RASHBA SPIN-ORBIT INTERACTION IN SEMICONDUCTOR NANOSTRUCTURES (REVIEW)

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In this work we review of the theoretical and experimental issue related to the Rashba spin-orbit interaction [1] in semiconductor nanostructures. The Rashba spin-orbit interaction has been a promising candidate for controlling the spin of electrons in the field of semiconductor spintronics. In this work I focus study of the electrons spin and holes in isolated semiconductor quantum dots and rings in the presence of magnetic fields. Spin-dependent thermodynamic properties with strong spin-orbit coupling inside their band structure in systems are investigated in this work. Additionally, specific heat and magnetization in two- dimensional, one-dimensional ring and quantum dot nanostructures with spin- orbit interaction are discussed.

Keywords: spin-orbit interaction, Rashba effect, two-dimensional electron gas, one-dimensional ring, quantum wire, quantum dot, semiconductor nanostructures.
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INTRODUCTION

The use of electron spin in electronic devices has been of great interest to scientists during the last three decades. The spin-orbit interaction is also called spin-orbit coupling or spin-orbit effect. It means that any interaction of a particle's spin with its motion. Spin degree of freedom is made by spin-orbit coupling which is respond to its orbital environment. Moving of the electron in an external electrical field leads to creating spin-orbit interaction and experiences an effective magnetic field in its own reference frame, that in turn couples to its spin through the Zeeman effect [2]. The magnitude of the spin-orbit interaction increases with the atomic number which is a relativistic effect. The spin-orbit interaction is found with asymmetry in the underlying structure in crystals in semiconductors systems [3]. In bulk it seems in crystals without an inversion center (e.g. zinc blende structures) and is called the Dresselhaus spin-orbit interaction [4].However, Rashba term is aroused from the structural asymmetry of the confining potential in heterostructures [5]. A set of practical information on the cyclotron resonance and also the combined resonance of two-dimensional electron gas at the GaAs-AlxGa1−xAs heterojunctions' interface [6,7], shown that the spin degeneracy was lifted in the inversion layer. For describing this experimental information in term of spin-orbit interaction is developed by the theory [1,5]. In semiconductor nanostructures, studies of transport phenomena and spin-dependent confinement have been progressing importantly since spintronics became a focus of recent interest. The first offer of Das and Datta assign that the basic elements of spintronic devices [8]. Several possible structures with the basic elements were analyzed. Different kinds of electron spin detection methods have been investigated. Lately the coherent spin transport has been showed in heterostructures and homogeneous semiconductors [9]. The most necessary property of III–V semiconductors to be used in all semiconductor spintronic devices is the spin–orbit interaction [4,5]. In III–V and II–VI semiconductors the spin–orbit interaction has been used successfully to interpret experimental results in different quantum wire and well structures. Additionally, it lifts the conduction state spin-degeneracy [5,11]. Exploiting the spin-orbit interaction in the conventional III–V nonmagnetic semiconductors to design basic and high-speed spintronic devices is reviewed in paper [12]. To achieve this [12], concentrate on spin-dependent electronic characteristics of semiconductor nanostructures.

RASHBA EFFECT IN TWO-DIMENSIONAL ELECTRON SYSTEM

Spin-orbit interaction has a vital role in spin relaxation, optical phenomena and transport, which are actively studied for entirely new applications in semiconductor spintronics. Study of the effects of spin-orbit interaction in two-dimensional electronic systems exposed to a perpendicular magnetic field and were initially associated with Landau volume levels: the spin-orbit interaction renormalization of energy dispersions, the interplay among various spin-orbit interaction mechanisms, effects of magnetic transport and electron-electron interaction. In general, the Hamiltonian described the spin-orbit interaction $H_{so} = (\alpha/\hbar)\nabla U \cdot (\sigma \times p)$, in here p is the momentum operator, α is the spin-orbit coupling parameter and having a dimension of length squared , which is proportional to the interface electric field and is sample dependent, σ is the Pauli matrices vector. The value of α determines the contribution of the Rashba spin -orbit coupling to the total electron Hamiltonian. When an external electric field is present, the relativistic correction introduces a relation between the electron spin and its own momentum. The coupling of the electron spin and its orbital motion lifted the spin degeneracy of the two dimensional

