Spin-Polarized Transport through Ferromagnetic Graphene Microstructures with Fermi Velocity Modulation

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Abstract

Theoretical and numerical modellings of a graphene-based spin-filter spintronic with Fermi velocity engineering are investigated. These graphene-based spintronic devices will open up new ways for creating a new generation of electronic devices which are smaller, faster and consumes less electric power. The spin filtering is a key issue for spintronic applications. The influence of velocity barrier (VB) on the spin transport of massless Dirac particles in ferromagnetic graphene are theoretically studied in a NG/FG/VB/NG junction. It consists of a ferromagnetic graphene region (FG) which is deposited by metallic gate and the velocity barrier is located on the left side of the ferromagnetic graphene where the propagation of massless Dirac fermion through a VB region of graphene with a position-dependent velocity. By biasing the FG region with the gate voltage (U), spin conductance is oscillating as function of Fermi velocity and its phase is shifted by varying U on ferromagnetic graphene. This system may be used as a tunable spin-polarized source.

Keywords: Graphene: Magnetic tunnel junction: Dirac equation: Spin polarization: Velocity modulation

Introduction

Graphene is a monolayer of carbon atoms arranged in a honeycomb structure, was first studied theoretically in 1947 by P.R. Wallace [1]. That has until it was isolated in 2004 by K. S. Novoselov, A. K. Geim at the University of Manchester [2]. One reason for the intensive attention that is the unique property of charge carriers in graphene they behave like the relativistic massless particles with the speed of light replaced by the Fermi velocity $v_F \approx 10^6 m/s$. This brings about a number of unusual phenomena, such as a Chiral tunnelling and the Klein paradox in graphene [3], an unconventional quantum Hall effect [4] and so on.

Recently, it has been shown that there are several ways to engineer the Fermi velocity, D.C. Elias et al [5]. Studied Dirac cones reshaped and found that the Fermi velocity can be as high $3\times10^6 m/s$ in suspended graphene through a change of the carrier concentration. And the Fermi velocity of charge carriers can be engineered by the effect of doping [6,7], by depositing a metallic gate on graphene [8], by modifying band engineering of superlattice [9], or by strained graphene [10,11].

As we all know, relativistic-like carriers propagate in graphene behavior like optic A. Concha and Z. Te'sanovi'c [12], first proposes a novel way to control the transport behavior of relativistic-like particles by using velocity-modulation engineering and found that the transmission of Dirac fermion in graphene with a velocity modulation is a highly anisotropic and Klein tunneling always occurs at normal incidence. For $\xi > 1$, Arnaud Raoux et al [8], found that the transmission probability decrease rapidly at the critical angles of injected particles because the localized state appears in the conduction band [13,14]. Physically, graphene is not ferromagnetism but Haugen et al [15] proposed that graphene could be induced into ferromagnetic correlation by putting in close proximity to a magnetic insulator EuO and found that it induced spin splitting roughly 5 meV. Then Yokoyama [16] found that spin transport properties in ferromagnetic graphene junction have an oscillatory behavior with respect to the potential gate on the ferromagnetic graphene region and shows the possibility of electrical tunable spin current. Recently, spin of massless Dirac fermions transmission through graphene nano-structure modulated with exchange field and velocity, which investigated by Zheng-Fang Liu et al [17], found that transmission probabilities of spin-up and spin-down electrons exhibit perfect spin precession behaviors under the normal incidence for the velocity ratio less than 1. Although, velocity ratio $\xi = 1.5$ electron does not penetrate through velocity modulation, but also exhibited the transmission of the spin-up electron does not decay exponentially to zero but tends to coincide.

In this paper, we study the spin transport properties of massless Dirac fermions pass through NG/FG/VB/NG graphene junction. We investigate that the effect of velocity engineering on the nature of the spin-transmission ability of relativistic particles.

