Resonant tunneling magnetoresistance in coupled quantum wells

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A three barrier resonant tunneling structure in which the two quantum wells are formed by a magnetic semiconductor is theoretically investigated. Self-consistent numerical simulations of the structure predict giant magnetocurrent in the resonant bias regime as well as significant current spin polarization for a considerable range of applied biases. The requirements for large magnetocurrent are spin resolved resonance levels as well as asymmetry (spatial or magnetic) of the coupled quantum wells. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2402878]

Semiconductor spintronics offers additional functionalities to the existing electronics technology by combining charge and spin properties of the current carriers.[1] Spin dependent resonant tunneling in double barrier heterostructures has been investigated both experimentally and theoretically with a magnetic quantum well (QW) made of semimetallic ErAs (Refs. 2 and 3) or dilute magnetic semiconductors (DMSs) such as GaMnAs (Refs. 4–9) or ZnMnSe (Refs. 10 and 11). Such diodes have been used as spin filters or spin detectors and effective injection of spin-polarized electrons into semiconductors has been demonstrated by employing interband tunneling devices based on GaMnSb.[12,13] A theoretical investigation of resonant tunneling through a nonmagnetic double barrier structure, e.g., AlAs/GaAs/AlAs, sandwiched between two bulk ferromagnetic DMSs, e.g., GaMnAs, shows a tremendous enhancement of the tunneling magnetoresistance (TMR) for low voltages if the thickness of the QW is properly tuned.[14] The effect has been demonstrated to be as high as 10 000% for generic parabolic bands and when including a more realistic *kp* band structure model still very high TMRs of about 800% have been obtained.[14] Such structures have already been grown and studied experimentally.[4,15,16]

Here we propose to use magnetic resonant tunneling diodes (RTDs) comprising coupled magnetic QWs and three nonmagnetic barriers, as spintronic devices offering large magnetocurrents (MCs). Corresponding nonmagnetic three barrier structures have been experimentally studied,[17–20] while electric field domain formation in magnetic multiple QWs was theoretically investigated in Ref. 21. The magnetic three barrier structure allows to establish parallel (P) and antiparallel (AP) magnetization configurations and to observe MC. The QWs are assumed to be made of ferromagnetic semiconductors.[5,22] We consider here generic parabolic *n*-type ferromagnetic QWs, though one expects to observe similar effects in coupled *p*-type ferromagnetic QWs. Several suitable *n*-type ferromagnetic semiconductors have been reported:[1] $HgCr_2Se_4$,[23] $CdCr_2Se_4$,[24] $CdMnGeP_2$,[25] or most promising ZnO and GaMnN;[22,27] the latter two are believed to exhibit room temperature (RT) ferromagnetism. To be specific we perform our numerical simulations for GaMnN-based structures.

However, it is still controversial if the reported RT ferromagnetism in transition metal doped GaN and ZnO is due to non-resolved precipitates or not. On the theoretical side several mechanisms have been proposed to be responsible for the observed ferromagnetic order.[26,27] What is needed for the functioning of our proposed device is a conduction band splitting of the order of 10 meV, regardless of the underlying mechanism. Experimental data suggest that the exchange splitting of the conduction band in GaMnN is about a few tens of meV[28] and that the ferromagnetic order sustains in thin layers of a few nanometer width.[28,29]

Performing realistic self-consistent calculations of the I-V characteristics we predict large magnetocurrents (MC=50 000% for a moderate spin splitting of 10 meV) at resonant voltages. These large values appear because of the suppression of the resonant tunneling due to the energy mismatch for the resonant levels of the coupled wells in the AP configuration. Although the predicted effect is rather robust, we provide hints on how to further tune the heterostructure parameters to maximize the MC.

