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Modeling the diluted magneto semiconductors (DMS) with results in giant magneto resistance

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There are new types of structures who present a magneto resistive character and these are called diluted magnetic semiconductors (DMS). In our work we try to understand these new structures, to find out if there are any kinds of structures or mixtures (layers doped) of structures and what are their properties. We had also analyzed the magneto-transport properties of such structures, in order to see witch are best to implement in multilayer structures.

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1. Introduction

Since 1960 the electronic devices are based on semiconductor materials in witch the carriers have a very important property: the spin. This can have only two values when projected on the magnetic field axis, ‘up’ or ‘down’. These states respond differently to the external magnetic, electric or optic field resulting a spin-polarized current, polarized light.

The reason for choosing this materials is that they can have a paramagnetic, ferromagnetic or anti-ferromagnetic state by doping them controllably with magnetic impurities [1, 7, 9, 10]. Furthermore, the electrons inside a semiconductor can have very large life-times and the spin can be manipulated from the exterior using an electromagnetic field.

The study of spin transport in semiconductor devices represents a new step in the quantum world and we believe that we will be able to realize quantum devices and in the next few years even quantum computers.

The magneto-resistance represents the change of the resistance caused by an external magnetic field, and it is defined as $\Delta\rho(H)/\rho_o=(\rho(H)-\rho_o)/\rho_o$ [12, 21] where $\rho(H)$ and ρ_o are the resistivities when we apply or not the magnetic field.

The main idea concerning the magneto-transport properties is the change of the resistance with the orientation of the spin of ions or free carriers [5,12].

Transport properties of diluted magnetic semiconductors are highly sensitive on the impurity concentration. Due to the presence of these impurities that act like defects, they are the main scattering centers involved in the transport.

2. History and physics of the process

The first measurements and investigations of spin polarized transport date back to sixties [16] when anomalous transport phenomena in Eu-calcogenide alloys were observed by Kasuya [15], and the seventies when Tedrow and Meservey [13] measured tunneling current through $Al/Al_2O_3/Ni$ hetero-structures. Afterwards, Julliere [14] measured tunneling conductance of F/I/F junctions in 1975, where the insulator was amorphous Ge. Following the analysis of conductance done by Tedrow and Meservey, Julliere developed a model for the change of the conductance between parallel and anti-parallel orientation of magnetization in the two ferromagnetic regions FM_1 and FM_2).

The magnetic properties of diluted magnetic semiconductors II – VI and III – V [9] are determined by: exchange interaction sp – d between impurity ions and band states; the exchange impurity – impurity or d – d between ions; electronic configuration of impurity ions; the concentration of magnetic ions and free carriers.

Mn and Co, as impurities, have the 3d layer incompletely occupied. In a II – VI semiconductor, the II group element is substituted by an equivalent valence of magnetic transition metal atoms (Mn, Co, etc.), and they provide only magnetic localized moments to the host. But, it is difficult to dope this type of semiconductors because of the dominance of the anti-ferromagnetic super exchange interaction among impurity spins witch yelds to paramagnetic, anti-ferromagnetic or spin-glass in these materials. The 3d orbital has two energetic levels witch correspond to the majority and minority states (occupied or unoccupied). These levels are splitting in the crystal field and they are brought back inside the bands by the hybridization with p orbital.

In the case of III – V semiconductors there are three types of scattering centers [7, 10]. As consequence, we can observe the presence of two characteristics in state densities of the impurity: the original states are localized below Fermi level. The new states correspond to group V elements witch fusion with valence band in the vicinity of Fermi energy [19].

3. Model

The possibility to implement diluted magnetic semiconductors in electronic devices begins with they're magnetic configuration (paramagnetic, anti-ferromagnetic, ferromagnetic) as we dope them. This is the main reason for witch the semiconductor act like a ferromagnetic material.

The modeling of these structures includes RKKY approach, spin wave approach, impurity band models, dynamical mean field theory or density functional theory [1,10, 23]

Aldo there are many models in literature [9, 10], we developed a model to include most of the diluted magnetic semiconductors.

