The spin-dependent electronic transport is investigated in a paramagnetic resonant tunnelling diode formed from Zn1-xMnxSe quantum well embedded between two Zn0.95Mn0.05Se barriers. Spindependent current-voltage characteristics in the presence of the magnetic field have been determined by solving the quantum kinetic equation for the Wigner distribution function and the Poisson equation by the self-consistent procedure. Two distinct peaks due to the giant Zeeman splitting of electronic levels have been obtained on the current-voltage characteristics in a qualitative agreement with experiment. Additionally, nonlinear effects and two types of bistability are also found on the current-voltage characteristics. The nonlinear effects lead to the bistability of the current spin polarisation as a function of the bias voltage and plateaus-like behaviour of the current spin polarisation as a function of the magnetic field.

Model

The paramagnetic resonant tunnelling diode (PMRTD) consisting of Zn1-xMnxSe quantum well sandwiched between two Zn0.95Mn0.05Se barriers is considered. Active region of the nanodevice is separated from n-doped ZnSe contacts by two spacer layers from left and right side, respectively. The sp-d exchange interaction between magnetic moments of the Mn2+ ions in the quantum well and spins of conduction electrons leads to the giant Zeeman splitting in presence of an external magnetic field at temperature lower than the Curie temperature for Zn1-xMnxSe. When the concentration of Mn is small the giant Zeeman splitting can be expressed by the formula [1]:

\[ \Delta E = N_{\text{m}} x \mu_B B \]  \( \tag{1} \)

where \( N_{\text{m}} \) corresponds to the sp-d exchange integral, \( x \) is the concentration of magnetic ions, \( \mu_B \) is the Bohr magneton, \( B \) is the Brillouin function of spin \( s \), \( m_l \) and \( T_{\text{sp-d}} \) are phenomenological parameters. Magnetic properties of Zn1-xMnxSe layer and difference between conduction band minimum of Zn1-xMnxSe and Zn0.95Mn0.05Se forms the spin-quasiparticle potential energy profile presented in Fig. 1.

\[ \sigma(z,B) = \frac{N_{\text{m}} x \mu_B B}{4 \hbar^2 k_F^2} \]  \( \tag{2} \)

Theory

In the first approximation, the transport properties of the nanodevice can be derived from the spin-dependent Wigner distribution function (WDF) by applying two-current model. Taking the z axis along the growth-direction of the layers and assuming the translational invariance in the lateral directions (x,y), the quantum transport equation for spin-dependent WDF can be effectively reduced to the one-dimensional form, namely

\[ \frac{\partial f(z,k)}{\partial z} = \frac{1}{2m^*} \bigg[ \frac{\partial}{\partial k} \tilde{U}^2(z,k) - \frac{e V_b}{h} \tilde{U}(z,k) \bigg] \]  \( \tag{3} \)

where \( m^* \) is the conduction band effective mass, \( \sigma \) is the spin index where the spin index \( \sigma \) corresponds to spin-up (1) and spin-down (2), respectively. The non-local Wigner potential for the spin channel \( \sigma \) is given by the formula

\[ U^\sigma(z,k) = 4 \hbar^2 k_F^2 \int_0^1 dz' \delta' \left[ \tilde{U}^\sigma(z',z,k) \right] \left| \psi_0^\sigma(z',k) \right|^2 \]  \( \tag{4} \)

where \( \tilde{U}^\sigma(z,k) \) is the total spin-dependent potential energy and consists of two parts, namely the spin-dependent conduction and component

\[ \tilde{U}^\sigma(z,k) = \tilde{U}^\sigma_{\text{cond}}(z,k) + \tilde{U}^\sigma_{\text{comp}}(z,k) \]  \( \tag{5} \)

The spin-dependent potential energy \( \tilde{U}^\sigma_{\text{comp}}(z,k) \) and the Hartree potential energy \( \tilde{U}^\sigma_{\text{Hart}}(z) \) is the same as for spin-down component and component

\[ \tilde{U}^\sigma_{\text{Hart}}(z) = \frac{e}{\hbar} \int_0^1 dz' \delta' \left[ \tilde{U}^\sigma(z',z) \right] \left| \psi_0^\sigma(z',k) \right|^2 \]  \( \tag{6} \)

The current-voltage characteristics \( \sigma(V) \) in the presence of the external magnetic field \( B \) for concentration of Mn \( x = 8.3 \% \) in case of the forward bias sweep (FBS) and the backward bias sweep (BBS) are calculated. Two distinct current peaks are observed at the current-voltage characteristics as it is shown in Fig. 2. Origin of these current peaks stems from the giant Zeeman effect of electronic levels in the paramagnetic quantum well and from the dependence on the magnetic field according to formula (1). Let us note that increasing magnetic field shifts the positions of the current maxima for spin-up towards the higher bias voltage while the positions of the current maxima for spin-down are shifted in the direction of the lower bias voltage.

Results

The current-voltage characteristics \( \sigma(V) \) in the presence of the external magnetic field \( B \) for concentration of Mn \( x = 8.3 \% \) in case of the forward bias sweep (FBS) and the backward bias sweep (BBS) are calculated. Two distinct current peaks are observed at the current-voltage characteristics as it is shown in Fig. 2. Origin of these current peaks stems from the giant Zeeman effect of electronic levels in the paramagnetic quantum well and from the dependence on the magnetic field according to formula (1). Let us note that increasing magnetic field shifts the positions of the current maxima for spin-up towards the higher bias voltage while the positions of the current maxima for spin-down are shifted in the direction of the lower bias voltage.

Concluding Remarks

In summary, we have performed the self-consistent simulations based on the Wigner-Poiseau model to investigate the spin-dependent tunnelling current through the resonant tunnelling diode which is formed from the Zn0.95Mn0.05Se/Zn0.95Mn0.05Se/Zn0.95Mn0.05Se layers. Two distinct current peaks corresponding to the spin-up and spin-down components can be observed at the current-voltage characteristics. The proper geometrical parameters of the structure have allowed us to find nonlinear effects including two types of bistabilities in the current-voltage characteristics. Additionally, as a consequence of nonlinear effects, bistability of the current polarisation as a function of the bias voltage and plateaus-like behaviour of the current polarisation as a function of the magnetic field have been predicted.

Acknowledgements

This paper has been supported by the Foundation for Polish Science MPD Programme co-financed by the EU European Regional Development. The spin-dependent electronic transport in paramagnetic resonant tunnelling diode

P. Wójcik*, B. J. Spisak, M. Wołoszyn and J. Adamowski

Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland

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