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Electric Field Controlled Magnetic Properties in Diluted Magnetic Semiconductor

Gezahegn Assefa*, P. Singh

Department of Physics, Addis Ababa University, **Ethiopia**

ABSTRACT

We report the effect of external electric field (EEF) on the magnetic properties of Mn_xGe_{1-x}, diluted magnetic semiconductor (DMS). We present a Kondo Lattice Model (KLM) type Hamiltonian with exchange coupling between localized spins, itinerant holes and the EEF. The magnetization, the dispersion and critical temperature (T_c) are calculated for different values of EEF parameters (α) using double time temperature dependent Green function formalism. The enhancement of the (T_c) with the EEF is shown to be a very distinct and is in agreement with recent experimental observation and much required for spintronics applications and devices.

PACs: 75.50.Pp, 75.30.Ds, 75.30.Hx

Keywords: Diluted magnetic Semiconductor, Spintronics, Electric field control of Ferromagnetism, Green function

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INTRODUCTION

Dilute magnetic semiconductors (DMS) are materials that recently studied because of their potential applications in spintronics, which uses both the charge and spin degrees of freedom for electronic applications [Wolf et al. (2001)]. DMS materials such as (Ga,Mn)As, (In,Mn)As, (Ga,Mn)N combine magnetic and semiconducting properties in a single material [Ohno (1998)]. High hole mobility, compatibility with the present silicon technology [Song et al. (2005), Li et al. (2006)] and magnetic ordering [Park (2002) and Cho (2002)] observed in Ge (Group IV) based DMS have attracted a great deal of attention for DMS based spintronics applications.
Recently Xiu *et al*. (2010) successfully fabricated self assembled Mn_xGe_{1-x} DMSQDs (with

* gzhgnassefa2@gmail.com

x=0.05) without metallic precipitates such as Mn_5Ge_3 and $Mn_{11}Ge_5$ which showed electric field controlled ferromagnetism, T_c above 400K. The presence of such metallic clusters strongly affect the magnetic properties of the Mn doped Ge due to low solubility of Mn in Ge [Dung et al. (2012)].

Control of the magnetic phase in DMS is one of the most important processes for magnetic recording and information storage. The use of electric-field-controlled magnetization reduce power consumption for storage devices[Ohno et al. (2000), Climente et al. (2005)] . Electric field control of ferromagnetism was so far demonstrated in a field effect transistor (FET) structure have been used for non-volatile spin logic devices via carrier-mediated effect [Xiu *et al*. (2010), Boukari et al. (2002)].

In this paper, we theoretically study the influence of electric field on the magnetic properties of Mn_xGe_{1-x} DMS, using the double time temperature dependent Green functions. Magnetization and the critical temperature are studied in relation to the EEF. The paper is organized as follows. In the model Hamiltonian which describes the DMS quantum dots charier- charier interaction, carrier- Mn interaction and the Mn-Mn interaction. In the next section, we present the numerical results of various physical quantities showing the effect of the electric field. Finally the conclusion and summary is presented in last section.

MODEL HAMILTONIAN

Our system consists of a Mn-Ge DMS of radius ***R*** and volume ***V*** containing donor impurity inside it. The Hamiltonian of the system will have the form

$$H = H_{ee} + H_I + H_{mag} \qquad (1)$$

We assume a parabolic energy band for the carriers and the second quantized electron Hamiltonian, H_{ee} is given by

$$H_{ee} = \sum_{k\sigma} \varepsilon_{k\sigma} c_{k\sigma}^{\dagger} c_{k\sigma}, \qquad (2)$$

where $c_{k\sigma}^{\dagger}(c_{k\sigma})$ are Fermionic creation (annihilation) operators for carriers in the DMS, $\varepsilon_{k\sigma}$ is energy of carriers within the system with momentum k, band σ (moments ↑ or ↓). $\mathbf{H_I}$ is the interaction Hamiltonian between the carriers and the localized magnetic ions, which can be written as

$$H_I = -2J_{sd} \sum_m S_m \cdot \sigma_m - \mu_e E \sum_m S_m^z \sigma_m^z \qquad (3)$$

