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Simulation of Spin-Dependent Electronic Transport through Resonant Tunnelling Diode with Paramagnetic Quantum Well

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The spin-dependent electronic transport is investigated in a paramagnetic resonant tunnelling diode formed from $Zn_{1-x}Mn_xSe$ quantum well between two ZnBeSe barrier layers. The spin-dependent current–voltage characteristics have been obtained in the presence of magnetic fields by solving the quantum kinetic equation for the Wigner distribution function and the Poisson equation in the self-consistent procedure. We have obtained two distinct current peaks due to the giant Zeeman splitting of electronic levels in a qualitative agreement with experiment. We have shown that the sign of spin current polarization can be reversed by tuning the bias voltage. Moreover, we have found the bias voltage windows with a nearly constant polarization.

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1. Introduction

An experimental realization of a heterostructure that contains a layer of the dilute magnetic semiconductor (DMS) between non-magnetic semiconductor layers allows us to investigate the spin-dependent electronic transport through a resonant tunneling nanodevice. In the DMS layers, a large spin-splitting of electronic levels is observed [1, 2]. This splitting results from the *sp–d* exchange interaction between localized magnetic moments of ions and spins of conduction band electrons. In the presence of the external magnetic field, the localized magnetic moments are aligned parallel to the field and the exchange interaction gives rise to the giant Zeeman splitting of electronic levels which generates the spin-dependent effective potentials [2].

In this paper, we present the results of calculations of the spin-dependent electronic transport through the heterostructure created from the Mn doped II–VI alloys, namely ZnBeSe/$Zn_{1-x}Mn_xSe$/ZnBeSe. In the limit of small concentration of Mn^{2+} ions, the giant Zeeman splitting can be expressed by the formula [1–3]

$$\Delta(B) = \pm\frac{1}{2}N_0\alpha x S_0 B_S\left(\frac{g\mu_B SB}{k_B T_{\text{eff}}}\right), \quad (1)$$

where $N_0\alpha$ is the *sp–d* exchange constant for conduction band electrons, x is the concentration of Mn^{2+} ions, S_0B_S is the effective Brillouin function for spin $S = 5/2$ which corresponds to spins of Mn^{2+} ions, g is the Landé factor, μ_B is the Bohr magneton, S_0 and T_{eff} are phenomenological parameters describing the Mn–Mn interaction.

2. Model of nanodevice and method of calculations

We consider the paramagnetic resonant tunnelling diode (RTD) formed with the $Zn_{1-x}Mn_xSe$ paramagnetic quantum well grown between two $Zn_{0.95}Be_{0.05}Se$ barrier layers. The active region of the nanodevice is separated from n-doped ZnSe contacts by two spacer layers located on the left and right side (cf. Fig. 1). The difference between the conduction band minima of $Zn_{1-x}Mn_xSe$ and $Zn_{0.95}Be_{0.05}Se$ gives rise to the spin-dependent potential energy profile (Fig. 1). We describe the transport properties of the nanostructure in the framework of the two-current model using the spin-dependent Wigner distribution function (WDF) [4]. Taking the z axis along the growth direction and assuming the translational invariance in the lateral directions (x, y), the quantum transport equation for the spin-dependent WDF can be effectively reduced to the one-dimensional form [5]:

$$\frac{\hbar k}{m}\frac{\partial\rho^w_\sigma(z,k)}{\partial z} = \frac{\mathrm{i}}{2\pi\hbar}\int \mathrm{d}k' U^w_\sigma(z,k-k')\rho^w_\sigma(z,k'), \quad (2)$$

where m is the conduction electron band mass, k is the z component of the wave vector, ρ^w_σ is the spin dependent WDF with the spin index $\sigma = \pm 1$, whereby the sign $+$ $(-)$ corresponds to spin up ($\uparrow$) and spin down ($\downarrow$), respectively, and $U_\sigma(z,k)$ is the non-local spin-dependent potential energy [5].

