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Rashba Spin Orbit Interaction Effect on Spin Current in a Quantum Wire with Magnetic Field

Research Article

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Abstract. We study the spin current in a quantum wire subjected to magnetic fields in the presence of Rashba spin orbit interaction. For an infinite superlattice wire, we find that the spin current density is strongly affected by the nature of the sub bands. The results are presented as a function of transverse coordinate, magnetic field and Rashba spin orbit interaction strength. Our results indicate an increase of spin current density with the increase of Rashba factor. The roles of confinement strength and magnetic fields as control parameters on the spin current have been demonstrated.

Keywords. Spin current; quantum wire; spin orbit interaction; magnetic field

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1. Introduction

The physical properties of low dimensional semiconductor structures viz. quantum wires, dots, wells etc., have drawn considerable interest in the past few years for their potential technological applications [1–4]. Quantum wires of all these structures have shown remarkable physical properties for finding applicability in future technologies like conducting nanowire in quantum computing devices [5]. They can be grown into desired radius using numerous semiconductor materials by different physical methods [6, 7].

Recently, spin-dependent phenomena in quantum wires have attracted much attention because of its abundance of physically observable phenomena and future spin electronic devices [8, 9]. A number of spintronics devices have been proposed with low power consumption, high speed, and a high degree of functionality [10–13]. In these devices, the spin degree of freedom is used for information processing in addition to the electron charge. Most of these devices are proposed to manipulate electron spin via spin orbit interaction (SOI). Two basic mechanisms of the SOI are Rashba SOI [14] and Dresselhaus SOI [15]. The former arises due to structural inversion asymmetry, while the latter is caused by bulk inversion asymmetry in noncentosymmetric materials. These spin orbit interactions lift the spin degeneracy of the subbbands for the non-zero wave vectors, called zero field spin splitting. The Rashba SOI has practical advantages that it depends on the electronic environment of the hetrosturucture and the strength of the Rashba SOI can be tuned by changing the gate voltage [16], so that the final spin orientation of electrons can be controlled. Moreover, for narrow gap semiconductor it dominates over Dresselhaus SOI.

Physical properties of condensed matter systems are often determined by the energy spectrum wave function of charge carriers. Much work has been devoted to investigate the Rashba SOI effects on the persistent spin current of the quantum wires [17–19]. Study of spin current is very useful to find out many prominent effects like spin Hall Effect [20, 21], and spin precession [21] which are mainly utilized in the field of spintronics [22]. Presence of an external magnetic field introduces additional features in the subband structure [23–25]. A lot of works have been performed to study the effects of SOI on persistent spin current [26–28]. To explore the properties in the field of spintronics further, we study the effect of external magnetic field and Rashba SOI on quantum wire for investigating persistent spin current for various spin split subbands in this paper. For solving this fruitful combination, we present a theoretical study of quantum wire under the influence of various fields. In general, spin orbit effects in the conduction band are most pronounced in structures comprising a low band gap conductive channel like InAs [29]. We present an analytic solution to one particle Schrodinger equation in presence of magnetic fields and Rashba SOI. This paper is organized as follows. In section 2, we present our model describing Rashba SOI in a parabolic confined quantum wire. In section 3, numerical results with discussions of the persistent spin of subbands are presented. Finally, conclusions are presented in section 4.

2. Theoretical Framework

We consider a two dimensional electron gas in x-y plane. The electron motion is confined in x-direction by a parabolic confinement making it a thin quantum wire along y-direction. When an external magnetic field, $\vec{B} = (0,0,B)$ whose corresponding vector potential is $\vec{A} = Bxe_y$ in the Landau gauge, is applied to the quantum wire, the single electron Hamiltonian is given as [28, 30]

$$H_0 = \frac{(\vec{p}+e\vec{A})^2}{2m^*} + \frac{1}{2}m^*\omega_0 x^2 + \frac{1}{2}g\mu_B\vec{\sigma}\cdot\vec{B} + H_R, \tag{2.1}$$

where ω_0 is the oscillator strength, m^* is the effective mass if charge carrier, g is the Lande's g factor, $\mu_B = \frac{e\hbar}{2m_0}$ the Bohr magnetron and σ is well known Pauli spin matrix vector. H_R in Eq. (2.1) is the Rashba SOI Hamiltonian term in presence of magnetic field, which is given by

$$H_R = \frac{\alpha}{\hbar}(\vec{\sigma} \times (\vec{p} + e\vec{A}))_z, \tag{2.2}$$

where α is the Rashba SOI factor which can be varied with the gate voltage.

