INNOVATIVE ECONOMY NATIONAL COHESION STRATEGY

FNP Foundation for Polish Science

EUROPEAN UNION EUROPEAN REGIONAL DEVELOPMENT FUND

AGH University of Science and Technology

Simulation of spin dependent electronic transport in paramagnetic resonant tunnelling diode

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

*pelekwojcik@gmail.com

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

The spin–dependent electronic transport is investigated in a paramagnetic resonant tunnelling diode formed from $Zn_{1-x}Mn_xSe$ quantum well embedded between two $Zn_{0.95}Be_{0.05}Se$ layers. Spin-dependent 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 plateau-like behaviour of the current spin polarisation as a function of the magnetic field.

¿¿¿¿¿¿¿¿¿

Oglne uwagi dotyczce tekstu plakatu: (1) uywaj pojcia "paramagnetic RTD" zamiast skrtu PMRTD, (2) pisz raczej "spin polarisation of the current" zamiast "current polarisation".

¿¿¿¿¿¿¿¿

Model

The paramagnetic resonant tunnelling diode (PMRTD) consisting of $Zn_{1-x}Mn_xSe$ quantum well sandwiched between two $Zn_{0.95}Be_{0.05}Se$ 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 Mn^{2+} 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 $Zn_{1-x}Mn_xSe$. When the concentration of Mn is small the giant Zeeman splitting can be expressed by the formula [1]

$$\Delta E = N_0 \alpha x s_0 B_s \left(\frac{s g \mu_B B}{k_B (T + T_{eff})} \right) \quad (1)$$

where $N_0\alpha$ corresponds to the *sp-d* exchange integral, x is the concentration of magnetic ions, g is the Lande factor, μ_B is the Bohr magneton, B_s is the Brillouin function of spin s, s_0 and T_{eff} are phenomenological parameters.

Magnetic properties of $Zn_{1-x}Mn_xSe$ layer and difference between conduction band minimum of $Zn_{1-x}Mn_xSe$ and $Zn_{0.95}Be_{0.05}Se$ forms the spin-dependent potential energy profile presented in Fig. 1.

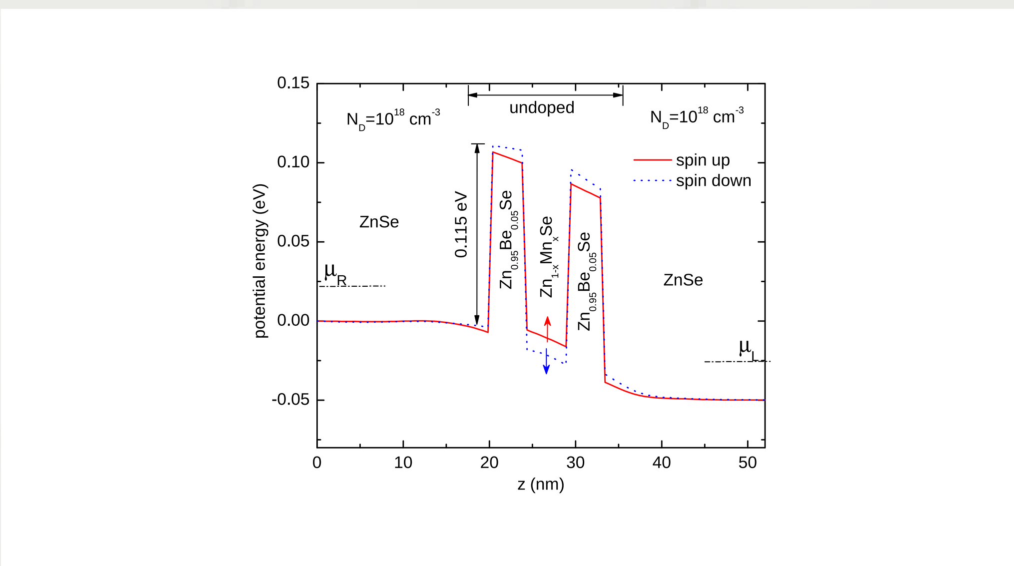

Figure 1. *The self-consistent potential energy profile in the PMRTD for spin up (solid line) and down (dots). The position is measured in the layer growth direction, $\mu_{L(R)}$ is the electrochemical potential of the left (right) doped contact ($N_D = 10^{18}$ cm^{-3}). The external magnetic field is applied along the z axis.*

