The influence of single barrier semimagnetic semiconductor spin filter on electrons spin polarization

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The spin-dependent tunneling across the single semimagnetic semiconductor barrier has been studied in $CdTe/Cd_{1-x}Mn_xTe/CdTe$ based system under the external magnetic and electric fields. The influence of parameters of such spin filter on the spin polarization of electrons has been revealed. The spatial distribution of polarized spins has been calculated as a function of the distance from the barrier. It has been shown that this distance depends on the relaxation times and may reach few micrometers. The polarization degree was studied as a function of carrier concentration, concentration of magnetic impurities in the barrier and kinetic parameters of the electron motion, mobility.

Исследовано спин-зависимое туннелирование через одиночный барьер в полумагнитном полупроводнике в системе на основе $CdTe/Cd_{1-x}Mn_xTe/CdTe$ под влиянием внешних магнитных и электрических полей. Обнаружено влияние параметров такого спинового фильтра на спиновую поляризацию электронов. Рассчитано пространственное распределение поляризованных спинов как функция расстояния от барьера. Показано, что это расстояние зависит от времени релаксации и может достигать нескольких микрометров. Исследована степень поляризации как функция концентрации носителей, концентрации магнитных примесей в барьере и кинетических параметров движения электронов, подвижности.

1. Introduction

During the last few years, different systems with a considerable level of the electron spin polarization were studied intensively, because of the developing and searching of new devices with properties defined mainly by the spin orientation. The electron spin polarization is a critical parameter, for example, in the quantum spin computers [1], spin transistors [2], etc. One way to provide a high level of the electron spin polarization is to use spin filters based on the effect of the spin-dependent electron tunneling across the semimagnetic semiconductor heterostructures with different barrier configurations [3–9]. In this work, the simplest single-barrier semimagnetic semiconductor tunneling structure with one magnetic layer under the external magnetic and electric fields is proposed as the spin filter. Fig. 1 shows schematically the proposed device. In semimagnetic semiconductors, a strong exchange interaction between the carriers and the localized spins of the magnetic ions (giant Zeeman splitting) results in a strong dependence of the barrier height on the external magnetic field and carrier spin. As a result, the electrons with different spin orientations have different transition coefficients. The level of the giant Zeeman splitting depends heavily on the external magnetic field and thus there is a possibility to tune the spin polarization level by an external parameter. In this work, the one-barrier system based on CdTe materials was studied. A similar spin polarization scheme for ZnSe based systems was studied in [4]. In contrast to [4, 5], in this work the dependence of the carrier polarization degree on the distance from the barrier was studied. The polarization degree was investigated as a function of the spin-lattice relaxation time.

2. The system under consideration

All calculations in this work were made for the CdTe based semimagnetic semiconductor system. The system under consideration consists on semimagnetic barrier formed by the $Cd_{1-x}Mn_xTe$ layer sandwiched between two CdTe layers. The electric and external magnetic fields are applied along the crystal growth direction z. The general design of such system and its band structure without applied fields are shown in Fig.1a and under the external electric and magnetic fields, in Fig 1b. We consider the regions outside the barrier to be conductive because an additional carrier concentration arose in the CdTe layer (due to donors, irradiation, external carrier source, etc.). First of all, we will calculate the current polarization relying on the electron transmission coefficients at different spin orientation.

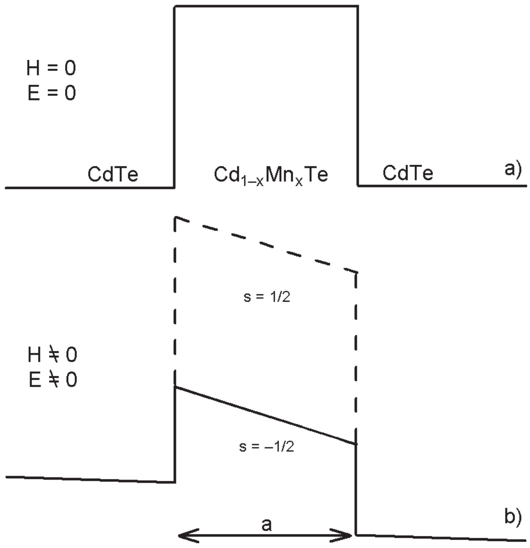

Fig. 1. A schematic diagram of the band aligment without (a) and under (b) the external electric and magnetic fields.

