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All-electrical manipulation of electron spin in a semiconductor nanotube

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HIGHLIGHTS

- The modification of spin in the semiconductor nanotube has been presented.
- We present analytical solutions with the Rashba spin–orbit interaction.
- The radial electric field results in the precession of electron spin.
- The longitudinal electric field generates the spin oscillation beats along the nanotube.

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ABSTRACT

A controlled manipulation of electron spin states has been investigated for a cylindrical two-dimensional electron gas confined in a semiconductor nanotube/cylindrical nanowire with the Rashba spin–orbit interaction. We present analytical solutions for the two limiting cases, in which the spin–orbit interaction results from (A) the radial electric field and (B) the electric field applied along the z-axis of the nanotube. In the case (A), we have found that only the superposition of bands with the same orbital momentum leads to the spin precession around the cylinder (nanotube) axis. In the case (B), we have obtained the damped oscillations of the z spin component with the period that changes as a function of the coordinate z. We have shown that the damped oscillations of the average value of the z spin component form beats localized along the nanotube axis. The position of the beats can be controlled by the bias voltage.

1. Introduction

The electron spin control induced by the electric field is a basic principle for the realization of spintronic devices, including the spin transistor [1,2], and the quantum operations on spin qubits [3,4]. For this reason the spin–orbit interaction (SOI) [5,6], which couples the momentum of the electron with its spin, has attracted the substantial interest in recent years. In the spintronic and quantum computing applications, the Rashba SOI [6] is very promising, since its strength can be controlled by the external electric field [7–9], which opens up a new possibility of manipulating the electron spin state by the gate voltages at zero magnetic field [10–12]. The spin manipulation due to the Rashba SOI has been recently demonstrated in the electric-dipole spin resonance (EDSR) experiments performed in the system of double quantum dots embedded in a gate InAs quantum wire [13–15]. In the EDSR, the Pauli blockade of the current, which occurs when the quantum dots are occupied by the electrons with parallel spins, is lifted by the Rashba SOI generated by the oscillating gate voltage.

Recently, the special attention has been directed towards non-planar low dimensional structures, in which interesting physical effects resulting from the curvature of the surface have been found [16]. Many research studies are focused on the cylindrical two-dimensional electron gas (2DEG). The nanostructure containing the cylindrical 2DEG can be fabricated by self-rolling of a thin strained semiconductor planar heterostructure grown by molecular-beam epitaxy [17–19]. This method allows us to obtain the free-standing semiconductor nanotubes with the radius that ranges from several nanometers up to several micrometers. The cylindrical 2DEG also appears in the core–shell nanowires, which are produced on the cylindrical substrate with a multilayer overgrowth [20,21]. Another method of the fabrication of the cylindrical 2DEG exploits the electrical neutrality which leads to the formation of the triangular quantum well in the thin region near the surface of the semiconductor nanowire [22]. The electrons confined in this quantum well form the cylindrical 2DEG with a radius of few nanometers. The electronic properties of the cylindrical 2DEG are strongly dependent on the curvature, which manifests themselves especially in the presence of the magnetic

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field. The electron states have been recently calculated by Ferrari et al. [23] for the cylindrical 2DEG in the transverse magnetic field. In this system, the electrons are coupled to the magnetic field component perpendicular to the surface that varies along the circumference of the cylinder. The gradient of magnetic field perpendicular to the surface causes that the electrons propagating in the opposite directions become localized in the opposite sides of the circumference [24], which leads to the experimentally observed Hall quantization [19,17].

The interplay between the curvature effects and the SOI in the cylindrical 2DEG has been studied in the recent papers [25–27]. In Ref. [25], the authors investigated the dimensional dependence of weak localization corrections and spin relaxation in cylindrical nanowires with the Rashba SOI. The spin dependent electric current through the cylindrical nanowire containing a region with the spin–orbit coupling has been investigated by Entin-Wohlman et al. [26] who have shown that the tunneling through the region with the SOI causes that each step of the quantized conductance splits into two separate steps with the spin polarization perpendicular to the direction of the current. The spin precession in the cylindrical semiconductor nanowire due to the Rashba spin–orbit coupling has been investigated by Bringer and Schäpers [27]. The authors [27] have taken into account the Rashba SOI generated by the radial electric field, which results from the inhomogeneous radial redistribution of charge near the surface of nanowire.

In the present paper, we have included the Rashba SOI stemming from the axially directed electric field that causes the flow of current and studied the possibility of spin manipulation in the semiconductor nanotube with the use of the radial electric field and the electric field acting along the cylinder axis. For both cases we have obtained the analytical solutions and discussed them in the context of spin modulation. The present results can be applied to both the semiconductor nanotubes with the few atomic monolayer thickness and cylindrical nanowires with the 2DEG electron gas accumulated near the surface.

The paper is organized as follows: in Section 2, we describe the theoretical model of the cylindrical 2DEG with the spin–orbit coupling, in Section 3, we present the results, and the conclusions are presented in Section 4.

2. Theory

We consider one-electron states in the cylindrical 2DEG with the spin–orbit interaction that originates from the radial electric field F_r and the homogeneous electric field F_z applied along the nanotube axis (Fig. 1).

