Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Discussion

Spin-dependent delay time and Hartman effect in asymmetrical graphene barrier under strain

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ARTICLE INFO

Article history:
Received 6 September 2017
Received in revised form 1 November 2017
Accepted 10 November 2017
Available online xxxx
Communicated by M. Wu

Keywords:
Asymmetrical graphene barrier
Tunneling time
Hartman effect
Spin polarization

ABSTRACT

We study the spin-dependent tunneling time, including group delay and dwell time, in a graphene based asymmetrical barrier with Rashba spin–orbit interaction in the presence of strain, sandwiched between two normal leads. We find that the spin-dependent tunneling time can be efficiently tuned by the barrier width, and the bias voltage. Moreover, for the zigzag direction strain although the oscillation period of the dwell time does not change, the oscillation amplitude increases by increasing the incident electron angle. It is found that for the armchair direction strain unlike the zigzag direction the group delay time at the normal incidence depends on the spin state of electrons and Hartman effect can be observed. In addition, for the armchair direction strain the spin polarization increases with increasing the RSOI strength and the bias voltage. The magnitude and sign of spin polarization can be manipulated by strain. In particular, by applying an external electric field the efficiency of the spin polarization is improved significantly in strained graphene, and a fully spin-polarized current is generated.

1. Introduction

Graphene, carbon atoms in two-dimensional honeycomb lattice, was first synthesized by Novoselov et al. in 2004 [1]. In low energy regime the charge carriers in graphene can be well described by the massless Dirac-like equation with an effective speed of $v_F \approx 10^6$ m/s near the K and K′ points, which leads to many unusual properties, including the half-integer quantum Hall effect [2], the minimal conductance [3] Klein tunneling [4], Zitterbewegung [5], gate-tunable optical transitions [6], Veselago lensing [7], and so on. The generation of a spin-polarized current is a fundamental prerequisite for the construction of spintronic devices [8].

In recent years, there have been some investigations on spin-dependent transport in two dimensional materials experimentally [9–11]. Godel et al. investigated the voltage-dependent magneto-transport properties of vertical spin-valve structures using a thick epitaxial MgO barrier as spacer layer and a graphene-passivated Ni film as bottom ferromagnetic electrode. They found that by varying the bias voltage, the TMR ratio systematically shows three distinct regimes, along with a number of sign reversals. The transitions between regimes are interpreted as the opening/closing of spin-polarized conduction channels [9]. The effect of injection bias current and gate voltages on the electrical and spin transport properties in graphene-hexagonal boron nitride van der Waals heterostructures have been studied by Godel et al. It is found that the spin transport measurements at different injection bias current and gate voltages confirms tunneling nature of spin injection through h-BN barriers [10]. Kamalakar et al. showed that in Ferromagnet Hexagonal Boron Nitride-Graphene van der Waals Heterostructures the spin filtering effect in cobalt few layer h-BN graphene junctions leading to a large negative spin polarization in graphene at room temperature [11]. In addition, graphene spintronics is one of the most promising research fields where graphene based materials are implied in the control of spin-polarized signal. There are two types of spin–orbit interactions in graphene; intrinsic and Rashba spin–orbit interaction. Intrinsic is negligibly small in pristine graphene [12,13], so its effects are usually ignored for most purposes. However, other spin–orbit coupling, which can also be regarded as the Rashba spin–orbit interaction (RSOI), is induced by different mechanisms such as an external electric field perpendicular to the graphene sheet, ad-atoms or presence of a substrate. Avsar et al. reported enhancement of the Rashba coupling as large as 17 meV in graphene due to proximity to WS_2 substrate [14]. It was recently shown that the interaction of Au atoms in graphene grown on Ni substrate produces a large Rashba splitting near 100 meV [15], also Calleja et al. observed a giant RSOI when Pb is intercalated between graphene and the iridium substrate [16]. The extrinsic Rashba originates instead from inter-

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https://doi.org/10.1016/j.physleta.2017.11.009
0375-9601/

actions with the substrate, presence of a perpendicular external electric field, or curvature of graphene membrane [17–20]. Furthermore, recent discoveries show that graphene grown on a flexible substrate is capable of sustaining elastic deformations as large as 20% [21]. This result suggests that the modulation of the electronic properties of graphene by strain is feasible. It is important to note that the strain in graphene nanobubble can produce a gigantic pseudo-magnetic field larger than 300 Tesla [22], and it is possible modulate the graphene energy-gap value from zero up to 900 meV by uniaxial strains [23]. Strain engineering of graphene can shift the Dirac points in reciprocal space. All these effects can change the transport properties of graphene. Strain in graphene be realized using an atomic force microscope (AFM) tip [24] or suitable substrate patterning [25,26]. Due to the effect of strain on the band structure of graphene, a number of papers studied transport properties of strained graphene [27–41]. Wu et al. studied the spin and valley-dependent transport in ferromagnetic graphene double junctions and found out that the strain combined with magnetic vector potentials breaks the valley degeneracy [37]. The valley and spin resolved transport in a two-terminal zigzag graphene nanoribbon with Rashba spin–orbit interaction has been investigated in Ref. [39]. Diniz et al. [39] showed that the strain plays an important role in the spin polarized current.