We have started by considering the magneto-resistive coefficient [4] of the semiconductor:

$$Coef = \frac{1}{B^2}\,\frac{\langle\mu\rangle - \left\langle \frac{\mu}{1+\mu^2B^2}\right\rangle - \dfrac{\left\langle \frac{\mu^2}{1+\mu^2B^2}\right\rangle^2 B^2}{\left\langle \frac{\mu}{1+\mu^2B^2}\right\rangle}}{\left\langle \frac{\mu}{1+\mu^2B^2}\right\rangle + \dfrac{\left\langle \frac{\mu^2}{1+\mu^2B^2}\right\rangle^2 B^2}{\left\langle \frac{\mu}{1+\mu^2B^2}\right\rangle}}$$

where μ is the mobility of the carriers. We have introduced the state densities [4,5] for the two types of carriers (electrons with spin 'up' and those with spin 'down') when calculating the means in the coefficient formula. Furthermore, we have worked in the molecular field approximation. In the end, we had wrote the magnetization as a function of spin projection S and the energy for the triplet and singlet states $A_{\alpha\beta}$ [13, 18].

So, we obtained:

$$Coef = \frac{e^{-E_{gap}/KT}\left(-1+\left(H+\frac{SA_{\alpha\beta}}{\mu_0}\right)^2\mu_0^2\right)}{e^2n^2 + \dfrac{e^{-E_{gap}/KT}\left(H+\frac{SA_{\alpha\beta}}{\mu_0}\right)^4\mu_0^4}{e^2n^2}}$$

4. Results

The diluted magnetic semiconductors are structures witch present magneto-resistive properties. Because of their not very high magneto-resistance, they are to be implemented in thin layers, as from witch results the giant magneto-resistance effect. Our purpose was to find out witch structures are to be introduced for best results.

The impurity ions have five or seven 3d electrons and two 4s electrons. Between the 3d spins of electrons uncompensated, parallel aligned there is a strong exchange interaction, and the energy levels of 3d electrons with opposite spins are located high above the conduction band edge because the Coulomb repulsive energy that is large for these localized electrons [8].

We had worked around room temperature and with a concentration for the magnetic impurities of 25%; we calculated some instant values for a small number of semiconductors doped with Mn or Co.

Table 1. Magneto-resistance for DMS.

No	Semiconductor	Magnetic impurity	Magneto resistance (%)
1.	InSb	Mn	30.9415
2.	GaN	Mn	3.9477
3.	InN	Mn	3.9469
4.	AlP	Mn	3.9482
5.	GaP	Mn	3.9487
6.	GaAs	Mn	3.9478
7.	AlAs	Mn	3.9469
8.	InP	Mn	3.9479
9.	InAs	Mn	7.6119
10	GaSb	Mn	1.7709
11	AlSb	Mn	3.9481
12	AlN	Mn	3.9475
13	ZnS	Co	3.9483
14	ZnSe	Co	3.9485
15	ZnTe	Co	3.9477
16	CdS	Co	3.9469
17	CdSe	Co	3.9480
18	CdTe	Co	3.9479
19	ZnO	Co	3.9480

The dependence of the magneto-resistance on the temperature for some diluted magnetic semiconductors has the shape:

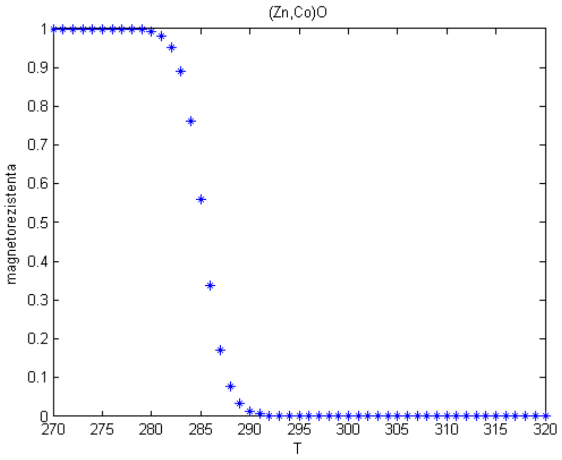

Fig. 1. Temperature(K) dependence of magneto-resistance(%) for (Zn,Co)O.

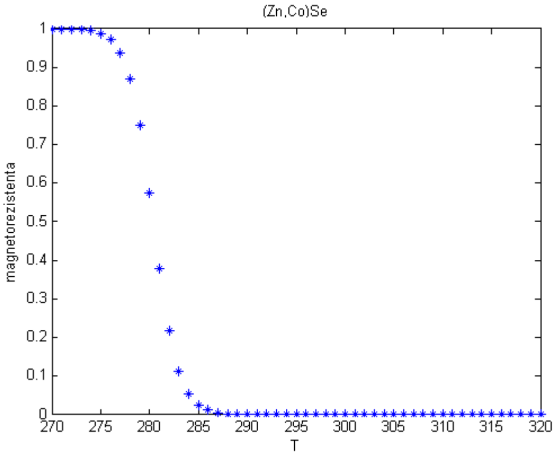

Fig. 2 Temperature(K) dependence of magneto-resistance(%) for (Zn,Co)Se.

