Magnitude of Magnetic Field Dependence of a Possible Selective Spin Filter in ZnSe/Zn$_{1-x}$Mn$_x$Se Multilayer Heterostructure

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Abstract

Spin-polarized transport through a band-gap-matched ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe multilayer structure is investigated. The resonant transport is shown to occur at different energies for different spins owing to the split of spin subbands in the paramagnetic layers. It is found that the polarization of current density can be reversed in a certain range of magnetic field, with the peak of polarization moving towards a stronger magnetic field for increasing the width of central ZnSe layer while shifting towards an opposite direction for increasing the width of paramagnetic layer. The reversal is limited in a small-size system. A strong suppression of the spin up component of the current density is present at high magnetic field. It is expected that such a reversal of the polarization could act as a possible mechanism for a selective spin filter device.

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It is indispensable to realize the effective spin-polarized electrons injection (spin injection) into semiconductor for spin-related semiconductor devices, such as spin transistors [1], etc. Two groups have been able to demonstrate the efficient spin injection into GaAs using semiferrimagnetic BeMnZnSe [2] and ferromagnetic GaMnAs epilayers [3], respectively. Physics governing spin injection and detection into semiconductor is now being understood [4, 5, 6]. More recently, new attempts to realize the devices where the spin character of the injected and detected electrons could be voltage selected [7], have been made. A magnetic resonant tunneling diode (RTD) is considered, in which the semiferrimagnetic Zn$_{1-x}$Mn$_x$Se is used as the spin-splitted well. Bias-dependent current polarization or spin filter can be expected, and the results demonstrate the possibility of devices based on tunneling through spin resolved energy levels. Theoretically, the spin-dependent tunneling through a similar structure is investigated by Sugakov et al. [8], and Egues et al. [9]. In this paper, we shall explore a magnetic field tunable structure, ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe. The Mn concentration in the paramagnetic layer (PL) is chosen so that the offsets of conduction and valence bands are nearly zero in the absence of an applied magnetic field, and the alternation of ZnSe and Zn$_{1-x}$Mn$_x$Se may be used to build up the spin superlattice. The results show an interesting phenomenon that reversal polarization of current density can be induced by tuning the magnitude, not its direction, of magnetic field because of resonant tunneling effect. In other words, spin injection can be selected by the magnitude of magnetic field.

Mn- or Fe-based spin superlattices were proposed by von Ortenberg [10], and realized by Chou et al. [11] and Dai et al. [12]. Time-resolved photoluminescence spectroscopy was used to investigate exciton lifetime and spin relaxation in magnetic semiconductor spin superlattices [13]. Egues [14] investigated spin filtering in a ZnSe/Zn$_{1-x}$Mn$_x$Se heterojunction with a single paramagnetic layer (SPL), and observed a strong suppression of the spin up component of the current density for increasing magnetic field. Guo et al. [15] investigated the bias-dependent spin transport in a SPL structure and spin filtering in ZnSe/Zn$_{1-x}$Mn$_x$Se with double paramagnetic layers (DPL). Theoretical investigations, as above mentioned, have not given a complete description about the size-dependence of spin transport, while the spin-dependent transport in these heterostructures is quite sensitive to size. So, it is our purpose to focus on this issue, and a DPL structure will be considered below.

Let us consider the conduction electron transport through a magnetic field tunable heterojunction such as ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe/Zn$_{1-x}$Mn$_x$Se/ZnSe with DPL, in which
$sp-d$ exchange interaction gives rise to a spin-dependent potential \[ V_{\sigma_z}(z) = -x N_0 \alpha \sigma_z \langle S_z \rangle [\Theta(z + W_L) - \Theta(z - b) \Theta(b + W_R - z)] \] in the Hamiltonian of the system. Here $N_0 \alpha$ is the electron $s$-$d$ exchange constant, $x$ is the Mn concentration, $\sigma_z$ are the electron spin components $\pm 1/2$ (or $\uparrow$, $\downarrow$) along the field, $\langle S_z \rangle$ is the thermal average of the $z$-th component of a Mn$^{2+}$ spin (a $5/2$ Brillouin function), $\Theta(z)$ is the Heaviside function, $W_L(R)$ is the width of left (right) Zn$_{1-x}$Mn$_x$Se layer, and $b$ is the width of the central ZnSe layer. The transmission coefficient (TC) of the single Zn$_{1-x}$Mn$_x$Se layer structure can be obtained by using the transfer matrix method \[ T_{\uparrow(\downarrow)} \text{ tot}(E) = \frac{T_{\uparrow(\downarrow)}^L T_{\uparrow(\downarrow)}^R}{(1 - \sqrt{R_{L}^{\uparrow(\downarrow)} R_{R}^{\uparrow(\downarrow)}})^2 + 4 \sqrt{R_{L}^{\uparrow(\downarrow)} R_{R}^{\uparrow(\downarrow)}} \cos^2 \phi_{\uparrow(\downarrow)}} \], (1)