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electron gas energy bands at $k \neq 0$ in the absence of a magnetic field. This coupling arises due to inversion asymmetry of the potential which confines the two dimensional electron gas system. This is described by Hamiltonian which is given many books and papers by:

$$H_{so} = \frac{\alpha}{\hbar}\left(\vec{\alpha}\times\vec{p}\right)_z = i\alpha\left(\sigma_y\frac{\partial}{\partial_x} - \sigma_x\frac{\partial}{\partial_y}\right) \quad (1)$$

Where the z axis is selected perpendicular to the two dimensional electron gas system lying in the x-y plane.

In the presence of the Rashba spin-orbit term the Hamiltonian of the two-dimensional electron gas systems in the plane (x,y) is given :

$$H = \frac{\vec{p}^{\,2}}{2m} + \frac{\alpha}{\hbar}\left(\vec{\sigma}_x \times \vec{p}\right)\hat{z} \quad (2)$$

The eigenvalues of this Hamiltonian is

$$E \pm \left(\vec{k}\right) = \frac{\hbar^2 k^2}{2m} \pm \alpha k = \frac{\hbar^2}{2m}\left(k_x \pm k_{so}\right)^2 - \delta_{so} \quad (3)$$

Here $k = \sqrt{k_x^2 + k_y^2}$ is the electron momentum modulus, $k_{so} = \frac{\alpha m}{\hbar^2}$ is a recast form of the spin orbit coupling constant and $\delta_{so} = \left(\frac{\alpha m}{\hbar}\right)^2$ which is neglected due to spin orbit coupling α is small. The eigenvectors of the Hamiltonian (1) relative to the spectrum (2) are plane wave's function of the momentum $\vec{k}$

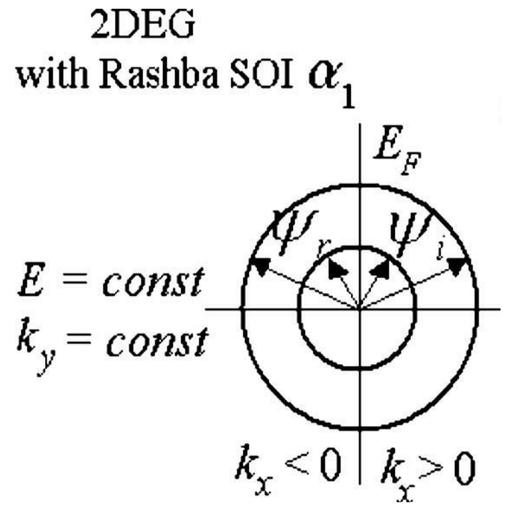
$$\psi + (x, y) = e^{i(k_x + k_y)}\frac{1}{\sqrt{2}}\binom{0}{1} i e^{-} i\theta \quad (4)$$

$$\psi - (x, y) = e^{i(k_x + k_y)}\frac{1}{\sqrt{2}}\binom{1}{-i} i e^{-} i\theta \quad (5)$$

Scattering geometry of two-dimensional electron gas with Rashba spin-orbit interaction on the spin-orbit lateral superlattice shown in Fig. 1 [13]

Fig.1.Two-dimensional electron gas scattering geometry with Rashba spin-orbit interaction on the spin-orbit lateral superlattice. The reflected ψ_r and incoming ψ_i spinors are the eigenstates of Rashba Hamiltonian with spin-orbit coupling constant α_1 and wave vectors belonging to the same Fermi contour [13].