Materials and Methods

Theoretical Framework

The effect of velocity barrier (VB) on the spin transport of massless Dirac particles in ferromagnetic graphene are theoretically studied in a NG/FG/VB/NG junction. It consists of a ferromagnetic graphene region (FG) which is deposited by metallic gate and the velocity barrier is located on the left side of the ferromagnetic graphene where the propagation of massless Dirac fermion through a VB region of graphene with a position-dependent velocity. Here, in our model study is shown schematically in Figure1 and the massless Dirac equation with position-dependent Fermi velocity as shown in this equation.

$$-i\hbar\sqrt{v(\vec{r})}\vec{\sigma}\cdot\nabla_r\sqrt{v(\vec{r})}\psi(\vec{r}) - \Delta_{\uparrow,\downarrow}\psi = E\psi(\vec{r}) \quad (1)$$

where $\Delta_{\uparrow,\downarrow}(x) = E_F$ for $x \le -D$ *and* $x \ge 0$ $\Delta_{\uparrow,\downarrow}(x) = E_F + U + \eta_{\uparrow,\downarrow}H$ for $-D \le x \le 0$, H is the ferromagnetic exchange field, U is the chemical potential shift can be tuned by the gate voltage , $\eta_{\uparrow} = 1, \eta_{\downarrow} -1$ for spin up and spin down electrons, respectively and $\vec{\sigma} = (\sigma_x, \sigma_y)$ is the vector of Pauli matrices acts on two sublattice spaces of the honeycomb lattice of graphene, and we assume translation invariance in the y direction. In addition Equation (1), it is assumed that the variation of the velocity is slow enough on the scale of the lattice constant. Let us focus on the Fermi velocity modulated combine with exchange field, which change alone the x direction as follows [5-8]:

$$v(x) = \begin{cases} v_{F,1} & , x \le -D \quad , -D \le x \le 0 \;\; and \;\; x \ge W \\ v_{F,2} & , 0 \le x \le W \end{cases} , \quad (2)$$

The wave functions of the electrons will exhibit chiral properties of the graphene. The solution of the Dirac Equation (1) for all regions can be written in the following spinor form,

$$\psi_I^{\uparrow,\downarrow}(x) = \sqrt{v_1}\begin{pmatrix} 1 \\ \dfrac{k_x + ik_y}{E/\hbar v_{F,1}} \end{pmatrix} e^{ik_x x} + r\sqrt{v_1}\begin{pmatrix} 1 \\ \dfrac{-k_x + ik_y}{E/\hbar v_{F,1}} \end{pmatrix} e^{-ik_x x} \quad (3)$$

$$\psi_{II}^{\uparrow,\downarrow}(x) = a_{\uparrow,\downarrow}\sqrt{v_{F,1}}\begin{pmatrix} 1 \\ \dfrac{p_x + ik_y}{(E+\eta_{\uparrow,\downarrow}H)/\hbar v_{F,1}} \end{pmatrix} e^{ip_x x} + b_{\uparrow,\downarrow}\sqrt{v_{F,1}}\begin{pmatrix} 1 \\ \dfrac{-p_x + ik_y}{(E+\eta_{\uparrow,\downarrow}H)/\hbar v_{F,1}} \end{pmatrix} e^{-iq_x x} \quad (4)$$

$$\psi_{III}^{\uparrow,\downarrow}(x) = f\sqrt{v_2}\begin{pmatrix} 1 \\ \dfrac{q_x + ik_y}{E/\xi\hbar v_{F,1}} \end{pmatrix} e^{iq_x x} + g\sqrt{v_2}\begin{pmatrix} 1 \\ \dfrac{-q_x + ik_y}{E/\xi\hbar v_{F,1}} \end{pmatrix} e^{-iq_x x} \quad (5)$$

$$\psi_{IV}^{\uparrow,\downarrow}(x) = t\sqrt{v_1}\begin{pmatrix} 1 \\ \dfrac{k_x + ik_y}{E/\hbar v_{F,1}} \end{pmatrix} e^{ik_x x} \quad (6)$$

where $k = (E+E_F)/\hbar v_{F,1}$

$p_{\uparrow,\downarrow} = (E+E_F+U+\eta_{\uparrow,\downarrow}H)/\hbar v_{F,1}$,

$q = (E+E_F)/\hbar v_{F,2}$ and

propagation of MDFs in a medium different of Fermi velocity we can identify $\xi = \dfrac{v_{F,2}}{v_{F,1}}$ is Fermi velocity ratio (FVR). From the conservation of momentum along the y axis, we have $k_y = p_y = q_y$. The wave functions have to be continuous at the interface x = *-D*, *x = 0* and *x = W*. The wave functions have to be continuous at the interfaces, so the boundary conduction can be given by [18-20]:

$$\begin{aligned} \psi_I^{\uparrow,\downarrow}(-D)^- &= \psi_{II}^{\uparrow,\downarrow}(-D)^+ \\ \psi_{II}^{\uparrow,\downarrow}(0)^- &= \sqrt{\xi}\,\psi_{III}^{\uparrow,\downarrow}(0)^+ \\ \psi_{III}^{\uparrow,\downarrow}(W)^- &= \frac{1}{\sqrt{\xi}}\psi_{IV}^{\uparrow,\downarrow}(W)^+ \end{aligned} \quad (7)$$

