Spin and Electron Transport in Different Semiconductor Heterostructures in the Presence of a Magnetic and an Electric Field

PhD theses

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Introduction

In recent decades, due to development of the semiconductor fabricating technology the industry has been able to produce such a heterostructures, so-called mesoscopic systems, whose characteristics are dominated by the wavelike properties of charged carriers. In these nanostructures whose size range has to be comparable to the electron's wave length, mean free path and phase coherence length new phenomena can be detected, which can be explained by the laws of quantum mechanics. While investigating transport processes, it was found that the spin of electrons (in what follows spin) can be used to mostly exploit the anticipated advantages of "spintronics", which is a relatively new discipline named after the role of spin in the transmission of information. In the field of spintronics discovery of the giant magnetoresistance effect was the first true breakthrough which in the 1990s revolutionized the computer industry by significantly increasing the storage capacity of hard disk drives. Although spin plays only an indirect role in the transmission of information by changing the resistance of the device, the device behaves classically, that is the information is determined by the amount of charge. This role has been intended for the spin in the more recent studies based on semiconductors. Furthermore, for quantum computing, the spin would be that two-level quantum system which would play the role of the quantum bit.

To do this the spin we must be able to perform three basic processes. First, the spin must be injected, i.e. we need to introduce suitably polarized, nonequilibrium spin into a semiconductor. Once this is done, we need to manipulate the injected spin in accordance with the purpose. Finally, the manipulated spin has to be detected to read the information. To achieve any of these three operations it is essential to be able to control the spin dependent transport processes by an applied magnetic or electric field [1].

A possible way to polarize spin is to use stacked, ultrathin layers (of the order of a few nanometers) of both differently diluted magnetic and nonmagnetic semiconductors. In the absence of a magnetic field, the electrons can traverse in these kinds of heterostructures, since the impurities do not significantly change the band structure of the semiconductor. However, in the presence of a magnetic field, a potential barrier arises for spin-up electrons and potential well for spin-down ones. Consequently, the transmission coefficient and conductance of electrons with opposite spins will be different, i.e. spin polarized current can be created by an applied electric field.

Scientific background

In heterostructures composed of stacked differently doped ultrathin semiconductor layers, the transport properties of the charged carriers are dominated by quantum interference effects. Due to the doping, some of the layers act as a barrier for incident electrons which can traverse in these layers only by tunneling. Tunneling is a quantum phenomenon. According to the laws of classical physics, it is energetically forbidden for electrons to cross these barriers, because the energies of the incident electrons are less than the height of potential barrier. However, according to quantum mechanics, electrons can cross these potential barriers due to the wave properties of matter and the probabilistic interpretation of the wave function. The probability of tunneling decreases exponentially as the width of the potential barrier increases. When a second barrier of the same width is added and the region between the barriers is comparable with the de Broglie wavelength of the electrons, which in semiconductors is typically of the order of 10-100 nanometers [1], then in certain incident energies the transmission coefficient can be very high, eventually up to 1 due to the resonant tunneling. Resonant tunneling occurs in that so-called resonant energies in which the energies of the incident electrons correspond to the energies of the quasi-bound eigenstates of the quantum well.

