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Numerical study of transport properties in monolayer graphene-based double-barrier(well) structures under a time-periodic potential

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ABSTRACT

We have analyzed the effect of various system parameters and external time-dependent field on the transport properties of monolayer graphene-based double-barrier(well) structures under a time-periodic potential. Results indicate that the Klein tunneling still exists. Besides, the transmission probability, conductivity, shot noise, and Fano factor exhibit various types of oscillatory behavior with changes in the system parameters, and they are either improved or suppressed in the presence of the time-periodic potential. We have also discussed the reasons underlying these phenomena. The results obtained in this study demonstrate that the transport properties can be controlled by manipulating the structural parameters of the system and the external field strength.

1. Introduction

Graphene is a two-dimensional allotrope of carbon comprising a one-atom-thick planar sheet of sp^2-bonded carbon atoms densely packed in a honeycomb crystal lattice. With the recent demonstration of the fabrication of freestanding graphene by Novoselov et al. [1], there has been increased interest in the study of the various physical properties of graphene. The low-energy dynamics of electrons in graphene is equivalent to the relativistic fermions, which are described by the Dirac-like Hamiltonian

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

$v_F \approx 10^6$ m/s is the Fermi velocity and $\sigma = (\sigma_x, \sigma_y)$ are the Pauli matrices. The Dirac equation is the direct manifestation of the crystal symmetry of graphene, wherein the honeycomb lattice is made up of two equivalent carbon sub-lattices. Near the Brillouin zone, the graphene gives rise to the linear energy spectrum, $E = \hbar v_F k$. This linear energy spectrum and chiral nature of the particles endow graphene with a number of unique electronic and transport properties. One of the interesting aspects is the Klein paradox, which is caused by the chirality of the electrons in graphene. It predicts that the relativistic electron can pass through the high potential barrier to approach the perfect transmission. In contrast, for the conventional non-relativistic tunneling, the transmission probability exponentially decays with an increase in the barrier height [2–6]. The Klein tunneling has been investigated both theoretically and experimentally in various graphene-based microstructures, including single-barrier and double-barrier structures, superlattices [2,7–9], quantum wells, and quantum dots [10–12].

The recent developments in the engineering of confinement potential and band structure have opened up the possibility of studying photon-assisted tunneling. For instance, Dayem and Martin reported the evidences of absorption or emission of photons by a single-tunneling electron, based on the experiments on tunneling between superconducting films in the presence of microwave fields [13]. Similarly, Tien and Gordon performed theoretical studies to qualitatively explain the multiphoton-assisted electron tunneling current in superconducting diodes [14]. In the presence of an additional time-periodic potential $V \cos \omega t$, an electron of energy E will generate several sidebands of energies $E + l\hbar\omega (l = 0, \pm 1, \pm 2, \ldots)$. Due to the exchange of energy between the electrons and the time-periodic potential, the wave function will contain the Bessel function. In a series of papers, Wagner studied photon-assisted transport through quantum barriers and wells under the time-periodic potential $V \cos \omega t$ on the basis of the transfer-matrix formalism [15–17]. Furthermore, Pedersen and Büttiker extended the scattering-matrix approach to describe the transport in phase-coherent conductors. Besides, they obtained the fluctuation spectrum in the presence of oscillating voltages applied to the contacts of the sample [18]. Trauzettel et al. used scattering theory to study the photon-assisted electron transport in ballistic graphene [19]. Zeb et al. analyzed the transport of Dirac electrons in monolayer graphene through a single barrier under time-periodic potential, and demonstrated the changes in the transmission probabilities of the central and sidebands with respect to the system parameters. According to

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their study, the system shows perfect transmission (Klein tunneling) at the normal and close to the normal incidence because of the chiral nature of the particles [20].

Shot noise is an inherent physical quantity in an electrical conductor, which originates due to the quantization of electric charge. The measurement of shot noise will enable the understanding of the transport mechanism in a mesoscopic system. Analysis of shot noise is expected to provide more information than conductance. For example, shot noise experiments can provide information on the charge and statistics of the quasiparticles from the viewpoint of transport, and reveal information on the potential profile and internal energy scales of mesoscopic system [21]. The well-known Schottky's formula $S_p = 2e\langle I \rangle$, which refers to the Poissonian shot noise, results from the Poissonian distribution in a macroscopic system [22]. The Fano factor, which describes the type of shot noise deviating from the Poissonian one, can be obtained from the noise spectral densities S and S_p, using the relation $F = S/S_p$. Accordingly, the shot noise can be classified as the Poissonian (F=1), Sub-Poissonian ($F < 1$), and Super-Poissonian ($F > 1$) types [23].

In this paper, we have investigated the transport properties of monolayer graphene-based double-barrier(well) structures under a time-periodic potential. We have theoretically determined the effect of external field and the system parameters on the transmission probability, conductivity, shot noise, and Fano factor. The transport properties of graphene show peculiar behavior in the presence of time-periodic potential, which in turn influences the conductivity, shot noise, and Fano factor. Results indicate that the shot noise and Fano factor are enhanced with an increase in the external field strength α ($\alpha = V_1/\hbar\omega$). This implies that the transport properties of the system can be tuned by adept control of the structural parameters.