Applying the boundary condition at the interface, we will be able to obtain the amplitudes appearing in the wave function, Equation (2). We therefore obtain the following expression for transmission probability of electron $T_{\uparrow,\downarrow}(E_F, H, \xi) \equiv |t_{\uparrow,\downarrow}|^2$

$$t_{\uparrow,\downarrow} = \frac{e^{-ik(D+W)}\cos\beta\cos\gamma\,\cos\theta}{A_1^{\uparrow,\downarrow}\sin(pD) + A_2^{\uparrow,\downarrow}\cos(pD)\cos\beta}, \quad (8)$$

$$\begin{aligned} A_1^{\uparrow,\downarrow} &= \cos\theta\sin(qW)(-1+\sin\beta\sin\gamma) + \\ &\quad i\cos(qW)\cos\gamma(-1+\sin\beta\sin\theta) \end{aligned}, \quad (9a)$$

$$\begin{aligned} A_2^{\uparrow,\downarrow} &= \cos(qW)\cos\gamma\cos\theta + \\ &\quad i\sin(qW)(-1+\sin\gamma\sin\theta) \end{aligned}, \quad (9b)$$

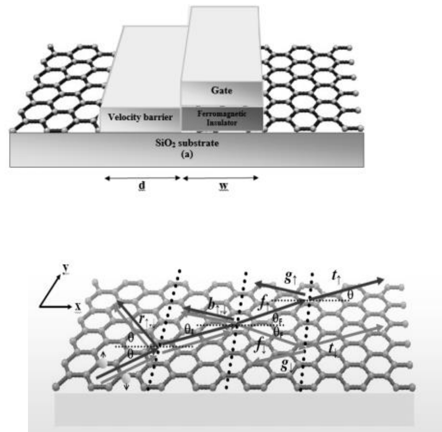


Figure 1 Schematic of NG/FG/VB/NG junction for the massless carriers changes along the x- direction according to the simple functional form defined by Equation (2).

To investigate massless Dirac fermions transmission through NG/FG/VB/NG tunnel junction, we will discuss transmission probability in case of the spin-up and spin–down electrons. In the numerical calculation, we take thickness of barrier a symmetry W = D and we focus on under zero external potential, we set E = 0 [16] and $k_F D = 4\pi$ [8] in Figure 1.

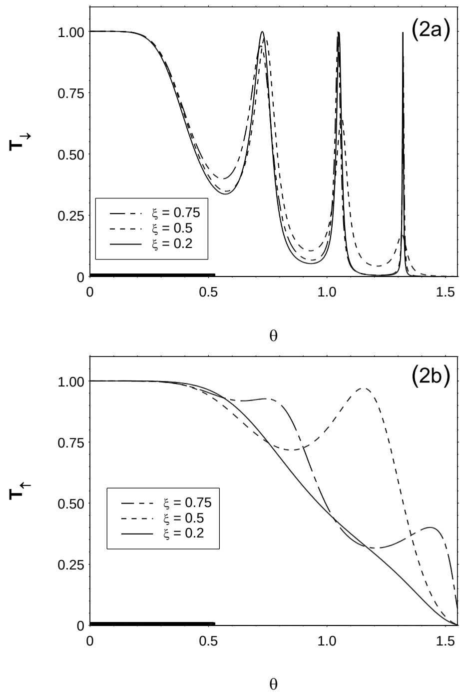
Results and Discussion

As all know, electron propagation in the different regions velocity, there is no confinement massless Dirac fermions for proportional to the velocity outside with velocity inside in barrier less than 1 [20], which total transmission refection occur, and when the incident angle exceed critical angle evanescence mode appear. Recently, Zheng – Fang Liu et al [17]. Studies spin – dependent transport properties of graphene nanostructures modulated by effective exchange field (EEF) and Fermi velocity and found that for the velocity ratio $\xi = 1.5$ the transmission of the spin – up electron does not decay exponentially to zero but tends to coincide with that of the spin – down electron due to the coupling effect between the spin–up and spin–down electrons induced by EEF.