The Shrödinger equation for the electron in such system is

$$\left[\frac{1}{2m}\left(\left(p_x-\frac{eH}{c}y\right)^2+p_y^2+p_z^2\right)+V-\frac{\mu}{s}\sigma H\right]\Psi(x,y,z)=E\Psi(x,y,z). \quad (1)$$

where m is the electron mass; σ, the spin projection on z direction; H, the magnetic field; V, the potential having value and shape dependent on the system inner parameters (for example, used materials and impurities concentration), external magnetic field and applied bias, $V=V_x(z)+V_H(z)+V_E(z)$.

The first item $V_x(z)$ describes the crystal lattice deformation caused by the replacement of cations by the magnetic impurity ions and its value does not depend on the spin. In this case, $V_x(z)$ is zero in CdTe layers and

$$V_x(z)=Q_V\Delta E_g \quad (2)$$

in the layer with impurities. ΔE_g is the valence band shift; Q_V, the system parameter determined experimentally. The second item $V_H(z)$ describes the exchange interaction between the electron and the magnetic ion spins and depends on the magnetic field H and the electron spin projection s_z.

$$V_H(z)=-xN_0\alpha\bar{S}_{Mn,z}(H)s_z. \quad (3)$$

Here, $N_0\alpha$ is the exchange integral; $\bar{S}_{Mn,z}(H)$, the average spin of the impurity ions. The exchange integral can be calculated theoretically but this calculation is very complicated, and thus its value was taken from the experiment. The average spin was determined using the semi-empirical formula

$$\bar{S}_{Mn,z}(H)=\bar{s}(x)B_{\frac{5}{2}}\left[\frac{g\mu_B H}{k_B\left[T+T_0(x)\right]}\right],$$

where $B_{\frac{5}{2}}(y) = \frac{6}{5}\coth\left(\frac{6}{5}y\right) - \frac{1}{5}\coth\left(\frac{1}{5}y\right)$ is a Brillouin function; $T_0(x) = \frac{35.37}{1+2.752x}x$; $\bar{s}(x) = S\left[0.265e^{-43.34x} + 0.735e^{-6.19x}\right]$ and $S = \frac{5}{2}$ [11,12]. The last item $V_E(z)$ characterizes the applied external electric field influence on the barrier shape:

$$V_E(z) = \begin{cases} 0, & z \le 0 \\ -\frac{z}{a}eU, & 0 < z \le a \\ -eU, & a < z \le \infty, \end{cases} \tag{4}$$

where U is the applied bias. Our calculations show that the barrier deformation caused by the charge redistribution is small in comparison with the barrier size and so can be neglected.

3. The current polarization

The current outside the barrier can be completely defined by the transition coefficient. Taking into account the fact that the potential V depends on the variable z (2), (3), (4) only and using standard methods, we can separate the variables in equation (1) $\Psi(x,y,z) = X(x)Y(y)\Psi(z)$. The proposed approach gives $E = \left(n + \frac{1}{2}\right)\hbar\omega_H + E_\perp - \frac{\mu\sigma}{s}H$ and the next wavefunction: $X(x) = e^{\frac{i}{\hbar}(p_x x)}$,

$Y(y) = \left(\frac{1}{\pi a_H^2}\right)^{\frac{1}{4}} \frac{1}{\sqrt{2^n n!}} e^{-\frac{(y-y_0)^2}{2a_H^2}} H_n\left(\frac{y-y_0}{2a_H}\right)$ for the x and y, respectively, where $H_n(\xi)$ is Hermite polynomial, $a_H = \sqrt{\frac{\hbar}{m\omega_H}}$, $\omega_H = \frac{eH}{mc}$, $y_0 = -\frac{p_x c}{eH}$. On the direction z, we have the one-dimensional equation

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + V(z) - E_\perp\right)\Psi(z) = 0. \tag{5}$$

The standard solution of this equation is

$$\Psi(z) = \begin{cases} e^{ik_1 z} + C_1 e^{-ik_1 z}, & z \le 0 \\ C_2 Ai(\xi_2) + C_3 Bi(\xi_2), & 0 < z \le a \\ C_4 e^{-ik_3 z}, & a < z \le \infty, \end{cases} \tag{6}$$

where $k_1 = \sqrt{\frac{2m}{\hbar^2}E_\perp}$, $k_3 = \sqrt{\frac{2m}{\hbar^2}(E_\perp + eU)}$, $\xi_2 = \sqrt[3]{\frac{2mW_2}{\hbar^2}}\left(\frac{V_2 - E_\perp}{W_2} - z\right)$ [3]. In the present case, $V_2 = V_{x,2} + V_{H,2}$, $W_2 = \frac{eU}{a}$. Standard joint of the wave function (6) and the numerical solution of the resulted system of equations gives the spin-dependent transition coefficient for the electron tunneling under the electric and external magnetic fields:

$$D_\sigma(U,H,E_\perp) = \frac{k_3}{k_1}|C_4|^2. \tag{7}$$

The carrier current density throughout the barrier (the layer $Cd_{1-x}Mn_xTe$) can be determined by the following formula:

$$j_\sigma(U,H) = j_0 B \sum_{n=0}^{\infty} \int_0^{+\infty} D_\sigma(U,H,E_\perp) \times \times \left\{ f\left[E_\perp + \left(n+\frac{1}{2}\right)\hbar\omega_H\right] - f\left[E_\perp + \left(n+\frac{1}{2}\right)\hbar\omega_H + eU\right]\right\} dE_\perp, \quad (8)$$

where $f[\chi] = \frac{1}{1+e^{\frac{\chi-\varepsilon_F}{k_B T}}}$ is the Fermi-Dirac distribution function; $\varepsilon_F = \frac{\hbar^2}{2m_e}\left(3\pi^2 n_e\right)^{\frac{2}{3}}$, the Fermi energy; n_e, the carriers concentration, $j_0 = \frac{e^2}{4\pi^2\hbar^2}$ [4, 5]. By the definition, the current polarization is determined as

$$P_j = \frac{j_+(U,H) - j_-(U,H)}{j_+(U,H) + j_-(U,H)}. \quad (9)$$

4. The charge carrier polarization

The spin filter described above allows passage of a highly polarized current of electrons. But the interaction of the electrons with the surrounding material results in the electron relaxation and in decreased spin polarization. The distance for which the spin polarization remains significant is defined by the crystal properties, such as the spin relaxation time, the electron mobility, etc. The polarization degree is the relative concentration difference of electrons with different spin projections:

$$P = \frac{n_+ - n_-}{n_+ + n_-}, \quad (10)$$

where n_+ and n_- are the concentrations of electrons with $s_z = 1/2$ and $s_z = -1/2$, respectively. The current density of electrons with different spin polarization is:

$$j_\pm = e\mu n_\pm E + eD\frac{dn_\pm}{dz}., \quad (11)$$

where D is the diffusion coefficient; μ, the electron mobility and $D = \frac{\mu k_B T}{e}$.

The density of electrons with different spin orientation and their polarization can be calculated in the two-component drift-diffusion transport model and described by the continuity equations:

$$\frac{\partial n_\pm}{\partial t} = \frac{1}{e} div j_\pm + \frac{n_\mp}{\tau_\mp} - \frac{n_\pm}{\tau_\pm}, \quad (12)$$

where $\tau_\mp$ and $\tau_\pm$ are the relaxation times (times of electron transition from the state with $s_z = -1/2$ to the state with spin $s_z = 1/2$ and vise versa). Taking into account (11), Eq. (12) in the steady state give the system of equations:

$$\begin{cases} D\frac{d^2 n}{dz^2} + \mu E\frac{dn}{dz} + n\mu divE = 0 \\ D\frac{d^2 p}{dz^2} + \mu E\frac{dp}{dz} + p\mu divE - p\left(\frac{1}{\tau_\pm} + \frac{1}{\tau_\mp}\right) + n\left(\frac{1}{\tau_\mp} - \frac{1}{\tau_\pm}\right) = 0 \end{cases} \quad (13)$$

where $n = n_+ + n_-$ and $p = n_+ - n_-$ [10]. According to Eq. (11), the boundary conditions for the total concentration and for the of electron concentration difference take the form:

$$j_+(0) + j_-(0) = e\mu n(0)E(0) + eD\left.\frac{dn(z)}{dz}\right|_0,$$
$$j_+(0) - j_-(0) = e\mu p(0)E(0) + eD\left.\frac{dp(z)}{dz}\right|_0, \tag{14}$$

where the coordinate origin $z = 0$ is located at the external boundary of the barrier and the values $j_+(0)$ and $j_-(0)$ are as calculated above (see (8)). We suppose that for a low temperature, the spin distribution at the infinity is normal, $p(\infty) \approx 0$, and the total carrier concentration is equal to the donor concentration $n(\infty) \approx N$.

