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Rashba Spin-orbit Interaction in Semiconductor Nanostructures (Review)

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

In this work I review of the theoretical and experimental issue related to the Rashba Spin-Orbit interaction 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 quantum ring and dot nanostructures with Spin Orbit Interaction are discussed.

Keywords: Spin-orbit interaction; Rashba effect; two dimension electron gas; one-dimensional ring; quantum wire; quantum dot; semiconductor nanostructures.

1. INTRODUCTION

The using 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

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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 [1]. The magnitude of the spin-orbit interaction increases with the atomic number which it is a relativistic effect. The spin-orbit interaction is found with asymmetry in the underlying structure in crystals in semiconductors systems [2]. In bulk it seems in crystals without an inversion center (e.g. zinc blende structures) and is called the Dresselhaus spin-orbit interaction [3]. However, Rashba term is aroused from the structural asymmetry of the confining potential in heterostructures [4]. Rashba-type spin-orbit interaction [4,5] has attracted the most attention, since it can be manipulated by external electric fields, which is of central importance for applications in spintronics. In a system with Rashba spin-orbit interaction, each spin-degenerate parabolic band splits into two parabolic bands with opposite spin polarization. The Rashba-type spin-orbit interaction is usually caused by structure inversion asymmetry which stems from the inversion asymmetry of the confining potential [4,5]. The Rashba-type spin-orbit interaction in systems with inversion symmetry breaking is particularly attractive for spintronics applications since itallows for flexible manipulation of spin current by external electric fields.

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 [4,5]. 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 [3,4]. The spin-orbit splitting in the dispersion relation for electrons in III-V semiconductor asymmetric quantum wells is studied within the standard envelope-function formalism starting from the eight-band Kane model for the bulk [10]. The Rashba spin-orbit splitting in the different subbands is obtained for both triangular and square asymmetric quantum wells. It is shown, that the Rashba splitting in AlAs/GaAs/Ga1−xAlxAs square quantum wells is of the order of 1 meV and presents a maximum as a function of the well width. 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 [4,11]. 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.

2. 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 was 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 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:

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

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:

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

The eigenvalues of this Hamiltonian is

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

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 $\vec{k}$

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

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

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

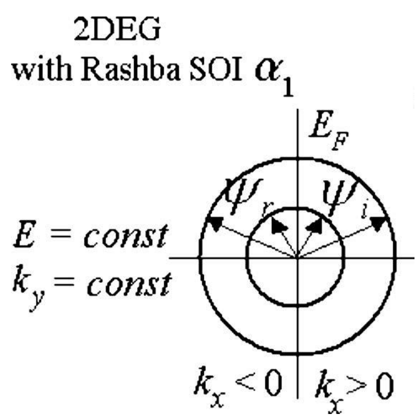

Fig. 1. Two-dimensional electron gas scattering geometry with Rashba spin-orbit interaction on the spin-orbit lateral superlattice.The reflected ψ_r and incoming ψ_i spinors are the eigenstates of Rashba hamiltonian with spin-orbit coupling constant α_1 and wave vectors belonging to the same Fermi contour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

In [23] deals with the problem of Nanosize Two-Gap Superconductivity. Here consider develop the theory of interactions between nanoscale ferromagnetic particles and superconductors. In [23] also consider the ideas of quantum computing and quantum information in mesoscopic circuits.

The influence of magnetic field and Coulomb field on the Rashba spin–orbit interaction in a triangular quantum well was studied [24] using Pekar variational method. Due to the influence of the Rashba effect, E of the bound magnetopolaron is split into spin-up and spindown branches. This phenomenon fully demonstrates that the influence of orbit and spin interactions in different directions on the energy of the polaron must be premeditated.

The purpose of paper [25] is to theoretically investigate the spin-orbit interactions of common semiconductor superlattices. Spin splitting and spin-orbit interaction coefficients are calculated based on interactions between the interface-related-Rashba effect and Dresselhaus effect. In this paper, demonstrated that the spin splitting of a superlattice can be greater than that of a single quantum well. Greater spin splitting is important for achieving spin polarization. The spin splitting of some sub-energy levels might not change with the size of some quantum wells in the superlattice, reducing the requirements for accuracy in the size of quantum wells.