In many two-dimensional electronic systems the main mechanism of spin relaxation is the Dyakonov – Perel spin relaxation mechanism [14, 15]. In this mechanism electron spins sense an effective momentum dependent magnetic field randomized by electron-scattering events, which leads to relaxation of electron spin polarization. In the last decade, a number of theoretical and experimental studies of the features of Dyakonov – Perel spin relaxation were published [16–19]. This has been shown in Ref. [20] that the spin relaxation time for two-dimensional electrons depends not only on the material parameters, for example, the spin-orbit interaction strength, electron mean free path, etc., but also on the initial spin polarization profile. The spin-orbit coupling defines the electrons spin-relaxation time in semiconductor heterostructures and in ordinary semiconductors [21]. So it has a significant role in the physics of diluted magnetic semiconductors [22].



ONE-DIMENSIONAL RING WITH SPIN–ORBIT INTERACTION

Nanostructures with ring geometry are of great interest, because they provide unique opportunities for studying quantum interference effects, for example, the persistent current and the Aharonov–Bohm effect.

The theoretically studying of the persistent current of electrons without free spin in the one dimensional ring was shown in Ref [23]. Founding shapes and periods of the current oscillations created great interest. The current oscillations' shapes and periods were found. Periodic dependence on a magnetic flux of the persistent current is one of the important properties of it. That effect occurs for the isolated ring [24] and also the ring connected to an electron reservoir [23, 25]. The theoretically studying of the magnetic moment of a 2D electron gas with the Rasba spin–orbit interaction in a magnetic field was investigated in Ref [26]. The persistent current, the electronic thermal capacity in the dimensional ring have been investigated in [30, 31], [32] respectively. Oscillations of the magneto transport [27–29], and the magnetic properties [33] in the dimensional ring have been studied. An obvious analytic expression is got by taking into account the spin-orbit interaction in the Rashba model [34] for the persistent current and magnetic moment of the electron gas in one dimensional ring.

Over the ten years, great attention has been dedicated toward control and engineering of freedom spin degree at mesoscopic scale, usually referred to as spintronics [35].

Diluted magnetic semiconductors is a prime class of materials for spintronics. These are solutions of the A2B6 or A3B5 with a high density of magnetic impurities (usually, Mn). For combining semiconductor electronics with magnetism DMS is one of the best candidates. The strong s-d exchange interaction between the local magnetic ions and the carriers leads to Diluted magnetic semiconductors offers us with an interesting possibility for tailoring the spin splitting and the spin polarization [36].

The spin-orbit interaction effects on the one-dimensional quantum ring properties has attracted much attention [37]. In Ref [38] have studied the Rashba SO interaction, the effect of the magnetic field the finite temperature and also the s-d exchange interaction on the conductance of a DMS hollow cylindrical wire.

The specific heat and magnetization of a diluted magnetic semiconductor (DMS) quantum ring in the presence of magnetic field have been calculated by us in the paper [39] and also we take into consideration the effect of Rashba spin-orbital interaction, the exchange interaction and the Zeeman term on the specific heat. Additionally, in diluted magnetic semiconductor quantum ring, we calculated the electrons energy spectrum. Furthermore, at finite temperature of a DMS (Diluted magnetic semiconductor) quantum ring, the specific heat dependency on the magnetic field and Mn concentration have been calculated by us. In Fig. 2 show us the average magnetization of diluted magnetic semiconductors quantum ring as a magnetic function and Rashba spin-orbit coupling constant $\alpha =$ 160 meV. nm at fixed Mn concentration x = 0.05 and T = 10 K.

The magnetization changes abruptly with a small increase in H and the peak is observed after which the magnetization starts to decrease.