Case 1: Energy below exchange field (E_F < H)

In our numerical calculations, we take widths of the velocity-modulation are symmetry D = W. In the Figures 2(a)-2(d), we shows transmission probability of the spin–up electron and spin–down electron through NG/FG/VB/NG tunnel junction as a function of incident angle with the different Fermi velocity ratio ξ for fixed length 100 nm with Fermi energy E = 5 meV and exchange field H = 10 meV, respectively. We note that $T(\theta) = T(-\theta)$ and transmission probability is perfectly occurs at the normal incident angle. In the Figures 2(a)-2(d) the results shows that there are obvious different form the value Fermi velocity ratio $\xi < 1$ and $\xi > 1$ for the spin–up electron and spin–down electron through NG/FG/VB/NG tunnel junction. In addition, electron does not confine by affected of Fermi velocity when $\xi < 1$ shows in Figures 2(a)–2(b) and we found that for the spin – down electron resonant peak decrease with the velocity ratio increase. For the value $\xi > 1$, we found that electrons cannot penetrate through NG/FG/VB/NG tunnel junction when angle of incident exceeds the critical angle as shown in Figure 2(c)–2(d). Figure 2(d) shows transmission probability spin–up electron confined by critical angle, which corresponding to incident angle $\theta > \theta_c = \arcsin(1/\xi)$ with the necessary condition $-1 \le \xi \sin\theta \le 1$

For $\xi < 1$



For $\xi > 1$

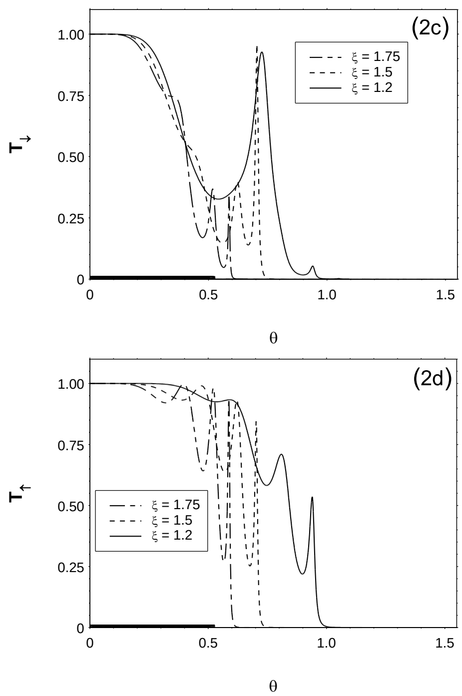


Figure 2 Transmission probability of spin up electron and spin–down electron through NG/FG/VB/NG tunnel junction as a function of incident angle for fixed E = 5 meV and H = 10 meV with different Fermi velocity ratio (2a)–(2b)

corresponding to ξ = 0.2, 0.5 and 0.75 for spin–up and spin down, respectively. (2c)–(2d) corresponding to ξ = 1.2, 1.5 and 1.75 for spin–up and spin–down, respectively.

Case 2: Energy equal exchange field (E_F = H)

Transmission probability of the spin-down electron when we limit $H/E_F \approx 1$[21,22], can be given by Equation (8)

$$T_{\downarrow,H\to E_F} = \frac{2\cos^2\theta(-1+\xi^2\sin^2\theta)}{2\Theta_1\cosh^2(kD\sin^2\theta)+\Theta_2\sin^2\theta} \quad , (10)$$

where

$$\Theta_1 = \cos^2\theta\cos^2(kD\sqrt{1-\xi^2\sin^2\theta})(-1+\xi^2\sin^2\theta) - \sin^2(kD\sqrt{1-\xi^2\sin^2\theta}) \quad , (11a)$$