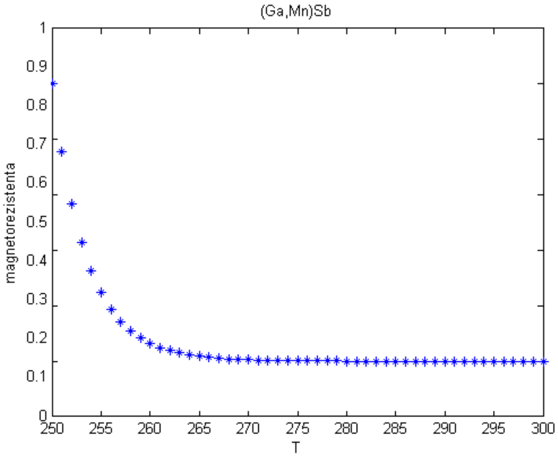

Fig. 3. Temperature(K) dependence of magneto-resistance(%) for (Ga,Mn)Sb.

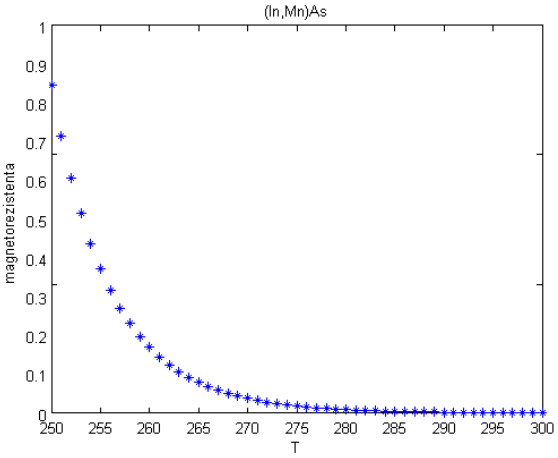

Fig. 4. Temperature(K) dependence of magneto-resistance(%) for (In,Mn)As.

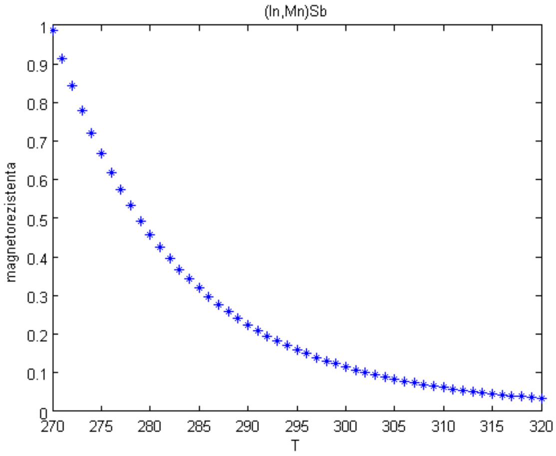

Fig. 5. Temperature(K) dependence of magneto-resistance(%) for (In,Mn)Sb.

5. Discussions

The magneto-resistance curves have unusual concave upward shapes. For each curve we can observe that there is a temperature at witch the magnetization is lost for each structure (Curie temperature). That is the temperature where the phase transition from ferromagnetic to paramagnetic takes place [6, 10, 21, 22].

We can see also that the semiconductors doped with Co have a much rapid transition to the paramagnetic state, when the ones doped with Mn have a much slower transition. This is due to the electronic configuration on the 3d level for each magnetic atom, but also to the fact that Co is used in permanent magnets.

For the few structures that we investigated we have observed a magneto-resistance of only few percents, but there is hope to find materials, as (In, Mn) Sb with larger magneto-resistive effects.

Performing Monte Carlo simulation [1,6] the results obtained in what concerns the shape of the curve are similar.

6. Conclusions

From these calculations we obtained very low magneto-resistance for this materials, but they are to be implemented in multilayer structures as ferromagnetic layer in order to obtain larger effects.

In our work we had tried to find out witch are the best materials to use in spintronic applications. As we now [9,10, 12] spintronic devices are based on multilayer in witch the ferromagnetic layers alternate with the non-magnetic ones. These diluted magnetic semiconductors are to be the ferromagnetic layers in these type of structures.

The diluted magnetic semiconductors represent a promising step in the future of electronics because they are obtained controllably and they have a phase transition from ferromagnetic to paramagnetic at or above room temperature witch give as the possibility to obtain magneto-resistive effect at room temperature. So, we can built magnetic memories and read-heads for hard disks at much higher densities witch can be commercialized.

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