Photon-Assisted Resonant Chiral Tunneling Through a Bilayer Graphene Barrier

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The electronic transport property of a bilayer graphene is investigated under the effect of an electromagnetic field. We deduce an expression for the conductance by solving the Dirac equation. This conductance depends on the barrier height for graphene and the energy of the induced photons. A resonance oscillatory behavior of the conductance is observed. These oscillations are strongly depends on the barrier height for chiral tunneling through graphene. This oscillatory behavior might be due to the interference of different central band and sidebands of graphene states. The present investigation is very important for the application of bilayer graphene in photodetector devices, for example, far-infrared photodevices and ultrafast lasers.

1 Introduction

Two-dimensional graphene monolayer and bilayer exhibit fascinating electronic [1–4] and optical properties [5, 6] due to zero energy gap and relativistic-like nature of quasiparticle dispersion close to the Fermi-level. With recent improvements in nanofabrication techniques [7] the zero-energy gap of graphene can be opened via engineering size, shape, character of the edge state and carrier density, and this in turn offers possibilities to simultaneously control electronic [8, 9] magnetic [10, 11] and optical [6, 12] properties of a single material nanostructure. Recent studies have also addressed electronic properties of confined graphene structure like dots, rings or nanoribbons. In particular, nanoribbons have been suggested as potential candidates for replacing electronic components in future nanoelectronic and spintronic devices [3, 13]. Recent research shows that graphene [14] is a suitable candidate to examine the photon-assisted tunneling and quantum pumps in the Dirac system.

The purpose of the present paper is to investigate the angular dependence of the chiral tunneling through double layer graphene under the effect of the electromagnetic field of wide range of frequencies.

2 Theoretical Formulation

In this section, we shall derive an expression for the conductance of a bilayer graphene by solving the eigenvalue problem Dirac equation. The chiral fermion Hamiltonian operates in space of the two-component eigenfunction, ψ, where Dirac eigenvalue differential equation is given by [14, 15]:

$$-\,i v_F\,\vec{\sigma}\cdot\vec{\nabla}\psi(r) = E\psi(r)\,, \tag{1}$$

where $\vec{\sigma}$ are the Pauli-matrices, V_F is the Fermi-velocity, and E is the scattered energy of electrons. It is well known that graphene junction have finite dimensions [14, 15], the motion of chiral fermions is quantized. This quantization imposes additional constrains on the directional tunneling diagram. So, accordingly, the value of the angle of incidence of electrons on the barrier could be obtained from boundary conditions along the y-direction as we will see below.

In order to solve Eq.(1), we propose a potential barrier of width, L, and height, V_0,. The eigenfunction, $\psi_L(r)$ in the left of the potential barrier is given by:

$$\psi_L(r) = \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\left\{e^{[i(k_x x+k_y y)]} + \right. \\ \left. + \frac{R_n(E)}{\sqrt{2}}\begin{pmatrix}1\\ s\,e^{i(\pi-\phi)}\end{pmatrix} e^{[i(-ik_x x+k_y y)]}\right\}, \tag{2}$$

where the angle $\phi = \tan^{-1}\left(\frac{k_y}{k_x}\right)$, in which $k_x = k_f\cos(\phi)$ and $k_v = k_F\sin(\phi)$,and k_F is the Fermi-wave number, and J_n is the n^{th} order Bessel function, V_{ac} is the amplitude of the induced photons of the electromagnetic field with frequency, ω, and $R_n(E)$ is the energy-dependent reflection coefficient.

The eigenfunction, $\psi_b(r)$, inside the potential barrier is given by:

$$\psi_b(r) = \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\left\{\frac{a}{\sqrt{2}}\begin{pmatrix}1\\ s'\,e^{i\theta}\end{pmatrix} e^{[i(q_x x+k_y y)]} + \right. \\ \left. + \frac{b}{\sqrt{2}}\begin{pmatrix}1\\ s'\,e^{i(\pi-\theta)}\end{pmatrix} e^{[i(-q_x x+k_y y)]}\right\}, \tag{3}$$

where the angle $\theta = \tan^{-1}\left(\frac{k_y}{q_x}\right)$, and the wave number qx is expressed as:

$$q_x = \sqrt{\frac{(V_0-\varepsilon)^2}{v_F^2} - k_y^2} \tag{4}$$

and $\varepsilon = E - eV_g - \hbar\omega$, V_0 is the barrier height, E is the energy of the scattered electrons, V_g is the gate voltage and $\hbar\omega$ is the photon energy.

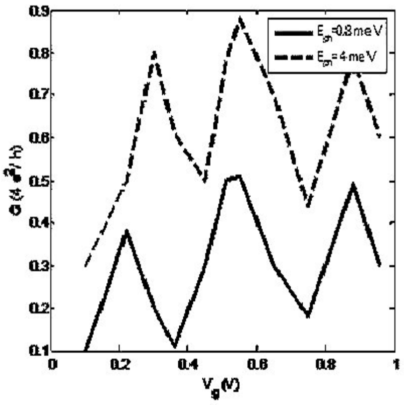

Fig. 1: The variation of the conductance, G, with gate voltage V_g, at different photon energies, E_{ph}.

