Research Article

Spin Polarized Transport in an AC-Driven Quantum Curved Nanowire

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Using the effective-mass approximation method, and Floquet theory, we study the spin transport characteristics through a curved quantum nanowire. The spin polarization, P , and the tunneling magnetoresistance, TMR, are deduced under the effect of microwave and infrared radiations of wide range of frequencies. The results show an oscillatory behavior of both the spin polarization and the tunneling magnetoresistance. This is due to Fano-type resonance and the interplay between the strength of spin-orbit coupling and the photons in the subbands of the one-dimensional nanowire. The present results show that this investigation is very important, and the present device might be used to be a sensor for small strain in semiconductor nanostructures and photodetector.

1. Introduction

In the rapidly growing field of semiconductor spintronics, the spin degree of freedom is used for information processing [1, 2]. Devices concepts have been proposed which offer lower power consumption and a higher degree of functionality [3]. Among the research area of spintronics, the spin-orbit coupling (SOC) creates another way to manipulate spins by means of an electric field [4]. The Rashba spin-orbit coupling effect [4] is found to be very pronounced in semiconductor heterostructure, for example, quantum dots, quantum wires, and quantum rings [5], and its strength can be controlled by gate voltage. The spin polarization in two-dimensional electron gas (2DEG) systems with spin-orbit coupling (SOC) has been attracted extensive attention by many authors [6–9]. Spin-orbit coupling (SOC) has been investigated in parallel quantum wires [10, 11], where universal conductance fluctuations are suppressed. More recently, ballistic spin resonance due to an intrinsically oscillating spin-orbit field has been realized experimentally in a quantum wire [12]. The observation of the one-dimensional spin-orbit gap in quantum wires has also been reported in [13] and also recently in [14].

The aim of the present paper is to investigate the spin transport characteristics through a curved quantum nanowire

under the effect of microwave (MW) and infrared (IR) radiations. The main difference between the straight nanowire and curved one is that the spin rotation is characterized by certain angles, as it will be shown below.

2. The Model

We will now derive an expression for both the spin polarization for spin injection current in the curved nanowire and the corresponding tunneling magnetoresistance (TMR) for a curved nanowire under the effect of induced photons of wide range of frequencies. This nanowire is connected to two metallic leads. The effective Hamiltonian for spin-injected electrons through one-dimensional nanowire can be written as three parts according the geometrical design of the curved nanowire as [15, 16]

$$\hat{H}_1 = -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial S^2} - i\alpha\sigma_{b1} \frac{\partial}{\partial S} + V_d + eV_g, \quad S \in (-\infty, 0), \quad (1)$$

where m^* is the effective mass of the electron, V_d is the barrier height at the interface with the leads, V_g is the gate voltage, and S is the arc length along the curve. The second

part of the curved nanowire including the Rashba spin-orbit coupling effect is given by

$$\hat{H}_2 = -\frac{\hbar^2}{2m^*a^2} \frac{\partial^2}{\partial \theta^2} - \frac{\hbar^2}{8m^*a^2} - \frac{i\alpha}{a} \left[\sigma_{b2} \frac{\partial}{\partial \theta} - \frac{1}{2} \sigma_{t2} \right], \quad (2)$$

$$\theta \in (0, \theta_\omega).$$

Also, the third part of the curved nanowire is

$$\hat{H}_3 = -\frac{\hbar^2}{2m^*} \frac{\partial^2}{\partial S^2} - i\alpha \sigma_{b3} \frac{\partial}{\partial S} + eV_{ac} \cos \omega t, \quad S \in (\theta_\omega a, \infty). \quad (3)$$

In (1), (2), and (3), the parameter S represents the arc length along the curved part of the nanowire, θ is the polar angle, θ_ω is the angle between two rectilinear parts of the nanowire and V_{ac} is the amplitude of the induced photons with frequency ω . The spin operators in (1), (2), and (3) are represented as follows [17]:

$$\begin{aligned} \sigma_{b1} &= -\sigma_x, \\ \sigma_{b2} &= -\sigma_x \cos \theta - \sigma_y \sin \theta, \\ \sigma_{b3} &= -\sigma_x \cos \theta_\omega - \sigma_y \sin \theta_\omega, \\ \sigma_{t2} &= -\sigma_x \sin \theta + \sigma_y \cos \theta. \end{aligned} \quad (4)$$