The first term in $\mathbf{H_I}$ is due to the interaction of the band carriers (holes) and the localized spin Mn^{2+} ions, expressed as Heisenberg type Hamiltonian, where J_{sd} is exchange coupling between the confined holes and the Mn^{2+} ions impurity spins S_m. σ_m represents the spin of the confined holes, which can be written a

$$\sigma_\alpha = \frac{1}{2} \sum_{\sigma\sigma'} c_{m\sigma}^{\dagger} \vec{\tau}_{\sigma\sigma'} c_{m\sigma,} \qquad (4)$$

where $\alpha = x, y, z$ and $\vec{\tau}_{\sigma\sigma'}$are the matrix elements of the Pauli spin matrices. The second term arises from interaction of the holes and the localized moments with the external electric field (EEF) **E**. It is Ising type Hamiltonian. The mean electric polarization is assumed to be proportional to the z-component of the carriers and the localized spins.

$\mathbf{H_{mag}}$ is give

$$H_{mag} = \frac{-1}{2}\sum_{mn} I_{mn} S_m \cdot S_n - g\mu_\beta H \sum_m S_m^z, \quad (5)$$

The first term in $\mathbf{H_{mag}}$ is the Hamiltonian of the localized Mn^{2+} spins, where $\mathbf{I_{mn}}$ is the exchange coupling between the localized spins $\mathbf{S_m(S_n)}$ at different sites. The second term gives the Zeemann energy when the external magnetic field ***H*** has been applied in the z-direction, where **g** is Lande' g factor and μ_β is the Bohr magneton.

The present Hamiltonian is similar to Hubbard Model with the onsite Coulomb potential is replaced by $\mathbf{H_I}$ and $\mathbf{H_{mag}}$. The spin operators in Hamiltonian can be written using the Holstein-Primakoff (HP) transformation as

$$S_m^- = \left(\sqrt{2xS - a_m^\dagger a_m}\right) a_m^\dagger \quad (6)$$

$$S_m^+ = \left(\sqrt{2xS - a_m^\dagger a_m}\right) a_m \quad (7)$$

$$S_m^z = xS - a_m^\dagger a_m, \quad (8)$$

where $a_m^\dagger (a_m)$are bosonic creation(annihilation) operators, x is the mean number of magnetic ions in the DMSQDs.

It is reasonable to use the approximation $\left(\sqrt{2xS - a_m^\dagger a_m}\right) \simeq \sqrt{2xS}$ in HP transformation at low temperature. Restricting the involved momentum in the first Brillouin zone and Fourier transforming the Fermionic and bosonic operators, the total Hamiltonian can be written in second quantized form as

$$\begin{aligned} H = \omega_0 + \sum_{k\sigma} \varepsilon_{k\sigma} c_{k\sigma}^\dagger c_{k\sigma} + \left(\frac{\mu_\beta E}{2N} - \frac{J_{sd}}{N}\right) \sum_{\sigma k q q'} \sigma a_{q'}^\dagger a_q c_{k-q,\sigma}^\dagger c_{k-q,\sigma} \\ - \frac{J_{sd}\sqrt{2xS}}{\sqrt{N}} \sum_{kq} \left(a_q^\dagger c_{k\uparrow}^\dagger c_{k+q\downarrow} + a_q c_{k+q\downarrow}^\dagger c_{k\uparrow}\right) \\ - g\mu_\beta \sum_q a_q^\dagger a_q + xS \sum_q \left(I_0 - I_q\right) a_q^\dagger a_q \end{aligned} \quad (9)$$

where

$$\omega_0 = -g\mu_\beta H - m\left(J_{sd} + \frac{\mu_e E}{2N}\right) \quad (10)$$

and

$$m = \frac{1}{N}\sum_q \langle c_{k\uparrow}^\dagger c_{k\uparrow}\rangle - \langle c_{k+q\downarrow}^\dagger c_{k+q\downarrow}\rangle \quad (11)$$

is the carrier spin polarization.