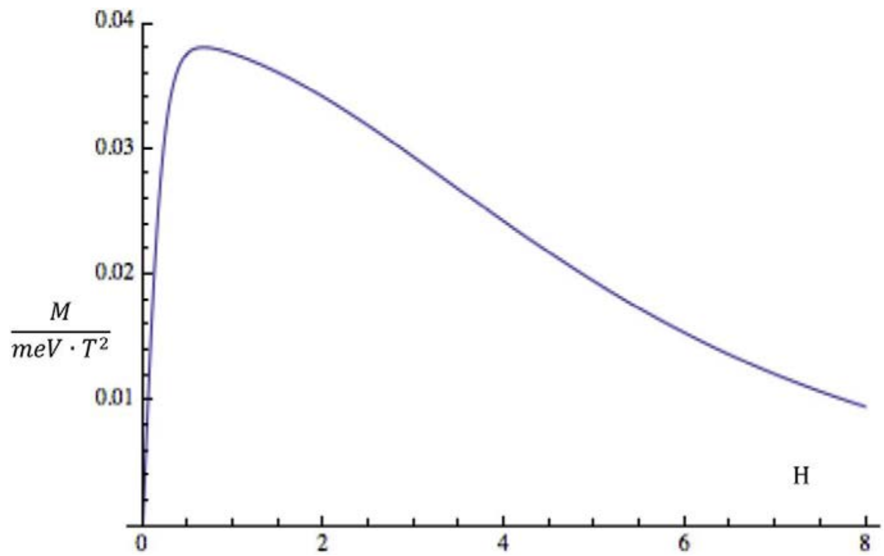


Fig. 2. The average magnetization of diluted magnetic semiconductors quantum ring as a function of magnetic with Rashba spin-orbit coupling constant $a = 160$ meV.nm at fixed Mn concentration x=0.05 and T=10 K [39].

The magnetization of electrons in a diluted magnetic semiconductor quantum ring have been investigated in the paper [40] by us. The Rashba spin-orbit interaction, the exchange interaction and the Zeeman term effect are taken into account by us and also we have calculated wave function and energy spectrum of the electrons in DMS quantum ring. Likewise, as a function of the magnetic field at finite temperature of a diluted magnetic semiconductor quantum ring for strong degenerate electron gas, the magnetic moment has been calculated.

We have theoretically studied the magnetic properties and electronic spectra of a Diluted magnetic semiconductors quantum ring in externally applied static magnetic field in the paper [41, 42]. It has been shown that if Mn concentration rise, the compensation points reduce Also, it was obtained that with increasing manganese content in the DMS quantum ring a transition to the paramagnetic from the antiferromagnetic properties one occurs for finding DMS ring electrons magnetization it is necessary to obtain in the ring, the expression of the electron gas's free energy. That equation can be determined from the classical partition function Z. We express the given non-degenerate energy spectrum by a sum over all possible states of the system

$$Z = \sum_{l,\sigma} e^{-\beta E_{l,\sigma}} \tag{6}$$

In here, $\beta = \dfrac{1}{k_B T}$ and k_B –is the Boltzmann constant and T is the thermodynamic equilibrium temperature.

$$F = -k_B T \ln Z \tag{7}$$

We use the expression of the free energy of the ring for calculation the magnetization of the electron gas:

$$M = -\frac{\partial F}{\partial H} \qquad (8)$$

As it is seen from Fig. 1, with changing of the AB flux at fixed temperature the magnetization for free electron model system (x=0) varies from negative to positive values, such a behavior is typical for antiferromagnetic systems.

The exchange interaction between the localized angular moments changes with increasing in the $Cd_{1-x}Mn_xTe$ solid solutions Mn concentration and this leads to change in the magnetization of the DMS quantum ring. The calculations showed that, a transition from the antiferromagnetic properties to the paramagnetic one is observed in a DMS quantum ring as the manganese content increases.

With changing the AB flux at fixed temperature, the magnetization x=0.0004 varies to negative values from positive for Mn concentration in the non-interacting DMS quantum rings, which is typical for paramagnetic systems. When = l and where l is integer or half integer, as it can be seen the magnitude of magnetization is equal to zero.

These points are called "Aharonov-Bohm compensation points" at that time the magnetization disappears at fixed temperature and magnetic flux varies.