In order to obtain a full system of kinetic equations for the electron density in the conduction band, the Eq.(13) must be complemented with the Poisson equation $\frac{dE}{dz} = \frac{e}{\varepsilon\varepsilon_0}(N - n)$. In combination, the Poisson equation and the total current equation give the electric field equation

$$\frac{d^2E}{dz^2} + \frac{e}{k_B T}E\frac{dE}{dz} - \frac{e^2 N}{\varepsilon\varepsilon_0 k_B T}E + \frac{j}{\varepsilon\varepsilon_0 D} = 0, \tag{15}$$

where N is the donor concentration. The boundary conditions for the electric field are formulated according to the following physical considerations. We suppose that the electrical field on the barrier/sample interface is continuous and equal to the electric field value inside the barriers, $E(0) = \frac{e\Delta V_E}{a}$. On the other hand, the electric field at infinity is constant, so the equation (15) gives $E(\infty) = \frac{jk_B T}{De^2 N}$. So, the system of equations (13) and (15) with boundary conditions defines completely the spin polarization of the electrons in the layer placed after the barrier.

5. Results and discussion

The spin-dependent electron transition coefficient in the case of the single $Cd_{1-x}Mn_xTe$ barrier was calculated for the electron effective mass $m_e = 0.096m_0$, the dielectric constant $\varepsilon = 9.7$, the exchange integral $N_{0\alpha} = 0.22$ eV and $Q_V = 0.4$ [13]. The shape and magnitude of the general potential was determined as a sum of components $V_x(z)$, $V_H(z)$, $V_E(z)$, where $V_H(z)$ was calculated according to the empirical formula (3), $V_E(z)$ according to the formula (4) and $V_x(z)$ according to (2). It was taken into account that $\Delta E_g = E_g^{Cd_{1-x}Mn_xTe} - E_g^{CdTe}$, $E_g^{Cd_{1-x}Mn_xTe} = E_g^{CdTe} + xdE_g$ and $dE_g = 1.592$ eV [14]. In such a system, the giant Zeeman splitting lets to tune the barrier height by the magnetic field. When the external magnetic field rises, the barrier height for the σ^+ current component decreases and for the σ^- component, it increases. Such dependence results in the transition coefficient dependence on the electron spin. Thus, outside the spin filter, we can form a region where the number of electrons with the spin –1/2 exceeds that of electrons with the spin 1/2.

Fig.2 shows the calculated current polarization dependence $P_J = \frac{j_+ - j_-}{j_+ + j_-}$ on the magnetic impurities concentration. As is seen from the Figure, the current polarization has a maximum. This maximum can be explained as follows. When the impurity concentration is low, the electron Fermi energy exceeds the barrier height and thus the electron does not fill the barrier transformations caused by the magnetic field. When the impurity concentration is high, the barrier height in both cases of electron spin polarization is so large that the electron does not fill the difference. It is seen from the Figure that in the present case, we can obtain the current polarization value close to 0.4.

Fig.3 shows the total current under applied voltage for several different donor concentrations. The parameters H and x in Fig. 3 were chosen to obtain the maximum current (and thus the

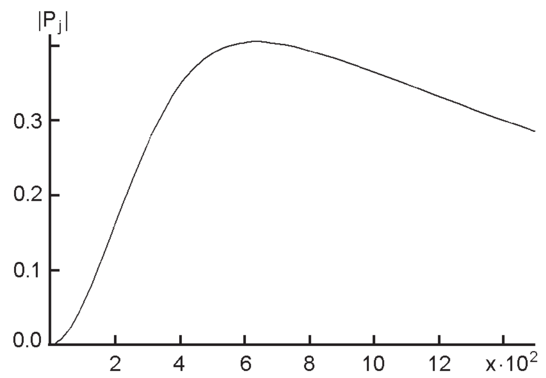

Fig. 2. Current polarization P_j as the function of magnetic impurities Mn^{2+} concentration. Dependence obtained at temperature $T = 2$ K and carriers concentration $n_e = 10^{18}$ cm^{-3}

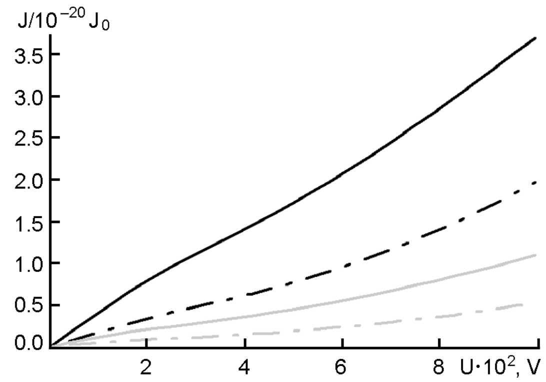

Fig. 3. Total current for the different values of donor concentration (energy of the Fermi level) as function of applied bias. Solid curves correspond to the current components with a spin –1/2, dashed curves to the spin 1/2. Black curves correspond to the carriers concentration $n_e = 10^{18}$ cm^{-3}, grey $n_e = 0.5*10^{18}$ cm^{-3}. All curves obtained at $x = 0.06$, $T = 2$ K, $a = 70$ Å and $H = 3$.

