Current density and state density in diluted magnetic semiconductor nanostructures

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Abstract. We study in this paper the spin-polarized current density components in diluted magnetic semiconductor tunneling diodes with different sample geometries. We calculate the resonant $J_xV$ and the density of states. The differential conductance curves are analyzed as functions of the applied voltage and the magnetic potential strength induced by the magnetic ions.

1. Introduction
The spintronics employs both the electron charge and spin as information carriers. The design of a basic device uses the proximity of the first ferromagnet gate from the left to align the electron spins, which are unpolarized when entering the semiconductor from the source. Magnetic field control of the magnetization of the second ferromagnetic gate parallel (antiparallel) to the first gate makes the transit of the current easier (harder). The current can be measured when it emerges from the drain. Recent advances [1–3] in experimental studies of the spin transport effect in semiconductor structures have moved the state of the art closer to the realization of novel spintronic devices. The employment of spin-related phenomena is expected [4] to extend the functionality of conventional devices at the classical level and address fundamental problems of electronics in the quantum limit [1–3]. Different types of semiconductor and hybrid spintronic devices [5, 6] have been proposed. Spintronic devices allow us to control the functionality by spin-orbit and magnetic interactions and can be used as magnetic sensors or programmable logic elements. In general, transport in semiconductor spintronic devices can be characterized by the creation of a non-equilibrium spin polarization in the device (spin injection), the measurement of the final spin state (spin detection), the external control of spin dynamics by the electric (gate modulation) or magnetic fields, and uncontrolled spin dynamics leading to loss of information in the device (spin relaxation or spin dissipation).

In particular, the research on diluted magnetic materials is a highly interesting topic because these materials are important for the fabrication of high performance electronic devices [7–11]. We study in this paper the spin-polarized current density components in diluted magnetic semiconductor tunneling diodes with different sample geometries. The charge buildup and its fluctuation on the resonant levels of a given geometry can help us to project efficient low voltage spin filter devices working with a small barrier offset at a small magnetic field. The idea of exploring and manipulating the spin degrees of freedom for carriers in semiconductor devices, a field named spintronics, has shown promising trends as well as new challenges.
2. Theoretical model
In this case we consider a simple one band tight-binding model (TB) for the spin dependent resonant tunneling (neglecting the spin-orbit interaction) in a double barrier heterostructure (DBH) of $Cd_{1-x}Mn_xTe - CdTe - Cd_{1-x}Mn_xTe$ (see, Figure 1).

![Figure 1](image-url) This scheme shows the configuration of the quantum dispositive or semiconductor nanostructure where the controlled impurities in the quantum well are affected by electric and magnetic fields. The different interactions between the nearest neighbors are studied by means of the tight-binding model.

The Hamiltonian of the system has the form:

$$H = \sum_{i,\sigma} \varepsilon_i c_{i\sigma}^\dagger c_{i\sigma} + \sum_{i,j,\sigma} V_{ij} c_{i\sigma}^\dagger c_{j\sigma} + \sum_{i,\sigma,\sigma'} A_{\sigma,i,\sigma'j} c_{i\sigma}^\dagger c_{j\sigma'} (1)$$

where $\varepsilon_i$ is the diagonal energy, $c_{i\sigma}^\dagger$ ($c_{i\sigma}$) is the creation (annihilation) operator of an electron with spin up ($S^+$) and spin down ($S^-$), in either the barrier or the well, and $V_{ij}$ is the hopping between neighboring sites i and j. In addition, $A_{\sigma,i,\sigma'j} = g_0 \mu_B \vec{\sigma} \cdot \vec{B}$ in the Equation (1) is the Zeeman term, where $g_0$ is the gyromagnetic ratio of the electron, $\mu_B$ is the Bohr magneton, $\vec{\sigma}$ represents the Pauli spin-vector and $\vec{B}$ is the applied magnetic field parallel to the current direction.