The energy spectrum and the unnormalized eigenstates for the two parts of the straight line of the nanowire are given by [18–20]

$$E^\mu = \frac{\hbar^2 k^2}{2m^*} - \mu \alpha k, \quad (5)$$

$$\begin{aligned} \Phi_{1,\lambda}^\mu &= e^{i\lambda k s} \cdot \chi_1, \\ \Phi_{3,\lambda}^\mu &= e^{i\lambda k s} \cdot \chi_3, \end{aligned} \quad (6)$$

where the symbol μ corresponds to the spin up $\uparrow$ and spin down $\downarrow$, and $\lambda = \pm$ which corresponds to the direction of motion along the nanowire. The eigenstate function and the energy eigenvalue for the curved section of the nanowire are given as [18–20]

$$\Phi_{2,\lambda}^\mu = e^{i\lambda n' \theta} \cdot \chi_2, \quad (7)$$

where n' is the orbit quantum number

$$E_{2,\lambda}^\mu = \Omega \left[\left(n' + \frac{1}{2} \lambda \right)^2 - \mu \left(n' + \frac{1}{2} \lambda \right) \sqrt{1 + \frac{\omega_{\text{Soc}}^2}{\Omega^2}} \right]. \quad (8)$$

The spinors χ_1, χ_2 , and χ_3 in (6), (10), and (7) are given by

$$\chi_1^\pm = \begin{pmatrix} \frac{\sqrt{2}}{2} \\ \pm \frac{\sqrt{2}}{2} \end{pmatrix},$$

$$\begin{aligned} \chi_2^+ &= \begin{pmatrix} \sin \frac{\xi}{2} \\ e^{i\theta} \cos \frac{\xi}{2} \end{pmatrix}, \\ \chi_2^- &= \begin{pmatrix} \cos \frac{\xi}{2} \\ -e^{i\theta} \sin \frac{\xi}{2} \end{pmatrix}, \\ \chi_3^\pm &= \begin{pmatrix} \frac{\sqrt{2}}{2} \\ \pm \frac{\sqrt{2}}{2} e^{i\theta} \omega \end{pmatrix}. \end{aligned} \quad (9)$$

In (8), we have the frequency associated with spin-orbit coupling ω_{Soc} and the parameter Ω which are defined as

$$\omega_{\text{Soc}} = \frac{\alpha}{a\hbar}, \quad \Omega = \frac{\hbar^2}{2m^*a^2}, \quad (10)$$

where α is the strength of the spin-orbit coupling and a is the radius of curvature.

The eigenfunctions corresponding to the spin transport through a curved wire are given by [18–20]

$$\begin{aligned} \psi_1 &= \sum_{n=-\infty}^{\infty} \sum_{\mu} J_n \left(\frac{eV_{ac}}{\hbar\omega} \right) \\ &\times \left[\cos(\phi) \Phi_{1,+}^\mu + \sin(\phi) \Phi_{1,+}^\mu + R_l \Phi_{1,-}^\mu + R_r \Phi_{1,-}^\mu \right], \\ \psi_2 &= \sum_{\mu} \sum_{n=-\infty}^{\infty} J_n \left(\frac{eV_{ac}}{\hbar\omega} \right) \left[C_1 \Phi_{2,+}^\mu + C_2 \Phi_{2,-}^\mu \right], \\ \psi_3 &= \sum_{\mu} \sum_{n=-\infty}^{\infty} J_n \left(\frac{eV_{ac}}{\hbar\omega} \right) \left[\Gamma_l \Phi_{3,+}^\mu + \Gamma_r \Phi_{3,-}^\mu \right], \end{aligned} \quad (11)$$

where $J_n(eV_{ac}/\hbar\omega)$ is the n th order Bessel function. The solutions of (11) must be generated by the presence of different subbands, n , in a quantum nanowire, which come with phase factor $\exp(-in\omega t)$, where ω is the frequency of the induced photons. Now, the tunneling probability $|\Gamma_\mu \text{ with photon}(E)|^2$ could be obtained by applying Griffith boundary conditions [20]. Accordingly, therefore, the expressions for the tunneling probabilities corresponding to spin-up and spin-down electrons, respectively, are given by

$$\left| \Gamma_{\uparrow \mu \text{ with photon}}(E) \right|^2 = \sum_n J_n^2 \left(\frac{eV_{ac}}{\hbar\omega} \right) \times \left[\frac{8A^2B^2 \left(\cos^2 \xi + \cos \phi \cos(\phi - 2\xi) \cos \left[(1 + 2\gamma)\theta + \sin^2(\phi - \xi) \right] \right)}{(A+B)^4 + (A-B)^4 - 2(A^2 - B^2)^2 \cos(2\beta\theta)} \right]. \quad (12)$$