The discovery of a giant anisotropic Rashba-like spin splitting along three momentum directions (3D Rashba-like spin splitting) with a helical spin polarization around the M points in the Brillouin zone of trigonal layered PtBi2 reported [26]. Due to its inversion asymmetry and reduced symmetry at the M point, Rashba-type as well as Dresselhaus-type spin-orbit interaction co-operatively yield a 3D spin splitting with in PtBi2. The experimental realization of 3D Rashba-like spin splitting not only has fundamental interests but also paves the way to the future exploration of a new class of material with unprecedented functionalities for spintronics applications. Spin-orbit interaction and structure inversion asymmetry in combination with magnetic ordering is a promising route to novel materials with highly mobile spin-polarized carriers at the surface [27].

3. ONE-DIMENSIONAL RING WITH SPIN–ORBIT INTERACTION

According to standard quantum mechanics, the motion of a charged particle can sometimes be influenced by electromagnetic fields in regions from which the particle is rigorously excluded [28,29]. This phenomenon has come to be called the Aharonov-Bohm effect, after the seminal 1959 paper entitled “Significance of Electromagnetic Potentials in the Quantum Theory,” by Aharonov and D. Bohm [29]. What AB effect teaches us about the significance of the electromagnetic potentials has since been discussed from several points, on the assumption that standard quantum mechanics is indeed a correct description of nature. In paper [28], Y. Aharonov and D. Bohm discussed some interesting properties of the electromagnetic potentials in the quantum domain and show that, contrary to the conclusions of classical mechanics, there exist effects of potentials on charged particles, even in the region where all the fields (and therefore the forces on the particles) vanish. Then here discussed possible experiments to test these conclusions; and, finally, we shall suggest further possible developments in the interpretation of the potentials.

The concept was introduced in Ref. [29] as follows: Consider the interference experiment illustrated in Fig. 2. Electrons enter from the left and the beam is split coherently in a two-arm interferometer. In principle, any change in the relative phase between the beams in the two arms can be observed as a shift in the interference pattern when the two beams are reunited at the right.

In the magnetic version of Aharonov-Bohm effect, a stationary magnetic field is introduced in region between the two beams, as in Fig. 2. The electrons are forever rigorously excluded from that region by some baffles. The return magnetic flux is made to avoid the regions where the electrons are permitted.

The purpose of book authors M. Peshkin and A. Tonomura [30] is twofold: to introduce the experiment by outlining the theoretical ideas that it tests, and to discuss the fundamental issues in physics that have been addressed by the theory and the experiment. Almost all of the discussion assumes nothing more than nonrelativistic quantum mechanics based on the Schrodinger equation or on algebraic consequences of the commutation relations

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 [31]. 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 [32] and also the ring connected to an electron reservoir [31,33]. 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 [34]. Oscillations of the magneto transport [35–37], and the magnetic properties [41] in the dimensional ring have been studied. The persistent current, the electronic thermal capacity in the dimensional ring have been investigated in [38,39], [40] respectively. An obvious analytic expression is got by taking into account the spin-orbit interaction in the Rashba model [42] 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 [43].

Diluted magnetic semiconductors is a prime class of materials for spintronics. These are solutions of the A^2B^6 or A^3B^5 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 [44]. The spin-orbit interaction effects on the one-dimensional quantum ring properties has attracted much attention [45]. In ref have studied the Rashba spin-orbital interaction, the effect of the magnetic field the finite temperature and also the s-d exchange interaction on the conductance of a diluted magnetic semiconductor hollow cylindrical wire.

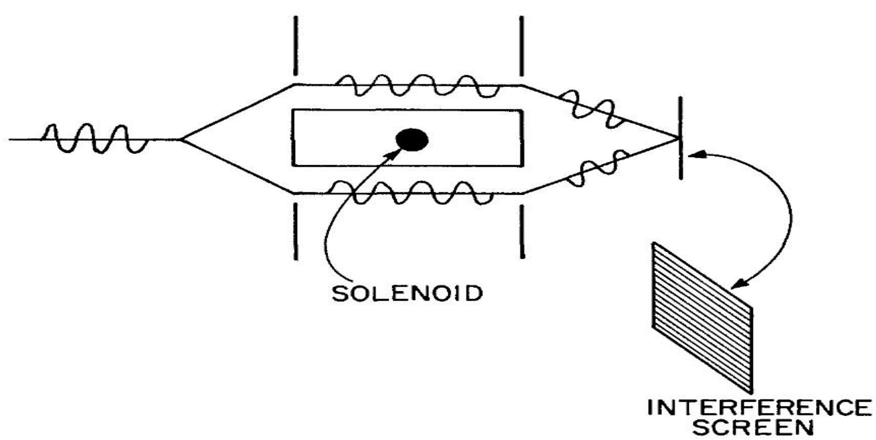

Fig. 2. Magnetic Aharonov-Bohm effect. The axis of solenoid is perpendicular to the page. The wave function is a split plane wave

The specific heat and magnetization of a diluted magnetic semiconductor quantum ring in the presence of magnetic field have been calculated by us in the paper [46] 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 diluted magnetic semiconductor quantum ring, the specific heat dependency on the magnetic field and Mn concentration have been calculated by us. In Fig. 3 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.