For the self-consistent calculations of the quasiparticle spectrum of the system described by the Hamiltonian in equation (9), we consider the following Green function (GF).

$$G_q(t,t') = \langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle \quad (12)$$

In order to evaluate the GF, we use the generalized equation of motion [Zubarev (1960)].

$$\omega \langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle_\omega = \frac{1}{2\pi}\langle [a_q, a_q^\dagger]\rangle + \langle\langle [a_q(t), H]; a_q^\dagger(t')\rangle\rangle \quad (13)$$

$$[a_q(t), H] = xS\sum_q (I_0 - I_q) + g\mu_\beta H a_q + \left(\frac{\mu_\beta E}{2N} - \frac{J_{sd}}{N}\right)\sum_{kq'\sigma} a_{q'}^\dagger\, c_{k-q,\sigma}^\dagger c_{k-q'\sigma} - \frac{J_{sd}\sqrt{2xS}}{\sqrt{N}}\sum_{kq} c_{k\uparrow}^\dagger c_{k+q\downarrow} + \quad (14)$$

Using equation (14) into equation (13), the GF becomes

$$\omega \langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle_\omega = \frac{1}{2\pi} + \Lambda_q \langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle_\omega - \frac{J_{sd}\sqrt{2xS}}{\sqrt{N}}\sum_k \langle\langle c_{k\uparrow}^\dagger c_{k+q\downarrow}; a_q^\dagger(t')\rangle\rangle_\omega + \left(\frac{\mu_\beta E}{2N} - \frac{J_{sd}}{N}\right)\sum_{kq'\sigma}\langle\langle a_{q'} c_{k-q,\sigma}^\dagger c_{k-q'\sigma}; a_q^\dagger(t')\rangle\rangle_\omega$$

where $\Lambda_q = xS\sum_q I_0 - I_q + g\mu_\beta H.$ (15)

The mixed type GF of the form $\langle\langle c_{k\uparrow}^\dagger c_{k+q\downarrow}; a_q^\dagger(t')\rangle\rangle_\omega$ can be decoupled

$$\langle\langle c_{k\uparrow}^\dagger c_{k+q\downarrow}; a_q^\dagger(t')\rangle\rangle_\omega = \langle\langle [c_{k\uparrow}^\dagger c_{k+q\downarrow}, H]; a_q^\dagger(t')\rangle\rangle = \left(\langle c_{k\uparrow}^\dagger c_{k\uparrow}\rangle - \langle c_{k+q\downarrow}^\dagger c_{k+q\downarrow}\rangle\right)\langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle_\omega$$

(16)

Employing the following decoupling procedure on the higher order GFs of the form $\langle\langle a_q c_{k-q\sigma}^\dagger c_{k-q'\sigma}; a_q^\dagger(t')\rangle\rangle_\omega$ [Zubarev (1960)],

$$\begin{aligned}\langle\langle a_q c_{k-q\sigma}^\dagger c_{k-q'\sigma}; a_q^\dagger(t')\rangle\rangle_\omega &= \langle\langle [a_q c_{k-q\sigma}^\dagger c_{k-q'\sigma}, H]; a_q^\dagger(t')\rangle\rangle \\ &= \delta_{qq'}\langle c_{k-q\sigma}^\dagger c_{k-q'\sigma}\rangle \langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle_\omega \\ &\langle c_{k-q\sigma}^\dagger c_{k-q'\sigma}\rangle\langle\langle a_q(t); a_q^\dagger(t')\rangle\rangle_\omega \end{aligned} \quad (17)$$