Potential energy $U_\sigma(z,k)$ is the sum of two spin-dependent contributions: the conduction band minimum energy $U^0_\sigma(z,B)$ and the Hartree potential energy $U^H_\sigma(z)$. The Hartree potential energy satisfies the Poisson equation

$$\frac{\mathrm{d}^2U^H_\sigma(z)}{\mathrm{d}z^2} = \frac{e^2}{\varepsilon_0\varepsilon}\left[N_D(z) - n_\sigma(z)\right], \quad (3)$$

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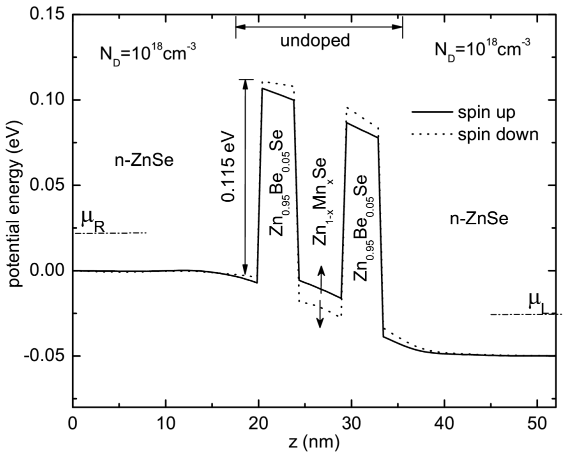

Fig. 1. Self-consistent potential energy profile in the paramagnetic RTD for spin up (solid line) and down (dotted line). Coordinate z is measured along the growth direction of the layers, μ_L (μ_R) is the electrochemical potential of the left (right) contact doped with donors. The undoped region consists of the paramagnetic quantum well with $Zn_{1-x}Mn_xSe$ layer sandwiched between two $Zn_{0.95}Be_{0.05}Se$ barrier layers.

where e is the elementary charge, ε_0 is the electric permittivity of the vacuum, ε is the relative static electric permittivity, N_D is the concentration of ionized donors, and $n_\sigma(z)$ is the spin-dependent electron density that can be expressed as follows:

$$n_\sigma(z) = \frac{1}{2\pi} \int \mathrm{d}k \rho_\sigma^w(z,k)\,. \tag{4}$$

The quantum kinetic Eq. (2) and Poisson Eq. (3) coupled through the electron density (4) constitute a nonlinear problem that can be solved numerically by a self-consistent procedure [6]. We assume the Dirichlet boundary conditions for the Poisson equation [7] and the open boundary conditions for the quantum kinetic equation [5]. The spin-dependent current–voltage characteristics for the independent spin channels can be obtained from the current density formula of the form

$$j_\sigma(z) = \frac{e}{2\pi} \int \mathrm{d}k \frac{\hbar k}{m} \rho_\sigma^w(z,k)\,. \tag{5}$$

Since we are dealing with the stationary problem the solutions are independent of both the time and coordinate variables. Therefore, we express the solutions as functions of the bias voltage V_b and the magnetic field B. In the following, $j_\sigma = j_\sigma(V_b, B)$.

The present calculations have been performed for the following nanodevice parameters: $N_D = 10^{18}$ cm^{-3}, the thickness of each contact is equal to 17 nm, the thickness of each spacer layer is 3 nm, the thickness of each potential barrier (quantum well) layer is 3 nm (5 nm), the height of the potential barrier $U_0 = 0.115$ eV [8] with respect to $U(0) = 0$ (in the absence of electric charge in the nanostructure), and total length L of the nanodevice $L = 54$ nm. The electrons are described by the conduction band mass of ZnSe, i.e., $m = 0.16 m_0$, where m_0 is the free electron mass. We take on the electric permittivity $\varepsilon = 8.6$ and the lattice constant $a = 0.5667$ nm as these characterizing ZnSe, the exchange constant $N_0\alpha = 0.26$ eV and parameters $S_0 = 1.18$ and $T_{\mathrm{eff}} = 2.55$ K are chosen according to Ref. [9] for $x = 8.3\%$.

