Magnetic Multilayers in $Ga_{1-x}Mn_xAs$/GaAs Structures

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Mn in $GaAs$ substitutes Ga as a p dopant and introduces a localized magnetic moment of $5\hbar/2$. $Ga_{1-x}Mn_xAs$ (for $x \approx 0.04$) has been proved to be an extremely interesting material, for its intrincated transport and magnetic properties. In the first part of this work a structure is considered in which a series of $Ga_{1-x}Mn_xAs$ layers is grown inside a $GaAs$ quantum well. The electron-electron interaction through a Hartree potential, together with the magnetic interaction with the DMS layers (assumed in the ferromagnetic phase) produces an effective potential corresponding to a sequence of small barriers which depend (height and width) on the hole spin orientation. For a large number of such layers it is shown that the model structure approaches a magnetic superlattice. A self-consistent calculation is performed for the electronic structure, resulting into spin-polarized energy levels. The polarized miniband Bloch transport properties are calculated for different structural arrangements. In the second part we calculate the transversal spin polarized current induced by an applied voltage through an $AlAs/Ga_{1-x}Mn_xAs/AlAs$ double barrier heterostructure (DBH). The magnetic layer is assumed in its metallic and ferromagnetic phase. As a consequence of the magnetic interaction a strong polarization of the hole subbands inside the quantum well. In that case the resonant tunneling occurs at different voltages for different spin orientation (parallel or anti-parallel to the average magnetization of $Ga_{1-x}Mn_xAs$) throughout. Based on a many-body field quantization formalism that makes use of the tight binding method we obtain, in an essentially exact way, an analytic expression for the spin polarized tunneling current and the escape rate from the right barrier of the DBH. The characteristic spin polarized I(V) curves, as well as the relaxation times, are obtained for different hole concentrations and magnetic layer widths, providing important informations for the possibility of building spin valves made those materials.

I Magnetic Multilayers

Recent advances on growing $Ga_{1-x}Mn_xAs$ multilayers opened a wide range of interest in heterostructures of that Diluted Magnetic Semiconductor (DMS) [1, 2], specially in spin-polarized transport due to potential applications in the area of quantum computers. Besides a magnetic impurity, Mn^{++} in this alloy is a strong p dopant. However, the density of carriers, as observed in measurements of the anomalous Hall resistance, is only a small fraction (of the order of 10%) of the Mn^{++} concentration, indicating that a major part of them remains neutral. The *sp-d* exchange interaction of Ruderman-Kittel-Kasuya-Yosida (RKKY) type has been recognized as the main origin of the observed ferromagnetism in the metallic phase of III-V based DMS [3, 4], and the possible magnetic ordering occurring in $Ga_{1-x}Mn_xAs$ heterostructures have been studied *via* Monte Carlo simulations on metallic samples [5]. Recently, a two component model has been suggested to contempt to the interplay of neutral and ionized Mn atoms in the magnetic interactions [6]. Chiba *et al* [7] investigated a trilayer structure and observed a ferromagnetic, although weak, interaction between two $GaMnAs$ ferromagnetic layers. More recently, ferromagnetic arrangements of $GaMnAs$ multilayers have been observed, forming a ferromagnetic superlattice [8]. Carriers, according to their polarization, are attracted or repelled by the magnetic layer. Therefore, the transport mean free path is expect to be different for each polarization. The aim of this work is to obtain the spin-polarized charge density, and to understand its effect on the spin-polarized transport in a model structure consisting of a sequence of $GaMnAs$ layers grown inside a thick non-magnetic $GaAs$ layer.

The spin-polarized electronic structure for holes is obtained self-consistently in the reciprocal space [9], taking into account the hole-hole interaction as well as their interaction with the magnetic impurities through

the contact potential:

$$U_{mag}(\vec{r}) = -I \sum_{i=1}^{N_i} \vec{s}(\vec{r}).\vec{S}(\vec{R}_i)\delta(\vec{r} - \vec{R}_i), \quad (1)$$