Plugging equation (17) and equation (16) into equation (15) the GF at $q \to 0$ can be written in the form

$$G_q(\omega) = \frac{1}{2\pi}\frac{1}{\omega-\Lambda_q+m\left(2xSJ_{sd}^2-J_{sd}-\frac{\mu_e E}{2}\right)} \tag{18}$$

Where

$$m = \frac{1}{N}\sum_k\left(\langle c_{k\uparrow}^{\dagger}c_{k\uparrow}\rangle - \langle c_{k+q\downarrow}^{\dagger}c_{k+q\downarrow}\rangle\right) = \frac{1}{N}\sum_k\left(\langle c_{k-q\uparrow}^{\dagger}c_{k-q'\uparrow}\rangle - \langle c_{k-q\downarrow}^{\dagger}c_{k-q'\downarrow}\rangle\right) \tag{19}$$

is the carrier spin polarization at $q \to 0$.

From the poles of the GF, we can obtain the excitation spectrum of the magnon as

$$\omega_q = xS\sum_q\left(I_0 - I_q\right) + g\mu_\beta H - m\left(2xSJ_{sd}^2 - J_{sd} - \frac{\mu_e E}{2}\right) \tag{20}$$

The exchange integral I_q is given by

$$\omega I_q = \frac{1}{N}\sum_{mn} I_{mn}e^{iq\cdot(R_m-R_n)} \tag{21}$$

The dispersion of the localized spin subsystem includes the simplest spin wave result when expanding I_q in the limit $q \to 0$ which leads to the dispersion law $\omega_q = Dq^2$, where D is spin wave stiffness and is given by $D = xS\sum_m(\hat{q}R_m)^2 I$ and $\hat{q} = \frac{q}{|q|}$ is the unit vector.

The dispersion of the localized spin subsystem, then can be written as

$$\omega_q = Dq^2 + g\mu_\beta H + m\alpha - m\gamma \tag{22}$$

$\alpha = \frac{1}{2}\mu_\beta E$ is called the external electric field parameter (EEFP), and $\gamma = 2xSJ_{sd}^2 + J_{sd}$ is a parameter associated with the coupling of carrier spin and the localized magnetic spin.

The number of magnon excited at temperature T can be calculated using the correlation function,

$$\langle a_q^{\dagger}(t')a_q(t)\rangle = lim_{\epsilon\to 0}\int_{-\infty}^{\infty}\frac{e^{-i\omega(t-t')}}{e^{\beta\omega}-1}\left(G_q(\omega+\epsilon) - G_q(\omega-\epsilon)\right)d\omega \tag{23}$$

The equal time (t=t') correlation gives the number of excited magnons and is obtained as

$$n_q = \frac{1}{e^{\beta\omega_q}-1} \tag{24}$$

The magnetization *M(T)* can be expressed using the Bloch law as

$$M(T) = \frac{g\mu_\beta}{V}\left(N_m S - \sum_q\langle n_q\rangle\right) \tag{25}$$

where N_m is the number of magnetic atoms in the system.

Using equations (and 12}), we have

$$M(T) - M(0) = \frac{g\mu_\beta}{V}\left(N_m S - \sum_q\frac{1}{exp\left[\beta\left(Dq^2+g\mu_\beta H+m\alpha-m\gamma\right)\right]-1}\right) \tag{26}$$

For small values of $\boldsymbol{q}$, the sum in the above can be replaced by an integral over the whole value of the $\boldsymbol{q}$-space, and it becomes

$$M(T) = \frac{g\mu_\beta N_m S}{V}\left(1 - \frac{V}{(2\pi)^3 N_m S exp\,[\eta\beta]}\int_{-\infty}^{\infty}\frac{d^3q}{exp\,[\beta(Dq^2)]}\right), \tag{27}$$

where $V = \frac{1}{4}a^3$ is the volume of the primitive cell of the face centered cubic lattice and $\eta = g\mu_\beta H + m\alpha - m\gamma$

$$3\}exp[-\beta(g\mu_\beta H + m\alpha - m\gamma)], \tag{28}$$
$$\frac{M(T)}{M(0)} = 1 - AT$$
where $M(0) = \frac{g\mu_\beta N_m S}{V}$ and $\frac{M(T)}{M(0)}$ is the reduced magnetization and A is a constant given by
$$A = \frac{1}{16\pi^2 N_m S}\left(\frac{k_\beta}{2IxS}\right)^{3/2} \tag{29}$$
Based on the above frame work, we can calculate the critical temperature and the spin wave dispersion of the localized spin.