2. Theory and model

In this study, we have considered double-barrier structure in the xy-plane of a monolayer graphene sheet. The potential barrier is set up along the x-direction, while the carriers are free along the y-direction, as indicated in the schematic shown in Fig. 1. In a graphene sheet of width W, a is the width of the static barrier(well) (darker region), L is the barrier(well) spacing (gray region), and V is the height of the static barrier(well), sinusoidally

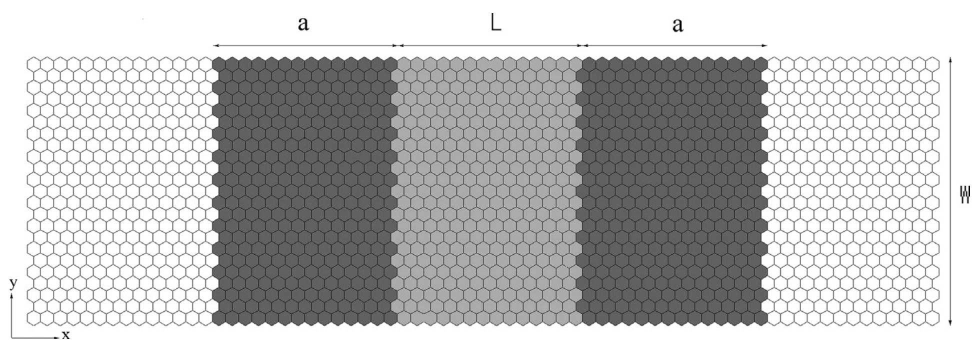

Fig. 1. Structure of a monolayer graphene-based double-barrier in the presence of a time-periodic potential. The darker regions denote static barrier while the gray regions denote the time-periodic potential.

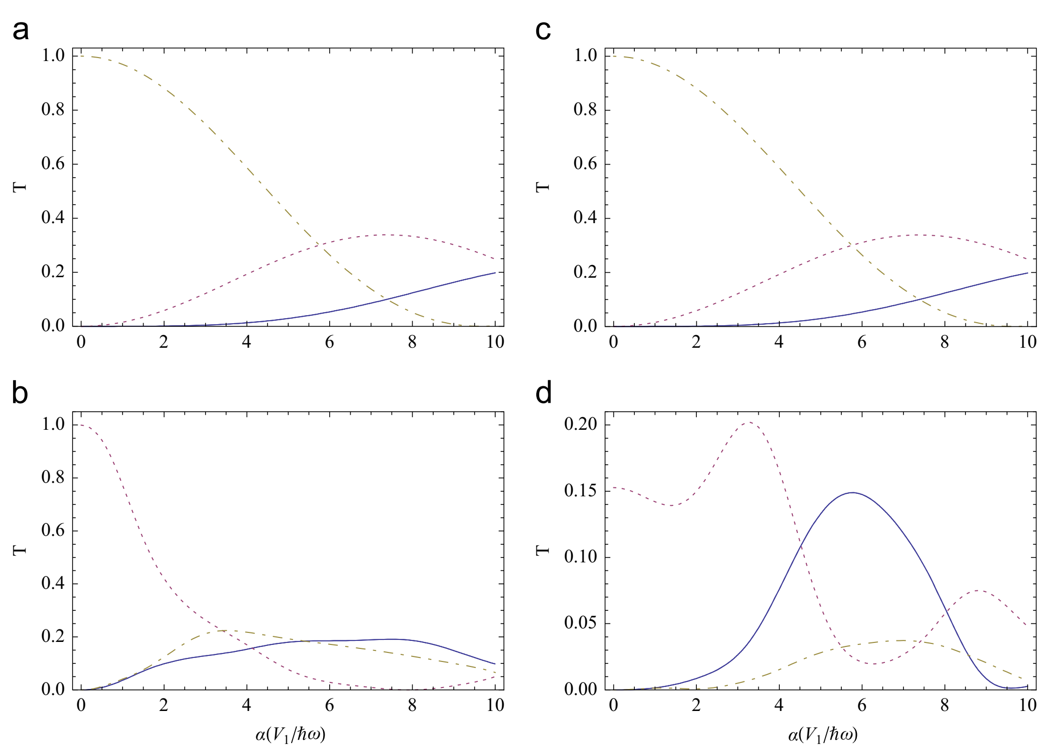

Fig. 2. Transmission probabilities of the central band and first sidebands as a function of α ($\alpha = V_1/\hbar\omega$) for the incident angle 0° [(a), (c)] and 30° [(b), (d)]. Solid, dotted, dotted–dashed lines correspond to $T_{\pm 2}$, $T_{\pm 1}$, T_0 [(a), (c)] and T_{-1}, T_0, T_{+1} [(b), (d)], respectively, for $V = -200$ meV [(a), (b)] and V=200 meV [(c), (d)].