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RESONANT TUNNELLING DIODE WITH MAGNETISED ELECTRODES

We analyse some basic properties of charge and spin transport in a semiconductor structure with an insulating barrier. In this system two semiconducting layers are separated by the insulator, creating a structure which is called a tunnel junction. The particles may pass through this junction according to the quantum tunnelling effect. By using two tunnel junctions with energy barriers made of insulating material, one can construct a quantum potential well . Inside the well the energy levels are quantised, which means that only discrete or quasi-discrete values of energy are allowed. Moreover, the probability of charge tunnelling through the system, which contains the potential well, depends on whether the energy of the incoming particles is in coincidence with the so-called resonant energy level. Such systems form the base of structures called resonant tunnelling diodes.

Keywords: resonant tunnelling diode, magnetic tunnelling diode, spintronics

1. INTRODUCTION: BASIC PROPERTIES OF A RESONANT TUNNELLING DIODE

Resonant tunnelling diodes (RTD) are one of the basic components of spintronics devices. They use the electrical and spin properties of electrons and they are important for current theoretical and experimental research. The fundamental phenomenon in a RTD is the tunnelling of particles which is a purely quantum effect. The particles can penetrate through the potential barriers by using their wave properties, allowed by the uncertainty principle. Therefore they can propagate through the classically forbidden region in which the energy of the electron is lower than the potential energy of the barrier. The solutions to Schrödinger's equation indicate that under the influence of an external magnetic field and voltage bias the intensities of tunnelling and contact currents depend on the resonance level energy and the geometrical characteristics of the structure [1].

The distinctive property of a RTD is that they are very sensitive to a small variation in the external bias voltage applied to the system. The structure consists

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of several layers of materials. In the RTD system, the potential barriers could be thin layers of an insulator or semiconductor.

Usually one considers double potential barriers with one layer between the barriers, which is then the central part of the structure. This potential well is the region where the energy of the particles can have only discreet or quasi-discreet values. This means that the energy spectrum inside the well is quantised, this is the quantum well (QW). If the energy of an incoming electron is in coincidence with the energy of the quantum states inside the well, then the probability of the electron for tunnelling through the QW grows enormously.

This effect implies that the tunnelling properties of the structure depend on the energy values of the (resonant) levels inside the QW. The energies will also depend on any external magnetic field which could be applied to the system [2-4]. To do so, one can use a ferromagnetic material as an external layer outside one of the two barriers of potential. This material is usually a diluted magnetic semiconductor (DMS). The magnetic field acts on the spins of the electrons and makes the current that flows through the structure spin polarised. The magnetic field causes the splitting of the energy level into two spin channels, each of which is associated with one of two possible orientation of spin. This is because the eigenstates of the electrons have two possible spin orientations in the presence of the magnetic field. The spin splitting of the electron energy makes a difference to the tunnelling probability because only one of the two split levels can be in coincidence with the resonant level. This means that the RTD can be spin selecting materials for the transmitted electrons. Hence we can make the statement that RTD diodes are useful structures as spin filters.

One of the fundamental properties that are studied in magnetic junctions is the electric and spin current behaviour as a function of different parameters, for example the energy of the resonant level, the geometry of the structure, the influence of different materials (semiconductors, metals, superconductors), the magnetic moments of the system, the symmetry of the structure, and the spin polarisation of the current. One of the important phenomena that comes due to the spin current tunnelling is the induced magnetisation of the QW. Spin splitting of the resonant level causes nonzero magnetic moments in the QW level along with the spin accumulation properties of the RTD. This means the material can be magnetised due to the tunnelling of particles with spin from an external magnetised region. The dependence between magnetic field ratio and the scale of the spin splitting of the levels inside the QW are intensively studied properties of multilayered quantum systems. Experimentally, in all described cases, the conductance of the structure has strong resonance peaks as a function of the voltage, and the peaks can be controlled by external parameters like, for example, the magnetic field.

In a recent paper [5] the authors have shown that spin-selection in RTD can be controlled by changing the voltage. The study of a structure based on (Zn,Mn,Be)Se, with the DMS inside the well, showed that if one subjects the diode to an external magnetic field, the resulting spin splitting of the levels leads to the splitting of the transmission resonance into two separate peaks. This could be used to design a voltage-controlled spin filter.