NUMERICAL RESULTS AND DISCUSSION

Controlling the magnetization of magnetic devices using an electric field will lead to new devices that will be energy efficient, fast and compact as compared to those devices tuned by electromagnets.

The following material parameters are used for the analysis. J_{sd} =2meV, I=20meV, a = 5.77$\acute{A}$, m = 0.9, S = 5/2.

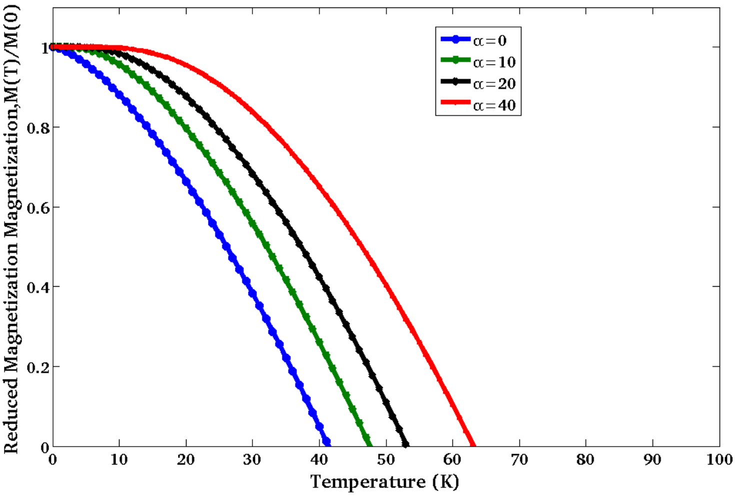

Fig. 1 Reduced Magnetization (M(T)/M(0)) as a function of temperature for different values of EEF parameter, α

In Figure 1 we plot the reduced magnetization as a function of temperature in different values of the electric field parameters. The magnetization of the system tends to increase towards the temperature as the electric field parameter increase. The electric field increases the coupling between localized spin and the itinerant holes spins and produces spin polarized carriers which in turn creates molecular field which is responsible to the higher magnetization of the Mn spins. The slow drop of the magnetization as compared to the Weiss mean field approximation is due to low- temperature approximation and the ignorance of the strong spin fluctuation. The effect of the external electric field on the magnetization is in agreement with the experimental work of [Ohno et.al. (2000). They reported that in the study of the anomalous Hall effect of the semiconductor field effect transistor(FET) structure, the hole induced ferromagnetism can be turned on and off by external electric field.

As can be seen from fig. 2 the spin wave dispersion gap increases when the electric field parameters increases.