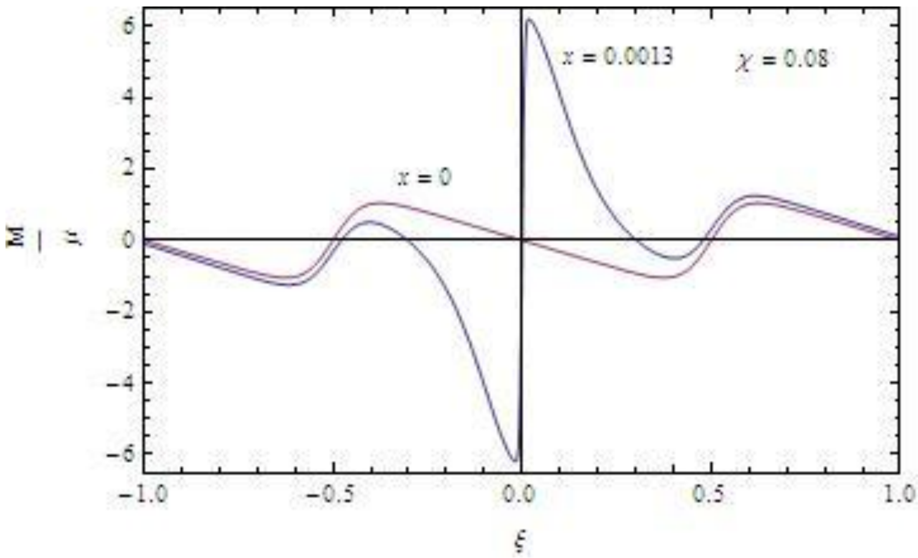


Fig.3. Dependence of the magnetization in terms of μ_B^* on the magnetic flux for the cases where Mn concentrations x=0, *g=0*, and *x=0.0013, g*=-1.67 for $x = 0.08$.

QUANTUM DOTS IN THE PRESENCE OF THE SPIN–ORBIT INTERACTION.

The spin of an electron confined in a semiconductor quantum dot is a promising candidate for a scalable quantum bit [43, 44]. The electron spin states in quantum dots are expected to be very stable, because the zero dimensionality of the electron states in quantum dots leads to a significant suppression of the most effective 2D spin-flip mechanisms [45].

During the past few decades, spin physics has attracted substantial attention in semiconductors. Experimental and theoretical studies have made it possible to fabricate Nano-structured semiconductor devices [46, 47] with quantum confinement in all spatial directions. The size of these structures are typically consist of several nanometers and are usually known as objects of zero size or, more technically called as quantum dots [48]. With the advent of modern manufacturing technologies, such as molecular beam epitaxy, selective ion implantation, nanolithography and etching and it has become possible to design such semiconductor quantum heterostructures in which the electrical properties of a quantum dot are very sensitive to the spin of electrons. In this context where devices are controlled by spin-polarization is "Spintronics" [49, 50]. This leads to offer of many devices like spin filter, spin transistors etc. Investigation of spin-dependent phenomena in low dimensional systems has attracted a rage over the years. Spin-dependent phenomena offer opportunities to advance many optoelectronic devices in which these devices can be controlled by intrinsic spin-orbit interaction. The presence of a heterojunction leads to inversion asymmetry of the confinement potential in semiconductor nanostructures, such as GaAs, InAs and In1-xGaxAs quntum dots, quantum wells and quantum wires.

