Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Scattering theory of electron transport in single layer graphene with a time-periodic potential

HaiYang Chen

School of Physics, Beijing Institute of Technology, Beijing 100081, China

ARTICLE INFO

Article history:
Received 30 January 2014
Received in revised form 29 April 2014
Accepted 2 May 2014
Available online xxxx
Communicated by V.M. Agranovich

Keywords:
Graphene
Scattering approach
Conductivity
Shot noise

ABSTRACT

We applied the scattering approach to studying the transport properties of charge carriers through single layer graphene in the presence of a time-periodic potential. Using the method, expressions for the second-quantized current operator, conductivity and shot noise are obtained. The results obtained in this study demonstrate that the applied external field provides sidebands for charge carriers to tunnel through the graphene, and these sidebands changed the transport properties of the system. The results obtained in this study might be of interest to basic understanding of photon-assisted tunneling (PAT) and designers of electron devices based on graphene.

1. Introduction

Graphene has become a subject of intense interest due to the successful fabrication experiment by Novoselov et al. [1]. Graphene is a single layer of carbon atoms densely packed in a honeycomb lattice, whose low-energy dynamics of electrons equivalent to the relativistic fermions is not described by the usual Schrödinger equation, but by the Dirac-like equation

$$\hat{H}_0 = -i\hbar v_F \sigma \nabla \tag{1}$$

$v_F \approx 10^6$ m/s is the Fermi velocity, $\sigma = (\sigma_x, \sigma_y)$ are the Pauli matrices. The eigenstates of the Hamiltonian (1) are two-component spinor wave function. Near the Brillouin zone the graphene has the linear energy spectrum, $E = \hbar v_F k$. The linear energy spectrum and chiral nature of the particles make the graphene possess a number of unique electronic and transport properties such as an unconventional Hall effect [2–5], finite minimal electrical conductivity [2,6], special Andreev refection [7,8], Klein paradox [9–13] and so on.

Photon-assisted tunneling (PAT) has been attracting much research interest. Basically, (PAT) originating from energy exchanges between the electrons and energy quanta (photons) of the applied oscillating field. In the presence of an additional time-periodic potential, the energy E of an electron state can be transferred to sidebands with energies $E + l\hbar\omega$ $(l = 0, \pm 1, \pm 2, \ldots)$. Dayem and Martin reported evidences of absorption or emission of photons by a single tunneling electron according to the experiments on the tunneling between superconducting films in the presence of microwave fields [14]. Tien and Gordon explained qualitatively the multiphoton-assisted electron tunneling current in superconducting diodes by calculation [15]. Yurke and Kochanski calculated the momentum transported across a barrier by the second-quantized and momentum-current operators [16]. Büttiker investigated the noise spectral density for multiterminal, multichannel conductors and compared these results with the intensity–intensity correlations of a photon wave guide [17]. Pedersen and Büttiker extended the scattering-matrix approach to transport in phase-coherent conductors, and the fluctuation spectrum in the presence of oscillating voltages applied to the contacts of the sample was obtained [18]. Zeb et al. studied the transport of Dirac electrons in monolayer graphene through a single barrier with a time-periodic potential, they found that at normal and close to normal incidence the system shows perfect transmission (Klein tunnelings) because of chiral nature of the particles [19]. In a series of papers, Wagner studied photon-assisted transport through quantum barriers and wells with driving $V \cos\omega t$ based on a transfer-matrix formalism [20–22].

Shot noise in an electrical conductor is one of the important physical quantities, it is a consequence of the quantization of the charge. With the development of single electron devices, shot noise attracts more and more attention, as it influences the performance of the devices. At the same time, by measuring shot noise, we can understand the transport mechanism of a mesoscopic system. We can get more information than conductance by researching shot noise, for example, determine the charge and statistics of the quasiparticles relevant for transport and reveal information on

E-mail address: chenhaiyang05@126.com.

http://dx.doi.org/10.1016/j.physleta.2014.05.004

the potential profile and internal energy scales of mesoscopic system by shot noise experiments [23].