where $\phi_{\uparrow(\downarrow)} = \theta_{\uparrow(\downarrow)}^L/2 - kb$ with $\theta_{\uparrow(\downarrow)}^L$ the phase of the 11 element of the transfer matrix of the SPL structure, and $k$ the wavevector in the ZnSe layer (we neglect the spin-dependent of the wavevector in layer ZnSe, for the split of the spin up and down induced by a magnetic field is small), $T_{\uparrow(\downarrow)}^L$ is the TC for a SPL structure and $L$ denotes the left PL in the DPL structure, $R_{L}^{\uparrow(\downarrow)}$ is the reflection coefficient. In the following, some parameters are assumed: the effective mass of electron $m^*_e = 0.16 m_e$ with $m_e$ the mass of bare electron, $W_L = W_R = W$, and an effective Mn concentration $x_{\text{eff}} = x(1-x)^{1/2}$ to account for the antiferromagnetic clustering effects \[ 14].

The degeneracy of spin subbands is removed because of the $sp-d$ exchange interaction in a PL, and a spin-dependent potential is induced. Up(down)-spin electrons see a barrier (well) in a PL. For a DPL structure, up(down)-spin electrons see a double-barrier (-well) structure (DB(W)S). The system under interest is a combination of DBS and DWS for different spin orientations simultaneously. Different phases $\theta_{\uparrow(\downarrow)}^L$ for a SPL structure give rise to different phases $\phi_{\uparrow(\downarrow)}$ for a DPL structure. The resonant transport can occur at $\phi_{\uparrow(\downarrow)} = (2n + 1)\pi/2$. This condition determines a splitting resonant energies $E_{n}^{\uparrow}$ and $E_{n}^{\downarrow}$ for up-spin and down-spin electrons, respectively.

For incident energies $E_z < x |\langle S_z \rangle| N_0 \alpha/2$, the wave of up-spin electrons is evanescent in the PL. However, the TC can be considerable for a DBS at the resonant tunneling case, which can even approach to unity when the system is symmetric. This feature is obvious, as shown in Fig. 1(a), and the lines of $n = 0$, $n = -1$ and $n = -2$ are displayed in Fig. 1(b). The crossing points of $\phi_{\uparrow}$ and these lines will determine the resonant tunneling energies or the quasi-bound states in the central ZnSe well. With increasing $b$, the position of the
FIG. 1: (color on line) The transmission coefficient $T_{\text{tot}}^\uparrow$ and the phase $\phi_\uparrow$ as functions of electron energy $E_z$. (a) $\log_{10}(T_{\text{tot}}^\uparrow)$; (b) $\phi_\uparrow$; (c) $T_{\text{tot}}^\downarrow$; (d) $\phi_\downarrow$. The parameters are taken as $W = 100$ Å, $B = 1$ T, $S = 5/2$, $\Theta = 1.32$ (Curie-Weiss temperature), $N_0\alpha = 0.26$ and $x = 0.06$.

quasi-bound states goes down (see $E_{\uparrow}^1$). This tendency gives rise to a shift of the resonant peaks of TCs to lower energies with increasing $b$, as shown in Fig. 1(a). For instance, when $b = 100$ Å, 150 Å, 180 Å, then $E_{\uparrow}^0 = 8.155$ meV, 3.663 meV, 2.257 meV, respectively. Recall that this feature is also present in the conventional semiconductor RTD [18, 20].