As the Hamiltonian is transitionally invariant along the wire, so the energy eigenstates ($\Psi(x,y)$) of 'H' can be written in terms of plane wave solution such that

$$\Psi_{\downarrow\uparrow}(x,y) = \phi_{\downarrow\uparrow}(u)\exp(ik_y y), \tag{2.3}$$

where k_y is wave number of the plane wave along the y-direction and $\phi_{\downarrow\uparrow}(u)$ is the transverse wavefunction in which $\uparrow(\downarrow)$ stands for spin up (down) state of electrons, $u = (x + x_0)/l_\omega$ is the dimensionless transverse coordinate with $l_\omega = \sqrt{\hbar/m^*\omega}$ (the typical spatial scale associated with the confinement potential). Where $\omega = (\omega_0^2 + \omega_c^2)^{1/2}$ is the effective cyclotron frequency and $\omega_c = \frac{eB}{m^*}$ is the cyclotron frequency and $x_0 = \frac{eB\hbar k_y}{m^2\omega^2}$ is the guiding center coordinate for the harmonic oscillator. On writing p_y in terms of k_y, for the weak Rashba SOC, the perturbation methods [30] results in the transverse eigenfunction

$$\begin{aligned}\phi_{\downarrow\uparrow}(u) = e^{-s^2/2}\Bigg[\frac{1}{\sqrt{\sqrt{\pi}2^n n!}}H_n(u) \pm \frac{1}{2\sqrt{2}}\frac{l_\omega}{l_\alpha}\Bigg\{\frac{1}{\sqrt{\sqrt{\pi}2^{n-1}(n-1)!}}\sqrt{n}H_{n-1}(u)\\ + \frac{1}{\sqrt{\sqrt{\pi}2^{n+1}(n+1)!}}\sqrt{n+1}H_{n+1}(u)\Bigg\}\Bigg],\end{aligned} \tag{2.4}$$

and the associated total eigenenergy

$$E_{\uparrow\downarrow}(n) = \frac{\hbar\omega}{2}\left(2n + 1 + (k_y l_\omega)^2 \pm \left(\frac{l_\omega}{l_\alpha}\right)k_y l_\omega\right), \tag{2.5}$$

with $n = 0,1,2,\ldots$; and $l_\alpha = \hbar^2/(2m\alpha)$ is the characteristic spatial scales associated with the Rashba SOC. In order to calculate the spin current density, we use the definition [26]

$$j_s = \mathrm{Re}\{\Psi^+ v s \Psi\}, \tag{2.6}$$

$$j_\omega = \mathrm{Re}\{\Psi^+ \omega \times s\Psi\}, \tag{2.7}$$

Where $v = p/m + (\alpha/\hbar)(\hat{z} \times \sigma)$ and $\omega = (2\alpha/\hbar^2)(p \times \hat{z})$ are the respectively the linaer and angular velocity operator of an electron with the spin s and unit vector $\hat{z}$. On keeping Eq (2.4) and (2.5) in to Eq. (2.6) and (2.7), the spin current density can be obtain directly. There are three non-zero elements of linear spin current density and one angular spin current density as discussed in ref. [26], out of which we are considering only

$$j_{s,xy} = -\frac{\alpha}{2}\left(\phi_\uparrow^*\phi_\uparrow + \phi_\downarrow^*\phi_\downarrow\right) + \frac{\hbar^2}{2m}\left(\phi_\downarrow^*\phi_\uparrow' + \phi_\uparrow^*\phi_\downarrow'\right), \tag{2.8}$$

where $\phi'_{\uparrow/\downarrow}$ represents its differentiation with respect to u. $j_{s,xy}$ represents an electron moving along the x direction with its spin in the y direction. For single transverse mode for $n = 0$ and $n = 1$, $j_{s,xy}$ can be calculated as

$$j^T_{s,xy} = -\frac{\alpha}{4\sqrt{\pi}} \frac{l^2_\omega}{l^2_\alpha} u^2 e^{-u^2}, \tag{2.9}$$

$$j^T_{s,xy} = -\frac{\alpha}{8\sqrt{\pi}} \frac{l^2_\omega}{l^2_\alpha} (1+2u^2) u^2 e^{-u^2}. \tag{2.10}$$

We have plotted Eq. (2.10) with the variations of other parameters like magnetic field and Rashba SOC factor.

