Physica E 72 (2015) 134–139

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Shot noise in magnetic field modulated graphene superlattice

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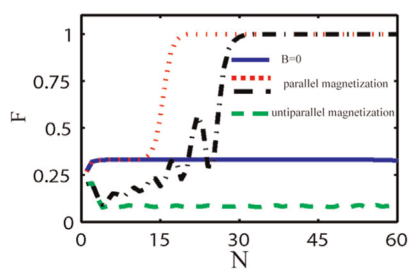
HIGHLIGHTS

- We investigate the shot noise properties through graphene superlattice.
- The Fano factor depends on the number of barriers.
- For the parallel configuration the Fano factor reaches a Poissonian value.
- For the antiparallel configuration the Fano factor at the Dirac point equals 1/3.

GRAPHICAL ABSTRACT

In the parallel magnetization configuration when the number of the barriers is large enough unlike antiparallel magnetization configuration the Fano factor reaches a Poissonian value for any barrier height.



ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form
22 April 2015
Accepted 28 April 2015
Available online 30 April 2015

Keywords:
Graphene superlattice
Shot noise
Fano factor
Dirac point

ABSTRACT

We investigate the shot noise properties in a monolayer graphene superlattice modulated by *N* parallel ferromagnets deposited on a dielectric layer. It is found that for the antiparallel magnetization configuration or when magnetic field is zero the new Dirac-like point appears in graphene superlattice. The transport is almost forbidden at this new Dirac-like point, and the Fano factor reaches its maximum value 1/3. In the parallel magnetization configuration as the number of magnetic barriers increases, the shot noise increases. In this case, the transmission can be blocked by the magnetic–electric barrier and the Fano factor approaches 1, which is dramatically distinguishable from that in antiparallel alignment. The results may be helpful to control the electron transport in graphene-based electronic devices.

1. Introduction

Graphene, two-dimensional material tightly packed into a monolayer honeycomb lattice of carbon atoms, which was synthesized by Novoselov et al. in 2004 [1,2]. In low energy regime, the quasiparticles in graphene close to the Dirac points (often referred to as K and K') are described by the massless Dirac-like equation. Such a peculiar band structure results in many unique electronic properties, including the unconventional quantum Hall effect [3], the nonzero conductivity at vanishing carrier concentration [4,5], the reflectionless Klein tunneling [6], the sub-Poissonian shot noise [7,8], special Andreev reflection [9], and many others.

In 1970 the superlattice was proposed by Esaki and Tsu [10], which attracted a great deal of researches over the past decades on the transport properties of the superlattice [11–14]. Motivated by the experimental realization of graphene superlattice [15–17], electronic bandgap structures and transport properties in graphene superlattice with electrostatic potential barrier was extensively investigated [18–23]. The transport properties in graphene-based superlattice structure were first studied by Bai and Zhang [18] the authors found that the conductivity of the graphene superlattice depends on the superlattice structural parameters. The conductance of a disordered graphene superlattice

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http://dx.doi.org/10.1016/j.physe.2015.04.025
1386-9477/

was investigated in Ref. [19], and the authors found that the conductance vanishes when the sample size becomes very large. In Ref. [20], the spin transport properties of graphene superlattice in the presence of Rashba spin–orbit interaction was studied and found that the magnetoresistance ratio shows a strong dependence on the number of barriers. To circumvent the Klein tunneling effect, it was suggested that a magnetic barrier can effectively block Klein tunneling and achieve confinement for massless Dirac fermions in graphene [24]. The required magnetic structures in graphene can be realized by depositing ferromagnetic stripes on the graphene layer [25,26]. There also exist many theoretical works which were studied transport properties through magnetic barriers and magnetic superlattice in graphene [27–34].

Shot noise originates from the fluctuation in the electrical signal due to the discreteness of electron charges. In addition, it is well known that shot noise is useful to obtain information of transmission that is not available through the standard conductance measurements [35,36]. The shot noise is characterized by the Fano factor F being the ratio of the noise power to mean current [37]. Recently, some papers focus on the shot noise in semiconductor superlattices and graphene based nano-structures both theoretically and experimentally [7,8,38–51]. Cheianov and Falko studied the unusual Fano factor in the graphene n–p junctions [38]. Tworzydlo et al. predicted that the Fano factor for a wide and short sample has a maximum value of 1/3 at the Dirac point, which is 1/3 of Poissonian value [39]. This is the same value as in the diffusive metals. Zhu and Guo investigated shot noise in the graphene-based double barriers and found that the shot noise with the Fano factor equal to 1/3 occurs at the Dirac point [40]. The transport properties and shot noise in Thue–Morse sequence graphene superlattice were investigated by Huang et al. [42], the authors found that the Fano factor has a maximum close to 1/3 in the vicinity of Dirac point. Also, experimental results of shot noise measurement in graphene structures are in good agreement with the theoretical predication [7,52]. It is generally accepted that the sub-Poisson shot noise of graphene originated from the peculiar band structure at the low energy regime near the Dirac point. In other words, the quasiparticles in graphene are described by the massless Dirac-like equation rather than the Schröedinger equation.