In order to treat the Green functions (GF) in this nonequilibrium case, we use the Keldysh [12] scheme, the full system is decoupled into two equilibrium ones [right (R) and left (L)] and the associated GF are obtained. Renormalized dressed GF for the non equilibrium case can be derived through the Dyson equation, making the two subsystems interact by means of a perturbed Hamiltonian. The average current density induced to T=0K in the double barrier system is calculated through the following expression [13].

$$\langle J \rangle = \frac{2eT}{h} \int_{-\infty}^{+\infty} d\omega [G_{01}^+ (\omega) - G_{10}^- (\omega)]$$

where $G_{01}^+$, $G_{10}^-$ are advanced and retarded Green functions and $\omega$ is the frequency. The above expression can be written in terms of the state density of the two subsystems in equilibrium, $\rho_{RL}(\hbar\omega)$, as:

$$J = 16\pi^3 J_0(B) T^2 \sum_n \int_{(n+1/2)\hbar\omega_c}^{E_F} \frac{\rho_L(\hbar\omega) \rho_R(\hbar\omega) d(\hbar\omega)}{|\Lambda(\hbar\omega)|^2}$$

where $T = V_{01} = V_{10}$, $J_0(B) = \frac{e^2 B}{4\pi^2 \hbar c}$, n runs over all Landau levels, $E_F$ is the Fermi energy, $\omega_c = \frac{eB}{m^* c}$ is the cyclotronic frequency, $m^*$ is the effective mass and

$$|\Lambda(\hbar\omega)|^2 = (1 - g_{LR}^a T^2)(1 - g_{LR}^a T^2)$$

where $g_{LR}^a$ corresponds to the advanced (retarded) GF of the right and left subsystems.
3. Results

We make use of the Green Functions formalism shortly described in the preceding paragraph to study the polarized current density behaviour as a function of the magnetic field through a systematic analysis of magnetism in $CdTe-Cd_{1-x}Mn_xTe-CdTe$ magnetic diodes. We consider also the exchange interaction Hamiltonian between spins in localized diluted magnetic $Mn^{++}$-ions [3, 4, 6] and in free carriers as additional positive and negative uniform magnetic potentials, $V_m(x) = \pm N_0 \alpha s_0(x) B_{5/2}[(5/2 g_M B B)/ (T - T_0(x))]$ [3, 5], for spin-up ($S^+$) and spin-down ($S^-$) carriers in the layer to the offset between layers, where $B_j(x)$ is the Brillouin function. For further details on this exchange-induced contribution to the energy separation of spin-split levels, see [6] and references therein. The parameters for $CdTe-Cd_{1-x}Mn_xTe$ layers are given in [3–5]. We have introduced a magnetic TB and considered the effects due to $V_m(x)$ on spin-up, spin-down and total tunneling current densities in the magnetic DBH.

![Figure 2](image-url)

**Figure 2.** Polarized current density with spin up (a) [spin down (b)] vs voltage for a $Cd_{1-x}Mn_xTe-CdTe-Cd_{1-x}Mn_xTe$ diode with different magnetic fields (0.2T, 0.4T, 0.6T, 0.8T and 1.0T) applied in the direction of the current. The barriers and the well are 30Å and 100Å respectively. The carrier density in the layer of the injector has a Fermi energy thick $E_F=20\text{meV}$.

In Figure 2 we show the behavior of the current density as a function of the bias voltage, for low and high magnetic fields strengths (0.2, 0.4, 0.6, 0.8 and 1.0T) in a quantum mechanical device. In this method we consider samples with fixed manganese concentration ($Mn, x=0.00898$) which allows us to increase the height of the potential barrier showing instantly a higher concentration of resonant states and instant magnetization. This substantially changes the current density in the system as the magnetic field strength increases and the voltage difference changes. Similarly, in this work, we also take into account that the barrier and well thicks are 30Å and 100Å respectively. It is important to note that the current density peaks (resonant states) are located near 0.03V, 0.15V and 0.32V for spin-up (Figure 2(a)). However, for the case of spin-down, the intensity peaks are located for values slightly lower, which implies a higher concentration of states that generates a carrier tunneling and show that the spin-down state in our system favors quantum transport information in this model. These resonances can be tuned by magnetic or electric fields since they determine both the energy and the spin-splitting between quantum well spin-polarized states in these devices. The strength peak is proportional to the tunnelling probability determined by the magnetic barrier height. In these figures too, we observe that the current intensity decreases in the intervals between 0.03V to 0.15V and between 0.32V and 0.40V showing a reversal in slope which implies a differential conductivity in the system. Also, in the second interval, the current density peak is lower than in the...
immediately preceding interval indicating saturation states because the supply voltage is large. Here, the last peak increases as the magnetic field strength increases, because the carriers are strongly localized in the nanostructure and favor the quantum tunneling of electrons.