We investigate a three barrier semiconductor heterostructure based on a GaN/$Al_{1-x}Ga_xN$/GaMnN material system. The conduction band profile at zero bias is schematically shown in Fig. 1. Assuming $x=9\%$ yields a barrier height of about 100 meV.[30] The whole structure is considered to be sandwiched between two leads consisting of n-doped GaN ($n=1.4\times10^{18}$ cm^{-3}) of 12 nm width. The effect of the polarization charges at the interfaces[30] is neglected and all simulations are performed at low temperatures $T=4.2$ K. We include 3 nm thick undoped GaN buffer layers between the leads and the active structure, which causes an upward band bending at zero bias.

Following the classic treatments of (two barriers) RTDs,[31–33] we assume coherent transport throughout the

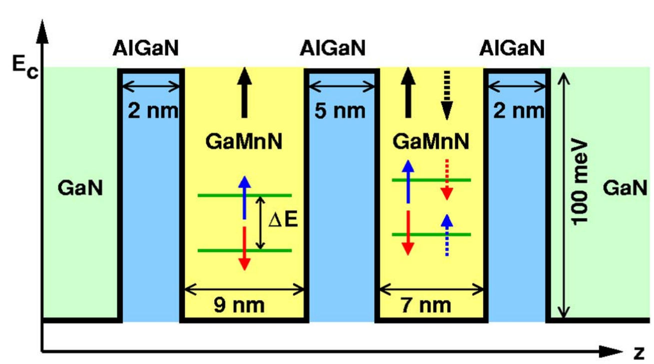

FIG. 1. (Color online) Schematic conduction band profile of an all semiconductor three barrier heterostructure comprising either paramagnetic (ZnMnSe) or ferromagnetic (GaMnN) quantum wells. The quasibound states in the quantum wells are splitted in spin up and down levels.

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whole active region. We calculate the spin dependent current flow by numerically solving the conduction band effective mass Schrödinger equation taking into account the spin dependent potential energy,

$$U_i(z) - e\phi(z) + \sigma\Delta E(z). \tag{1}$$

Here, U_i is the intrinsic conduction band profile, e is the elementary charge, and $\sigma=\pm 1/2, (\uparrow, \downarrow)$ labels the spin quantum number. The electrostatic potential ϕ is obtained from the Poisson equation, which is solved together with the Schrödinger equation in a self-consistent way. The current density of electrons with spin σ is calculated by

$$j_\sigma = \frac{e}{(2\pi)^3}\int d^3k v_z T_\sigma(E_l,E_t)[f(E) - f(E+eV_a)], \tag{2}$$

where E_l and E_t are, respectively, the longitudinal and transverse components of the electron total energy E, V_a denotes the applied voltage, $T_\sigma(E_l,E_t)$ is the electron transmission function, v_z labels the longitudinal component of the electron group velocity, and $f(E)=1/[1+\exp(E-E_f)/k_BT]$ is the Fermi function at the lattice temperature T with the Fermi energy E_f and the Boltzmann constant k_B. Assuming parabolic bands and using the same effective mass $m_*/m_0=0.228$ (Ref. 30) (with m_0 denoting the free electron mass) for all layers of the heterostructure, the transmission function only depends on the longitudinal energy, $T(E_l,E_t)=T(E_l)$. This allows to reduce Eq. (2) to the Tsu-Esaki formula.[34] The current spin polarization is then determined by $P_j=(j_\uparrow - j_\downarrow)/(j_\uparrow + j_\downarrow)$.

We assume that the magnetization of the first QW is fixed, whereas the second is "soft," which means that it is sensitive to local changes of an external magnetic field. Hence, a MC can be defined as the relative difference of the current I for P and AP alignments of the magnetization of the two QWs, $\mathrm{MC}=(I_\mathrm{P}-I_\mathrm{AP})/I_\mathrm{AP}$. The proposed structure aims in producing very high MCs based on the following idea of operation. High resonant tunneling throughout the whole structure is possible if the middle barrier is thin enough and if two quasibound states of the same spin of the adjacent QWs are aligned energetically. Such resonant condition for the lowest energy states in the case of P magnetization is illustrated in the inset of Fig. 2. The inset shows the local density of states of the conduction electrons and clearly demonstrates the exchange splitting of the quasibound states into spin up and spin down states. Here, the orientation of the magnetic field is assumed such that the spin down (up) energy levels are shifted downwards (upwards) in energy. Due to the interaction of the two QWs the resonant energy levels are further split into bonding and antibonding states. The splitting is observable in the local density of states if it is greater than the natural energy broadening of the quasibound state. For our structure the middle barrier is too thick to resolve this additional splitting in the plot of the local density of states. The inset of Fig. 2 also shows higher quasibound states at about 60 and 110 meV, which are, however, not in resonance.