In 1974 resonant tunneling was observed by Tsu, Esaki, and Chang [2] in a $Ga_{1-x}Al_xAs/GaAs/Ga_{1-x}Al_xAs$ heterostructure in which a potential barrier arises since the band gap of the $Ga_{1-x}Al_xAs$ is greater than the band gap of the GaAs. Before experimental proof, Tsu and Esaki [3] investigated the transport properties in a finite superlattice and found a negative differential resistance which they explained with resonant tunneling. Its simplest model is a potential well placed between two potential barriers having equal widths [4]. Resonant tunneling was obtained by applying a voltage to the barriers to achieve matching between the Fermi level in cathode and the resonant states of the well. Since the potential barrier in the $Ga_{1-x}Al_xAs$ layers does not depend on the spin, this nanostructure cannot be used for spin polarization. The impurities must be magnetic to use this kind of heterostructure for spin polarization. Mn- or Fe-based diluted magnetic spin superlattices were proposed by von Ortenberg [5] and achieved by Dai et al. [6] and Chou et al. [7]. Recently, many creative experimental works and many theoretical studies have been done by exploiting this spin-dependent phenomenon. The tunneling of electrons in $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure was investigated by Egues [8] to control spin polarization of electrons by using an external magnetic field. By multiplying the number of paramagnetic layers, the electrons can traverse the heterostructure only by resonant tunneling. The effective potential of these kinds of heterostructure depends not only the spin but also on the electric and magnetic field and on the change of symmetry of the heterostructure [9]. Therefore, using the combination of these effects, the spin polarization can be better controlled and this property increases the possibility of these devices being used in the future. The energy spectrum and the electron states of the structures was studied parallel with the investigation of transport properties of structures based on resonant tunneling [10, 11, 12], too. These investigations can help the deeper understanding of transport properties.

The simplest type of system, where giant magnetoresistance effect can arise, consists of a layer of non-magnetic metal sandwiched between two layers of a magnetic metal [13]. If the direction of the magnetization is the same in both magnetic layers, then it is called a parallel arrangement and if the direction of magnetization in the two magnetic layers is opposed, it is called an antiparallel arrangement. The magnetoresistances are significantly different in the parallel and antiparallel arrangements. Therefore, changing the direction of magnetization of one of the magnetic layers will significantly change the magnetoresistance of the device. This phenomenon can be exploited in many areas. In later experiments, between the two ferromagnetic layers a few atomic layers thick insulator or semiconductor layer is grown on which electrons are only able to traverse by tunneling. This phenomenon cannot only be achieved by growing stacked layers with different magnetic properties but it can be achieved by depositing two parallel ferromagnets on the top and bottom of a two-dimensional electron gas [12, 14]. These heterostructures based on tunneling are more advantageous because much more resistance to change can be achieved by applying a much smaller magnetic field. Due to the way of the permeation of charged carriers this resistance is called tunneling magnetoresistance. The role of the spin in the change of magnetoresistance is negligible in this latter type of system in contrast with heterostructures based on ferromagnetic layers. The magnetoresistance ratio (MRR) can be further increased by increasing the number of ferromagnetic strips that are deposited on the top and bottom of the heterostructure.

Motivations and goals

Nowadays, because of its inherent, yet untapped potential, spintronics has been extensively studied. A basic condition for using spintronic devices allows us to write, manipulate, as well as read the information based on spin. The current state of the art in spin-dependent transport in heterostructures shows that spintronic devices based on resonant tunneling can be used to accomplish several different important aims and functionalities necessary for future spintronic applications [1].

For all these reasons, we aimed to investigate theoretically spin polarized current due to spin dependent tunneling of electrons in a diluted magnetic semiconductor ZnSe/$Zn_{1-x}Mn_xSe$/$Zn_{1-y}Mn_ySe$/ZnSe/$Zn_{1-x}Mn_xSe$/ZnSe heterostructure in the presence of parallel magnetic and electric fields. In the asymmetric system, the transmission of electrons and the degree of spin polarization depend on the strength of the magnetic and electric fields and on the direction of the applied bias. Therefore, we aimed to investigate the influence of magnetic and electric fields on spin polarization, i.e. how a high degree of polarization can be achieved in addition to the relatively high value of current flowing through the system.

Furthermore, we aimed to investigate theoretically the spin-dependent tunneling of electrons in asymmetric double quantum wells and barriers composed of different sequences of diluted magnetic and nonmagnetic well and barrier materials for ZnSe based semiconductor heterostructures in the presence of parallel magnetic and electric fields. If one of the semiconductor layers is doped with a non-magnetic material, a structural asymmetry will be built into the system. This structural asymmetry can be changed over a wide range with magnetic and electric fields to regulate the spin polarization and the current.

