z') = \widetilde{G}_0(z, z') - e^2 \chi_1 \widetilde{G}_0(z, z_1)\, \widetilde{G}(z_1, z') - e^2 \chi_2 \widetilde{G}_0(z, z_2)\, \widetilde{G}(z_2, z'). \quad (3)$$

We next set $z = z_1$ and $z = z_2$ in Eq. (3) to obtain a system of algebraic equations for the unknown values of $\widetilde{G}(z_1, z')$ and $\widetilde{G}(z_2, z')$,

$$\left[1 + e^2\chi_1\widetilde{G}_0(z_1, z_1)\right]\,\widetilde{G}(z_1, z') + e^2\chi_2\widetilde{G}_0(z_1, z_2)\,\widetilde{G}(z_2, z') = \widetilde{G}_0(z_1, z'), \quad (4)$$

$$e^2\chi_1\widetilde{G}_0(z_2, z_1)\,\widetilde{G}(z_1, z') + \left[1 + e^2\chi_2\widetilde{G}_0(z_2, z_2)\right]\,\widetilde{G}(z_2, z') = \widetilde{G}_0(z_2, z'). \quad (5)$$

For a layer of oxide with the (relative) dielectric function $\varepsilon_{\rm ox}(\omega)$, which occupies region $0 \le z \le h$ and is surrounded by vacuum, one finds [6]

$$\widetilde{G}_0(z_1, z_1) = \widetilde{G}_0(z_2, z_2) \;=\; \frac{2\pi}{q\varepsilon_{\rm ox}}\frac{(1-\lambda)(1-\lambda\Delta)}{1-\lambda^2\Delta}, \quad (6)$$

$$\widetilde{G}_0(z_1, z_2) = \widetilde{G}_0(z_2, z_1) \;=\; \frac{2\pi}{q\varepsilon_{\rm ox}}\sqrt{\Delta}\frac{(1-\lambda)^2}{1-\lambda^2\Delta}, \quad (7)$$

where $\lambda = (1-\varepsilon_{\rm ox})/(1+\varepsilon_{\rm ox})$ and $\Delta = {\rm e}^{-2qh}$. Using Eqs. (6) and (7) one can solve Eqs. (4) and (5) to obtain $\widetilde{G}(z_1, z')$ and $\widetilde{G}(z_2, z')$, which need to be substituted in the right-hand side of Eq. (3) to yield a final expression for the full GF, $\widetilde{G}(z, z')$.

One can derive a dispersion relation for all eigenmodes in a sandwich structure with two graphene sheets by making the determinant of the coefficients in the left-hand sides of the system in Eqs. (4) and (5) vanish. As an illustration, we assume that the graphene sheets have equal polarization functions, $\chi_1 = \chi_2 = \chi$, in which case we obtain two dispersion relations corresponding to anti-symmetric and symmetric coupling between collective modes at the opposite surfaces of this sandwich structure,

$$1 + \varepsilon_{\rm ox}\tanh(qh) + \frac{4\pi e^2}{q}\chi = 0, \quad \text{and} \quad 1 + \varepsilon_{\rm ox}\coth(qh) + \frac{4\pi e^2}{q}\chi = 0. \quad (8)$$

3. RESULTS AND CONCLUDING REMARKS

To obtain dispersion relations of our sandwich structure, we use $\varepsilon_{\rm ox}(\omega)$ from Ref. [3] for a 5 nm thick layer of Al_2O_3, which includes two TO phonon modes at 48 meV and 71 meV with zero damping. If we take the long wavelength limit of the polarization function for both graphene sheets, $\chi = -q^2E_F/\left(\pi\hbar^2\omega^2\right)$ with $E_F = 200$ meV, then each of the dispersion relations in Eq. (8) becomes a cubic equation in ω^2 and it may be in principle solved analytically. The resulting six dispersion curves are shown in the left panel of Fig. 1 for symmetric (red curves) and anti-symmetric coupling (green curves) of two pairs of the surface TO phonons and two Dirac plasmons. Alternatively, one may plot the so-called loss function, $-\Im\left[1/\varepsilon(q,\omega)\right]$ where $\varepsilon(q,\omega)$ is the dielectric function of the entire sandwich structure obtained by an *ab initio* method [7]. In the right panel of Fig. 1 we see that the peak positions in the loss function follow quite closely the analytically obtained dispersion curves in the left panel, showing versatility of the GF approach.

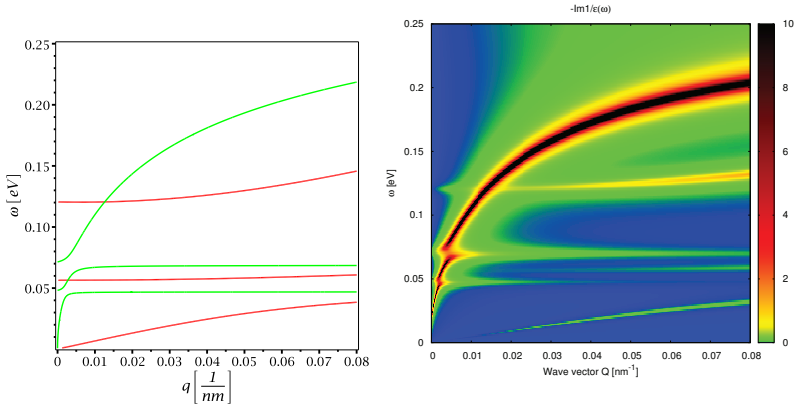

Figure 1. Analytical result for dispersion relations of hybridized modes, Eq. (8), (left) and *ab initio* result for loss function, $-\Im\left[1/\varepsilon(q,\omega)\right]$, (right) in Al_2O_3 layer between two graphene sheets with Fermi energies $E_F = 0.2$ eV.

Acknowledgements

T.Dj., L.K. and I.R. acknowledge support from the Ministry of Education, Science and Technological Development of the Republic of Serbia (Projects No. 171023, 32039, and 45005, respectively). V.D. acknowledges support from the Ministry of Science, Education and Sports of the Republic of Croatia. Z.L.M. acknowledges support from the Natural Sciences and Engineering Research Council of Canada.

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CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

537.56(082)
539.186.2(082)
539.121.7(082)
533.9(082)

SUMMER School and International Symposium on the Physics of Ionized Gases (28 ; 2016 ; Beograd)
Contributed Papers & Abstracts of Invited Lectures, Topical Invited Lectures, Progress Reports and Workshop Lectures / 28th Summer School and International Symposium on the Physics of Ionized Gases - SPIG 2016, [August 29 - September 2], 2016, Belgrade ; editors Dragana Marić ... [et al.]. - Belgrade : University of Belgrade, Faculty of Physics, 2016 (Beograd : Skripta Internacional). - 474 str. : ilustr. ; 24 cm

Tiraž 200. - Str. 5: Preface / editors Dragana Marić ... [et al.]. - Napomene i bibliografske reference uz tekst. - Bibliografija uz svaki rad. - Registar.

ISBN 978-86-84539-14-6
1. Marić, Dragana, 1973- [уредник] [аутор додатног текста]
a) Јонизовани гасови - Зборници b) Атоми - Интеракција - Зборници
c) Плазма - Зборници
COBISS.SR-ID 225356044