The energy-dependence of $T_{\text{tot}}^\downarrow$ and $\phi_\downarrow$ is depicted in Figs. 1(c) and (d), respectively. The TCs increase with increasing $E_z$ and approach to unity when the conditions $\phi_\downarrow = (2n+1)\pi/2$ or $T_{L(R)}^{\downarrow} = 1$ and $b = W_{L(R)} = W$ are satisfied (as in the case $b = 100$ Å), while the resonant peaks move to lower energies: as $b = 150$ Å, 180 Å, 200 Å, $E_{\downarrow}^1 = 5.257$ meV, 2.892 meV, and 2.099 meV, respectively. Because of the split of resonant energies $E_{\uparrow}^n$ and $E_{\downarrow}^n$, the TC of up-spin electrons at the resonant energy may be larger than that of down-spin electrons at the same energy (which may be the off-resonant energies for down-spin electrons). This character will lead to a split of the current density for different spin orientations, and may be the origin of the reversal of polarization (see below).
FIG. 2: (color on line) The magnetic field dependence of \( \log_{10}(T^\uparrow_{\text{tot}}) \) (a) and \( T^\downarrow_{\text{tot}} \) (b), where \( W = 100 \, \text{Å} \), and \( E_z = 1 \, \text{meV} \). The transmission coefficient \( \log_{10}(T^\uparrow_{\text{tot}}) \) (c) and \( T^\downarrow_{\text{tot}} \) (d) versus the width of the paramagnetic layer \( W \) for different \( b \), where \( B = 1 \, \text{T} \), and \( E_z = 4 \, \text{meV} \). The other parameters are the same as those in Fig. 1.

Increasing the magnetic field will lead to a higher barrier for up-spin electrons while to a deeper well for down-spin electrons, giving rise to the probability that the up-spin electrons penetrate into the barrier will be lowered. As a result, the up-spin electrons prefer staying in the ZnSe layer, while down-spin electrons prefer staying in the semimagnetic semiconductor layer, coined as spin superlattice \([10, 11, 12]\). This manifests itself as the decreasing of TC for up spin except the resonant peaks and may raise the positions of the quasi-bound states as well as the phase \( \phi^\uparrow \) in the central ZnSe layer. For wider central ZnSe layer, stronger magnetic field is needed to raise the quasi-bound states to match the incident energy and generate a resonance. So the resonant peaks of \( T^\uparrow_{\text{tot}} \) shift to a larger \( B \) with increasing \( b \), as shown in Fig. 2(a). The variation of \( T^\downarrow_{\text{tot}} \) with \( B \) is depicted in Fig. 2(b). The \( b \)-dependence of the resonant peaks for down-spin electrons seems to be opposite to that for up-spin electrons, i.e. the peaks shift towards lower \( B \). It is observed that the phase \( \phi^\downarrow \)
decreases with increasing the magnetic field.

The $W$ dependence of $T^{↑,↓}_{\text{tot}}$ is shown in Figs. 2(c) and (d). Apart from a few sharp resonances, $T^{↑}_{\text{tot}}$ is overall decreasing with increasing $W$ because of the evanescent wave in the barrier. For down-spin electrons, $T^{↓}_{\text{tot}}$ is oscillating with increasing $W$, and the crossing points where the total TCs are unity, are observed at particular $W$’s for different $b$. This latter property occurs because the TCs of SPL structure are unity (i.e. $T^{↑}_L = T^{↓}_R = 1$), implying that the SPL is completely transparent for down-spin electrons, and the electrons travel through it without any reflections.

Now let us investigate the polarized current density through the DPL structure. It is necessary to sum the contribution of discrete Landau levels $n$ which are filled to Fermi energy. The spin-dependent current density $J^{↑}_1$ ($J^{↓}_1$) can be calculated in the manner similar to that in Ref. [14]. A small-bias limit, i.e. $eV = E_f \approx 5$ meV, is assumed for numerical calculation, and let $J_0 \equiv e^2/4\pi^2\hbar^2c$. To evaluate the spin-polarized effect on the current density, it is useful to get the spin polarization of the transmitted beam which is defined as

$$P = \frac{J^{↑}_1(B) - J^{↓}_1(B)}{J^{↑}_1(B) + J^{↓}_1(B)}.$$

The magnetic field dependence of the current density $J^{↑}_1$ ($J^{↓}_1$) and the current polarization $P$ are shown in Fig. 3. The variation of the current density with the magnetic field under consideration is not very similar to that in Ref. [15], but it also depends closely on features of $T^{↑(↓)}_{\text{tot}}$. $J^{↑}_1$ (dotted lines in Fig. 3(a) and (c)) first decreases, then goes to a maximum, and then decreases almost to vanishing with increasing $B$. The quasi-bound resonances manifest themselves in $J^{↑}_1$ by resonant peaks which vary with $b$. The resonant peaks corresponding to larger $b$ appear at larger $B$. However, for a very large $b$ (e.g. $b = 500$ Å [15] or 1000 Å [14]), the current density for spin up decreases exponentially with increasing the magnetic field and the resonant peaks are almost vanished. $J^{↓}_1$ (solid lines in Fig. 3(a) and (c)) is not strongly suppressed by $B$ because the wave functions of down-spin electrons are traveling waves. The suppression of up-spin component leads almost to a perfect spin filter effect at a stronger magnetic field [15], i.e. only down-spin electrons transmit and $P$ is almost equal to $-1$ (Fig. 3(b)).