2. MANIPULATION OF THE MAGNETIC MOMENT IN A SINGLE TUNNEL JUNCTION

In the case of a single tunnel junction, there is an arrangement, in which two layers of a material (either semiconductor or metal) are separated by a thin layer of insulator [8,9]. At the interface of two layers we have a jump in the potential resulting from a difference in the band structures of the two materials. Often in electronic systems, we have to deal with two semiconductor interconnects (e.g. a semiconductor diode) or metal-semiconductor connectors (a so-called Schottky diode) in which two layers come in contact along a common plane and the energy barrier is formed by electric polarisation [10,11]. In our case, the electron transport through the coupling takes into account the effect of the magnetising of the structure and the resulting Zeeman splitting, and in particular the influence of the external magnetic field on the energy levels of the materials. An important role is played by the influence of the magnetic field on the tunnelling effect of the coupler. One must take into account the spin polarisation effect of the charge carriers and thus the influence of the magnetic field on the tunnelling [12]. In particular, attention is paid to the presence of the resonant energy levels, which significantly affect the probability of tunnelling charges.

If we take into account the spin polarisation of the resonant levels, we can consider the dependence of the efficiency of the spin transport on the intensity of the magnetic field covering the structure [13,6,7]. These tests are the basic element of accounts for two or more magnetic tunnelling systems. Thus, we have the ability to determine the characteristics of tunnel diodes, which are based on the flow of electric and spin currents through the tunnel barrier [14].

3. THE RESONANT TUNNELLING CONNECTOR

RTDs are the subject of intense study due to their specific characteristics and properties [14-16]. These devices have a high operating speed in excess of 2 THz (while in conventional CMOS systems speed is 215 GHz). The rapid development of RTD allows for a number of applications in high-resolution communications and high-resolution radar systems [17]. RTD, similarly to conventional diodes, have selective paths for the direction of charge transport. In the case of traditional complementary metal–oxide–semiconductor (CMOS) systems, the electrons flow through a special conducting channel in the system, however in the case of RTD the main effect, which makes transport of charge and spin possible, is tunnelling [18,19]. This transport is additionally strongly enhanced and depends on the quantised resonance energy level inside the cavity or well [1,7,20].

The tunnel diode includes a *p*-*n* junction, where both *p* and *n* regions are in a degenerate state [7]. There is a significant concentration of electrons in the conduction band of the *n*-type material with empty states in the valence band of the *p*-type material [10]. As a result, the Fermi level remains constant as long as the diode is in thermodynamic equilibrium without an external voltage applied. If the voltage is increased, the Fermi energy decreases in the *p*-type material and increases in the *n*-type. If the saturation area is very thin (< 10nm), then the electrons can easily flow through the barrier [21]. Depending on how many electrons are energetically compensated by the empty valence states of the *p* region, this current will either increase or decrease. As the potential difference increases, the current induced by the diffusion of charge carriers will increase the current flowing through the diode [22-24].

If a reverse external voltage is applied to the diode, the electrons in the *p* region are energetically compensated with the empty states in the *n* region, leading to a significant tunnel current in the direction of the applied voltage [21]. Current-voltage (or *I*-*V*) characteristics show negative differential resistance in the RTD. This means that in the range of voltages with these characteristics, an increase in the potential difference corresponds to a reduction in the current flowing through the diode. As a result, the current turns out to be a decreasing function of voltage. This property is particularly important in the context of applications because it allows one to correlate voltage-controlled logic states with the local maxima and minima of the current flow. In the case of a RTD, we have a QW with equal homogeneous contacts which can achieve a similar *I*-*V* characteristic. The diode consists of two highly-dispersive materials with a small energy barrier[8,9]. The structure of the diode reproduces a system composed of an emitter, a QW between two barriers, an energy gap and a collector area. Often, the materials used for this type of system consist of gallium arsenide compounds. The typical barrier width is about 5 nm and the barrier width ranges from 1.5 to 5 nm.