The Hamiltonian of the system takes on the form (see Appendix A)

$$\hat{H} = \left[-\frac{\hbar^2}{2m}\left(\frac{1}{r_0^2}\frac{\partial^2}{\partial\varphi^2}+\frac{\partial^2}{\partial z^2}\right) - eF_z z\right]\hat{\mathbb{1}} + \hat{H}_{SO}, \tag{1}$$

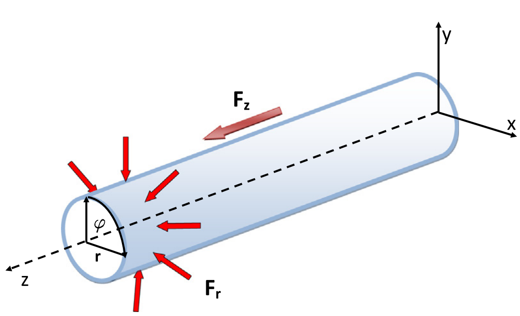

Fig. 1. Schematic of the nanotube with 2DEG.

where φ and z are the cylindrical coordinates (see Fig. 1), e is the elementary charge, r_0 is the radius of the nanotube, m is the electron effective band mass, $\hat{\mathbb{1}}$ is the 2×2 unit matrix, and $\hat{H}_{SO}$ is the Hamiltonian of the spin–orbit interaction.

The spin–orbit interaction couples the spin $\vec{s}$ of the electron with its linear momentum $\vec{p}$ via the electric field $\vec{F} = -\nabla V/e$. The SOI Hamiltonian can be expressed as (Appendix A)

$$\hat{H}_{SO} = -\frac{e\gamma}{\hbar}\vec{\sigma}\cdot(\vec{F}\times\vec{p}) = \begin{pmatrix} -\frac{ie\alpha}{r_0}\frac{\partial}{\partial\varphi} & e^{-i\varphi}\left(-eF_z\frac{i\gamma}{r_0}\frac{\partial}{\partial\varphi}+e\alpha\frac{\partial}{\partial z}\right) \\ e^{i\varphi}\left(-eF_z\frac{i\gamma}{r_0}\frac{\partial}{\partial\varphi}-e\alpha\frac{\partial}{\partial z}\right) & \frac{ie\alpha}{r_0}\frac{\partial}{\partial\varphi} \end{pmatrix} \tag{2}$$

where $\vec{\sigma}$ is the vector of Pauli matrices, $\vec{s} = (\hbar/2)\vec{\sigma}$ and γ is the coupling constant determined by the band structure of the semiconductor. In the present paper, we will also use the effective coupling constant $\alpha = -\gamma F_r$ that takes into account both the band structure and the radial electric field effects.

The eigenstate of Hamiltonian (1) is the spinor with the two components corresponding to the same total angular momentum $(l+1/2)(\hbar/2)$ [27]

$$\Psi(\varphi,z) = \begin{pmatrix} \Psi^{\uparrow}(\varphi,z) \\ \Psi^{\downarrow}(\varphi,z)\end{pmatrix} = \frac{e^{il\varphi}}{\sqrt{2\pi}}\begin{pmatrix} f(z) \\ e^{i\varphi}g(z)\end{pmatrix}, \tag{3}$$

where l is the orbital quantum number. After inserting Eq. (3) into the eigenequation of Hamiltonian (1) we obtain

$$-\frac{\hbar^2}{2m}\frac{d^2f(z)}{dz^2}+\frac{\hbar^2l^2}{2mr_0^2}f(z)-eF_zzf(z)+\frac{e\alpha l}{r_0}f(z) + eF_z\frac{\gamma(l+1)}{r_0}g(z)+e\alpha\frac{dg(z)}{dz} = Ef(z), \tag{4a}$$

$$-\frac{\hbar^2}{2m}\frac{d^2g(z)}{dz^2}+\frac{\hbar^2(l+1)^2}{2mr_0^2}g(z)-eF_zzg(z) -\frac{e\alpha(l+1)}{r_0}g(z)+eF_z\frac{\gamma l}{r_0}f(z)-e\alpha\frac{df(z)}{dz} = Eg(z), \tag{4b}$$

where energy E is measured with respect to the lowest energy of the size-quantized motion in the radial direction.

In general, the system of Eqs. (4a) and (4b) is not solvable analytically. Nevertheless, we have found that – in the two limiting cases – the analytical solutions exist. These are

(A) zero axial electric field (F_z=0), then the SOI is due to the radial electric field F_r,
(B) zero radial electric field (F_r=0, i.e., $\alpha = 0$), then the SOI is due to the electric field F_z applied along the nanotube axis.

3. Results

In this section, we present the analytical solutions for the InAs nanotube/cylindrical nanowire, for which we take on the following values of the parameters: electron band effective mass $m = 0.026m_0$, where m_0 is the free electron mass, the radius of the nanotube $r_0 = 50$ nm, and the spin–orbit interaction constants $\gamma = 1.17$ nm^2 and $\alpha = 10$ meV nm [28,29]. We discuss the results obtained for two limiting cases (A) and (B). In both the cases, the analytical solutions are applied to describe a possible control of spin precession.

3.1. Effect of radial electric field

If the axial electric field is equal to zero (F_z=0) and the electric field has only the radial component, the solution of Eqs. (4a) and