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SA-phonon-assisted cyclotron resonance via two-photon process in graphene on GaAs substrate

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ABSTRACT

The phonon-assisted cyclotron resonance (PACR) effect in a single-layer graphene on a GaAs substrate are theoretically studied via one and two-photon absorption processes. The result is limited by the combined interaction of the extrinsic potential of piezoelectric surface acoustic phonons of the substrate (PA) and of the intrinsic deformation potential of acoustic phonons of graphene (DA). The two-photon absorption process gives a significant contribution to magneto-optical absorption coefficient compared to one-photon process. It is shown that in the regime of low magnetic fields and temperatures the PA phonons dominate the magneto-optical absorption coefficient and half-width at half-maximum (HWHM). This finding would be useful to examine in subsequent research about HWHM in graphene. The present results have also demonstrated that the optical properties of graphene on a GaAs substrate can be controlled via extrinsic piezoelectric coupling.

1. Introduction

With its fascinating physical properties [1–3], graphene [4,5] has been expected to be a promising material for future applications in nano-electronic and optical technologies [6,7] and for quantum metrology [8]. For awaited new functionalities, the electron-phonon interaction in graphene structures can play a very important role. This can strongly affect the working efficiency of the optoelectronic devices. Therefore, a detailed understanding of the interaction between Dirac fermions and phonons in graphene is not only of fundamental interest but also of practical applications. This interesting issue has been reported in both theoretical [9–13] and experimental [14–17] studies. Up to now, most of the graphene devices investigated are situated on a SiO_2 substrate. This overcomes constraints associated with transport properties of suspended graphene [18].

Recently, with the expectation to make a high-quality graphene electronic, graphene devices on such promising substrate materials as SiC [19,20], h-BN [21], MgO(111) [22] and GaAs [8,23,24] have been fabricated and studied. With its senior surface quality and stronger hydrophilicity preventing folding of large scale graphene sheets, GaAs has a significantly larger dielectric constant in comparison with other substrates [25,26]. This improves the electrical screening of substrate defects. Therefore, the study of electron–phonon scattering in graphene on piezoelectric GaAs substrate, especially in such high-purity GaAs, can provide a useful tool for studying opto-electronic properties of graphene. In Ref. [26], Zhang et al. have studied the energy and temperature relaxation of electrons in graphene on a piezoelectric substrate. The authors have considered the scattering from

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the potential of extrinsic piezoelectric surface acoustical (PA) phonons of the substrate and from the potential of intrinsic deformation acoustical (DA) phonons of graphene in the case of non-degenerate Dirac fermions gas. The results showed that in the regime of low energies or temperatures the PA phonons dominate the relaxation and change qualitatively its character. Besides, the mobility of Dirac fermions [25] and the generation and amplification of GHz surface acoustic phonons [27] in monolayer graphene on GaAs substrate by the combined action of the PA and DA phonons have discussed. It was found that the interaction between PA phonons and Dirac fermions is quite strong and can dominate the intrinsic interaction of DA phonons.

In this work, we study the magneto-optical absorption properties of degenerate Dirac fermions gas in monolayer graphene situated on a GaAs substrate via two-photon absorption process. Similarly with previous reports [26], here we focus mainly on the range of low temperatures where the intrinsic graphene optical phonons [28–31] and surface optical phonons of substrate [32–35] are not effective and can be neglected in studying the optical absorption properties. Meanwhile, in this range of temperature, the surface acoustic phonons play an important role in electron–phonon scattering [36]. The main purpose of the present study is to examine how carriers in graphene interact with surface acoustic phonons via intra- and inter-transitions. Here we calculate magneto-optical absorption coefficient (MOAC) and half-width at half-maximum (HWHM) through scattering from the PA and DA phonons. The nonlinear optical absorption phenomenon is studied via investigating PACR effect, which has been demonstrated to be a useful tool for examining transport behavior of carriers in graphene [37]. We found that in the range of low magnetic fields and temperatures the PA phonons take dominant roles in the MOAC and HWHM in comparison with those of the DA phonons. This prediction would be useful to examine in subsequent research about HWHM in graphene on a GaAs substrate. Besides, the present result demonstrated that the optical properties of graphene on a GaAs substrate can be controlled via extrinsic piezoelectric coupling.