where I is the exchange, $\vec{R}_i$ denotes the positions of the N_i impurities Mn , $\vec{S}(\vec{R}_i)$ is the (classical) spin of the impurity, and $\vec{s}$ is the spin of the hole. We assume the magnetizations of the many layers to be oriented in a single direction, each of them in their metallic and (internally) in the ferromagnetic phase. In doing so, the spin of the hole is well defined in that direction, being polarized either up (parallel) or down(anti-parallel). When integrating the magnetic term in the Hamiltonian over $\vec{r}$, we assume the magnetic impurities as uniformly distributed in the $Ga_{1-x}Mn_xAs$ DMS layers, all of them in each magnetic layer j having the same magnetization, namely the thermal average magnetization $< \vec{M} >_j$. Therefore,

$$< U_{mag}(\vec{q}) >= I \int d^3r \exp[i(\vec{q} - \vec{q}').\vec{r}] \sum_{i=1}^{N_i} \vec{s}(\vec{r}).\vec{S}(\vec{R}_i)\delta(\vec{r} - \vec{R}_i) \simeq N_0\beta x \frac{\sigma}{2} \sum_j < M >_j F^j_{DMS}(q_z - q'_z)(2\pi)^3 \delta^2(\vec{q}_\| - \vec{q}'_\|), \quad (2)$$

where N_i / V is the impurity density, and $\sigma = \pm 1$ for the hole spin orientation up (parallel) or down (anti-parallel). F^j_{DMS} is the integral performed on the z -coordinate across the j-th DMS layer:

$$F^j_{DMS}(q) \equiv \frac{1}{2\pi} \int_{DMS}^{(j)} dz \exp[iq.z]. \quad (3)$$

As usual, $N_0\beta = I/v_0$, where v_0 is the volume of the Mn^{++} ion. A net magnetization $< M >_j$ polarizes the hole gas by introducing additional effective confining potentials given by

$$V^{eff}_{mag}(z) = -N_0\beta x \frac{\sigma}{2} \sum_j < M >_j g_j(z), \quad (4)$$

where $g_j(z) = 1$ if z lies inside the j-layer, and $g_j(z) = 0$ otherwise. With the use of

$$U_{eff}(q) = \frac{1}{2\pi} \int dz \exp[iq.z][U_c(z) + V^{eff}_{mag}(z) + U_i(z)], \quad (5)$$

where $U_c(z)$ and $U_i(z)$ are, respectively, the confining and the interaction potentials, the secular equation reads:

$$\det \left\{ \left[\frac{\hbar^2 q^2}{2m^*} - E \right] \delta(q - q') + U_{eff}(q - q') \right\} = 0. \quad (6)$$

Each DMS layer works effectively as a barrier or a well for spins parallel or anti-parallel to the local average magnetization, depending on the sign of $N_0\beta$. For $x = 0.05$, and for $N_0\beta = -1.2eV$ [10] this corresponds to band offsets of $\pm 30 < M >_j meV$. Throughout the calculation we made the hole density $p = 1.\times 10^{20} cm^{-3}$, a fraction of roughly 10% of the Mn concentration, T=$0K$, and $< M >_j = 5/2$. Due to the high carrier density, several subbands are occupied.

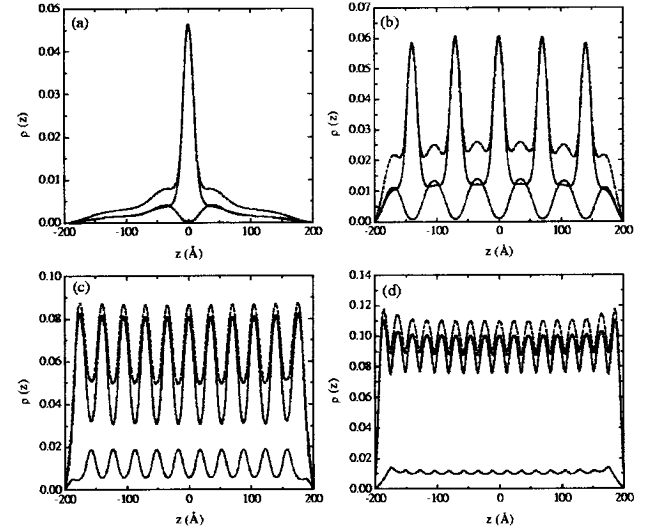

Figure 1. Spin-polarized charge density distributions for : (a) one, (b) five, (c) eleven, and (d) seventeen $Ga_{0.95}Mn_{0.05}As$ layers of 20Å. Solid line for total charge density, dotted line for spin ↑ (parallel), dashed line for spin ↓ (anti-parallel).