In Figure 3 we show the results of the density of states with spin-up and spin-down for our DBH with conditions similar to those presented in Figure 2, as a function of the voltage with different magnetic fields applied in the direction of the current. We note that the number of quasi-bound states depends on the width of the quantum well, which is clearly correlated with the number of peaks in the Figure. The first peak, localized between 0.0 and 0.1eV, has a greater intensity which increases as the applied magnetic field increases. This implies a large concentration of localized states which increases the flow of a bigger number of carriers in the DBH. This indicates in turn growth in quantum information due to the spin. However, to the extent that the energy increases between 0.1 and 0.3eV, the height of the peaks decreases abruptly indicating that the quantum transport decreases due to the limited presence of the resonant states. In both figures we observe a similar behavior, except for the fact that in the case of the spin-down results, the quasi-bound states are localized in lower values of the energy that occur in lower voltages (see Figure 2(b)) favoring the passage of information.

![Figure 3.](image)

In Figure 4(a) we show the differential conductance with spin up (spin down in Figure 4(b)) vs voltage for the same structure shown in Figure 2. We observe that when the magnetic field amplitude increases, the differential conductance increases as a function of the voltage; this is because the values of the voltage applied to the device allow the electrons to tunnel through the conduction band of the structure \(Cd_{1-x}Mn_xTe - CdTe - Cd_{1-x}Mn_xTe\) with different applied magnetic fields (0.2T, 0.4T, 0.6T, 0.8T and 1.0T) in the direction of the current. The height of the potential barrier is \(\Delta E=187\)meV, corresponding to a concentration of Mn \((x=0.00898)\) and the barriers and the well are 30Å and 100Å thick, respectively.

In Figure 4(a) we show the differential conductance with spin up (spin down in Figure 4(b)) vs voltage for the same structure shown in Figure 2. We observe that when the magnetic field amplitude increases, the differential conductance increases as a function of the voltage; this is because the values of the voltage applied to the device allow the electrons to tunnel through the conduction band of the structure \(Cd_{1-x}Mn_xTe - CdTe - Cd_{1-x}Mn_xTe\) with spin up and spin down, since there are resonant states in the emission layer. The higher the magnetic field strength is, the more pronounced the peaks in the figure are. However, for small values of the voltage between 0 to 0.05V, three peaks rise in the characteristic curve \(J_0(V)\), where there is a reversal of the conductance in the last of them for both spin up to spin down. Moreover, between 0.3 to 0.4V, we show a reversal in the differential conductance when the magnetic field increases which allows the tunnelling of carriers because the wave function is strongly localized and the cyclotron frequency is higher in the system. We can also see in these graphs that
values of the voltage lower than 0.1 V, the change in the differential conductance is appreciable for different strengths of the magnetic field for both spin up and spin down. This shows that resonant states are also produced for these voltage values allowing the passage of information via the spin system. We conclude that the information flow in diluted magnetic materials is produced via spin step at small potential differences.

![Figure 4. Differential conductance with spin up (a) [spin down (b)] vs voltage for the same structure as in Figure 2.](image)

In conclusion, in this paper we have shown the behavior of the current density in magnetic DBH tunnelling systems considering diluted magnetic impurities having ferromagnetic and antiferromagnetic orientations as a function of the magnetic field intensity, the magnetic ion concentration, the sample designed geometry and the potential bias. We have shown that the magnetic impurities have enhanced the spin-filter effect of quantum tunnelling in such systems with one of the spin-polarized tunnelling population being notably favored when different magnetic orientations are present.

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