Analysis of the energy spectrum and states of an electron is essential to more deeply understand its transport properties. Therefore, we aimed to investigate these quantities in a non-magnetic/magnetic ZnSe/$Zn_{1-x}Mn_xSe$ quantum well placed between two materials acting as barriers for electrons. A potential step is formed at the interface between the non-magnetic and magnetic material in the presence of a magnetic field since spin-up electrons see a barrier whereas the spin-down ones see a well. This leads to a spatial segregation of spin-up and spin-down electrons, which produces a rich band structure. Our model is formed by infinitely high barriers. It consists of a non-magnetic and a magnetic layer. Furthermore, we aimed to study the electron states, which, together with generalization to barriers of finite height can create an opportunity to investigate the transport properties of the quantum well.

In the newer generation of devices utilizing magnetoresistance, the tunneling magnetoresistance is used when the device is working. This phenomenon can also be created by depositing ferromagnetic strips on the top and bottom of a heterostructure. Therefore, we aimed to study theoretically how the number of ferromagnetic strips changes the magnetoresistance and modified magnetoresistance of two-dimensional electron gas in a GaAs heterostructure.

Applied methods

For the theoretical studies of transport properties of the ZnSe-based systems, it is widely agreed that transport can be considered ballistic. This means that there is no electron scattering, i.e. the electron's mean free path is comparable to the dimensions of the sample. This simplification can be done for low electron density and high-purity samples. We are getting closer to this latter condition with the progress in fabrication technology. In our model, we used the single-electron effective mass approximation, and we assumed a single-electron effective mass throughout the heterostructure. For the Hamiltonian of an electron, we considered the interactions of an electron with an external magnetic field and an applied electric field, the Zeeman splitting of the electron, the spin-dependent exchange interaction, and the zero magnetic-field potential profile due to the conduction band offset among the different doped layers. The exchange interaction between the Mn^{2+} ions depends on the thermal average of the z component of the Mn^{2+} spin which is given by the modified 5/2 Brillouin function. In the layers doped with different Mn concentrations, the Mn-Mn interaction is also different. This was considered by adding a temperature value depending on the Mn-Mn interaction in that layer, to the temperature of the whole heterostructure. In our model we used Landau-levels so that the motion along the magnetic field is decoupled from the motion perpendicular to the magnetic field. In this case the spin-dependent conduction-band edge of the heterostructure can be approximated with one-dimensional potential wells and barriers. By using the transfer matrix method, the reduced one-dimensional single-electron Schrödinger equation can be solved in each region and the transmission coefficient through the whole structure can be obtained. The current density is computed as the average of the product of the transmission coefficient and the group velocity with the Fermi-Dirac function.

A $ZnSe/Zn_{1-x}Mn_xSe$ heterostructure placed between two oxide layers was considered as a quantum well which is confined by infinitely high barriers. For the Hamiltonian of an electron we followed procedure described in the preceding paragraph. However in this case the concentration of Mn in the Mn-doped layer is so low that we could neglect a conduction band offset between the Mn-doped paramagnetic layer and the non-magnetic layer in line with the earlier studies [8, 9, 15, 16]. When the magnetic field is perpendicular to the two-dimensional electron gas, by using Landau-levels the motion along the magnetic field is decoupled from that in the plane perpendicular to magnetic field. Then the wave function can be written as a product so the motion of the electrons can be reduced to a one-dimensional problem. When the magnetic field is in the plane of the two-dimensional electron gas, the Schrödinger equation was written using the Landau gauge. Since the in plane components of momentum commute with the Hamiltonian, the wave function is also sought as a product.

The magnetic field of the ferromagnetic strips that are deposited on the top and bottom of the two-dimensional electron gas was approximated by effective delta functions. The Hamiltonian describing such a system was written in the single-particle effective mass approximation. The magnetic vector potential can be written in the Landau gauge. Because the system is translationally invariant, the wave function can be written as a product. By introducing dimensionless units, the problem was reduced to a one-dimensional tunneling problem. We calculated the conductance for ballistic transport as the electron flow averaged over half the Fermi surface.