2. Theoretical calculation

2.1. Interaction Hamiltonian

In this work, we consider a single-layer graphene situated on a GaAs substrate. In the presence of magnetic field of magnitude B and perpendicular to the graphene sheet, the Hamitonian of the Dirac fermion-SA phonon systems is given by

$$\mathscr{H} = \sum_n \varepsilon_n a_n^\dagger a_n + \sum_{\mathbf{q}} \hbar\omega_{s\mathbf{q}} b_{s\mathbf{q}}^\dagger b_{s\mathbf{q}} + \mathscr{H}_{e-ph}^{s}, \tag{1}$$

where $\varepsilon_n = S_n\hbar\omega_c\sqrt{n}$ is the energy spectrum for a carrier with $\hbar\omega_c = \beta\sqrt{2}/a_c$ the effective magnetic energy, $a_c = (\hbar/eB)^{1/2}$ the magnetic length, β the band parameter, and $S_n = +1$ and -1 stand for, respectively, the conduction and valance bands [38–40]. Here, n is an integer denoting a LL in the conduction ($n > 0$) or valence bands ($n < 0$). The $n = 0$ LL is both the bottom of the conduction and the top of the valence bands. The wave function associated with the energy spectrum ε_n has been presented in Refs. [39,40]. Also $a_n^\dagger(a_n)$ is the carrier creation (annihilation) operator. The second term of Eq. (1) is the phononic Hamiltonian, where $b_{s\mathbf{q}}^\dagger(b_{s\mathbf{q}})$ represents the acoustic phonon creation (annihilation) operator for the s-th mode (s = PA, DA) with frequency $\omega_{s\mathbf{q}} = qv_s$, where v_s is the velocity of Rayleigh waves. The last term of Eq. (1) is the Dirac fermion–phonon interaction part of the Hamiltonian, which is given in the following.

The Hamiltonian of a piezoelectric interaction between surface acoustic phonon of the substrate and Dirac electrons in the graphene sheet can be written as [25–27].

$$\mathscr{H}_{e-ph}^{PA} = \frac{1}{\sqrt{\mathscr{A}}} \sum_{\mathbf{q}} \gamma_q^{PA} e^{i\mathbf{q}\cdot\mathbf{R}} b_{\mathbf{q}} + c.c., \tag{2}$$

where $\mathscr{A}$ is the normalization area, $\mathbf{q}$ and $\mathbf{R}$ are the two-dimensional wave vector and spatial vector in the graphene plane, respectively. The electron-phonon coupling γ_q^{PA} is defined as follows

$$\left|\gamma_q^{PA}\right|^2 = c_{PA}^2 \left(\frac{q_x q_y}{q^2}\right)^2 \frac{\hbar^2 v_{PA}}{p_0 \bar{\tau}_{PA}} e^{-2qd}, \tag{3}$$

where the characteristic wave vector $p_0 = 2.5 \times 10^6\ \mathrm{cm}^{-1}$ is related to the optical phonon energy in GaAs and the numerical factor $c_{PA} \approx 4.9$ is determined by the elastic properties of GaAs [25–27,41]. Here, as in Refs. [25–27], we use the nominal time $\bar{\tau}_{PA} = 8$ ps, and d is the distance between the graphene sheet and the GaAs substrate. The strongest electron-PA phonon interaction takes place for surface phonons propagating along the diagonal direction with $q_x \approx q_y$, so that in Eq. (2) we can approximate $(q_x q_y/q^2)^2 \approx 1/4$ [25–27]. However, unlike in Refs. [25–27] where γ_q^{PA} is independent of q resulting from the approximation $e^{-2qd} \approx 1$, here we can see that γ_q^{PA} is dependent on q, which is significant.

For the electron-acoustic phonon interaction caused by the deformation potential in graphene, the Hamiltonian can be written as

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