3. Results and Discussions

In this work, we study the persistent spin current at different Rashba SOC and magnetic field intensities. For the calculations, we consider the InAs material parameters for which the effective mass of an electron in conduction band is $0.03m^0$ where m^0 is the rest mass of electron.

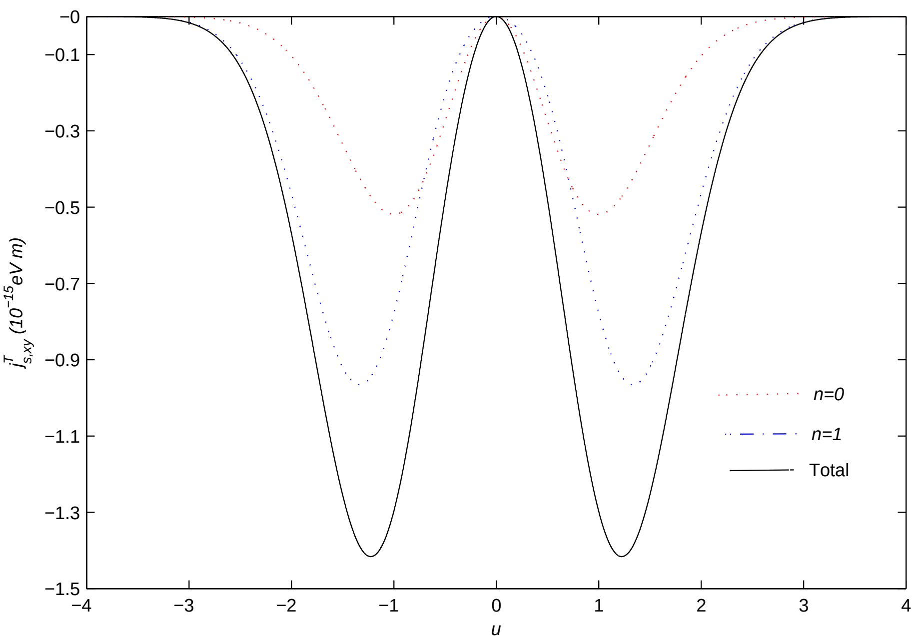

Figure 1. Variation of spin current density in units of eVm with the dimensionless transverse coordinate u at $B = 0$ and $\alpha = 10^{-10}$ eVm, where the dotted (red) line for the contribution of states $n = 0$, the dashed (blue) for the states $n = 1$ and the dark line for the total respectively

Figure 1, demonstrate the variation of spin current density in units of eVm with the dimensionless transverse coordinate u at $B = 0$ and $\alpha = 10^{-10}$eVm. From this figure we can see that for $j^T_{s,xy}$ (in the scale of 10^{-15}) the contribution of the states in sub band $n = 1$ is greater than that of the states in sub band $n = 0$. This is because as the number of the mode increases, more quantum channels are occupied, so the oscillation becomes more intense. Furthermore, we can find a symmetrical relation and this relation is also found in the quantum wire confined by a parabolic potetial confined quantum wire for dresselhaus spin orbit interaction [25]. Therefore one can enhance the spin current by selecting the mode.

Figure 2 shows the variation of spin current density in units of eVm with the dimensionless transverse coordinate u at different values of magnetic fields e.g. $B = 0, 5, 10, 15$ at fixed value of Rashba spin orbit interaction. We see that the spin current density decreases with the increase of the magnetic fields. Figure 3 is showing the variation of spin current density in units of eVm with the dimensionless transverse coordinate u at different values of Rashba spin orbit interaction and fixed values of magnetic field.