Theory

In the first approximation, the transport properties of the nanostructure 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, namelyčiteBiegel1996

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

where m is the conduction band effective mass, $\sigma = \pm 1$ is the spin index where the sign $+(-)$ corresponds to spin-up ($\uparrow$) and spin-down ($\downarrow$), respectively. The non-local Wigner potential for the spin channel σ is given by the formula

$$U^w_\sigma(z, k-k') = \int dz' \left[U_\sigma(z+z'/2) - U_\sigma(z-z'/2)\right] \exp\left[-i(k-k')z'\right], \quad (3)$$

where $U_\sigma(z)$ is the total spin-dependent potential energy and consists of two parts, namely the spin-dependent conduction band component $U^0_\sigma(z;B)$ and the Hartree potential energy $U^H_\sigma(z)$.

The conduction band component $U^0_\sigma(z;B)$ has the form

$$U^0_\sigma(z;B) = \sum_{i=1}^{N} U_i \Theta(z-z_i)\Theta(z_{i+1}-z) + \Delta(B)\sum_{j=1}^{M}\Theta(z-z_j)\Theta(z_{j+1}-z), \quad (4)$$

where $z_{i(j)}$ is the position of a barrier-well (paramagnetic–non-magnetic) interface, $\Theta(z - z_{i(j)})$ is the Heaviside step function, U_i is the height of the i-th barrier.

The Hartree potential energy satisfies the Poisson equation

$$\frac{d^2 U^H_\sigma(z)}{dz^2} = \frac{e^2}{\varepsilon_0 \varepsilon}\left[N_D(z) - n_\sigma(z)\right], \quad (5)$$

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

$$n_\sigma(z) = \frac{1}{2\pi}\int dk\, \rho^w_\sigma(z,k). \quad (6)$$

Moreover, the spin-dependent current-voltage characteristics for independent spin channels can be obtained from the current density formula, namely

$$j_\sigma(z) = \frac{e}{2\pi}\int dk\, \frac{\hbar k}{m}\rho^w_\sigma(z,k). \quad (7)$$

The quantum kinetic equation (2) and Poisson equation (5) coupled through the electron density (6) constitute a nonlinear problem which is solved numerically by a self-consistent procedure.

Results

The current–voltage characteristics $I(V_b)$ in the presence of the external magnetic field B, for concentration of Mn $x = 8.3$ % and 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.