The magnetization of electrons in a diluted magnetic semiconductor quantum ring have been investigated in the paper [47] 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 [48,49]. It has been shown that if Mn concentration rise, the compensation points reduce. Also, it was obtained that with increasing manganese content in the diluted magnetic semiconductors quantum ring a transition to the paramagnetic from the antiferromagnetic properties one occurs for finding diluted magnetic semiconductors 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

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

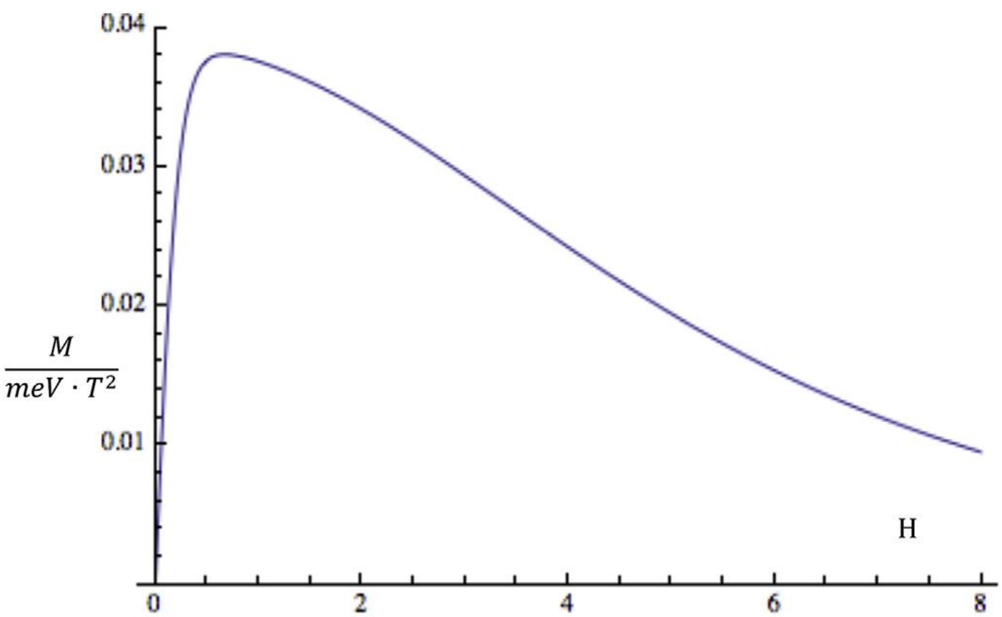

Fig. 3. The average magnetization of diluted magnetic semiconductors quantum ring as a function of magnetic with Rashba spin-orbit coupling constant $\alpha = 160$ meV.nm at fixed Mn concentration x=0.05 and T=10 K [46]

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

$$F = -k_B T \ln Z \qquad (7)$$

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. 4, With changing of the Aharonov–Bohm effect B 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 diluted magnetic semiconductors quantum ring. The calculations showed that, a transition from the antiferromagnetic properties to the paramagnetic one is observed in a diluted magnetic semiconductors quantum ring as the manganese content increases.

With changing the Aharonov-Bohm flux at fixed temperature, the magnetization x=0.0004 varies to negative values from positive for Mn concentration in the non-interacting diluted magnetic semiconductors quantum rings, which is typical for paramagnetic systems. When $\xi = l \left(\xi = \frac{\mu_B^* H}{2\varepsilon} \right)$ 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.

4. 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 [50]. 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 [51].