The spin-polarized charge density distributions are shown in Fig. 1 for (a) one, (b) five, (c) eleven, and (d) seventeen DMS layers. We considered symmetric structures containing a number of $Ga_{0.95}Mn_{0.05}As$ layers of width d = 20Å, separated by 20Å width $GaAs$ layers, inside a $GaAs$ QW of width 400Å. A single $Ga_{0.95}Mn_{0.05}As$ layer occupying partially a $GaAs$ quantum well can be ferromagnetic for widths smaller than the case where the DMS occupy completely the quantum well, as it has been shown by Monte Carlo simulations [11]. However, a single layer of 20Å is probably too much thin to be ferromagnetic. As the number of layers increases, the spin-polarized charge density distribution approaches that of a semiconductor superlattice with a band offset of $\pm 75meV$. Holes with the spin polarized parallel to the average magnetization occupy the regions interstitial between the magnetic layers, being repelled by the Mn layers due to the negative value of $N_0\beta$. Holes polarized anti-parallel to the average magnetization, on the contrary, are mostly located inside the DMS layers. Their density, however, is much lower than that of the anti-parallel spin holes, because the lowest occupied sub-bands are for this spin orientation. We expect the concentration of charge in the magnetic region to result in raising the transition

temperature of the system as compared to the single-layered structure, a fact that may be related with the recent experiments of Sadowski *et al.* [8]

II RTD Spin Valve

In this section we discuss the behaviour of a spin valve made of a double barrier resonant tunneling device (RTD) in which the well is made of $Ga_{1-x}Mn_xAs$ with barriers made of $AlAs$. The device is shown in Fig. 2a.

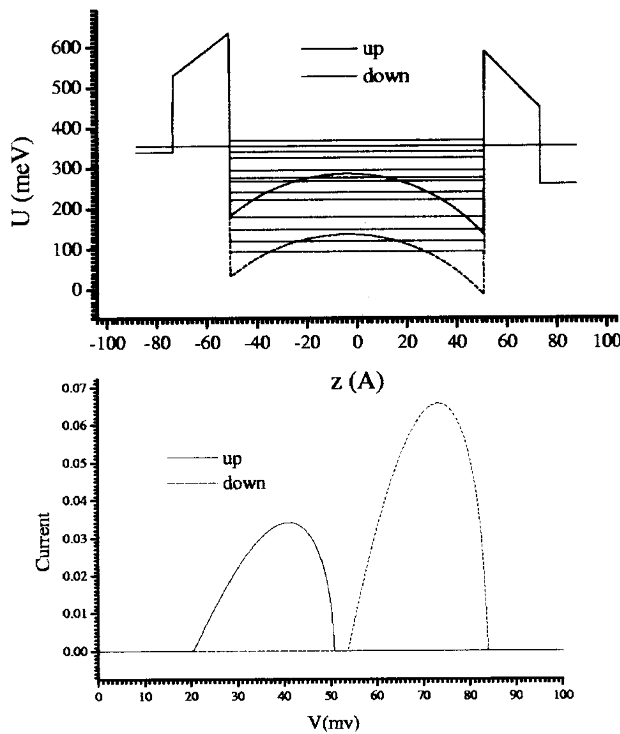

Figure 2. a) The spin dependent profile and levels. Solid line for spin ↑ (parallel to the magnetization), dashed line for spin ↑ (anti-parallel). b) Spin polarized currents.

The ferromagnetism of the well produces a strong internal magnetic field. Therefore the positions of the levels at the well are strongly spin dependent. Due to this fact the transmittance for holes with spin up is completely different fron the transmittance for spin down holes. For a clean system in which the transport could be considered ballistic, the current through the double barrier is proportional to the transmitance. As a consequence we get a spin polarized current. It is clear that the same device could be used as an analizer, making the device suitable for quantum computation.

Our system is described by the same Hamiltonian as in the previous section to which we added a term describing the applied electric field. In order to solve such open system we developed a formalism consisting in solving the scattering region, i. e., the doble barrier, uncoupled from the emitter and the collector. After that we use a renormalization procedure that permits to reconnect the three regions in an exact way.

The procedure described above is very efficient to calculate the transmittance for each spin. These transmitances are then integrated to obtain the electric current.

The I(V) characteristic curve is shown in Fig. 2b.

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