carriers) polarization in the case when the carrier concentration is $n_e = 10^{18}$ cm^{-3}. It is seen that the current absolute value increases when the charge carrier concentration rises. Fig.3 also shows that the current value rises by an order of magnitude as the donor concentration grows twice. The current polarization also depends on the system parameters such as widths of the barriers and temperature. The calculations show that the temperature affects critically the spin filter efficiency. For example, if at a low temperature we can reach the situation when the number of tunneling electrons with the spin –1/2 exceeds that of electrons with the spin 1/2 twice, at the temperature $T = 20$ K and physically motivated U such value is inaccessible. A similar behavior as a function of temperature was observed in experimental work [15] for a system based on ZnSe. Another important parameter which influences the current absolute value and the polarization value is the barrier width. The barrier must be wide enough for the electron might fill it but it cannot be too wide to suppress the electron tunneling. For example, when the barrier width rises by 100 Å, the current value decreases by one decimal order.

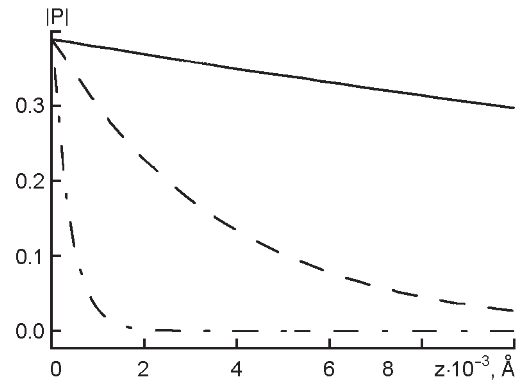

Fig. 4. Spin density polarization degrees $P = (n_+ - n_-)/(n_+ + n_-)$ as function of the distance from the border of the barrier. Solid curves correspond to the $\tau_+ = \tau_- = 10^{-9}$ s, dashed – $\tau_+ = \tau_- = 10^{-10}$ s, dot-dashed – $\tau_+ = \tau_- = 10^{-11}$ s. For all curves $n_e = 10^{18}$ cm^{-3}, $x = 0.06$, $T = 2$ K, $a = 70$ Å and $H = 3$.

Fig.4 shows the carriers spin polarization dependence on the distance from the barrier boundary. It is seen that for the specified parameters, the electron spin polarization may exceed 40%. As could be expected, the relaxation time increase results in higher polarization of the carriers in the sample. The spin-lattice relaxation time depends on the sample conditions (the presence of impurities, the electron-phonon interaction, etc.), and may reach the nanosecond range in II-VI semiconductors [2, 15, 16]. Fig.4 shows that the polarization penetration depth critically increases as the electron spin relaxation time increases. For example, when the relaxation time increases from 10^{-11} to 10^{-9} s, the polarized region increases from a few hundred angstroms to few dozen of thousand angstroms (i.e. μm). The calculations also show that the penetration depth increases when the electron mobility μ grows.

6. Conclusion

In this work, the spatial spin distribution of electrons tunneled across the one-barrier heterostructure $CdTe/Cd_{1-x}Mn_xTe/CdTe$ was studied under external electric and magnetic fields. It has been shown that the polarization level may reach 40% even for the simplest one-barrier semimagnetic system at certain values of the system parameters and the external field. We expect that the polarization degree can be increased by adding the few additional barriers. It has been shown that for the relaxation time $\tau = 10^{-9}$ s, the distance at which a high degree of carrier polarization is maintained could reach several micrometers. The current polarization dependence on temperature, concentration of magnetic ions, the barrier width was obtained.

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Вплив однобар'єрного напівмагнітного напівпровідника як спінового фільтра на спінову поляризацію електронів

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Досліджено спінозалежне тунелювання через одиночний бар'єр у напівмагнітному напівпровіднику у системі $CdTe/Cd_{1-x}Mn_xTe/CdTe$ під впливом зовнішніх магнітних та електричних полів. Виявлено вплив параметрів такого спінового фільтра на спінову поляризацію електронів. Обчислено просторовий розподіл поляризованих спінів як функцію відстані від бар'єру. Показано, що ця відстань залежить від часу релаксації та може досягати кількох мікрометрів. Досліджено ступінь поляризації як функцію концентрації носіїв, концентрації магнітних домішок у бар'єрі та кінетичних параметрів руху електронів, рухомості.