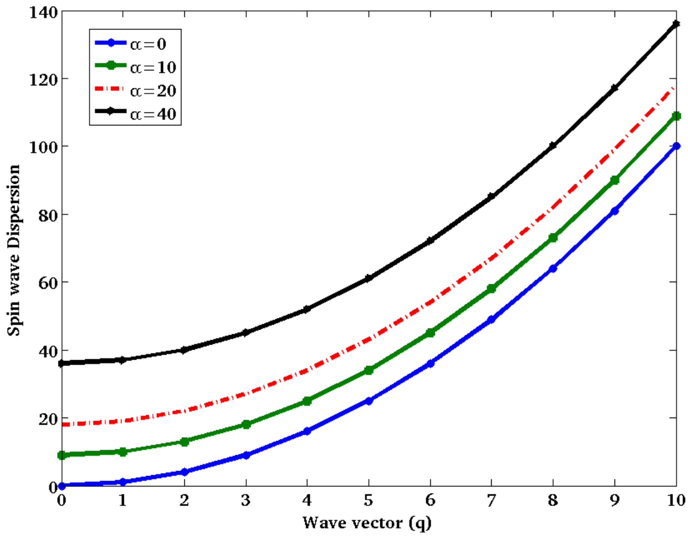

Fig. 2. Spin wave dispersion as a function wave vector, q

The dependence of the reduced magnetization on the electric field is observed on fig. 3. one can notice that the increase of magnetization of the system as electric field increases, which subsequently enhances the critical temperature T_c.

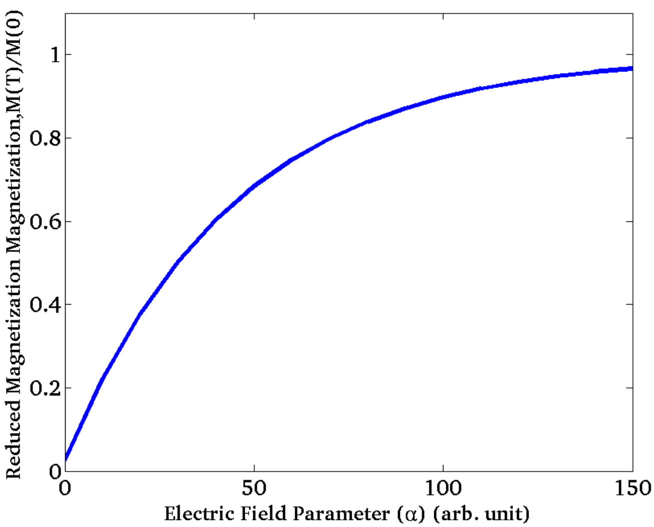

Fig. 3. Reduced Magnetization (M(T)/M(0)) as a function of EEF parameter, α

In Figure 4, we have plotted the variation of the critical temperature with the EEF. An increase in critical temperature is observed as the EEF increases. As can be seen from the curve, it is not a monotonic increase rather it is a parabolic increase, which shows there is a saturation for critical temperature at high values of the EEF. This is in good agreement with the experimental work of Chiba and Ono, *2013.*

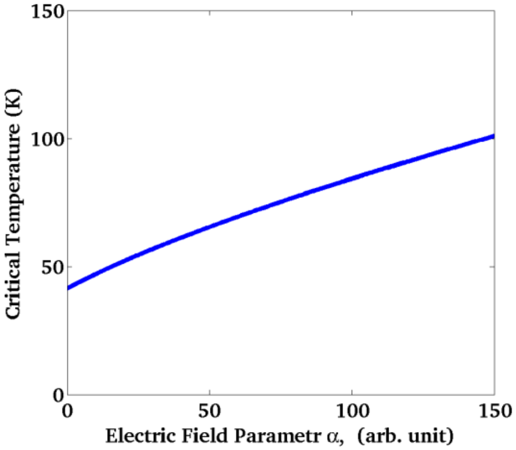

Fig. 4. Critical temperature as a function of EEF parameter,

CONCLUSIONS

We have shown that the magnetic properties of the DMS Mn-Ge system greatly affected by the application of EEF. The magnetization shows an increase with increasing EEF. This confirms that the internal molecular field due to the Carrier-Mn coupling leads to high Curie temperature Ferromagnetism. This could be explained by the fact that the EEF would accumulate large enough spin polarized carriers which affect the orientation of the Mn ions and induce ferromagnetism. In addition, the critical temperature (T_c) and the spin wave dispersion gap increases with increasing EEF. These electric field dependent magnetic properties will lead to the control of the magnetism by an electric field which is essential for the spintronics applications. In conclusion, we see that our system can be tuned by the external applied electric field.

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