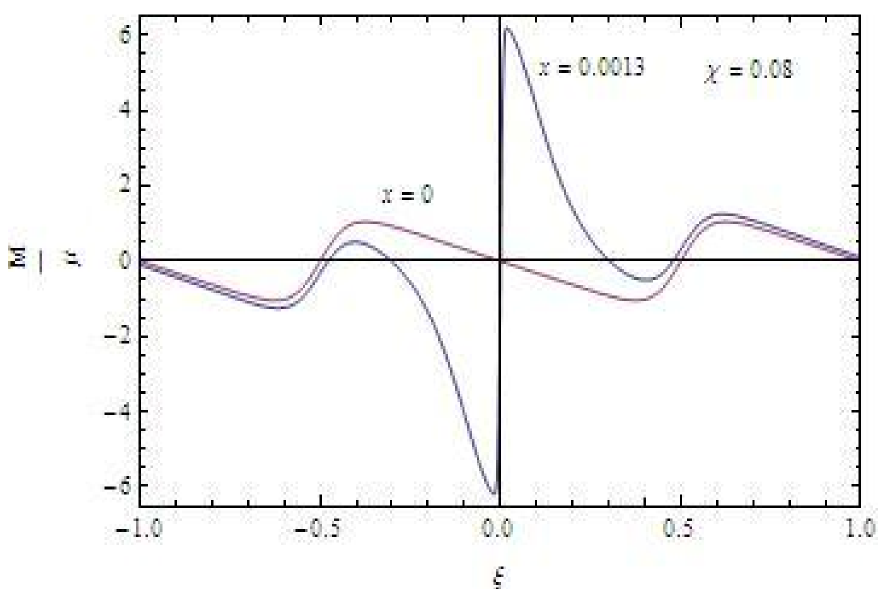

Fig. 4. Dependence of the magnetization in terms of μ_B^* on the magnetic flux for the cases where Mn concentrations x=0, g=0, and x=0.0013, g=-1.67 for $\chi = 0.08$

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 [52,53] 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 [54]. 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” [55,56]. 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 [60] that the Rashba Spin-Orbit interaction 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 [52–56,66–68] 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. Spin effects in single and vertically coupled double quantum dots are studied [61] using an unrestricted self-consistent Hartree–Fock approximation. In a single dot, spin-parallel electrons occupy the two uppermost levels in magnetic fields, which leads to a cusp structure recently observed in the experiment in the magnetic-field dependence of addition spectra. Additionally, an extensive study of magnetic properties of nanosystems [62-65] 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 [66]. The design of the magnetic properties of semiconductor quantum dots and energy shells is controlled by the electron spin [54-56]. 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 [67]. Moreover, In Ref. [67] 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 [57-60]. 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 [68]. At low temperature they observed a Schottky-like anomaly in heat capacity while that anomaly approaches a saturation of 2kB with rising temperature. Boyacioglu et al [69] 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. [71].

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 [71]. In [72] have been investigated the thermodynamic properties of an InSb quantum dot in the presence of Rashba spin-orbit interaction and a static magnetic field. In the paper [73] the thermal and magnetic properties of a cylindrical quantum dot in the presence of external electric and magnetic fields. The energy spectrum and wave functions for the quantum dot of asymmetric confinement are obtained by solving the Schrödinger wave equation analytically. The energy levels are employed to calculate the canonical partition function, which in turn is used to obtain specific heat, entropy, magnetization and susceptibility. These thermal and magnetic quantities are found to have direct dependence on confinement length, magnetic field, and temperature, thus the parameters of the system can be tuned to fit into more than one application. Fundamental part of materials for spintronics forms diluted magnetic semiconductors. 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 [74].

In Fig. 5 we demonstrate as function of temperature and Mn concentration at fixed H = 5*Tl* the specific heat of the diluted magnetic semiconductors 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 structure

Applicability of the method of intermediate problems to the investigation of the energy eigenvalues and eigenstates of a quantum dot formed by a Gaussian confining potential in the presence of an external magnetic field is discussed [75].

In [76] a method of intermediate problems, which provides convergent improvable lower bound estimates for eigenvalues of linear half-bound Hermitian operators in Hilbert space, is applied to investigation of the energy spectrum and eigenstates of a two-electron two-dimensional quantum dot formed by a parabolic confining potential in the presence of external magnetic field.

The properties of the first excited state of a magnetopolaron in a patabolic quantum dot are studied [77] with the Lee-Low-Pines unitary transformation and variational method of Pekar-type. In [77] find that the external magnetic field and the motion of the electron can trigger the Rashba effect in the first excited state and they play a virtual role in determining properties of the magnetopolaron in the parabolic system. This results indicate the Rashba spin-orbit coupling, confined potential, electronphonon coupling, magnetic field and phonon wave vector promote a variation of the first excited state energy.