In the absence of an external voltage, most electrons and holes are deposited in the emitter and collector layers in a stationary manner. When an external voltage is applied to the system, an electric field is generated, which forces the electrons to move from the emitter to the collector through the dispersive states located in the potential well [2]. These energy states, through which electrons can tunnel, can mediate the conductivity. As more electrons in the emitter area have the same energy as quasi-bound states, more of them can overlap through the cavity, leading to an increase of current as a higher voltage is applied to the diodeo. As soon as the electric field reaches the intensity at which the energy level of the emitter electrons is in coincidence with the energy level of the resonant state, the current reaches its maximum value. The resonance tunnelling occurs within the range of specific resonant energy levels associated with the dopant energy levels and the quantum cavity width [21]. As the external voltage applied to the diode rises, more and more electrons have too much energy to be able to tunnel through the resonant states, resulting in a falling current. As the bias increases, the current rises again due to electron thermo-emitting. Incorporation of these two phenomena leads to the appearance of a valley on the *I-V* characteristics of the RTD [23,1]. RTDs have a significant advantage over conventional tunnel diodes. When a high reverse voltage is applied to the tunnel diode, a very high reverse current is generated [23]. Unlike conventional tunnel diodes, RTDs have the same type of doping and concentration of charge in the collector and in the emitter. This results in a symmetrical *I-V* curve when both the voltage and current are applied to the diode in the opposite direction. As a result, the very strong "leakage" current that appears in a normal tunnel diode is eliminated in the RTD. This makes resonant tunnel diodes promising structures as a correction elements [13]. This system is characterised by low resistance and short travel times.

4. MODEL

We consider a structure consisting of several layers of semiconductors, with a tunnel junction as shown in Fig. 1. The dashed line in the QW of ZnSe corresponds to the energy level E_0. The layer in the left side of the structure, $x<0$, is based on a DMS.

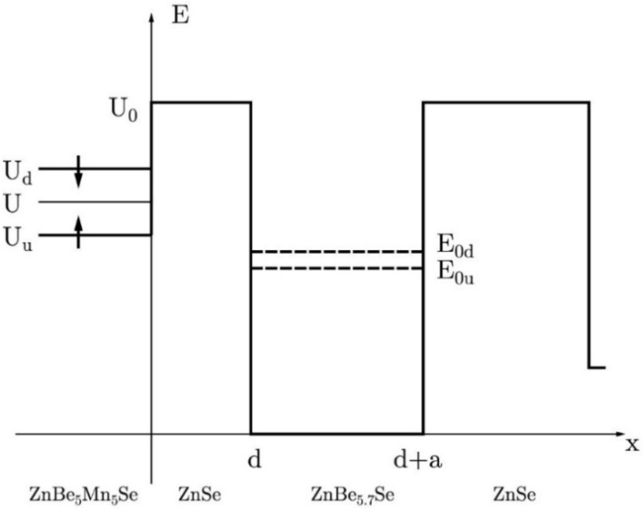

Fig. 1. Model of the multilayer structure with two potential barriers, where $U_{u,d}$ refers to electrons with spins up and down respectively, and U_0 is the potential barrier.

There is a spin splitting of the energy level in the layer due to a magnetic field. We can consider tunnelling of states into the rectangular QW restricted by two barriers both of the same potential height. First, we use Schrödinger's equation to get the wave function for the structure in the area $d < x < d+a$. Then we consider the non-equilibrium problem, in which the plateaus of the top of the potential barriers are becoming oblique. In this structure, the potential energy is a function of the coordinate x. This case is useful for finding the magnetization inside the QW when there is a current through the structure. We used numerical calculations to find the current inducted magnetization as a function of the bias. The results demonstrate a strong influence of the magnetic field in small extent of the bias. We use experimental data for a five-layers structure.

We also used the results of numerical calculations to demonstrate the relation between the magnetic field and the energy level for four different values of the width d of the barrier. The width of the barriers was approximately $d = 1.5\times10^{-7}$ cm, the distance between them, which scales the well about $a = 2.5\times10^{-7}$ cm. The height of the barriers was $U_0 = 0.126\times10^{-12}$ J. The spin splitting inside the well is a consequence of the splitting in the DMS. We discuss the situation in which the energy level on the left side of the structure is lower than the height of the barrier at the interface at $x=d+a$, hence we are able to discuss it for realistic values of the parameters.