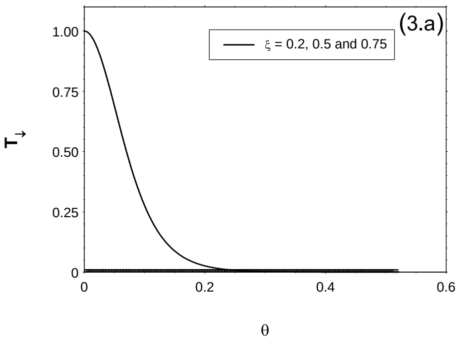
$$\Theta_2 = \xi^2\{\cos(2\theta)-\cosh(2kD\sin\theta)\}\sin^2(kD\sqrt{1-\xi^2\sin^2\theta}) + 2\cos^2(kD\sqrt{1-\xi^2\sin^2\theta})(-1+\xi^2\sin^2\theta)\sinh^2(kD\sin\theta) - \xi\sin\theta\sqrt{1-\xi^2\sin^2\theta}\,\sin(2kD\sqrt{1-\xi^2\sin^2\theta})\sinh^2(2kD\sin\theta) \quad , (11b)$$

In Equation (10) we investigated at small angle for the value $\xi < 1$, we found that transmission probability spin–down electron does not depends on Fermi velocity ratio show in Figure 3(a), but it depends on the widths of VB region in graphene. When we consider at the small angle which corresponding to $\xi^2\sin^2\theta << 1$, therefore form Equation (10) we obtain

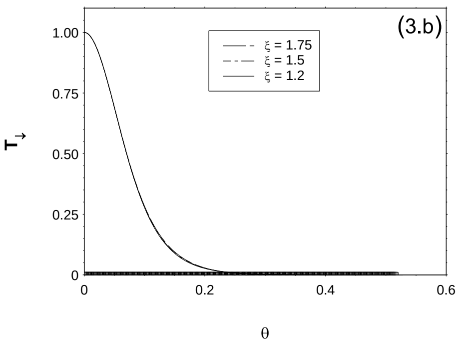
$$T_{\downarrow} = \frac{1}{\cosh^2(kD\sin\theta)} \quad (12)$$

However, for the value $\xi > 1$ we find that transmission probability spin – down electron affected of velocity ratio as incident angle and the result is shown in Figure 3(b). In addition, for the transmission probability spin-up electron in Figure 3(c), we found that electron cannot through NG/FG/VB/NG tunnel for junction when incident angle exceeds critical angle. However, for in Figure 3(d) shows that transmission probability of spin–up electron as a function exchange filed for fixed E = 10 meV and Fermi velocity ratio $\xi = 1.2$ at different exchange field, we found that resonant peak decrease with exchange interaction increase for the confined electron with Fermi-velocity manipulation.

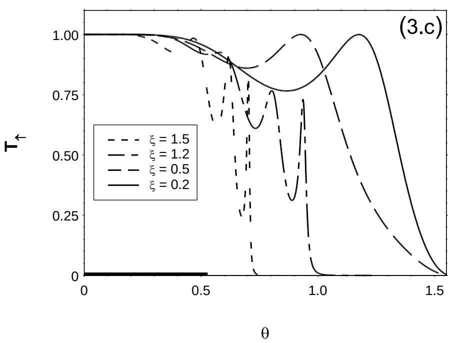
$\xi < 1$



For $\xi > 1$



For $\xi < 1, \xi > 1$



For $\xi > 1$

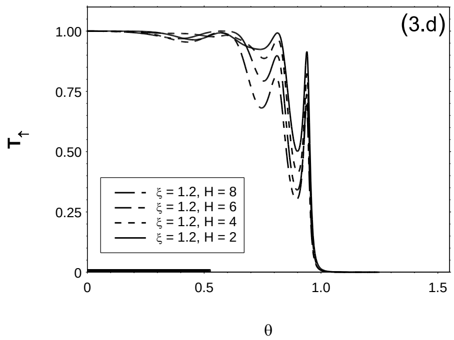
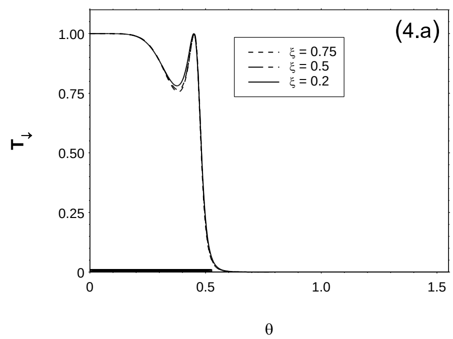


