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Research article

Effect of magnon-exciton coupling on magnetic phase transition of diluted magnetic semiconductors

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Abstract: This article reports effects of magnon-exciton interaction on magnetic ordering in diluted magnetic semiconductors (DMS). Quantum field theory is employed using the double time temperature dependent Green function technique to obtain dispersion. It is understood that interaction of the two quasi particles take place in the exciton cloud and consequently the spontaneously ordered localized electrons might be partly trapped and subjected to different angular precision resulting in increase of the number of magnons. According to our analysis the exciton-magnon coupling phenomena may be the reason for the attenuation of spontaneous magnetization and ferromagnetic transition temperature T_C. Further observations indicate that there is a significant departure of magnetic impurity concentration, x_m, vs. T_c relation from the linearity as suggested by electronic calculations and experimental estimations near absolute zero temperature.

Keywords: DMS; exciton; magnetization; phase transition; spinwaves

1. Introduction

The study of diluted magnetic semiconductors (DMSs) has been a front line research topic due to an attempt to make use of charge and spin degree of freedom in modern semiconductor technology [1–6]. Virtually, such kind of spintronic devices are believed to solve scenarios like integration of information processing and storage facilities in a single crystal with enhanced speed, extending battery life and non volatility of memories [4].

The most difficult problem is how to control the spin degree of freedom and ensure room temperature functionality. Because, the difference between experimental and theoretical findings still continue though the later predicts promisingly; as already shown for $(Ga, Mn)As$ and $(Ga, Mn)N$, except that x_m vs. T_c direct relation remains for certain temperature range [7–10]. Theoretical estimations usually exceed perhaps due to challenges in removing interstitial, antisite and other degrading defects during experiment [11].

It is broadly accepted that the 3d sub orbital electrons play the role of magnetism being mediated by the hole formation due to partial substitution of magnetic impurity in host semiconductors [1,5,6,12]. Theoretical and experimental investigations also suggest that interaction of elementary excitations can affect the thermodynamic property of diluted magnetic semiconductors [12,13] by controlling the hole intervention process and enhancing fluctuations. Among these are, the formation of exciton-magnon coupling. The fundamental source of magnon-exciton coupling energy has been accepted as arising from the coupling between a pair of nearest-neighbor ions and excited electronic states [14].

In this article the effect of magnon-exciton coupling on density of magnons and ferromagnetic phase transition temperature T_c of bulk diluted magnetic semiconductors are described employing the double time temperature dependent Green function technique [15]. The approach is used in calculating the average of dynamical quantities due to the many-particle nature of the problem. The Hamiltonian describing the system is constructed based on the standard models and understanding that excitons are always there where there are magnon excitations.

2. Formulation of the problem

The general Hamiltonian that accounts for the description of systems consisting of two different species of Bosons interacting with each other [16] is given by

$$H = H^{mag} + H^{ex} + H^{mag-ex} \tag{1}$$

The first term refers to free magnon energy,

$$H^{mag} = \sum_{k} \omega_k b_k^+ b_k \tag{2}$$

neglecting the interaction of spin waves, where $b_k^+(b_k)$ is magnon creation (annihilation) operator and $\omega_k = 2x_m J_{nm} S z k^2 a^2 + g\mu_B B$ is the free magnon dispersion in which $J_{nm} = J(r_n - r_m)$ is the exchange integral between spins at sites r_n and r_m measured from an arbitrary origin, z is for the number of nearest neighbors. S represents localized spins per atom and a in Angstrom, Å, is the lattice constant of the DMS assumed to be the same as of the host semiconductor. $\boldsymbol{k}$ is magnon wave vector, g the g-factor, μ_B the Bohr magneton and B magnitude of applied field. This can be obtained starting with the Heisenberg model and using the Holstein-Primakoff representation [17]. Since spin deviations are not localized to a particular lattice site but propagates throughout with wave-vector $\boldsymbol{k}$, it is necessary to use magnon variables b_k^+, b_k [17]. The second term on the right-hand side of Eq 1,

$$H^{ex} = \sum_{k'} \beta_{k'} c_{k'}^+ c_{k'} \tag{3}$$

represent free exciton energy where $\beta_{k'} \propto k'^2$ is exciton dispersion, $\boldsymbol{k}'$ is the exciton wave vector [18] and $c_{k'}^+(c_{k'})$ is the exciton creation (annihilation) operator. The third term on the right-hand side of Eq 1,

$$H^{mag-ex} = \sum_{k} \Theta(c_{k'}^+ b_k + c_{k'} b_k^+) \tag{4}$$

signify the magnon-exciton interaction energy where Θ is taken as independent of wavenumber [19] and describes the coupling strength of the exciton-magnon in which the cooperative propagation is ceased.