Electron-phonon interaction plays an important role in defining the transport and other properties of quantum dots. Electron-phonon interaction leads to various physical phenomena, such as superconductivity, polaronic effect, magneto phonon anomalies etc. Thus it is our main target to learn the polaronic effects in the energy states of an electron and other quantum structures. It was theoretically studied in Ref [51] that the RSOI effect on an electron polaronic energy spectrum in a 2D parabolic quantum dot of a polar semiconductor. There is extended investigate to the bound polaron difficulty where the electron is bound to a Coulomb impurity. Thanks to modern advanced technologies, it has become possible to study the energy levels of electrons of various types of quantum dots. In [38–42, 52–54] has extensively studied the orbital and spin magnetization of those systems over the last years. The point of interest is that the magnetization provides information on the multi particle dynamics of the dots in an external magnetic field. Additionally, an extensive study of magnetic properties of nanosystems [56-59] is required by recent development of sprintronics. The spin states in the quantum dots are promising candidates for realizations of qubit in the quantum computing [60]. The design of the magnetic properties of semiconductor quantum dots and energy shells is controlled by the electron spin [48-50]. For III–V semiconductor nanostructures the interaction among orbital angular and spin momenta [5] has an important role in the energy spectrum formation (spin–orbit interaction). When the potential through which the carriers travel is inversion asymmetric, the spin–orbit interaction eliminates the spin degeneracy of the energy levels even without external magnetic fields. The effect of the spin–orbit interaction on the electron magnetization of small semiconductor quantum dots is theoretically studied in Ref [61]. Moreover, In Ref. [61] a study of the effect of the spin–orbit interaction on the magnetic susceptibility of small semiconductor quantum dots. These characteristics show quite interesting behavior at low temperature. There are many investigations on the thermodynamic properties of quantum dots, because of their huge potential for future technological applications **[**51-54**].** In the presence of the spin Zeeman effect the specific heat and entropy of GaAs quantum dot and Gaussian confinement have been studied Boyacioglu and Chatterjee [62]. At low temperature they observed a Schottky-like anomaly in heat capacity while that anomaly approaches a saturation of 2kB with rising temperature.

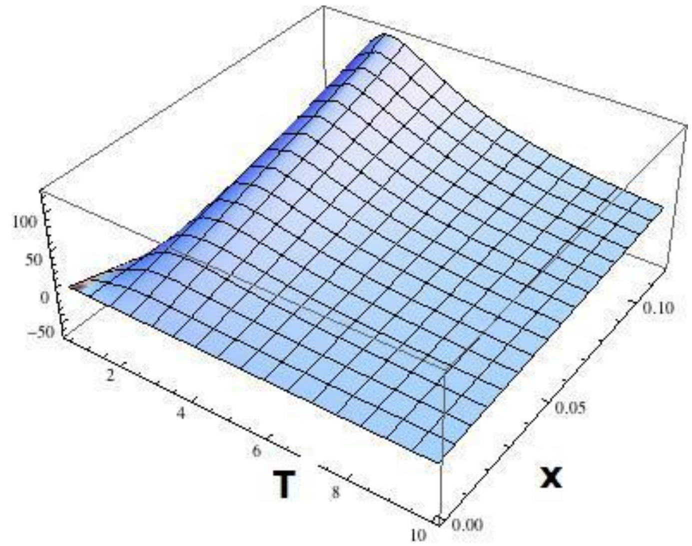


Fig. 4. The dependence of $\frac{c_\upsilon}{k_B}$ as function of temperature and Mn concentration at fixed H =5Tl.[68].

Boyacioglu et al [63] investigated that diamagnetic and paramagnetic effects in a Gaussian quantum dot can create the total magnetization and susceptibility. The magnetic properties of a quantum ring and dot using a three-dimensional model are calculated by Climente et al. [64].

In the presence of external electric and magnetic field the thermal and magnetic properties of a cylindrical quantum dot with asymmetric confinement has been studied in the paper [65]. In [66] have been investigated the thermodynamic properties of an InSb quantum dot in the presence of Rashba spin-orbit interaction and a static magnetic field. Fundamental part of materials for spintronics forms diluted magnetic semiconductors (DMS). They are A^2B^6 or A^3B^5 solutions with high density of magnetic impurities (usually, Mn).The Zeeman effects and exchange terms are taken into account on the heat capacity of diluted magnetic semiconductors quantum dots and the electron is assumed to be moving in an asymmetrical potential in the paper [68].

In Fig.3 we demonstrate as function of temperature and Mn concentration at fixed H = 5*Tl* the specific heat of the DMS quantum dot in the presence of exchange interaction and Zeeman term. According to this figure as the temperature is rised the specific heat unexpectedly increases and then reduces giving a peak-like structur.

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Declaration of Competing Interest

The author declares that he does not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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