The split of $J^{↑}_1$ and $J^{↓}_1$ induced by the split of the phases of different spin components leads to the polarization of the transmitted current density. It makes $J^{↑}_1$ larger than $J^{↓}_1$ at certain range of $b$, and $P$ will be positive, as shown in Fig. 3(b). It can be seen that the
FIG. 3: (color on line) Current density $J_\uparrow (J_\downarrow)$ and the polarization $P$ versus the magnetic field for different $b$ in (a) and (b) and for different $W$ in (c) and (d), dot (solid) lines for $J_\uparrow (J_\downarrow)$ in (a) and (c). In (a), the digits sitting on the curves in (a) are magnitudes of $b$ correspond to $b = 2, 3, 4$ nm, respectively. And $W = 100$ Å in (a) and (b). In (c), the digits correspond to $W = 8, 9, 10, 11$ nm, respectively. $b = 40$ Å in (c) and (d). $E_f = 5$ meV for all the four figures and the other parameters are the same as those in Fig. 1.

Polarization $P$ is reversed from negative to positive for increasing $B$, and approaches to its maximum, then decreases to $-1$. This reversal of $P$ exists in a distinct wide range of $B$ for appropriate $b$. $P$ tends to $-1$ for a stronger magnetic field, suggesting a perfect spin filter effect. The peaks of $P$ move to larger $B$ for increasing $b$ corresponding to the shift of the resonant peaks of TC with $B$ in Fig. 2(a). The similar $B$ dependence of $J_\uparrow (J_\downarrow)$ and $P$ are shown in Fig. 3(c) and (d) at different $W$. It can be found that the resonant peaks move to weaker magnetic field for increasing $W$. This tendency is just opposite to the shift of peaks with increasing $b$ in Fig. 3(a) and (b). This is owing to the opposite $W$ and $b$ dependence of the phase $\phi$. The reversal of the polarization disappear when the width of PL is small and very large.
The positive $P$ exists in a certain size of the system. To substantiate this point, we show a contour plot of a 3D graph in which the $z$ axis is the largest $P$ in a range $B \in [0, 2T]$ for a fixed $b$ and $W$ in Fig. 4. A positive maximum $P$ means that there is the reversal of $P$ in the range $B \in [0, 2T]$ which is the bright region in Fig. 4. On the contrary, the dark region means there is no the reversal of the polarization of the current. It is interesting to note that the reversal is limited to a finite region where the layers should be thin, and thicker layers may suppress this effect. It may be caused by the splitting of the resonant transport for different spin orientations.

FIG. 4: (color on line) A contour plot of the maximum $P$ in $[0, 2T]$ versus $b$ and $W$, where $E_f = 5$ meV, and the others are the same as those in Fig. 1.

In summary, the spin-polarized transport through a band-gap-matched $\text{ZnSe/Zn}_{1-x}\text{Mn}_x\text{Se/ZnSe/Zn}_{1-x}\text{Mn}_x\text{Se/ZnSe}$ multilayer structure is investigated. In an external magnetic field, the paramagnetic layers serve as barriers for up-spin electrons and wells for down-spin electrons simultaneously. The system under interest is then the combination of a DBS for up-spin electrons and a DWS for down-spin electrons. The resonant transport will occur at different energies for electrons with different spins because of
the split of the energy levels in the layers. The phases $\phi_{\uparrow,\downarrow}$ also split, and $\phi_{\uparrow(\downarrow)} = (2n+1)\pi/2$ determines the resonant energies manifested itself in the transmission coefficients for up-spin and down-spin electrons. The consequent result is that the polarization of the current density can be reversed in a certain range of magnetic fields. It should be pointed out that the reversal results from the splitting of the resonant transport through DBS and DWS. This reversal mechanism is different from that presented in Ref. [8]. Here, the reversal is limited to a small-size system. It is found that the peak of the polarization moves towards stronger magnetic fields for increasing the width of the central ZnSe layer, while shifts towards an opposite direction for increasing the width of paramagnetic layer. A strong suppression of the spin up component of the current density is present at high magnetic fields. It is expected that such a reversal of the polarization could act as a mechanism for a possible selective spin filter device.

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