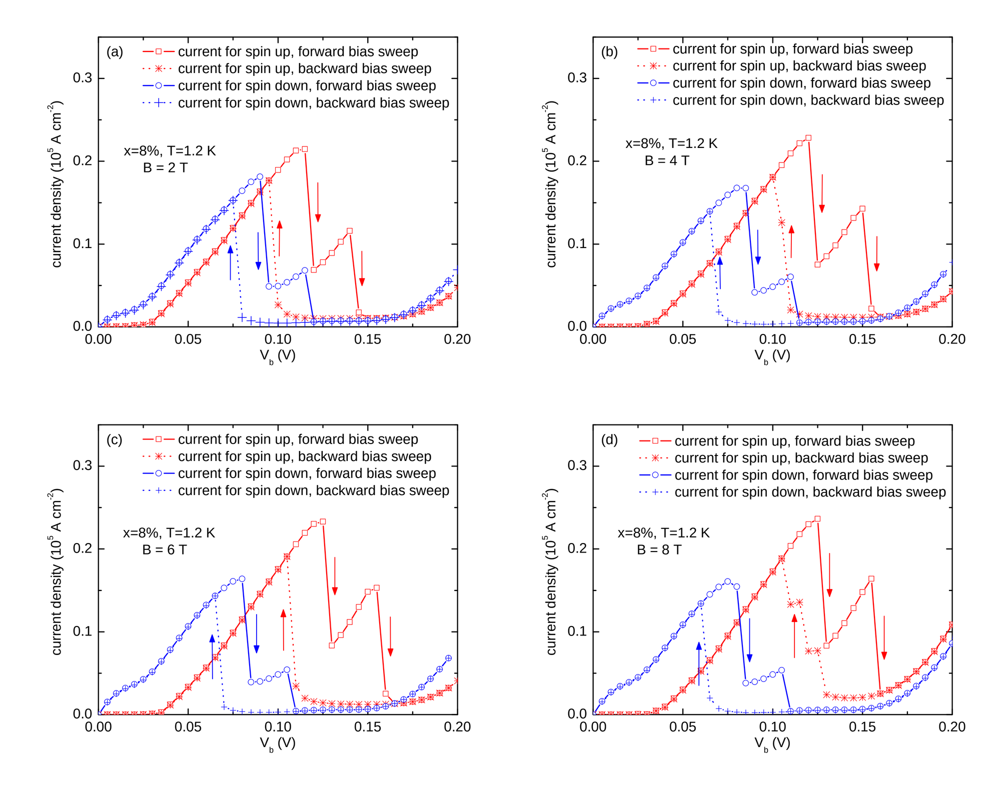

Figure 2. *The current-voltage characteristics of PMRTD for spin up and down components calculated for the concentration of magnetic dopants $x = 8.3\%$ and the magnetic field (a) $B = 2$ T (b) $B = 4$ T, (c) $B = 6$ T and (d) $B = 8$ T. Forward and backward bias sweeps are marked by solid and dotted lines, respectively.*

In Fig. 3 we present electron density distribution in the nanostructure for the magnetic field $B = 6$ T and the bias voltage $V_b = 0.075$ V corresponding to the current maxima for spin up component and $V_b = 0.12$ V corresponding to the current maxima for spin down component. At $V_b = 0.12$ V, high concentration of spin-up electrons and simultaneously depletion of spin-down electrons in the quantum well can be observed. This indicates that the resonance conditions are satisfied only for spin up component. The opposite situation occurs for $V_b = 0.075$ V where stronger accumulation of spin-down electrons can be observed indicating the resonance conditions are satisfied for spin down component. Fig. 2 shows that the current–voltage characteristics obtained for the increasing bias (solid curves) differ from those for the decreasing bias (dashed curves) for both spins and all values of magnetic field. Two types of bistability may be distinguished: occurring before and after resonant peak. The physical processes standing behind these two types of bistability are completely different. The bistability occurring before resonant peak is due to charge accumulation in the paramagnetic quantum well while the second one, called plateau-like structure is due to charge accumulation in the region of the left contact (see Fig. 4)

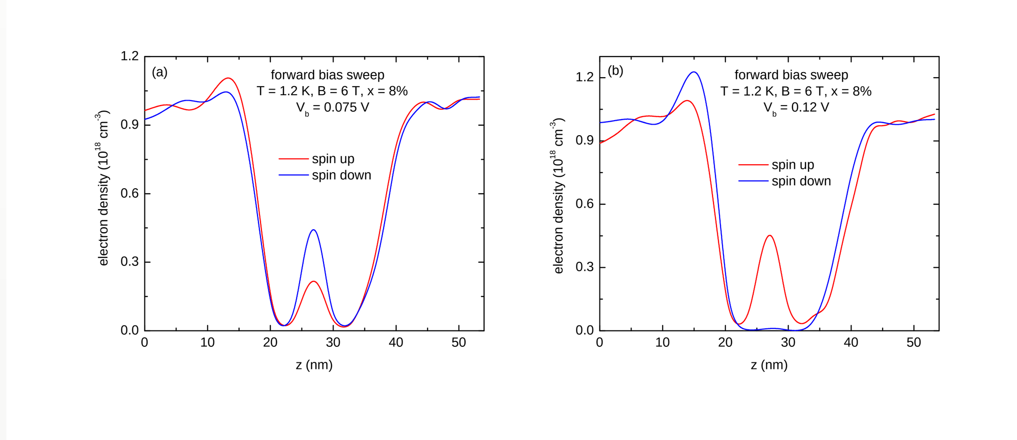

Figure 3. *Electron density distribution calculated for the magnetic field $B = 6$ T and (a) $V_b = 0.075$ V related to current maxima for spin down, (b) $V_b = 0.12$ V related to the current maxima for spin up in the case of FBS.*

