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ABSTRACT
Starting with a Kondo lattice model type Hamiltonian, the effects of the magnetic field, electric field, and magnetic anisotropic energy on the magnetic properties of the Fe/GaSb diluted magnetic semiconductor are studied. The analytical technique is employed to analyze magnon dispersion, magnetization, and critical temperature, \( T_c \). The enhancement of the temperature with increasing impurity concentration \( x \) and/or with the magnetic field and electric field is established, which is in good agreement with recent experimental observations. It is clearly shown that magnon dispersion and magnetization can be controlled with these fields applied, magnetic anisotropic energy, and impurity concentration alternatively or all together. Due to the inclusion of the magnetic anisotropic energy, we could identify a significant escalation of magnon dispersion/bandgap energy and a slight reduction of magnetization.

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I. INTRODUCTION
The realization of materials that combine semiconducting behavior with robust magnetism has long been a dream of material physics.\(^1\)\(^2\)\(^3\) One strategy for creating systems that are simultaneously semiconducting and magnetic was initiated in the late 1970s. It involves the introduction of local moments into well-understood semiconductors. The result is a new class of materials now known as diluted magnetic semiconductors (DMSs).\(^7\)

Since the initial discovery of DMSs in alloyed II–VI semiconductors,\(^7\) reports have been published in investigating electronic, magnetic, optical, thermal, and transport properties in popular magazines as well.\(^7\) This interest not only comes from DMSs themselves as good theoretical and experimental subjects, but also the prospective for future spintronics applications.\(^7\) Even though the origin of ferromagnetism in diluted magnetic semiconductors is not yet well understood and explained adequately, there are different theoretical models and experimental techniques proposed to explain the ferromagnetism passably. However, the room temperature functionality of III–V element based spintronic devices has not yet been realized due to insufficient control mechanisms of interband spin fluctuations.

Currently, there is tremendous interest in research activities of GaSb-based systems.\(^8\) As a matter of fact, this compound has proved to be an interesting material for both basic and applied research and applicable as an infrared detector.\(^8\)

Recently, a lot of experimental work has shown the appearance of a ferromagnetic ordering above room temperature in III–V semiconductor hosts heavily doped with Fe atoms, in particular, (In, Fe)As,\(^9\)\(^10\)\(^11\) (Ga, Fe)Sb,\(^6\)\(^7\) and (Al, Fe)Sb\(^6\) thin films. Accordingly, with incorporation of 23% and 25% sizable amounts of Fe impurity relative to the Ga content into the GaSb semiconductor host, (Ga, Fe)Sb thin film layers were prepared by Molecular Beam Epitaxy (MBE) without the formation of second-phase, demonstrating
ferromagnetic properties up to a temperature of 300 K and 340 K, respectively. This indicates that further analysis is required using different techniques.

In this article, magnetic properties of the Fe/GaSb DMS system are theoretically investigated using the Kondo lattice model type standard Hamiltonian to explain the influence of an applied electric field (EF), magnetic field (MF), and magnetic anisotropic energy (MAE).

II. DETERMINATION OF MAGNON ENERGY AND DISPERSION IN DMS

The model Hamiltonian used to describe the system is given by

$$\hat{H} = -\sum_{ij} J_{ij} \hat{S}_i \cdot \hat{S}_j - g_\mu_B \mathbf{B} \sum_i \hat{S}_i^z - \mu_s \mathbf{E} \sum_i \hat{S}_i^z + D' \sum_i \hat{S}_i^z. \tag{1}$$