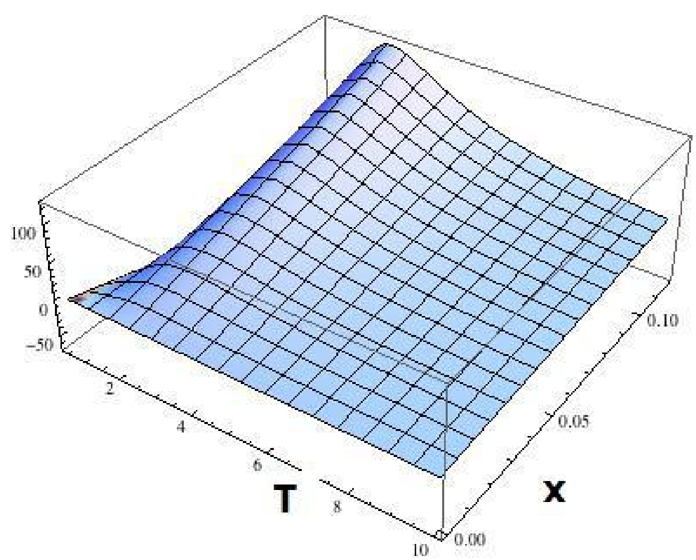

Fig. 5. The dependence of $\frac{c_\upsilon}{k_B}$ as function of temperature and Mn concentration at fixed H =5Tl [74]

In paper [78] calculated the energies of the ground and the first excited states of a free polaron and that of a polaron bound to a Coulomb impurity in a quantum dot with harmonic confinement in the presence of Rashba spin-orbit interaction. Splitting here also investigate the combined effect of Rashba and polaronic interactions in the presence of an external magnetic field using the Rayleigh-Schrödinger perturbation theory. Application this results to GaAs and CdS quantum dots shows that the suppression of the phonon-induced size-dependent Zeeman splitting in a quantum dot is reduced by the Rashba coupling.

The binding energy of a hydrogenic-like donor complex (*D*0) placed in a two-dimensional Gaussian quantum dot GaAs semiconductor is determined [79] incorporating the Rashba and Dresselhaus spin-orbit interactions in the presence of an externally applied magnetic field.

5. CONCLUSION

The results indicate that the Rashba spin-orbit interaction and the confining potential reduce the energy of the donor complex whereas the magnetic field enhances it. Here also are studied the effect of magnetic field and spin-orbit interactions on the magnetic moment and susceptibility. In the paper [80], are studied the influences of the temperature and the Rashba spin-orbit interaction on the oscillation period of the bound polaron in the quantum pseudodot using the Lee-Low-Pines unitary transformation, the variational method of Pekar-type and the quantum statistical theory. Here derived the oscillation period of the bound polaron in the superposition state and reported the temperature dependences and the Rashba spin-orbit interaction effects of the oscillation period of polaron when the wave vector, the electron-LO phonon coupling, the Coulomb bound potential and the chemical potential take different values.

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DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the author.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Greiner W. Relativistic quantum mechanics. Springer; 1987.
2. Winkler R. Spin-orbit coupling effects in two-dimensional electron and hole systems (Springer Berlin); 2003.
3. Dresselhaus G. Spin-orbit coupling effects in zinc blende structures phys. Rev. 1955;100:580.
4. Bychkov YA, Rashba EI. Oscillatory effects and the magnetic susceptibility of carriers in inversion layers. Journal of Physics C:Solid State Physics. 1984;17: 6039.
5. Rashba E. Effects of rashba spin-orbit coupling, Zeeman splitting and gyrotropy in two-dimensional cavity polaritons under the influence of the Landau quantization Fiz. Tverd. Tela (Leningrad). 1960;2:1224.
6. Stein D, Klitzing KV, Weimann G. Electron spin resonance on GaAs−AlxGa1−xAs Heterostructures Phys. Rev. Lett. 1983;51: 130.
7. Stormer HL, Schlesinger Z, Chang A, Tsui DC, Gossard AC, Wiegmann W. Energy structure and quantized hall effect of two-dimensional holes phys. Rev. Lett. 1983;51:126.
8. Datta S, Das B. Electronic analog of the electro-optic modulator Appl. Phys. Lett. 1990;56:665.
9. Kikkawa JM, Smorchkova IP, Samarth N, Awschalom DD. Room-temperature spin memory in two-dimensional electron gases science. 1997;277:1284-1287.
10. de Andrada e Silva EA, La Rocca GC, Bassani F. Spin-orbit splitting of electronic states in semiconductor asymmetric quantum wells Phys. Rev. B. 1997;55: 16293.
11. Voskoboynikov O, Lee CP. Spin–orbit interaction and all-semiconductor spintronics. Journal of Superconductivity. 2003;16:361–363.
12. Khomitsky DV. Scattering on the lateral one-dimensional superlattice with spin-orbit coupling Phys. Rev. B. 2007;76: 033404.