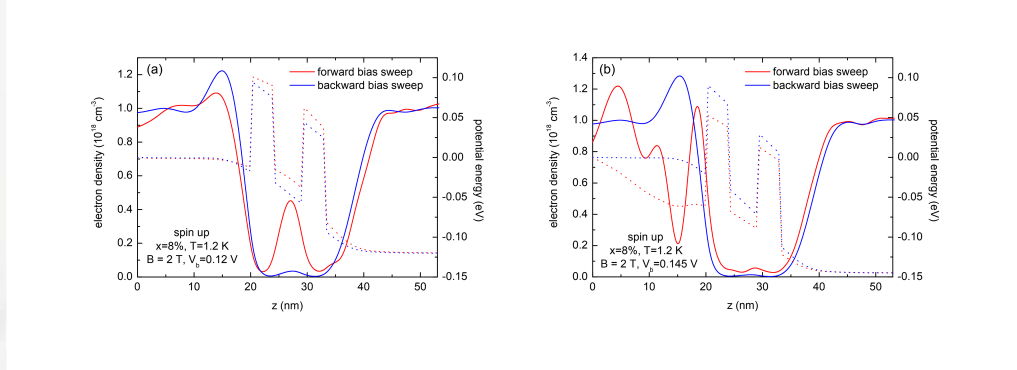

Figure 4. *Electron density distribution and potential energy profile for the magnetic field $B = 6$ T, spin up, and $V_b = 0.12$ V related to bistability occurring before resonant peak (a) and $V_b = 0.145$ V related to bistability occurring after resonant peak (b).*

The bistability phenomena of current–voltage characteristic described above have a meaningful influence on current polarisation in the PMRTD. In Fig. 5(a)(b) current polarisation as a function of the bias voltage in the FBS and BBS case and as a function of the magnetic field in the FBS case is presented. All of these curves exhibit the bias voltage windows, where the nearly constant value of the current density polarisation is observed for different magnetic fields. This is a consequence of the plateau-like structure which emerges in the region of the negative differential resistance at the current–voltage characteristics.

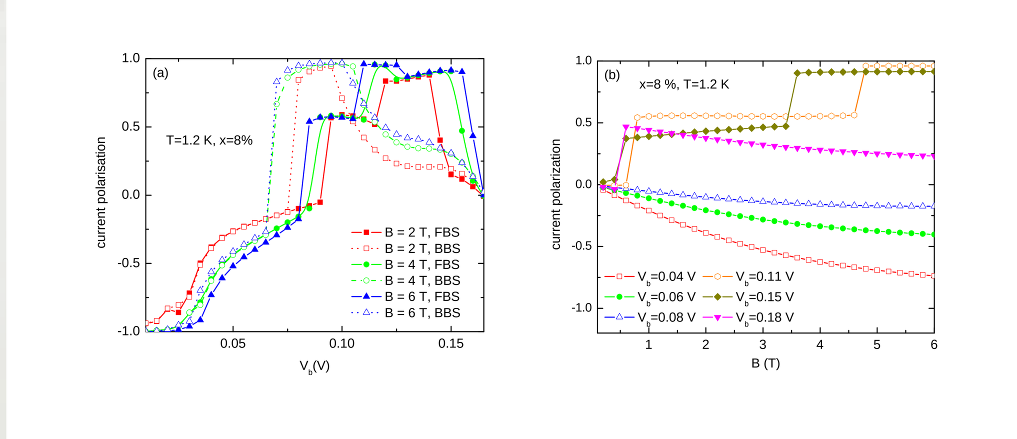

Figure 5. *Current polarisation as a function of (a) the bias voltage in the FBS and BBS case, (b) the magnetic field for FBS at fixed bias voltage.*

Concluding Remarks

In summary, we have performed the self-consistent simulations based on the Wigner-Poisson model to investigate the spin-dependent tunnelling current through the resonant tunnelling diode which is formed from the $Zn_{0.95}Be_{0.05}Se/Zn_{1-x}Mn_xSe/Zn_{0.95}Be_{0.05}Se$ 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 plateau-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.

References

[1] Slobodskyy A, Gould C, Slobodskyy T, Becker C R, Schmidt G and Molenkamp L W 2003 *Phys. Rev. Lett.* **90** 246601

[2] Biegel B A and Plummer J D 1996 *Phys. Rev. B* **54** 8070