In order to determine density of magnons, magnetization, and the Curie temperature Eq 1 is set in to the typical Green function equation of motion,

$$\varepsilon_k\langle\langle b_k; b_k^+\rangle\rangle = \frac{1}{2\pi}\langle[b_k, b_k^+]\rangle + \langle\langle[b_k, H]; b_k^+\rangle\rangle \tag{5}$$

and the total dispersion $\varepsilon_k \cong \eta k^2 - \Theta$, where $\eta = J_{nm}x_m S z a^2$ is obtained for small field, B. Note also that random phase decoupling approximation is applied during the course of derivation. To calculate the number of magnon excitation, the correlation relation $< b(t)b(t') >$ [15] is used. where $\langle ... \rangle$ refers to the quantum statistical average, from which the average number of magnons excited at temperature T is obtained. Hence,

$$\varepsilon_k = \frac{1}{\beta}\ln\left[\frac{1}{\langle n_k\rangle} + 1\right] \tag{6}$$

indicating dispersion and number of magnon have a logarithmic relationship, where $\langle n_k\rangle = (e^{\beta(\eta k^2-\Theta)} - 1)^{-1}$ for a single mode and equal time correlation $t' = t$, and $\beta = \frac{1}{k_B T}$. For all modes of excitation $\sum_k\langle n_k\rangle$ can be expressed in terms of $\gamma T^{3/2}$ and $\gamma'\Theta T^{1/2}$ where $\gamma = \frac{1}{(x_m z)^{3/2}a^3}\lambda$ and $\gamma' = \frac{1}{(x_m z)^{3/2}a^3}\nu$ are for lower and higher temperatures, respectively; $\lambda \sim (\frac{k_B}{J_{nm}S})^{3/2}$ and $\nu \sim \frac{k_B^{1/2}}{(J_{nm}S)^{3/2}}$.

3. Result and discussion

Figure 1 is plotted for the $T^{1/2}$ dependent term and dominant near absolute temperature. The outcome reveals that the coupling energy enhances the density of magnons ($\sum < n_k > /\gamma[or\ \gamma']$), perhaps, due to denser exciton concentration in the region.

Consequently, the spontaneously ordered localized electrons might be partly trapped in the exciton cloud and subjected to different angular precision.

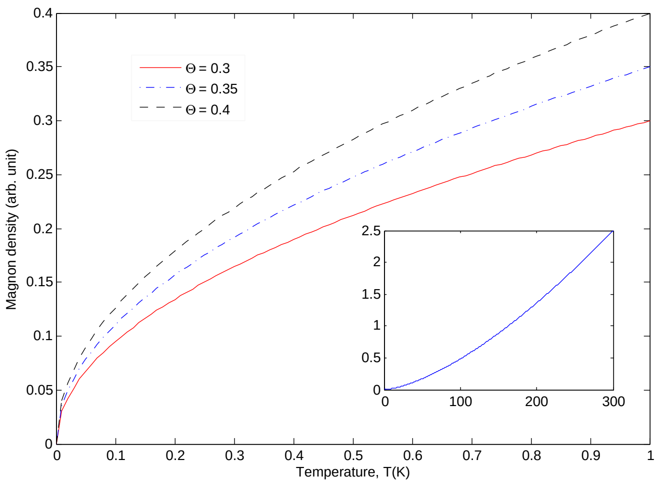

Figure 1. (Color on line) Density of magnons vs. temperature for lower and higher temperatures (the inset).

The inset curve in Figure 1 refers to the most substantial feature of magnon density at higher temperatures. Due to the fact that electron-hole pair formation is lower, magnon-exciton coupling would be poorly significant and leads to the typical $T^{3/2}$ Bloch law for magnetization.

Following the famous Bloch relation [20], curves are plotted for reduced magnetization, $\frac{M(T)}{M(0)}$, vs. temperature T, as illustrated in Figure 2. Accordingly, the effect of coupling of exciton field to the magnon field could pronounce at lower temperatures and suppress the spontaneous magnetization by reinforcing scattering in localized magnetic spins. The inset in Figure 2 also reveals that higher temperature magnetization is not affected by the interaction of the two quasi particles meaningfully in agreement with previous studies which suggested that, holes prefer regions of higher local concentration of magnetic impurity, where they lower their total (magnetic and kinetic) energy by polarizing the localized spins and hopping among several nearby magnetic impurity sites. As a result, these regions of higher magnetic impurity become spin polarized at higher temperatures [21].