13. Dyakonov MI, Perel VI. Spin relaxation of conduction electrons in non-centrosymmetric semiconductors, Soviet Physics Solid State. 1972;13(12):3023-3026.
14. Dyakonov MI, Kachorovskii VY. Spin relaxation of two dimensional electrons in noncentrosymetric semiconductors, soviet physics: Semiconductors, Sov. Phys. Semicond. 1986;20:110.
15. Koralek JD, Weber CP, Orenstein J, Bernevig BA,. Zhang SC, Mack S, Awschalom DD. Emergence of the persistent spin helix in semiconductor quantum wells. Nature _London. 2009; 458:610.
16. Kleinert P, Bryksin VV. Electric-field-induced long-lived spin excitations in two-dimensional spin-orbit coupled systems. Phys. Rev. B. 2009;79:045317.
17. Duckheim M, Maslov DL, Loss D. Dynamic spin-Hall effect and driven spin helix for linear spin-orbit interactions, Phys. Rev. B. 2009;80:235327.
18. Tokatly IV, Ya E. Sherman, Ann. Phys. 2010;325:1104.
19. Pershin YV. Phys. Rev. B. Long-Lived Spin Coherence States in Semiconductor Hetero-structures. 2005;71:155317.
20. Kikkawa JM, Awschalom DD. Lateral drag of spin coherence in gallium arsenide. Nature. 1999;397:139.
21. Sanvito S, Theurich G, Hill NA. Density func-tional calculations for III–V diluted ferromagnetic semi-conductors: a review. J Supercond. 2002;15:85.
22. Kruchinin S, Nagao H, Aono S, Modern aspect of superconductivity: theory of superconductivity. World Scientific. 2010; 232.
23. Shu-Ping Shan, Shi-Hua Chen. Influence of magnetic field and Coulomb field on the Rashba effect in a triangular quantum well Pramana – J. Phys. 2020;94:15. Available:https://doi.org/10.1007/s12043-019-1878-0
24. Ya-FeiHao. Spin-orbit interactions in semiconductor superlattice Physics Letters A; 2019. Available:https://doi.org/10.1016/j.physleta.2019.126092
25. Ya Feng, Qi Jiang, Baojie Feng, Meng Yang ,Tao Xu , Wenjing Liu, Xiufu Yang, Masashi Arita, Eike F. Schwier, Kenya Shimada , Harald O. Jeschke , Ronny Thomale, Youguo Shi, Xianxin Wu8, Shaozhu Xiao, Shan Qiao&Shaolong He . Rashba-like spin splitting along three momentum irections in trigonal layered PtBi2 Nature Communications | Available:https://doi.org/10.1038/s41467-019-12805.
26. Yu IA. Usachov D, Nechaev A, Poelchen G, Guttler M, Krasovskii EE, Schulz S, Generalov A, Kliemt K, Kraiker A, Krellner C, Kummer K, Danzenb¨acher S, Laubschat C, Weber AP, Chulkov EV, Santander-Syro AF, Imai T, Miyamoto K, Okuda T, Vyalikh DV. Observation of a cubic Rashba effect in the surface spin structure of rare-earth ternary materials. . arXiv: 2002.01701 v1 [cond –mat. mes-hall.]; 2020.
27. Aharonov Y, Bohm D. Significance of electromagnetic potentials in the quantum theory phys. Rev. 1959;115(3):485-491.
28. Wu TT, Yang CN. Concept of nonintegrable phase factors and global formulation of gauge fields. Rev. D. 1975;12:3845.
29. Peshkin M, Tonomura A. The aharonov–bohm effect, in lecture notes in physics. Springer-Verlag, Berlin. 1989;340 1989.
30. Fai Cheung H, Gefen Y, Riedel EK, Shih WH. Persistent currents in small one-dimensional metal rings, Phys. Rev. B. 1988;37:6050.
31. Loss D, Goldbart P. Period and amplitude halving in mesoscopic rings with spin, Phys. Rev. B. 1991;43:13762.
32. Moskalets MV. Oscillations of the thermodynamic properties of a one-dimensional mesoscopic ring caused by Zeeman splitting, JETP Lett. 1999;70:602.
33. Margulis VA, Mironov VA. Magnetic moment of a 2D electron gas with spin-orbit interaction, JETP. 2009;108:656.
34. Aronov AG, Lyanda-Geller YB, Spin-orbit Berry phase in conducting rings, Phys. Rev. Lett. 1993;70;343.
35. Wang XF, Vasilopoulos P. Spin-dependent magnetotransport through a mesoscopic ring in the presence of spin-orbit interaction, Phys. Rev. B. 2005;72:165336.
36. Molnar B, Peeters FM, Vasilopoulos P. Spin-dependent magnetotransport through a ring due to spin-orbit interaction, Phys. Rev. B. 2004;69:155335.
37. Splettstoesser J, Governale M, Zulicke U. Persistent current in ballistic mesoscopic rings with Rashba spin-orbit coupling, Phys. Rev. B. 2003;68:165341.
38. Sheng JS, Chang K. Spin states and persistent currents in mesoscopic rings:

Spin-orbit interactions, Phys. Rev. B. 2006;74;235315.
39. Yang X.-E, Zhou Y.-C. Magnetism and structural distortion in the La0.7Sr0.3MnO3 metallic ferromagnet, Phys. Rev. B. 1996;53:10167.
40. Chen H.-Y, Pietilainen P, Chakraborty T. Electronic optic and magnetic properties of quantum ring in Novel systems,Phys. Rev. B. 2008;78;073407.
41. Margulis VA, Mironov VA. Magnetic moment of an one-dimensional ring with spin–orbit interaction Physica E. 2011;43:905–908.
42. Wolf SA et al. Spintronics: a spin-based electronics vision for the future, Science. 2001;294:1488.
43. Wolff PA. Semiconductors and semimetals, in: J.K. Furdyna, J. Kossut (Eds.), Diluted Magnetic Semiconductors, Academic, New York; 1988.
44. Chaplik AV, Magarill LI, Effect of the spin-orbit interaction on persistent currents in quantum rings, Superlattice. Microst. 1995;18:4.
45. Mehdiyev BH, Babayev AM, Cakmak S, Artunc E. Rashba spin-orbit coupling effect on a diluted magnetic semiconductor cylinder surface and ballistic transport, Superlattice, Microst. 2009;46:4.
46. Babanlı AM, Ibragimov BG. Specific heat in diluted magnetic semiconductor quantum ring Superlattices and Microstructures. 2017;111:574-578.
47. Babanlı AM, Ibragimov BG. Magnetic moment of electrons in diluted magnetic semiconductor quantum ring. AJP Fizika. 2019;XXV(01);35-38.
48. Babanlı AM, Ibragimov BG. Magnetic moment of the lattice of non-interacting diluted magnetic semiconductor ring .Modern Trends in Physics International Conference; 2019 Baku.
49. Babanlı AM, Ibragimov BG. Aharonov-bohm paramagnetism" and compensation points in noninteracting diluted magnetic semiconductor quantum ring. Journal of Magnetism and Magnetic Materials. 2020;495;165882.
50. Loss D, DiVincenzo DP. Quantum computation with quantum dots, Phys. Rev. A. 1998;57:120.
51. Vandersypen LMK et al. in Quantum Computing and Quantum Bits in Mesoscopic Systems (Kluwer Academic, New York, 2003); quant-ph/0207059. A.V. Khaetskii and Y.V. Nazarov, Spin relaxation in semiconductor quantum dots, Phys. Rev. B. 2000;61(12):639.
52. Can-Ming Hu, Junsaka Nitta, Tatsushi Akazaki, Jiro Osaka, Pfeffer P, Zawadzki W, Polaronic and bound polaronic effects in the energy states of an electron in a two-dimensional parabolic quantum dot in the presence of Rashba spin-orbit interaction, Phys. Rev. B. 1999;60: 7736.
53. de Andrada e Silva EA, La Rocca GC, Bassani F. Spin-orbit splitting of electronic states in semiconductor asymmetric quantum wells, Phys. Rev. B. 1997;55(16):293.
54. Johnson NF. J. Phys.: Condens. Matter 7 965 .Quantum dots: few-body, low-dimensional systems; 1995.
55. Datta S, Das B. Appl. Phys. Lett. Electronic analog of the electro-optic modulyator. 1990;56:665. Available:https://doi.org/10.1063/1.102730
56. Kane BE, A silicon-based nuclear spin quantum computer, Nature London. 1998;393:133.
57. Kuntal Bhattacharyya, Ashok Chatterjee Polaronic, Bound Polaronic. Effects in the energy states of an electron in a two-dimensional parabolic quantum dot in the presence of rashba spin-orbit interaction aip conference proceedings. 2019;2142: 090008.
Available:https://doi.org/10.1063/1.5122452
58. Bimberg D. Quantum dots: Paradigm changes in semiconductor physics, Semiconductors. 1999;33:951.
59. Steffens O, Suhrke M, Rössler U, Physica B. 1998;256–258:147.
60. Taruchaet S al. Spin e ects in semiconductor quantum dot structures, Physica E (Amsterdam). 1998;3:112.
61. Tamura H. Magneto-photoluminescence in high magnetic fields from InGaAs/GaAs quantum dots formed in tetrahedral-shaped recesses, Physica B. 1998;249–251:210.
62. Prinz GA, Magnetoelectronics, Science. 1998;282:1660.
63. Kane BE. A silicon-based nuclear spin quantum computer, Nature (London). 1998;393:133.
64. Awschalomand DD, Kikkawa JM. Phys. Today. Electron Spin and Optical Coherence in Semiconductors; 1999.
65. Das S, Sarma J, Fabian X, Hu, I Žutic, Solid State Commun. Spin-Polarized