The first term $\sum_{ij} J_{ij} \hat{S}_i \cdot \hat{S}_j$ is the Heisenberg type Hamiltonian describing spin–spin interaction of the Fe atoms localized spins. $J_{ij}$ is the exchange coupling energy between the localized spins $\hat{S}_i$ and $\hat{S}_j$ that run over sites $i$ and $j$, positive for ferromagnetic ordering. The second term, $g_\mu_B \mathbf{B} \sum_i \hat{S}_i^z$, gives the Zeeman energy that arises when the magnetic field (MF) $\mathbf{B}$ is applied, where $g$ is the degeneracy factor (or gyromagnetic ratio) and $\mu_B$ is the Bohr magneton. The third term, $\mu_s \mathbf{E} \sum_i \hat{S}_i^z$, and the fourth term, $D' \sum_i \hat{S}_i^z$, arise from the interaction of localized moments with the applied electric field (EF) $\mathbf{E}$ and magnetic anisotropic energy (MAE) $D'$, respectively, where $\mu_s$ is the electric dipole moment. For the two sites $i$ and $j$,

$$\hat{S}_i \cdot \hat{S}_j = \frac{1}{2} \left( (\hat{S}_i^x \hat{S}_j^x + (\hat{S}_i^y \hat{S}_j^y) + \hat{S}_i^z \hat{S}_j^z \right), \tag{2}$$

where $S_k = i S_y$ and $S_k = S_x - i S_y$.

The atomic spin operators can be converted into a more standard many-body interacting problem by replacing the spins with boson creation and annihilation operators $\hat{a}_k$ and $\hat{a}^\dagger_k$, respectively, using the Holstein–Primakoff (HP) transformation.

The spin operator $\hat{S}_i$ is related to the spin operators by the Holstein–Primakoff (HP) transformation as

$$\hat{S}_i^\dagger = \left[ 2xs(1 - \frac{\hat{a}^\dagger_k \hat{a}_k}{xs}) \right]^{1/2} \hat{a}_k,$$

$$\hat{S}_i^- = \left[ 2xs(1 - \frac{\hat{a}^\dagger_k \hat{a}_k}{xs}) \right]^{1/2} \hat{a}_k^\dagger,$$

where $s$ and $x$ are, respectively, the total number of magnetic spins per atom and the mean magnetic ions at the cation sites in the DMS.

In this transformation, the Hamiltonian $\hat{H}$ consists of infinitely many terms, in which, reasonably, there is a physical justification for terminating the infinite series from Tyler’s expansion of the terms under radical. In such a case, one can limit to the lowest powers and hence, ignore spin wave scattering, which sounds well as the temperature increases.

Approximating these functions around the state of saturation magnetization,

$$\hat{S}_i^\dagger = \sqrt{2xs} \hat{a}_k, \quad \hat{S}_i^- = \sqrt{2xs} \hat{a}_k^\dagger,$$

and

$$\hat{S}_i^z = xs - \hat{n}_i,$$

where $\hat{n}_i = \hat{a}_k^\dagger \hat{a}_k$ represents the spin reversal, and substituting into Eq. (1),

$$\hat{H} = -J \sum_{i,\delta} \left[ \frac{1}{2} \left( (\hat{a}_i \hat{a}_i^\dagger + \hat{a}_i^\dagger \hat{a}_i) \right) \right] + \left( x^2 s^2 - 2xs \hat{n}_i \right) \hat{a}_i + \frac{\mu_s}{2} \mathbf{E} \sum_i (xs - \hat{a}_i \hat{a}_i + \hat{a}_i \hat{a}_i^\dagger) \right]$$

$$- 2\mu_B \mathbf{B} \sum_i (xs - \hat{a}_i \hat{a}_i) - \mu_s \mathbf{E} \sum_i (xs - \hat{a}_i \hat{a}_i + \hat{a}_i \hat{a}_i^\dagger) \right]$$

$$+ D' \sum_i (xs - \hat{a}_i \hat{a}_i)^2. \tag{4}$$

Here, an average of $J_{ij} = J$ is considered and $\delta$ represents the nearest-neighbor distance.