First, we construct the wave function of charge carriers through single layer graphene in the presence of external field. Then obtain the second-quantized current operator on the base of the scattering approach. Furthermore, we calculate the expressions for the conductivity and shot noise and explain the obtained results. The present results will be helpful for the basic understanding of photon-assisted tunneling (PAT) and designers of electron devices based on graphene.

2. Theory and model

For simplify, the discussion will be confined to one-dimensional case, and we use the same setup as in Ref. [19], a monolayer graphene sheet in the xy plane. The square potential barrier is set up in the x direction while carriers are free in the y direction. The width of the barrier is a and the height of the barrier is oscillating sinusoidally around V with amplitude V_1 and frequency ω. Charge carriers with energy E are incident from one side of the barrier in graphene with an angle ϕ_0 with the x axis. The Hamiltonian H of the system is as follows:

$$H = H_0 + H_1 \tag{2}$$

among them

$$H_0 = -i\hbar v_F \sigma \cdot \nabla + V,$$
$$H_1 = V_1 \cos(\omega t) \tag{3}$$

V and V_1 are the static square potential barrier and the amplitude of the oscillating potential, respectively. By solving the Dirac equation in the absence of the oscillating potential [9], one can obtain the functions through the barrier from the left (ψ_1) and right (ψ_2), respectively [19]

$$\psi_1 = e^{ik_{1y}y} \sum_{l=-\infty}^{\infty} \begin{pmatrix} \phi_{11}(x,y,t) \\ \phi_{12}(x,y,t) \end{pmatrix} \tag{4}$$

and

$$\psi_2 = e^{ik_{2y}y} \sum_{l=-\infty}^{\infty} \begin{pmatrix} \phi_{21}(x,y,t) \\ \phi_{22}(x,y,t) \end{pmatrix} \tag{5}$$

where

$$\psi_{1i} = e^{ik_{1y}y} \sum_{l=-\infty}^{\infty} \begin{pmatrix} \delta_{l0} \\ s_0 e^{i\phi_0}\delta_{l0} \end{pmatrix} e^{ik_1^0 x} e^{-i(E_1+l\hbar\omega)t/\hbar} \tag{6}$$

$$\psi_{1r} = e^{ik_{1y}y} \sum_{l=-\infty}^{\infty} r_l \begin{pmatrix} 1 \\ -s_l e^{-i\phi_l} \end{pmatrix} e^{-ik_1^l x} e^{-i(E_1+l\hbar\omega)t/\hbar} \tag{7}$$

$$\psi_{1t} = e^{ik_{1y}y} \sum_{l=-\infty}^{\infty} t_l \begin{pmatrix} 1 \\ s_l e^{i\phi_l} \end{pmatrix} e^{ik_1^l x} e^{-i(E_1+l\hbar\omega)t/\hbar} \tag{8}$$

$$\psi_{2i} = e^{ik_{2y}y} \sum_{l=-\infty}^{\infty} \begin{pmatrix} \delta_{l0} \\ s_0 e^{-i\phi_0}\delta_{l0} \end{pmatrix} e^{-ik_2^0 x} e^{-i(E_2+l\hbar\omega)t/\hbar} \tag{9}$$

$$\psi_{2r} = e^{ik_{2y}y} \sum_{l=-\infty}^{\infty} r_l \begin{pmatrix} 1 \\ -s_l e^{i\phi_l} \end{pmatrix} e^{ik_2^l x} e^{-i(E_2+l\hbar\omega)t/\hbar} \tag{10}$$

$$\psi_{2t} = e^{ik_{2y}y} \sum_{l=-\infty}^{\infty} t_l \begin{pmatrix} 1 \\ s_l e^{-i\phi_l} \end{pmatrix} e^{-ik_2^l x} e^{-i(E_2+l\hbar\omega)t/\hbar} \tag{11}$$

where

$$s_l = \mathrm{sgn}(E + l\hbar\omega),$$
$$k_1^l = \sqrt{\left(\frac{E + l\hbar\omega}{\hbar v_f}\right)^2 - k_y^2},$$
$$\phi_l = \tan^{-1}\left(\frac{k_y}{k_1^l}\right) \tag{12}$$

the subscripts i, r, t represent the incident, reflected, and transmitted wave functions, respectively. δ_{l0} is the Dirichlet function.