Bipolar Transport and Its Applications. 2001;119:207.
66. Lossand D, DP DiVincenzo, Phys. Rev. Quantum Computation with Quantum Dots. 1998;57-120.
67. Voskoboynikova O. Magnetic properties of parabolic quantum dots in the presence of the spin–orbit interaction.
68. Boyacioglu B, Chatterjee A. J. Appl. Phys.. Heat capacity and entropy of a GaAs quantum dot with Gaussian Confinement. 2012;112:083514.
DOI: 10.1063/ 1.4759350.
69. Boyacioglu B, Chatterjee A. Phys. E Dia- and paramagnetism and total susceptibility of GaAs quantum dots with Gaussian Confinement. 2012;44:1826.
DOI: 10.1016/j.physe. 2012.05.001
70. Climente JI, Planelles J, Movilla JL. Phys. Rev. B, Magnetization of nanoscopic Quantum Rings and Dots. 2004;70: 081301.
DOI: 10.1103/PhysRevB.70.081301
71. Sukirti Gumber, Manoj Kumar, Monica Gamblur, Man Mohan, Pradip Kumar Jha, Can. Thermal and magnetic properties of cylindrical quantum dot with asymmetric confinement, J. Phys. 2015;93:1e5.
72. Sukirti Gumber, Manoj Kumar, Pradip Kumar Jha, Man Mohan, Thermodynamic behavior of Rashba quantum dot in the presence of magnetic field, Chin. Phys. 2016;25(5):056502.
73. Gumber S, Metal, Thermal and magnetic properties of cylindrical quantum dot with asymmetric confinement, Canadian Jour. of Phys. 2015;93(11):1264-1268.
74. Babanlı AM, Ibragimov BG. Heat capacity of electrons in diluted magnetic semiconductor quantum dot. The 6 th International conference on Control and Optimization with Industrial Applications. 2018;2:89-91.
75. Soldatov AV, Bogolyubov NN, Jr., SP Kruchinin. Method of intermediate problems in the theory of Gaussian quantum dots placed in a magnetic field Condensed Matter Physics. 2006;1(45): 151–159
76. Bogolubov NN Jr. AV Soldatov SP Kruchinin On the Energy Spectrum of Two-Electron Quantum Dot in External Magnetic Field. Proceedings of NATO ARW “Nanotechnology in the Security Systems”. 2015;55-67.
77. Ying-Jie Chen, Cheng-Feng Cui, Wen-Fang Liu, Feng-Lan Shao Influences of Rashba Spin-Orbit Coupling on First Excited State of Magnetopolaron in Parobolic Quantum Dot. International Journal of Theoretical Physics.
Available:https://doi.org/10.1007/s10773-020-04449-6
78. Kuntal Bhattacharyya, Debika Debnath, Ashok Chatterjee. Role of Rashba Spin-orbit Interaction on Polaron Zeeman Effect in a Two-dimensional Quantum Dot with Parabolic Confinement. Journal of Magnetism and Magnetic Material; 2020.
DOI:https://doi.org/10.1016/j.jmmm.2020.166745
79. Pooja Sainia, Aalu Bodab, Ashok Chatterjeea,Effect of Rashba and Dresselhaus spin-orbit interactions on a D0 impurity in a two-dimensional Gaussian GaAs quantum dot in the presence of an external magnetic field. Journal of Magnetism and Magnetic Materials. 2019; 485:407–412.
80. Chen YJ *, Liu WF, Shao FL. Influences of temperature and Rashba spin-orbit interaction on oscillation period of bound polaron in quantum pseudodot. Physica E: Low-dimensional Systems and Nanostructures. 2019;110:15–19.

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