Since the system is periodic (propagates throughout), we are looking for excitation, which can be characterized by the well-defined (crystal momentum), so we define the Fourier transformed variables, $\hat{a}_k$ and $\hat{a}_k^\dagger$, which satisfy the bosonic relations $[\hat{a}_k, \hat{a}_k^\dagger] = \delta_{k,k'}$, and hence,

$$\hat{a}_i = \frac{1}{\sqrt{N}} \sum_k \hat{a}_k e^{i\frac{\sqrt{2}s}{xs} \delta_{k,i}}$$

$$\hat{a}_i^\dagger = \frac{1}{\sqrt{N}} \sum_k \hat{a}_k^\dagger e^{-i\frac{\sqrt{2}s}{xs} \delta_{k,i}} \tag{5}$$

Introducing Eq. (5) into Eq. (4) and rearranging,

$$\hat{H} = 2jxs \sum_{k,k'} \hat{n}_k \hat{n}_{k'} - (J + 2N\mu_B \mathbf{B} + N\mu_s \mathbf{E})sx^2$$

$$s + N(D' - J)s^2 + (2xs + 2\mu_B \mathbf{B} + \mu_s \mathbf{E} - 2sD') \sum_k \hat{n}_k$$

$$+ (D' - J) \sum_k (\hat{n}_k)^2 \tag{6}$$

where $\hat{n}_k = \hat{a}_k^\dagger \hat{a}_k$ is the total number of magnons in state $k$.

Employing the limit to long wavelength excitation ($k a \ll 1$) for one dimensional $x$ number of nearest neighbors, Eq. (6) can be rewritten as

$$\hat{H} = \sum_k \hat{n}_k \omega_k - (J + 2N\mu_B \mathbf{B} + N\mu_s \mathbf{E})sx^2$$

$$+ N(D' - J)s^2 + (D' - J) \sum_k (\hat{n}_k)^2 \tag{7}$$

Denoting $[-(J + 2N\mu_B \mathbf{B} + N\mu_s \mathbf{E})sx^2 + N(D' - J)s^2 + (D' - J) \sum_k (\hat{n}_k)^2]$ by $\hat{H}_{\text{magnon}}$, the magnon energy can be written as

$$\hat{H}_{\text{magnon}} = \hat{H} - \hat{H}_o$$

where $\omega_k = jxsx^2\alpha^2 + 2\mu_B \mathbf{B} + \mu_s \mathbf{E} - 2sD'$ is the overall magnon dispersion.

For the purpose of analysis, the following parameters are used: (GaFe)Sb has an fcc lattice structure and lattice parameter
The total number of excited magnons in all modes at tempera-
ture $T$ can be approximated to $\sum_1 (n_\nu)$, where
\[
n(k) = \frac{1}{e^{\beta \omega_k} - 1}
\]
from the Bose–Einstein (BE) distribution, in which $\beta = \frac{1}{kT}$. Substi-
tuting into Eq. (10),
\[
M(T) = M(0) - g\mu_B \sum_k \frac{1}{e^{\beta \omega_k} - 1},
\]
where $R = f gs a^2$ and $F = 2\mu_0 B + \mu_e E - 2sD$.
Since the system is attributed to the resonance in bulk, Eq. (12) can be re-
written as
\[
M(T) = M(0) - \frac{g\mu_B}{(2\pi)^2(2\pi)^2} \int_0^{\infty} \frac{1}{e^{\beta \omega} - 1} d\omega,
\]
where $c = e^{\beta F}$ and $\nu = \beta R$. Let $\nu k^2 = x_1$; then,
\[
M(T) = M(0) - \frac{g\mu_B}{(2\pi)^2(2\pi)^2} \int_0^{\infty} e^{\frac{1}{x_1}} dx.
\]
Since the Bose–Einstein (BE) function is given by
\[
B_{\nu} = \frac{1}{\Gamma(\nu)} \int_0^{\infty} x^{\nu - 1} e^{-x} dx,
\]
for $\nu > 1$, we can use the proceeding expression for small $z$, ($z < 1$) and the classical limit $T > 0$,
\[
B_{\nu - 1}(z) = \sum_{n=1}^{\infty} \frac{z^n}{n^{\nu}}.
\]
From Eqs. (15) and (16), we get
\[
\sum_{n=1}^{\infty} \frac{z^n}{n^{\nu}} \Gamma(\nu) = \int_0^{\infty} x^{\nu - 1} e^{-x} dx.
\]
Substituting Eq. (17) into Eq. (14) with $\nu = \frac{3}{4}$ and $z = \frac{1}{c} = e^{-\beta F}$,
\[
M(T) = M(0) - \frac{g\mu_B}{2(2\pi)^2} \sum_{n=1}^{\infty} \frac{e^{-\beta F}}{n^{\frac{3}{4}}} \Gamma\left(\frac{3}{4}\right).
\]
Assuming that the first term ($n = 1$) is much larger than all the other terms gives
\[
M(T) \approx M(0) - \frac{g\mu_B}{2(2\pi)^2} \frac{1}{\Gamma\left(\frac{3}{4}\right)} e^{-\frac{1}{4} F}.
\]
From Eq. (19), the reduced magnetization $M_T(0)$, where $M(0)$ is the
magnetization at absolute temperature and $g = 2$ for a system of spin $\frac{1}{2}$ particles, becomes
\[
\frac{M(T)}{M(0)} = 1 - AT^{\frac{3}{2}} e^{-\frac{1}{2} F},
\]
where $A$ is a constant given by
\[
A = \frac{1}{\sqrt{\pi}} \frac{g_0}{\hbar} \left( \frac{k_B}{m} T \right)^{\frac{3}{2}}.
\]
Figures 3–7 show reduced magnetization as a function of tempera-
ture for constant and varied values of concentration $x$ and/or applied
B, E, and D, where $n = \frac{x}{2}$. 