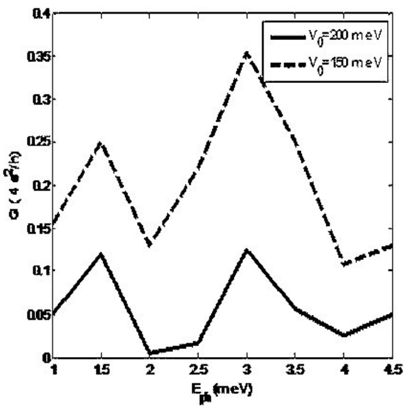

Fig. 2: The variation of the conductance, G, with the photon energy, E_{ph}, at different values of barrier height, V_0.

The eigenfunction, $\psi_R(r)$, in the right region to the potential barrier which represents the transmitted electrons is given by:

$$\psi_R(r) = \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\left\{\frac{\Gamma_n(E)}{\sqrt{2}}\begin{pmatrix}1\\ s\,e^{i\theta}\end{pmatrix} e^{[i(k_x x+k_y y)]}\right\}, \qquad (5)$$

where $\Gamma_n(E)$ are the transmitted electron waves through the barrier. The parameters s and s' are expressed as:

$$s = \operatorname{sgn}(E) \qquad \text{and} \qquad s' = \operatorname{sgn}(E - V_0)\,. \qquad (6)$$

Now, the coefficients $R_n(E), a, b, \Gamma_n(E)$ could be determined by applying the continuity conditions of the eigenfunctions, Eqs.(2,3,5), at the boundaries as follows:

$$\left.\begin{array}{l}\psi_L\,(x=0,\,y) = \psi_b\,(x=0,\,y)\\ \text{and}\\ \psi_b\,(x=L,\,y) = \psi_R\,(x=L,\,y)\end{array}\right\}. \qquad (7)$$

So, the transmission probability, $|\Gamma_n(E)|^2$, could be determined from the boundary conditions Eq.(7) and is given by:

$$|\Gamma_n(E)|^2 = \sum_{n=-\infty}^{\infty} J_n^2\left(\frac{eV_{ac}}{\hbar\omega}\right)\times$$
$$\times\left\{\frac{\cos^2(\theta)\cos^2(\phi)}{[[\cos(Lq_x)\cos\phi\cos\theta]^2 + \sin^2(Lq_x)(1-ss'\sin\phi\sin\theta)^2]}\right\}. \qquad (8)$$

The conductance, G, is given by [16, 17]:

$$G(E) = \frac{4e^2}{h}\int dE\,|\Gamma_n(E)|^2\left(-\frac{\partial f_{FD}}{\partial E}\right), \qquad (9)$$

where f_{FD} is the Fermi-Dirac distribution function. Now, substituting Eq.(8) into Eq.(9), we get a complete expression for conductance which depends on the angles ϕ, θ, and on the barrier height, V_0, and its width, the gate voltage, V_g, and the photon energy, $\hbar\omega$.

3 Results and Discussions

The conductance, G, has been computed numerically as a function of the gate voltage, V_g, and photon energy, $E_{ph} = \hbar\omega$ of the induced electromagnetic field. For the bilayer graphene, the effective mass of the fermion quasiparticle m^* equals approximately 0.054 m_e [14, 15]. The parameter m_e is the free mass of the electron. The main features of the present results are:

(1) Fig.(1) shows the variation of the conductance, with the gate voltage, V_g, at different values of the photon energies of the induced electromagnetic field. We notice an oscillatory behavior of the conductance. The electromagnetic field induces resonant peaks in the photon-assisted chiral tunneling conductance.

(2) Fig.(2) shows the dependence of the conductance on the energy of the induced photons at different values of the barrier height, V_0. An oscillation of the conductance is observed.

The observed oscillations in conductance for Figs.(1,2) can be explained as Follows: For grapheme under the effect of the electromagnetic field, the chiral tunneling of electrons can undergo transitions between the central band to several sidebands by means of photon emission or absorption. Such process is referred to as photo-assisted tunneling [18–20]. Also, the phase correlations during chiral tunneling can be directly tuned by applying of an external electromagnetic field leads to a resonance trend in the conductance of a bilayer graphene.

The present results show a good concordant with those in the literature [21–23].

4 Conclusion

The present investigation shows that the chiral tunneling of Dirac electrons through graphene enables ultra-wide band tunability. The rise of graphene in photonics and optoelectronics is shown by several results ranging from photo-detectors, light emitted devices, solar cells and ultra-fast lasers [23, 24].

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