New scientific results

1. We have investigated theoretically the spin-dependent tunneling of electrons in a diluted magnetic semiconductor ZnSe/$Zn_{1-x}Mn_xSe$/$Zn_{1-y}Mn_ySe$/ZnSe/$Zn_{1-x}Mn_xSe$/ZnSe heterostructure in the presence of parallel magnetic and electric fields. We have calculated the transmission coefficient, spin polarization and current polarization. Our model is appropriate for any dilute magnetic II-VI semiconductor system. We have shown in this asymmetric system that the transmission of electrons and the degree of spin polarization depend on the strength of the magnetic and electric field and on the direction of the applied bias. We have shown that for suitable magnetic and electric fields, the output current of the system exhibits a nearly 100% spin polarization, therefore the device can be used as a spin filter [I]
2. We have investigated theoretically the spin-dependent tunneling of electrons in asymmetric double quantum wells and barriers composed of different sequences of diluted magnetic and non-magnetic well and barrier materials based on ZnSe/$Zn_{1-y}Be_ySe$/ZnSe/$Zn_{1-x}Mn_xSe$/ZnSe and ZnSe/$Zn_{1-z}Cd_zSe$/ZnSe/$Zn_{1-x}Mn_xSe$/ZnSe heterostructures in the presence of parallel magnetic and electric fields. We have calculated the transmission coefficient, the spin polarization and the current polarization. We have shown that in these systems the transmission of electrons and the degree of spin polarization depends on the strength of the magnetic fields (due to the *sp–d* exchange-enhanced spin splitting) and electric fields and on the direction of the applied bias, resulting in a highly spin polarized gas. We have demonstrated that the difference in the effective potential leads to a distinctively different transmission for electrons with opposite spins and it is enhanced by increasing the magnetic field. Our results show that the degree of spin polarization can be adjusted by the direction of the electric field. We have also shown that these structures display features of a diode, while for suitable magnetic field value the spin-up currents are blocked. Therefore, under suitable external magnetic and electric fields these structures can play a double role: having a spin-filtering function and a diode function [II].
3. We have calculated the energy spectrum, states, velocity and density of states of an electron in a ZnSe/$Zn_{1-x}Mn_xSe$ (non-magnetic/magnetic) heterostructure placed between two materials acting as barriers in the presence of a magnetic field perpendicular or parallel to the well. We have shown that a potential step is formed at the interface between the non-magnetic and magnetic material in

the presence of a magnetic field since spin-up electrons see a barrier whereas the spin-down electrons see a well. This leads to a spatial separation of spin-up and spin-down electrons. We have demonstrated that an unusual group velocity for the electrons and density of states with an unusual structure is obtained. We have shown that as a result a rich band structure is obtained which can be tuned by a perpendicular electric field. Furthermore, we have shown how the electron states can be manipulated by such an electric field. We have also shown that this manipulation is due to an electric-field induced spatial shift of the electron wave function at constant electron density. Based on our model, it is obvious that similar results should be obtained for confined non-magnetic/magnetic heterostructures other than the particular one studied in the present work [III].

4. We have studied the giant magnetoresistance effect, which can be achieved by depositing parallel ferromagnets on the top and the bottom of a GaAs heterostructure. We have demonstrated that the magnetoresistance ratio is greatly influenced by the number of unit cells, and using even a double unit the amplification rate is about 4.9×10^{13}. We have demonstrated that the modified magnetoresistance ratio shows oscillations, where the number of peaks is determined by the number of units. We have also shown that for experimentally accessible parameters for a GaAs heterostructure, the value of the modified magnetoresistance ratio can be as high as 55% for a realistic electron density. We have also demonstrated that resonance splitting occurs around the Fermi energy in the modified magnetoresistance ratio curves when it is plotted as a function of the Fermi energy. It is indicated that these kinds of magnetic structures may be promising for selective electron injection devices [IV].

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