Repeat the derivation of Ref. [19] to obtain the transmission amplitudes for central band t_0 and first sidebands t_l ($l = \pm 1$) as follows:

$$t_0 = \frac{e^{-ik_1^0 a}\cos\theta_0\cos\phi_0}{\cos\theta_0\cos\phi_0\cos[k_2^0 a] + i\sin[k_2^0 a](1+\sin\theta_0\sin\phi_0)} \tag{13}$$

$$t_l = \frac{1}{2}\frac{J_l(\alpha)}{J_0(\alpha)}\frac{t_{s0}t_{sl}}{\cos\phi_l}\Big[\Gamma_l^+ + \Gamma_l^- e^{i(\phi_0+\phi_l)} + \Delta_l\big(e^{i(\phi_0+\phi_l)} + e^{i(\phi_l+k_1^0 a)}\big)\Big] \tag{14}$$

where

$$k_2^l = \sqrt{\left(\frac{E - V + l\hbar\omega}{\hbar v_f}\right)^2 - k_y^2},$$
$$\Gamma_l^\pm = \Lambda_l^\pm - \Lambda_0^\pm,$$
$$\Lambda_l^\pm = \cos\big[k_2^l a \pm \theta_l\big]/\cos\theta_l,$$
$$\Delta_l = \Omega_l - \Omega_0,$$
$$\Omega_l = i\sin\big[k_2^l a\big]/\cos[\theta_l] \tag{15}$$

a is the width of the barrier.

2.1. Average current

In terms of these wave functions one can obtain the second-quantized field operator $\hat{\psi}$ as [16]

$$\hat{\psi} = \hat{\psi}_1 + \hat{\psi}_2 \tag{16}$$

where

$$\hat{\psi}_1 = \int_0^\infty dE_1' \psi_1(E_1', r)\hat{\alpha}_1(E_1')e^{-iE_1't/\hbar}$$
$$= \sum_{l=-\infty}^{\infty}\int_0^\infty dE_1' \begin{pmatrix} \phi_{11}(E_1', r) \\ \phi_{12}(E_1', r) \end{pmatrix}\hat{\alpha}_1(E_1') \tag{17}$$

$$\hat{\psi}_2 = \int_0^\infty dE_2' \psi_2(E_2')\hat{\alpha}_2(E_2')e^{-iE_2't/\hbar}$$
$$= \sum_{l=-\infty}^{\infty}\int_0^\infty dE_2' \begin{pmatrix} \phi_{21}(E_2', r) \\ \phi_{22}(E_2', r) \end{pmatrix}\hat{\alpha}_2(E_2') \tag{18}$$

where $E_1' = E_1 + l\hbar\omega$, $E_2' = E_2 + l\hbar\omega$, and annihilation $\hat{\alpha}_1(E_1')$ and $\hat{\alpha}_2(E_2')$ satisfy the relation [23]

$$\langle \hat{\alpha}_{\alpha k}^+(E_1)\hat{\alpha}_{\beta l}(E_2)\rangle = \delta_{\alpha\beta}\delta_{kl}\delta(E_1 - E_2)f_\alpha(E_1) \tag{19}$$

where $f_\alpha(E_1)$ is the Fermi distribution function

$$f_\alpha(E_1) = \frac{1}{e^{\frac{(E_1-\mu_\alpha)}{K_B T_\alpha}} + 1}, \quad \alpha = 1, 2 \tag{20}$$