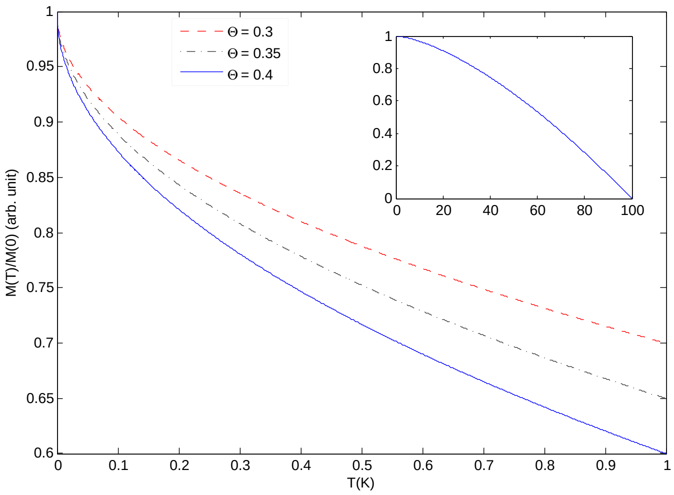

Figure 2. (Color on line) Reduced magnetization vs. lower and higher (the inset) temperatures.

When $\frac{M(T)}{M(0)}$ approaches zero, the temperature T approaches the phase transition T_c [22]. The magnetic contribution x_m, then, becomes linearly related to T_c and $T_c^{1/3}$ at higher and lower temperatures, respectively.

Figure 3 demonstrates the significance of exciton magnon coupling strength Θ on T_c in which the impurity concentration is intentionally varied. The lower temperature limit shows zero T_c for certain impurity concentration and up ward curvature, contrary to high temperature findings from Ab initio calculation for GaMnAs and GaMnN with additional hole doping [4, 23], and abruptly raising eventually with lugging performance as the coupling strength increases with a significant departure from linearity. The inset curve, however, shows the typical $T_c \propto x_m$ in agreement with experimental and theoretical studies [4, 12, 24].

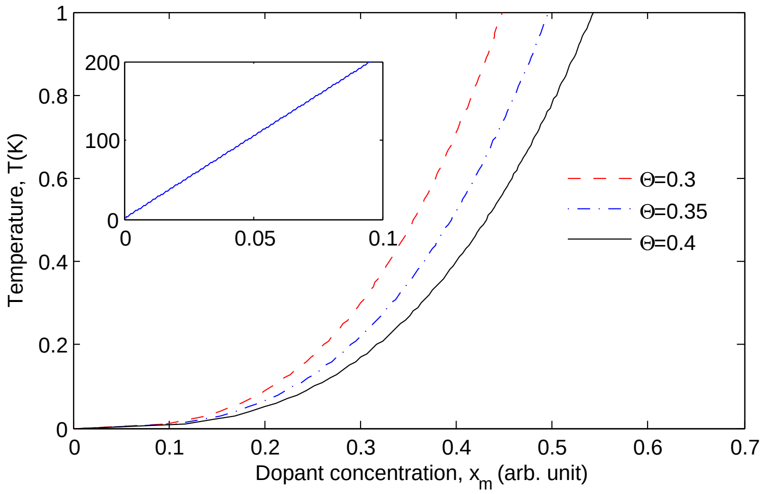

Figure 3. (Color on line) Shows variation of magnetic phase transition temperature T_c vs. magnetic impurity concentration x_m, such that $T_c = (\alpha'^{-1}x_m)^3$ or $\alpha^{-1}x_m$ where $(\alpha' = \frac{1}{(4S)^{2/3}z}\nu$ and $\alpha = \frac{1}{(4S)^{2/3}z}\lambda)$ for lower and higher temperatures, respectively, at different coupling parameters.

4. Conclusion

Magnons and excitons are invariably present in DMSs and hence interact. In our view the interaction significantly affect the thermodynamic property of the system specially at lower temperatures. This role of the magnon and exciton coupling is studied by the green function technique and the effects are illustrated. Our findings also indicate that $\langle n_k \rangle = 0$ near zero temperature in agreement with the result obtained by Sato et al. [4, 23]. Further scrutiny shows the dropping of the ferromagnetic transition temperature with enhancement of magnon-exciton coupling strength and exceedingly with magnetic impurity concentration. It is also understood that exciton formation would suppress the density of free holes/electrons believed responsible for ferromagnetic orientation of localized electrons from metallic dopant impurities.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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