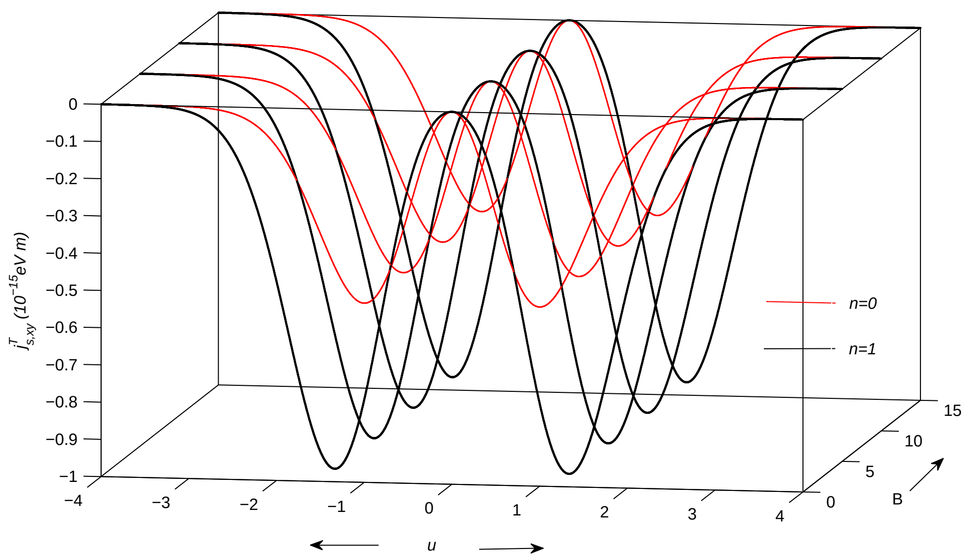

Figure 2. Variation of spin current density in units of eVm with the dimensionless transverse coordinate u at different values of magnetic fields e.g. $B = 0, 5, 10, 15$, $\alpha = 10^{-10}$ eVm, where the red line for the contribution of states $n = 0$, the black line for the states $n = 1$ respectively

By comparison with Figure 2, we can see that the spin current density increases with the increase of the Rashba factor. With the increase of the strength of the Rashba spin-orbit coupling, the spin current density greatly increases, which has been theoretically proved by Sun et al. [27]. Therefore, in our case, for a Rashba spin-orbit coupling quantum wire, the net linear spin current should also induce a linear electric field. These characteristics of the induced electric field, which is measurable, may offer a way to detect the spin current [27].

Hence by using these parameters on quantum wire, some richer useful spin transport based devices can be made. The strength of the Rashba spin-orbit coupling is tunable by the gate voltage, and the gate voltage can be varied experimentally, which may offer a new method to detect spin currents. All of these spin current characteristics will be very important for detecting and controlling spin current, and especially for designing new spintronics devices in the future.

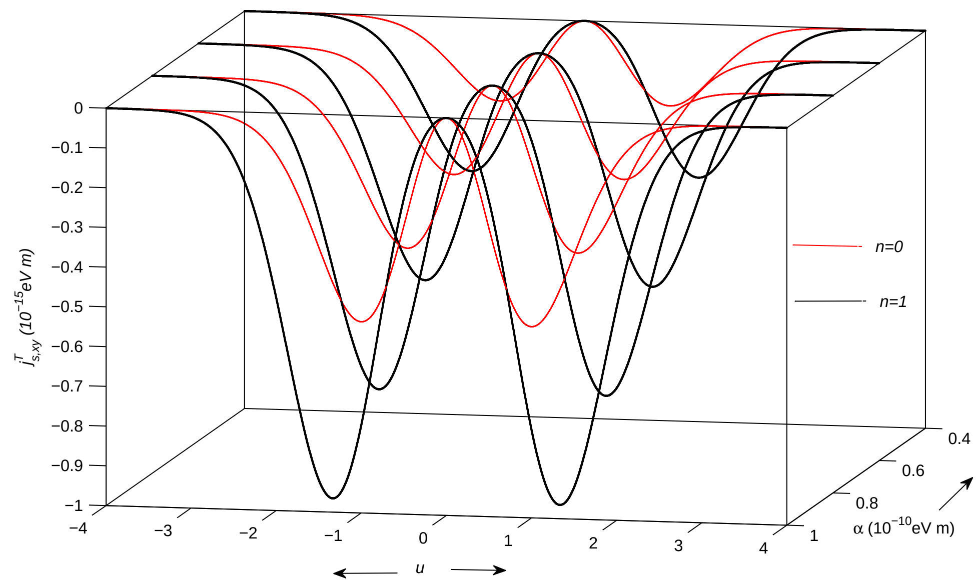

Figure 3. Variation of spin current density in units of eVm with the dimensionless transverse coordinate u at $B = 5T$ and for different values of e.g. $\alpha = (0.4, 0.6.\ 0.8, 1) \times 10^{-10}$ eVm, where the red line for the contribution of states $n = 0$, the black for the states $n = 1$ respectively

4. Conclusions

We have investigated the effect of the Rashba spin orbit interaction and magnetic field on a spin current density for quantum wire. The variations of the spin current density with magnetic field and Rashba spin orbit interaction are demonstrated. We have found that spin current density can be increased by selecting the sub bands. It was found that the magnetic field red decreases the spin current density for both sub bands. Whereas the Rashba spin orbit interaction factor increases the spin current density for both subands. These facts would be useful for making and designing new type of spin based devices.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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