In the case of P magnetization the spin up and down quasibound states are equally shifted in both QWs, whereas for AP alignment they are shifted energetically in opposite directions. Assuming QWs of the same width, i.e., with the same quasibound energy spectrum, there are hence at equilibrium open resonant conduction channels for the P alignment, whereas the transmission is blocked for the AP configuration. However, when a small finite voltage is applied to the structure the resonant channels of the P magnetization are "destroyed," since the energy levels of the second QW are shifted more deeply to lower energies than those of the first QW by the applied bias. To overcome this shortcoming, we propose to use asymmetric QWs. Here, we take the second QW to be thinner than the first one. This gives rise to a higher ground state energy in the second QW and the resonant condition is therefore adjusted at a finite voltage, leading to high currents. Alternatively, one can use a material with a different spin splitting to fulfill the asymmetry condition.

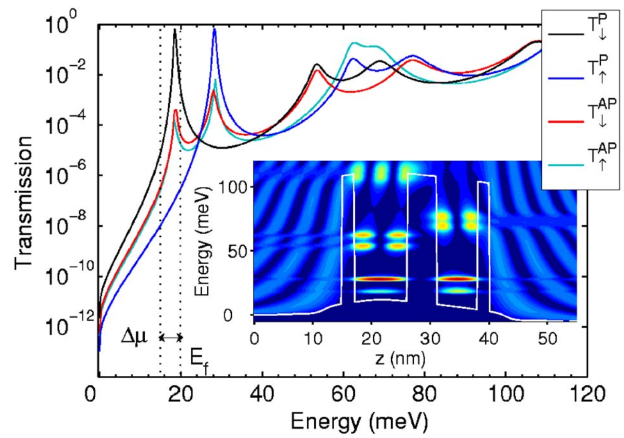

FIG. 2. (Color online) Spin resolved energy dependent transmission function at $T=4.2$ K for parallel (P) and antiparallel (AP) magnetizations in the case of a given exchange splitting of $\Delta E=10$ meV and a resonant applied voltage of $V_a=5$ meV. The inset shows a contour plot of the local density of states vs energy and growth direction z at resonance ($V_a=5$ mV) for parallel magnetization and $\Delta E=10$ meV. The solid line indicates the self-consistent conduction band profile. The higher quasibound states (at about 60 and 110 meV) are not in resonance.

In order to maximize the MC we pursue the following strategy for determining the different layer widths. At low temperatures the current is given, in good approximation, by the quadrature of the transmission function over the energy window $\Delta\mu=[E_f-eV_a,E_f]$. To obtain high currents for the P alignment, the layer widths should be chosen such that the resonant tunneling condition, $T(E)\approx 1$, is fulfilled at a finite voltage for energies belonging to the interval $\Delta\mu$. On the other hand, for the AP configuration the transmission function should be made as small as possible in the energy window $\Delta\mu$. To meet both demands at the same time, we use a relatively thin middle barrier, which effectively controls the coupling of the QWs. Figure 2 shows the spin resolved transmission function versus energy for the resonant voltage $V_a=5$ mV. The double peak structure of the transmission function for the AP configuration corresponds to the lowest quasibound state in both QWs, which have in that case different energies leading to two "half-resonances." The transmission for the AP alignment can be strongly hampered by choosing thick QWs. The variation of the thickness of the first and third barriers barely influences the MC, since the transmission is then either reduced or increased for both P and AP magnetizations. By changing the buffer layer thicknesses one can tune the amount of band bending and hence the relative position of the quasibound energies to the Fermi level. The dimensions of the structure finally used in our numerical calculations are indicated in Fig. 1.