**III. MAGNETIZATION AND FERROMAGNETIC TRANSITION TEMPERATURE**

At a temperature $T$, the magnetization per site is given by
\[
M(T) = M(0) - g\mu_B \sum_k \hat{n}_k
\]
Figure 3 illustrates the increase in critical temperature with an increase in the magnetic impurity concentration $x$, which is in good agreement with the experimental results reported by Tu et al.\textsuperscript{6}

The increase in the critical temperature with the increases in the magnitude of the MF and EF at concentration $x = 20\%$ is demonstrated in Figs. 4 and 5. The magnetization of the system tends to increase as the applied magnetic and electric fields increase. Perhaps, the applied fields increase the coupling between the localized spin and the itinerant hole spin and produce spin polarized carriers, which in turn creates a molecular field, which is responsible for the enhancement of magnetic ordering. The slow drop of the magnetization is due to the low temperature approximation and the rejection of the strong spin fluctuation compared to the Weiss mean field approximation. These results are also in good agreement with the experimental work of Ohno et al.\textsuperscript{15} and Chiba et al.,\textsuperscript{16} which suggested that the hole induced ferromagnetism could be turned on and off by the applied fields.
Figure 6 demonstrates the slight reduction of magnetization due to the increase in magnetic anisotropy energy comparatively and Fig. 7 shows the further increase in the critical temperature when both MF and EF are turned on.

IV. CONCLUSION

This paper reports the effects of the electric field, magnetic field, and magnetic anisotropy energy on the magnetic properties of the Fe/GaSb diluted magnetic semiconductor. At all temperatures, magnetization and magnon dispersion are found enhanced with an increase in these fields and percentage of magnetic spin concentration, x at a time or alternatively. Due to the inclusion of magnetic anisotropy energy, we could identify the escalation of magnon dispersion/bandgap energy significantly and a slight reduction of magnetization. Hence, the magnetic critical temperature $T_C$ can be controlled by careful tuning of the electromagnetic field sources and a concentration limit in such multiferroic systems. However, once the Fe concentration becomes sufficiently high, there could be considerable overlap of orbitals making the localized electrons mobile/itinerant and overshadowing semiconductivity and/or leading to precipitation and spin glass ordering, as occurs in many DMSs\textsuperscript{17} and superconductors.\textsuperscript{18}

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The data that support the findings of this study are available within the article.

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