The question of the time spent by a particle or wave packet in a given region of space has been largely debated for decades [42–49]. Many tunneling time definitions have been so far suggested, the dwell time τ_d and Wigner delay or group delay time τ_g, as two definitions of tunneling time, are considered well established [47]. The group delay time can be calculated by the method of stationary phase and defined by the energy derivative of the transmission phase shift [50,51], and the dwell time is defined as the difference between the time spent by a particle in the barrier region $0 < x < L$ and the time spent in the same region in the absence of the barrier [43,52]. Interestingly, due to the evanescent mode the group delay time for a quantum tunneling particle saturate with increasing barrier length for an opaque barrier, it leads to the Hartman effect which exhibits superluminal and unlimited velocities [44,49,51]. Recently, some papers focus on the tunneling time in various systems [27,53–68]. Yang and Guo investigated dwell time in semiconductor superlattices. They define a semiclassical delay to illustrate the behavior of the dwell time in superlattices [60]. Zhu et al. showed that in silicene unlike the graphene barrier, superluminal tunneling is observable at the normal incidence [63]. Zhai and Lu found that the difference between the group delay and dwell time comes from both the interference delay and the decaying modes [64]. The effect of magnetic field on the group delay time in graphene barriers has been studied by Ban et al. It is found that the dwell time to be equal to net group delay plus the group delay contributing from the lateral Goos-Hänchen shifts [66].

In this paper, we focus on the spin-dependent tunneling time, dwell and group delay time, through an asymmetric barrier in monolayer graphene with Rashba spin–orbit interaction in the presence of strain, which to the best of our knowledge was not already been reported. The asymmetry barrier can be obtained dynamically by applying an external electric field to the barrier [54, 69–72]. In asymmetric barrier with built-in external electric field, RSOI provides coupling between spin and the electron's spatial motion in the plane perpendicular to the direction of the structure growth [72]. We show that when the armchair direction strain is applied to a monolayer graphene barrier unlike the zigzag direction the group delay time even at the normal incidence depends on the spin state of electrons and superluminal tunneling is observable due to the evanescent mode. Also, our results show that in a graphene based asymmetrical barrier the polarization reaches almost 100% efficiency with down and up spin. The paper is organized as follows. In Section 2 we introduce our model and describe the theoretical formalism. In Section 3 the results of the numerical calculations are presented. Section 4 is the conclusion of the paper.

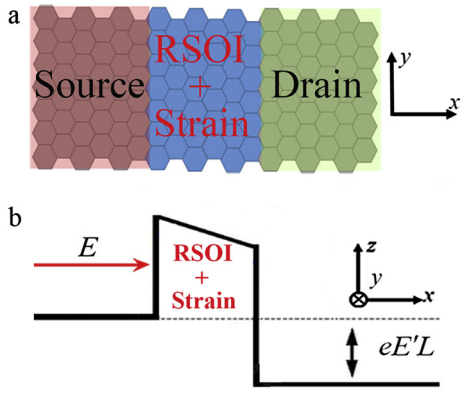

Fig. 1. (a) Schematic of the setup of a normal graphene/strained graphehe/normal graphene junction with Rashba spin–orbit interaction and barrier potential in the strain region. (b) Graphene barrier with Rashba spin–orbit interaction and strain under an applied external electric field (E').

2. Model and theory

In the present study we consider an asymmetric monolayer graphene barrier, which can be realized by applying an external electric field to the rectangular graphene barrier. The barrier region with the RSOI strength $\lambda_R = const$ and uniaxial strain is separated by normal graphene (NG) in which there is no RSOI interaction. The schematic of the structures is shown in Fig. 1. The effect of strain on the Hamiltonian is given by the two-dimensional reductions of the strain tensor can be written as [73]:

$$\epsilon = \varepsilon \begin{pmatrix} \cos^2\alpha - \mu\sin^2\alpha & (1+\mu)\cos\alpha\sin\alpha \\ (1+\mu)\cos\alpha\sin\alpha & \sin^2\alpha - \mu\cos^2\alpha \end{pmatrix}, \tag{1}$$

where, α denotes the directions of applied strain with respect to the x axis. $\alpha = 0$ and $\alpha = \pi/2$ refer to strain along the zigzag and armchair directions, respectively. Poisson's ratio μ for the graphene is 0.14 [74]. ε is strain modulus inside the barrier and its value is zero otherwise. Potential profile of the systems along x axis in the presence of an external electric field (E'), applied between $x = 0$ and $x = L$, is given by:

$$V(x) = \begin{cases} U_0 - eE'x, & \text{for barrier,} \\ -eE'x, & \text{elsewhere,} \end{cases} \tag{2}$$

here U_0 and E' are the barrier height and external electric field, respectively. Because the strain effects result in both deformation of the Dirac cones and displacement of the Dirac points in reciprocal space, the strained Hamiltonian with RSOI interaction (K point) can be written as [75–78]

$$\hat{H} = \hat{H}_0 + \hat{H}_{RSO} + V(x)\hat{I}, \tag{3}$$

in which,

$$\hat{H}_0 = \hbar v_F U^{\dagger}(\alpha)\left[\sigma_x(1-\lambda_x\varepsilon)q_x + \sigma_y(1-\lambda_y\varepsilon)q_y\right]U(\alpha),$$
$$\hat{H}_{RSO} = \lambda_R(\tau_x\sigma_y - \tau_y\sigma_x), \tag{4}$$

where, $\hat{\sigma} = (\sigma_x, \sigma_y)$ and $\hat{\tau} = (\tau_x, \tau_y, \tau_z)$ are the real spin Pauli matrices and sublattice pseudospin respectively, $v_F \approx 10^6$ m/s is the Fermi velocity in graphene, $\lambda_x = 2.2$, $\lambda_y = -0.31$ [75], and $\hat{I}$ is the 4×4 unit matrix. q_x and q_y are the components of the quasiparticle wave vectors along the x and y direction, respectively. $U(\alpha) = \mathrm{diag}(1, e^{-i\alpha})$ is the unitary matrix representing a rotation

Please cite this article in press as: F. Sattari, S. Mirershadi, Spin-dependent delay time and Hartman effect in asymmetrical graphene barrier under strain, Phys. Lett. A (2018), https://doi.org/10.1016/j.physleta.2017.11.009