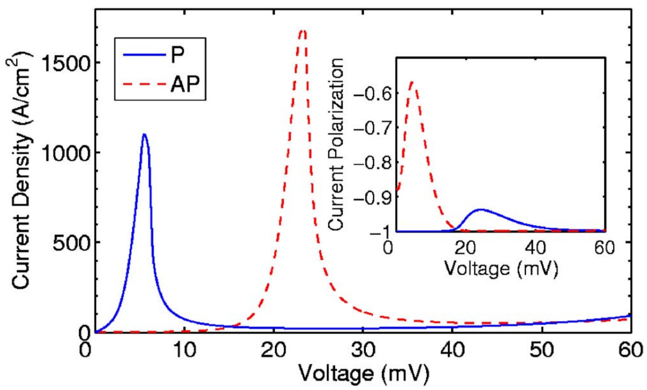

FIG. 3. (Color online) Current-voltage characteristics of the structure for parallel (P) and antiparallel (AP) magnetizations at the temperature $T=4.2$ K and the exchange splitting of $\Delta E=10$ meV. The inset displays the current polarization as a function of the applied voltage.

The obtained current-voltage characteristics for P and AP magnetizations and a fixed exchange splitting of $\Delta E=10$ meV are displayed in Fig. 3. In the case of P magnetization, the lowest quasibound energy levels of the adjacent QWs are already aligned at a small voltage of about 5 mV, whereas for the AP configuration a much higher voltage is necessary to obtain resonant tunneling. The current spin polarization is plotted in the inset of Fig. 3. Since the spin down state has a lower energy than the spin up state, the current for P magnetization is almost all spin down polarized at low voltages. For higher voltages also spin up states contribute to the current thereby diminishing the polarization. In the case of AP magnetization, spin up current can flow at low voltages due to the lowest spin up state in the second QW. By increasing the voltage this state gets off resonance, which leads again to significant spin down polarization. The obtained MCs for different exchange splittings are shown in Fig. 4. The transmission for AP magnetization is strongly reduced by increasing the energy splitting ΔE. Hence, the current for AP magnetization becomes very small at the peak voltage of the P configuration and our simulations reveal very high MCs up to 5000 for reasonable spin splitting. Simulations performed at a higher temperature $T=100$ K show that the MC is reduced to about 20% of its value at $T=4.2$ K. Although the temperature effect is quite large, the MC remains significant.

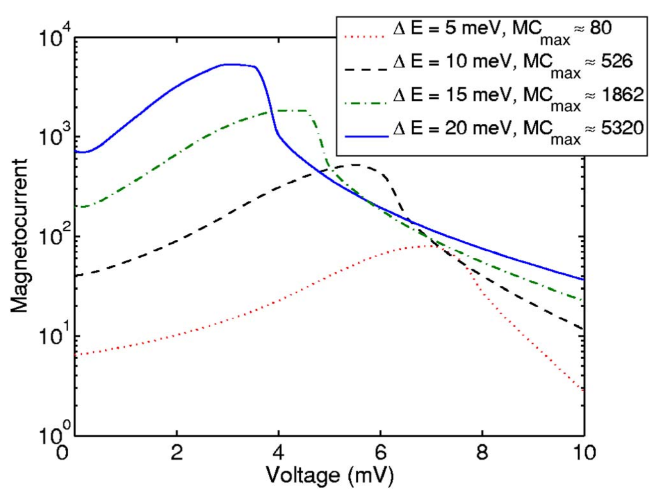

FIG. 4. (Color online) Magnetocurrent (MC) as a function of applied voltage for different exchange splittings ΔE.

To summarize, we have numerically investigated an all semiconductor three barrier resonant tunneling structure, comprising two QWs made of a magnetic material. Our simulations predict very high MCs demonstrating the device potential of the proposed structure.

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