The purpose of this paper is to study the shot noise in magnetic field modulated graphene superlattice by using the transfer matrix method. The effect of the number of barriers on the Fano factor is taken into account. We show that for the antiparallel magnetization configuration or when magnetic field is zero the Fano factor reaches its maximum value 1/3, whereas for the parallel magnetization configuration it can be approached to 1 due to the transmission blockage. In particular, our probe shows that for the parallel magnetization and when the number of barriers, N, are larger than 50 the Fano factor reaches a Poissonian value, which is dramatically distinguishable from the semiconductor superlattice. In the semiconductor superlattice when all the barriers are identical, in the $N \to \infty$ limit the shot noise approach 1/3 of the Poissonian value [50,51]. The rest of the paper is organized as follows; our method and formalism are described in the next section. In Section 3 we present and discuss our results, and finally we end the paper with a brief conclusion.

2. Model and theory

In this paper, we consider two kinds of systems. In both cases, a monolayer graphene covered by a thin insulating layer and parallel ferromagnetic (FM) stripes are deposited on top of the dielectric layer [25,26]. Further, a gate voltage is applied to the FM stripes in order to produce an electrostatic barrier. In both cases, FM stripes

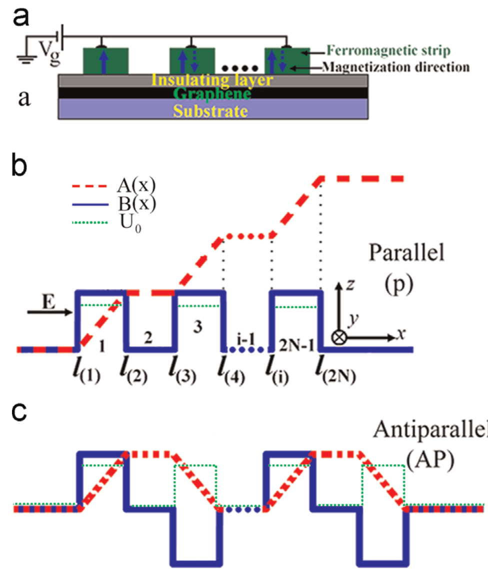

Fig. 1. (a) Schematic diagram of the model, the monolayer graphene covered by a thin insulating layer, parallel FM stripes are deposited on top of the insulating layer. Each FM stripe has a rectangular cross section and a magnetization parallel to the z axis. The gate voltage V_g applied on the FM stripes induces potential barrier in the graphene sheet. The FM stripes have magnetization parallel (P) or antiparallel (AP) to the z axis. (b) Magnetic field profile $B(x)$ (red dashed line), corresponding vector potential $A(x)$ (blue solid line) and the electrostatic potential U_0 (green dotted line) for the P alignment. (c) The same as in (b) but for the AP alignment.

have magnetization perpendicular to the graphene in the x–y plane. In the first and the second cases FM stripes with magnetization parallel (P) or antiparallel (AP) perpendicular to the graphene in the x–y plane are deposited on top of the dielectric layer, respectively. As known, the magnetic field generated by such a strip is non-uniform and depends on both its size and the distance to the studied 2D system. However, for sufficiently thin ferromagnetic strip, it is almost constant under the strip and vanishes outside this region [53]. Thus, the systems under consideration are graphene superlattice modulated by magnetic field. The magnetic field $B(x)$ emerging from the FM stripes will influence locally the motion of Dirac electrons in the graphene x–y plane and is assumed to be homogeneous in the y direction, but varies along the x direction. The schematic of the structures is shown in Fig. 1. According to the above discussion, the potential profile of the system consists of a sequence of N electrostatic barriers of equal height U_0 and width b, modulated by N magnetic barriers. Where, electrostatic and magnetic barriers separated by well regions (nonmagnetic regions) of width w.

Here, the effects of electron–electron and electron–phonon interactions are neglected by considering a single electron transmission at zero temperature. Therefore, the charge carriers in our model are described by the following Hamiltonian

$$\hat{H} = \hat{H}_0 + V(x)\hat{I}, \tag{1}$$

in which,

$$\hat{H}_0 = v_F\,\vec{\sigma}.\,(\vec{p} + e\vec{A}), \tag{2}$$

$$V(x) = \begin{cases} U_0 & \text{in barrier,} \\ 0 & \text{in well,} \end{cases} \tag{3}$$

where $\vec{p} = (p_x, p_x)$ is the quasiparticle momentum (setting $\hbar = 1$), $\vec{\sigma} = (\sigma_x, \sigma_x)$ is the 2D Pauli matrix, $v_F \approx 10^6\ ms^{-1}$ is the Fermi