5. MAGNETIZATION IN A MAGNETIC FIELD

We assume that the diluted magnetic semiconductor (DMS) is located at $x < 0$. In the DMS, there are a large number of magnetic ions but the interaction between the magnetic moments of these ions is assumed to be very small, so that the moments are not ordered, and the average magnetization at $H = 0$ is zero. If the external field H acts on the DMS, it leads to the ordering of the moments, and the average magnetization M is nonzero. The relation between the magnetization M and magnetic field at finite temperature T is given by the equation [25]

$$M = xN_0 g\mu_B J B_S\left(\frac{g\mu_B JH}{kT}\right) \tag{1}$$

where $x = N_i/N_0$ is the relative density of magnetic ions (N_i is the concentration of magnetic ions and N_0 the number of sites in the crystal lattice), g is the Landé factor, μ_B is the Bohr magneton, J is the magnetic moment of a magnetic impurity, and $B_J(x)$ is the Brillouin function

$$B_J(x) = \frac{2J+1}{2J} coth\left(\frac{(2J+1)x}{2J}\right) - \frac{1}{2J} coth\left(\frac{x}{2J}\right) \tag{2}$$

The interaction between a free electron of spin 1/2 with the average magnetization M leads to the Zeeman splitting of the conduction band, which can be presented as

$$U_{u,d} = U(0) \mp \frac{1}{2} xN_0 \alpha J B_J\left(\frac{g\mu_B JH}{kT}\right) \tag{3}$$

where α is a constant and $U(0)$ is the energy of the bottom of the conduction band at H=0. The value of $N_0\alpha$ is the exchange constant of the conduction electrons and $U_{u,d}$ refers to electrons with spin up and down,respectively. In this approach we neglect the interaction between magnetic ions.

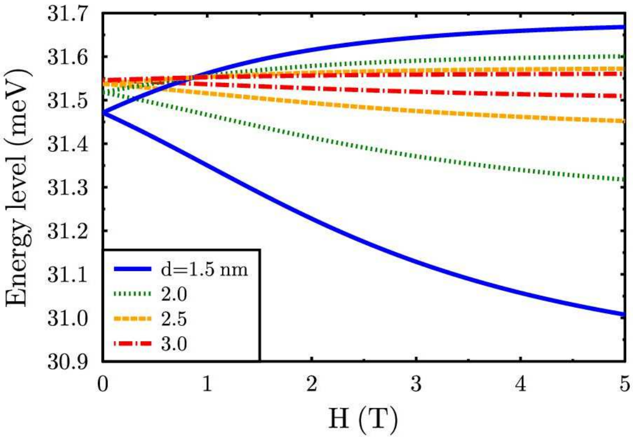

Fig. 2. Level positions as a function of magnetic field at T = 4.2K for different barrier widths d

We also have to take into account the density of states. In the one-dimensional case we can put the Fermi level in the place of energy E. At T = 0 the chemical potential is equal to the Fermi level, so if the energy E is lower than the Fermi level, the distribution function is equal one. In the three-dimensional case we calculate the magnetization and current integrals with respect to the wave vector **k**.

On the left side of the structure (Fig. 1) we choose the Fermi level to be higher than the value E of the energy for spin down oriented electrons. For that reason we consider tunnelling through both of the barriers. We solved numerically the dependence of magnetization M on energy for different values of temperature. The dependence of the energy levels on magnetic field H is presented in Fig. 2.

6. MAGNETIC SPLITTING OF THE QUANTUM LEVEL IN EQUILIBRIUM

We consider two different cases. If $U > E_0$, the penetration of the wave function of the states localised in the QW exponentially decays in the ZnBeMnSe layer. As a result, there is a quantisation level in the QW. Its energy can be calculated as a function of U (Fig. 3), where U is the conduction band edge in ZnBeMnSe. The variation of U is related to the magnetization in the DMS.

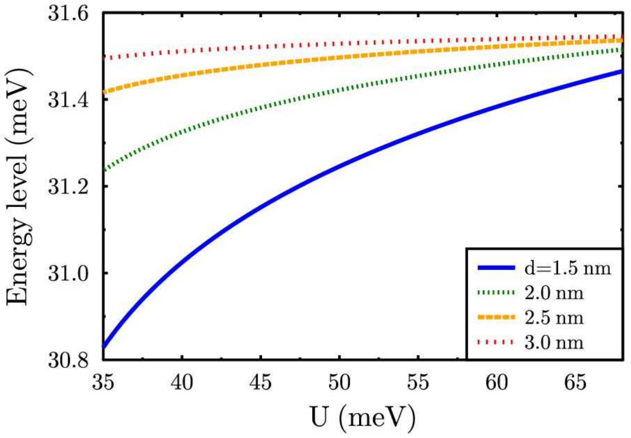

Fig. 3. The dependence of level position E_0 on U for different values of the barrier width d. The calculation is valid only for $E_0 < U$