And that for spin-down as

$$\left| \Gamma_{\downarrow\mu \text{ with photon}}(E) \right|^2 = \sum_n J_n^2 \left(\frac{eV_{ac}}{\hbar\omega} \right) \left[\frac{8A^2B^2 \left(\cos^2(\phi - \xi) - \cos\phi \cos(\phi - 2\xi) \cos[(1 + 2\gamma)\theta] + \sin^2\xi \right)}{(A+B)^4 + (A-B)^4 - 2(A^2 - B^2)^2 \cos(2\beta\theta)} \right]. \quad (13)$$

where the parameters, in (12) and (13), A , B , β , and γ , are expressed as

$$\begin{aligned} A &= \sqrt{\left(\frac{\alpha}{\hbar} \right)^2 + \frac{2(E_F + V_d + eV_g + n\hbar\omega)}{m^*}}, \\ B &= \sqrt{\left(\frac{\alpha}{\hbar} \right)^2 + \frac{2(E_F + (\Omega/4) + V_d + eV_g + n\hbar\omega)}{m^*}}, \\ \beta &= \frac{B\hbar}{2a\Omega}, \quad \gamma = -\frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{\omega_{\text{Soc}}^2}{\Omega^2}}, \\ \tan\phi &= -\frac{\omega_{\text{Soc}}}{\Omega}. \end{aligned} \quad (14)$$

So, the spin polarization of the tunneled electrons [21] is

$$P = \frac{\left| \Gamma_{\uparrow\mu \text{ with photon}}(E) \right|^2 - \left| \Gamma_{\downarrow\mu \text{ with photon}}(E) \right|^2}{\left| \Gamma_{\uparrow\mu \text{ with photon}}(E) \right|^2 + \left| \Gamma_{\downarrow\mu \text{ with photon}}(E) \right|^2}, \quad (15)$$

In order to investigate the spin injection tunneling through the curved nanowire, we could calculate the tunneling magnetoresistance (TMR) which is related to the spin polarization (15) as [21–23]:

$$\text{TMR} = \frac{P^2}{1 - P^2 + \Gamma_S}, \quad (16)$$

where Γ_S is the relaxation parameter and is given by [21–23]:

$$\Gamma_S = \frac{e^2 N(0) R_T A \ell}{\tau_S}, \quad (17)$$

where $N(0)$ is the normal-state density of electrons calculated for both spin-up and spin-down distribution function $f_\sigma(E)$, which is expressed as [21–23]

$$f_\sigma(E) \cong f_0(E) - \left(\frac{\partial f_0}{\partial E} \right) \cdot \mu \delta f, \quad (18)$$

where δf is the shift of the chemical potential, τ_S is the spin relaxation time, A is the cross-sectional area of the nanowire, and R_T is the resistance at the interface of the tunnel junction.

3. Result and Discussion

The nanowire is the semiconductor heterostructure InAs-InGaAs with characteristic values $m^* = 0.023m_e$, $E_F = 11.13 \text{ meV}$, $|\theta| \leq \pi$ [14, 16, 17]. The features of our present results are the following.

FIGURE 1: The variation of the spin polarization with the strength of the spin-orbit coupling, α , at different values of the radius of curvature of the nanowire.

(i) Figure 1 shows the variation of the spin polarization with the strength of the spin-orbit coupling, α , at different values of the radius of the curvature of the nanowire. The results show periodic oscillations of the polarization. Also, the peak heights vary in a quantized form for the two values of a (radius of curvature).

(ii) Figure 2 shows the variation of the tunneling magnetoresistance (TMR) with the strength of the spin-orbit coupling, α . As in Figure 1, periodic oscillations of the tunneling magnetoresistance (TMR) are observed. Also, peak heights vary in a quantized form for the two values of the radius of the curvature for nanowire. Such results show that the spin transport through curved nanowire is very sensitive to the geometrical shape of the nanowire. The strength of the spin-orbit coupling, α , can be controlled by the gate voltage, the energy of the induced photons and the geometrical shape. Such results are found to be concordant with those in the literature [7, 11, 14].

(iii) Figure 3, shows the variation of polarization with the photon energy at different values of the strength of the spin-orbit coupling, α . An oscillatory behavior of the polarization is observed. This is due to Fano-type resonance [24–27].

(iv) Figure 4 shows the variations of the tunneling magnetoresistance (TMR) with the photon energy at different values of the strength of SOC. Oscillations are observed as

FIGURE 2: The variation of the tunneling magnetoresistance (TMR) with the strength of the spin-orbit coupling, α , at different values of the radius of curvature of the nanowire.

FIGURE 3: The variation of the spin polarization with the photon energy at different values of the radius of curvature of the nanowire.

in the case of the spin polarization (Figure 3). These results show a good concordance with those in the literature [24–27]. These results show that the location and line shape of Fano-type resonance can be controlled by both the frequency of the induced photons and the strength of the spin-orbit coupling.

We can conclude that the present investigation is very important for devising a mesoscopic nanowire with controllable curvature. By this device, we can determine very minute strain in semiconductor heterostructure solids [28]. Also, this nanowire can be used as a photodetector [29].

FIGURE 4: The variation of the tunneling magnetoresistance (TMR) with the photon energy at different values of the strength of SOC.

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