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Feasibility of a drift-induced instability in modulated graphene

M.S. Hussain [a], B. Rasul [a,*], A.H. Nizamani [b], M. Tahir [a]

[a] Department of Physics, University of Sargodha, Sargodha 40100, Pakistan
[b] Institute of Physics, University of Sindh, 76080 Jamshoro, Pakistan

HIGHLIGHTS

- We consider modulated graphene monolayer in the presence of an external perpendicular magnetic field and a drifted momentum induced by constant current.
- We employ the self-consistent field approach to derive analytically the magnetoplasmon modes: inter- and intra-band magnetoplasmon spectra.
- We explore and numerically discuss the unstable regime in the plasmon spectrum.
- This can be further used as Terahertz radiation source.

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ABSTRACT

We examine the feasibility of a drift-induced instability of Dirac fermions in monolayer graphene in a weak periodic potential, taking into account of a steady current. In this work, we treat magnetic field induced Landau quantization including the effects of drift induced current (an in-plane dc electric field), and analyze both the inter-and the intra-Landau band aspects of the magnetoplasmon spectrum. We employ the framework of self-consistent-field approximation to determine the plasmon spectrum. The existence of the drift induced instability regions in the intra-Landau band magnetoplasmon spectrum as a function of inverse magnetic field is shown and discussed. The unstable intra-Landau band plasmon excitation could be a potential source of THz radiation with electronic device applications.

1. Introduction

Recently, the fabrication of crystalline graphene monolayers [1–4] has generated a great interest in the field of condensed matter physics due to its unique properties. The study of this two-dimensional material is not only of academic interest but there are serious efforts underway to investigate whether graphene can serve as the basic material for carbon-based electronics [5–7]. In its honeycomb lattice of carbon atoms, quasiparticles have a band structure in which electron band and valence band touch at two points in the Brillouin zone. At these Dirac points the quasiparticles obey the massless Dirac equation. In other words, they behave as massless chiral Dirac fermions leading to a linear dispersion relation $\varepsilon_k = V_F \hbar k$ (with the characteristic velocity $V_F \simeq 10^6$ m/s).

The role of electron–electron interactions [8] in electronic properties of graphene is a major area of investigation with several open questions. In this regard, plasmon modes have been identified that arise due to electronic correlations and observed in graphene [9–16]. In the presence of a magnetic field, these magnetoplasmons [17,18] occur at frequencies that oscillate with the magnetic field. When this system is subjected to a weak electric modulation [19,20], broadening of the Landau levels occurs resulting in both inter- and intra-Landau band magnetoplasmons. The former arise as a result of electronic transitions between different Landau bands, whereas the latter are due to transitions within a single Landau band.

In this paper, we address the effects of a drift current on both the inter- and the intra-Landau band magnetoplasmons in graphene within the self-consistent-field (SCF) approach. We find that the intra-Landau band magnetoplasmons exhibit an instability which can be controlled by an applied magnetic field. It might be possible to harness this effect as a source of THz radiation for future optoelectronic applications of graphene. The basic physical mechanism behind the current-driven plasmon instability is the transfer of energy from the current to the growing plasmon waves of a given system. With a suitable coupling arrangement, this energy can be further converted to electromagnetic radiation.

Plasmons in graphene were studied as early as the 1980s [21] and more recently [22–25]. Drift induced instability has been observed in high mobility electron transistor [26] and calculated theoretically in layered graphene system [27]. In addition, a variety of theoretical and experimental work has been done on drift induced current instability in conventional two-dimensional

* Corresponding author. Tel.: +92 4892 30914.
E-mail address: bilalrasul@uos.edu.pk (B. Rasul).

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electron gas (2DEG) system with the identification of the drift induced instability regime which occurs when the drift velocity is of the order of/twice the Fermi velocity [28–38].

2. Formulation

We consider a monolayer of graphene in the xy-plane along with a constant perpendicular magnetic field applied in the z-direction. We employ the Landau gauge $(0, Bx, 0)$ to include the magnetic field induced effects on our system. The low energy two-dimensional Dirac-like Hamiltonian [17–20] is expressed as

$$H = V_F \overline{\sigma}.\overline{\pi} \tag{1}$$

where V_F is the Fermi velocity, $\overline{\sigma} = (\overline{\sigma}_x, \overline{\sigma}_y)$ are Pauli spin matrices and $\overline{\pi} = \overline{p} + eBx$ is the conjugate momentum. To study the effects of a drift-induced steady current, we include a drift-induced momentum $p_{dr} = \hbar k_{dr}$ in the Hamiltonian given in Eq. (1) in the y-direction as

$$H = V_F \begin{pmatrix} 0 & \pi_x - i(\pi_y - p_{dr}) \\ \pi_x + i(\pi_y - p_{dr}) & 0 \end{pmatrix} \tag{2}$$

The energy eigenvalues of the above Hamiltonian given in Eq. (2) are obtained as

$$\varepsilon_n^2 = \alpha^2 n \tag{3}$$

where $\alpha^2 = 2V_F^2\hbar^2/l_B^2 = \hbar^2\omega_g^2$, with n being the Landau level index, $\omega_g = V_F\sqrt{2eB/\hbar}$ is the cyclotron frequency of graphene, and $l_B = \sqrt{\hbar/eB}$ is the magnetic length. The corresponding eigenfunctions are given as

$$\Psi(n, k_y, k_{dr}) = \sqrt{\frac{1}{2L_y l_B}} \begin{pmatrix} -i\phi_{n-1}\left(\frac{x+x_0-x_{dr}}{l_B}\right) \\ \phi_n\left(\frac{x+x_0-x_{dr}}{l_B}\right) \end{pmatrix} \exp(ik_y y) \tag{4}$$