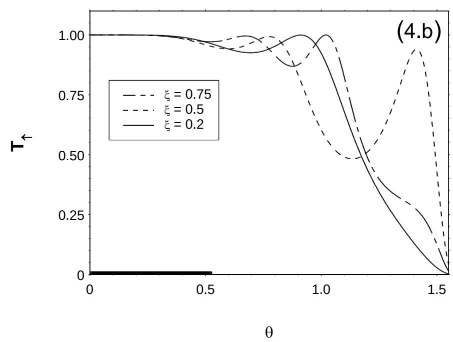
Figure 3 Transmission probability of spin – up electron and spin–down electron through NG/FG/VB/NG tunnel junction as a function of incident angle for fixed E = 5 meV and H = 5 meV with different Fermi velocity ratio 2(a) corresponding to ξ = 0.2, 0.5 and 0.75 for spin –down and 2(b) corresponding to ξ =1.2, 1.5 and 1.75 3(c) corresponding to ξ = 0.2, 0.5, 1.2, 1.5 for spin –up 3(d) Transmission probability of spin–up electron as a function of incident angle for fixed ξ = 1.2 when various exchange field H = 2, 4, 6 and 8, respectively.

Case 3: Energy above exchange field (E_F > H)

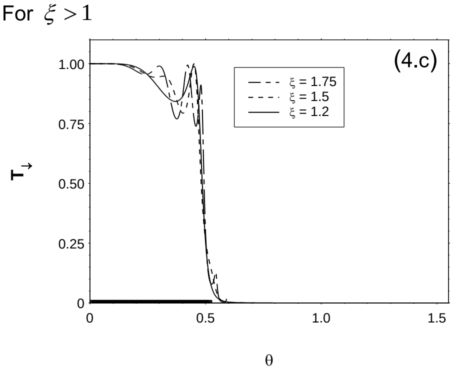
In this case, we consider the localized state of electron transmission through NG/FG/VB/NG tunnel junction for the Fermi energy greater than exchange field for fixed E_F = 10 meV and H = 5 meV. In Figure 4(a), it is shown that resonant peak decrease when velocity ratio increase for the spin–down electron with $\xi < 1$, but In Figure 4(c) we found that multiple resonant peak occurs when Fermi velocity ratio greater than 1 increase. However, in Figure 4(b) show that electron cannot confined with velocity barrier for the spin–up electron, but resonant peak occurs when velocity ratio increase. For the case of Fermi velocity ratio grater than 1 we find that the Dirac electron depends on the velocity ratio show in Figure 4(d) and find that the massless Dirac fermions penetrate through NG/FG/VB/NG tunnel junction when incident angle exceeds critical angle but resonant peak increase with $\xi > 1$ increase peak occurs with both for $E_F < H$ and $E_F > H$, but the massless fermions does not confined in case $E_F < H$ for $\xi < 1$. For the spin–up electron we find that, for the case $\xi < 1$ shows cannot confine electron through NG/FG/VB/NG tunnel junction with Fermi velocity ratio, but we find that in case $\xi > 1$ when the incident angle exceeds the critical angle the electron does not penetrate through NG/FG/VB/NG tunnel junction. Finally, we hope these phenomena may lead to the tuned spin filtering applications in graphene – based electronic devices.

For $\xi < 1$





For $\xi > 1$



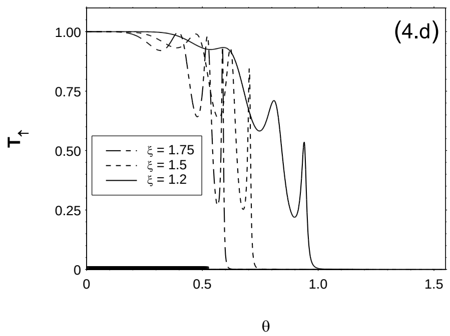


Figure 4 Transmission probability of spin – up electron and spin–down electron through NG/FG/VB/NG tunnel junction as a function of incident angle for fixed E = 10 meV and H = 5 meV with different Fermi velocity ratio 4a–4b corresponding to ξ = 0.2, 0.5 and 0.75 for spin –up and spin – down ,respectively. 4c–4d corresponding to ξ = 1.2, 1.5 and 1.75 for spin–up and spin–down, respectively.

Conclusions

For the massless Dirac fermions transmission through NG/FG/VB/NG tunnel junction has been described the Weyl-Dirac Equation with velocity modulation. We found that, transmission probabilities for spin–down does not depend on Fermi velocity ratio at the small angle for $H \rightarrow E_F$ and resonant.

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