3. Results and discussion

The calculated current–voltage characteristics are plotted in Fig. 2. For each magnetic field B we observe two current peaks at two different bias voltages. These current peaks stem from the giant Zeeman splitting of electronic levels in the paramagnetic quantum well. This splitting depends on the magnetic field [cf. Eq. (1)]. In each spin conduction channel, the resonant tunnelling conditions are satisfied for different bias voltages, which leads to the spin-filtering of conduction electrons in the nanodevice. We note that the increasing magnetic field shifts the positions of the current maxima for spin up (down) electrons towards the higher (lower) bias voltage.

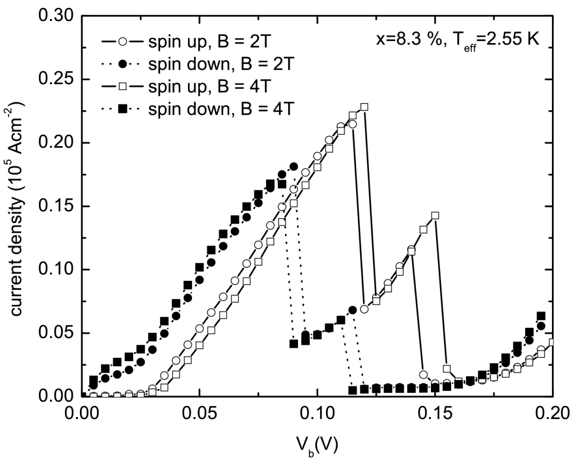

Fig. 2. Current–voltage characteristics of paramagnetic RTD for spin up and down electrons for magnetic field $B = 2$ T and $B = 4$ T.

One of the major characteristics of the spin-dependent electronic transport is the current density spin polarization defined as:

$$P_j = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}\,, \tag{6}$$

which is expressed as a function of V_b and B. The calculated current density spin polarization is presented in Fig. 3 for fixed concentration of Mn ions ($x = 8.3\%$). We observe that all of the curves in Fig. 3 exhibit the bias voltage windows, in which the current density spin polarization is nearly constant and almost the same for different magnetic field B. This effect is a consequence of the "plateau-like" structure that emerges in the region of the negative differential resistance at the current–voltage

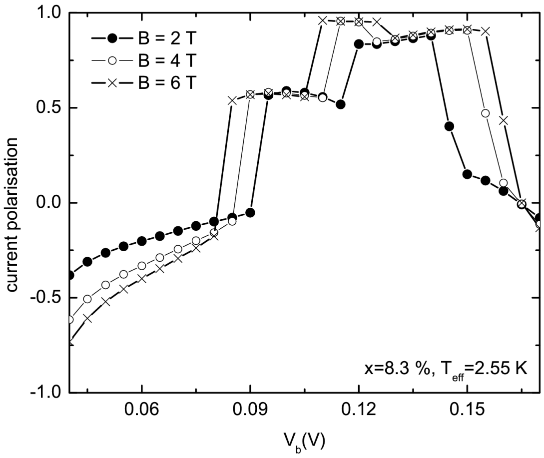

Fig. 3. Spin polarization of the current as a function of bias voltage V_{b} and magnetic field B.

characteristics (cf. Fig. 2). The origin of the "plateau-like" structure can be explained by the nonlinear effects associated with the accumulation of electrons in the paramagnetic quantum well, which modifies the spin-dependent potential and leads to the interaction with electrons accumulated in the quantum well created in the region of the left contact (cf. Fig. 1). The electron–electron interaction has the strong influence on the spin-dependent distribution of electron density in the nanodevice and therefore the current density in each spin conduction channel leads to the non-trivial dependence of the spin polarization on the bias voltage in the presence of magnetic field.

4. Conclusions

We have performed the self-consistent simulations based on the Wigner–Poisson method to investigate the spin-dependent tunnelling current through the RTD that is formed from the layer heterostructure $Zn_{0.95}Be_{0.05}Se/Zn_{1-x}Mn_xSe/Zn_{0.95}Be_{0.05}Se$. We have analyzed the influence of the magnetic field on the current–voltage characteristics and shown that the sign of the density current polarization can be reversed in the certain region of the bias voltage. For the positive values of the spin polarization we have found the bias voltage windows, in which the spin polarization takes on the nearly constant values. We argue that these bias voltage windows are associated with the negative differential resistance region, in which the "plateau-like" structures occur in the current–voltage characteristics.

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