where $\phi_n(k_y, k_{dr}) = (1/(\sqrt{\pi}2^n n! l_B)^{-1/2}) \exp(-(x+x_0-x_{dr})/2l_B)\ H_n((x+x_0-x_{dr})/l_B)\ e^{ik_y y}$, as the above Hamiltonian explicitly depends on the x-coordinate and is independent of the y-coordinate so $\exp(ik_y y)$ is the plane wave solution in the y-direction. L_y is the length of the graphene sheet in the y-direction, $x_0 = l_B^2 k_y$ is the centre of the oscillator described by Eq. (2) and $x_{dr} = l_B^2 k_{dr}$ is the shift in the centre of the oscillator due to drift-induced current. We consider the effect of a weak periodic modulation potential with the following Hamiltonian:

$$H' = V_0 \cos\left(\frac{2\pi}{a}x\right), \tag{5}$$

here a is the period of modulation with amplitude V_0. Energy eigenvalue of this modulation potential can be found by perturbation theory as single particle Landau-quantized energies ε_n are taken to be much larger than V_0. The first-order correction in energy can be calculated by the expectation value of modulation potential as

$$\varepsilon_n' = \langle \Psi_{n,ky} | H' | \Psi_{n,ky} \rangle. \tag{6}$$

Solving for eigenvalue of energy correction to the unmodulated energy by applying first-order perturbation theory, we obtain

$$\varepsilon_n' = V_n \cos\left(\frac{2\pi}{a}(x_0 - x_{dr})\right), \tag{7}$$

where $V_n = (V_0/2)\exp(-X/2)[L_n(X) + L_{n-1}(X)]$, with $X = (2\pi/a)^2\hbar/2eB$ and $L_n(X)$ is an associated Laguerre polynomial with Landau level index n. Total energy eigenvalues of the present system in the presence of perpendicular magnetic field, drift and modulation potential can be rewritten as

$$\varepsilon(n, k_y, k_{dr}) = \varepsilon_n + \varepsilon_n' = \varepsilon_n + V_n \cos\left(\frac{2\pi}{a}(x_0 - x_{dr})\right). \tag{8}$$

In this equation, we must note the effect of drift in cosine term: $(2\pi/a)(x_0 - x_{dr})$. Essentially this term is responsible for the effects of drift induced current. In the limit of zero drift induced effects, these results are same as in Refs. [19,20]. Alternatively, to ensure the symmetry properties, above expression can be rewritten as

$$\varepsilon(n, k_y, k_{dr}) = \varepsilon(n, k_y \pm k_{dr}) = \varepsilon_n + V_n \cos\left(\frac{2\pi}{a}(x_0 \pm x_{dr})\right).$$

The width of the Landau band spectrum is given as

$$W = 2|V_n| \cos\left(\frac{2\pi}{a}x_{dr})\right)$$

3. Polarization function in the presence of drift induced effects

The static and dynamic response properties of an electron system are all embodied in the polarization function. We employ Ehrenreich and Cohen SCF approach [39] to calculate the polarization function. SCF treatment presented here has already been successfully employed in order to investigate electron correlation effects with and without magnetic field in conventional 2DEG system [28–38,40–43] and also recently in graphene [19,20,22–25]. This is demonstrated by the excellent agreement of SCF predictions of plasmon spectra with experiments [9–16]. Following the SCF approach, polarization function for monolayer graphene in the presence of drift induced potential can be derived and discussed.

To determine the effects of steady current with drift-induced momentum p_{dr}, a drifted equilibrium distribution function can be written as $f(\varepsilon_{n',k_y-q_y}) \Rightarrow f(\varepsilon_{n',k_y-q_y-k_{dr}})$. With this fact, the polarization function $\Pi(\overline{q}, \omega)$ with shift in k_y integration variable i.e. $K_y = k_y - k_{dr}$, can be modified as

$$\Pi(\overline{q}, \omega) = \frac{1}{A}\sum_{n,n'K_y} C_{nn'}\left(\frac{\hbar\overline{q}^2}{2eB}\right) \frac{f(\varepsilon_{n'}, K_y - q_y) - f(\varepsilon_n, K_y)}{\varepsilon(n', K_y + k_{dr} - q_y) - \varepsilon(n, K_y + k_{dr}) + \hbar\omega + i\eta} \tag{9}$$

where for $n' \le n$

$$C_{nn'}(w) = \left(\frac{n'!}{n!}\right) e^{-w} w^{n-n'} (L_{n'}^{n-n'}(w))^2$$

with

$$\frac{w = \left(\frac{l_B^2\overline{q}^2}{2}\right) = \hbar\overline{q}^2}{2eB}$$

The polarization function and the dielectric response function $\varepsilon(\overline{q}, \omega)$ including effects of electron–electron interactions are related as

$$\varepsilon(\overline{q}, \omega) = 1 - v_c(\overline{q})\Pi(\overline{q}, \omega), \tag{10}$$

where $v_c(\overline{q}) = 2\pi e^2/k\overline{q}$ is the two-dimensional Coulomb potential, k is the background dielectric constant. Alternatively, this can be written in the following form $\Pi(\overline{q}, \omega) = \Pi_+(\overline{q}, \omega) + \Pi_-(\overline{q}, \omega)$ with

$$\Pi_\pm(\overline{q}, \omega) = \frac{2eB}{\pi a\hbar}\sum_{n,n'} C_{nn'}\left(\frac{\hbar\overline{q}^2}{2eB}\right) \times \int_0^a dx_0 \frac{f(\varepsilon(n, x_0))}{\varepsilon(n, x_0 \pm x_{dr}) - \varepsilon(n', x_0 + x_0' \pm (x_{dr} + x_{dr}')) \pm \hbar\omega \pm i\eta}, \tag{11}$$