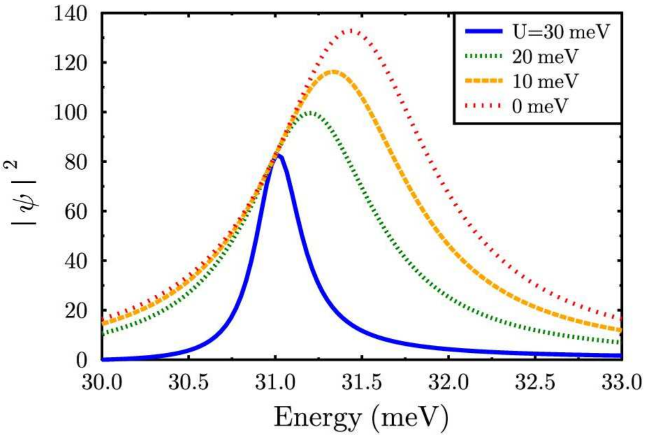

Fig. 4. The probability $|\psi|^2(E)$ for different U in the case of $U < E_0$

In the case of $U < E_0$ there is a tunnelling from the level into the conduction band of ZnBeMnSe. The level is quasi-discrete since there are states with all energies $E > U$. We calculated the distribution $|\psi|^2(E)$ where ψ is the wave function inside the QW (at $x = 0$) (Fig. 4). The peak of the dependence on energy corresponds to the position of the quasi-discrete levels in the QW. The maximum of each curve goes to a higher E as U goes down. However, the luminescence can start from the lowest possible energy, i.e., from the energy U even though the density of states in the QW for $E = U$ is rather low.

7. CONCLUSIONS

The effect which makes RTD materials especially important for spintronics is the possibility to select currents associated with two spin orientations, namely the spin currents. The difference in probabilities for two spin channels leads to a spin splitting of the quantum well energy levels and causes the induced magnetization inside the RTD. The spin splitting of the resonant level gets larger as the magnetic field on the outside region of the barrier is getting stronger. The spin filtering properties of RTDs make them important elements or the manipulation of spin currents. By changing the configuration of magnetic moments, one can affect the spin transport properties, especially the spin polarisation of the current. We can also predict and study the value of magnetization induced inside the quantum well by the spin splitting of the resonant level. That means that RTD spin currents can be controlled and manipulated by a magnetic field acting on the DMS material. This makes such elements very important for spintronic devices.

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REZONANSOWA DIODA TUNELOWA Z ELEKTRODAMI MAGNETYCZNYMI

Przedstawiono podstawowe własności transportu ładunku i spinu poprzez wielowarstwowe struktury półprzewodnikowe, zawierające warstwy izolatorów. Układ półprzewodników przedzielonych warstwą izolatora stanowi rodzaj złącza tunelowego, poprzez które cząstki przedostają się wykorzystując zjawisko tunelowania kwantowego. Za pomocą dwóch złącz tunelowych zawierających bariery energetyczne w postaci materiału izolatora, konstruujemy kwantową studnię potencjału. W jej obszarze poziomy energetyczne ulegają skwantowaniu, przyjmując wyłącznie wartości dyskretne lub quasi-dyskretne. Ponadto prawdopodobieństwo tunelowania ładunków przez układ zawierający studnię potencjału zależy od tego czy energia padających cząstek znajduje się w koincydencji z dozwolonym w jamie tzw. rezonansowym poziomem energetycznym. Tego typu systemy stanowią podstawę funkcjonowania tzw. rezonansowych diod tunelowych. Przeanalizowano zależności od różnych parametrów układu, takich jak energia poziomu rezonansowego, szerokość barier potencjału, oraz wpływ pola magnetycznego na elektryczne oraz spinowe własności transportowanych cząstek. Badania te mają kluczowe znaczenie w projektowaniu urządzeń na potrzeby spintroniki. Wykorzystują one polaryzację spinową prądu, akumulację spinu w studniach potencjału, manipulowanie spinem w układach elektronicznych przy wykorzystaniu pola magnetycznego oraz indukowanie magnetyzacji w obszarze studni kwantowej zawierającej rozszczepione spinowo poziomy rezonansowe.

Słowa kluczowe: rezonansowa dioda tunelowa, magnetyczna dioda tunelowa, spintronika.

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