Spin transport through GaAs/GaMnAs/GaAs

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This work addresses spin-dependent transport in the heterostructure GaAs/GaMnAs/GaAs. The diluted ferromagnetic semiconductor GaMnAs layer behaves, within mean field approximation, as a potential well for spin-down carriers and a potential barrier for spin-up ones. Thus the transport would be spin-dependent. The goal of this work is to devise spin filters relevant for spin-dependent optoelectronics.

PACS numbers:

I. INTRODUCTION

III-V compound semiconductor heterostructures have been the test bench for new ideas and a rich field for new physics, owing to its capability of obtaining atomically abrupt heterojunction interfaces in a virtually impurity-free environment. It is also used in electronic and optical devices such as high-speed transistors and lasers. Magnetism, especially ferromagnetism, has not been a part of the activity in III-Vs because of the lack of material technologies that allow us to introduce magnetic cooperative phenomena into III-V-based heterostructures. The success in synthesis of magnetic III-Vs, alloys of III-Vs and transition elements like Mn [1], and subsequent discovery of ferromagnetism in them [2, 3], introduced a new and unexplored degree of freedom, which can be combined with all the freedoms we currently enjoy working with.

Electronic and optoelectronic semiconductor devices, controlled by a weak magnetic field, and electric-field controlled ferromagnetism in semiconductors[4]promise new functionality of memory, detectors, and light-emitting sources. Possible device implementations of spin electronics are high-electron-mobility transistors, Si/Si and GaAs/Si spin-valve transistors, spin light-emitting diodes, quantum computers, and integration of non-volatile storage and logic. Efficiency of spin injection depends on the interface quality; all-semiconductor structures should benefit the performance of spin-electronic devices. Recent achievement in materials research resulted in ferromagnetic semiconductor material lattice matched to III-V semiconductors: the highest ever ferromagnetic critical temperature in semiconductors Tc = 110 K has been observed in metallic samples of $\mathrm{Ga}_{1-x}\mathrm{Mn}_x\mathrm{As}$ (x = 0.053) [5, 6].

The discovery of ferromagnetism in diluted magnetic semiconductors (DMSs) can provide an opportunity to study spin-polarized transport phenomena, which make it possible to combine the information processing and data storage in one material. The origin of ferromagnetism in the DMS can be explained by using a picture in which uniform itinerant carrier spin mediates a long-range ferromagnetic order between the Mn^{2+} ions with spin S = 5/2. [7]

Electronic spin filters, i.e., devices which would produce spin-polarized injection currents, are relevant for spin-dependent optoelectronics [8]. Spin filters could be used to devise circularly polarized light sources, e.g., light emitting diodes and lasers, operating with polarized injection currents.

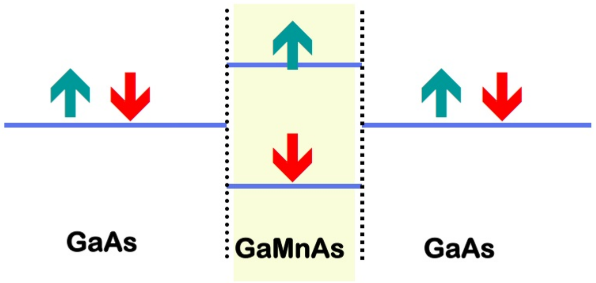

FIG. 1: The schematic diagram of carriers passing through the heterostructure GaAs/GaMnAs/GaAs. The s-d exchange interaction would give rise to a spin-dependent potential. Spin-up carriers see a barrier while spin -down ones a well.

In this paper, we report the theoretical investigation on electronic spin filtering in perpendicular transport through a magnetic-field tunable GaAs/GaMnAs/GaAs heterostructure.

II. MODEL

We consider the heterostructure GaAs/GaMnAs/GaAs as shown in Fig. 1, in which two GaAs layers are separated by a thin layer of DMS GaMnAs. They are assumed to be the $x - y$ plane and to be stacked along the z direction. For the DMS layer, we apply a two-band model with energy difference Δ between the highest energies of the majority and minority valence subbands, $E_\uparrow$ and $E_\downarrow$, with the spins parallel and antiparallel to the local magnetization respectively. In the Fig. 2, E_0 is the average value of $E_\uparrow$ and $E_\downarrow$, and E_F is the Fermi energy.

The Hamiltonian in the GaAs layer can be given by:

$$H_{GaAs} = -\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial r^2} + U \qquad (1)$$

wher the terms on the right-hand side are, respectively, the kinetic energy with the effective mass m^* of a hole and the barrier height measured from E_0.

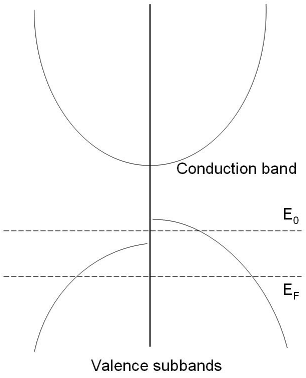

FIG. 2: Schematic illustration of valence subbands of a ferromagnetic GaMnAs.

The hole Hamiltonian in the DMSs is given by:

$$H_{DMS} = -\frac{\hbar^2}{2m_p}\frac{\partial^2}{\partial r^2} - \mathbf{h}(z)\cdot\sigma \tag{2}$$

where the first term on the right side is the kinetic energy with m_p the mass of a hole in GaMnAs and the second term is internal exchange with the molecule field $h(z)$ and σ the conventional Pauli spin operator. This term actually comes from the $s-d$ interaction with mean field approximation. It would give rise to a spin-dependent potential[9]. Spin-up carriers see a barrier while spin-down ones a well, as seen in Fig. 1.

Assume the GaMnAs layer is located between $a/2$ and $-a/2$. We then have three regions with different potential, $z > a$, $a/2 > z > -a/2$, $z < -a/2$. By the continuity of wavefunction and its derivative, we can solve the wavefunction, and hence the transmission coefficient. For different spin species, the potential in the region $a/2 > z > -a/2$ is different. Therefore we would have different wavefunctions $\Psi_\uparrow$, and $\Psi_\downarrow$, so are the transmission coefficients $T_\uparrow$, and $T_\downarrow$. Hence we obtain a spin-dependent transport. The spin-dependent transport is manifested by the current. The spin-dependent current density is given by

$$j_{\sigma_z}(r) = e\sum v_z(k_z)T_{\sigma_z}(k_z)|\Psi(r)|^2 \tag{3}$$

where $v_z(k_z) = \hbar k_z/m$ is the z component of the carrier velocity, and k_z is the z component of the momentum.

It is of practical interest to know the temperature dependence of transport. This can be achieved by considering the temperature dependence of the average Mn spin $\langle S_z\rangle$ in the DMS GaMnAs layer. The expression for $\langle S_z\rangle$ is deduced as[10]:

$$\langle S_z\rangle = \frac{5}{2}B_s\left(\frac{(-J^{Mnh}\langle j_z\rangle + g_{Mn}\mu_B B)S}{kT}\right) \tag{4}$$

where J^{Mnh} is the Mn-h exchange coupling constant, $g_{Mn} = 2$, and B_s is the Brillouin function. The average spin would give rise to the effective molecule magnetic field in eq.(2) Hence the temperature dependence of $\langle S_z\rangle$ would make the potential temperature dependent, thus making the transport temperature dependent.

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