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Research Article

Electric Field Controlled Itinerant Carrier Spin Polarization in Ferromagnetic Semiconductors

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Electric field control of magnetic properties has been achieved across a number of different material systems. In diluted magnetic semiconductors (DMSs), ferromagnetic metals, multiferroics, etc., electrical manipulation of magnetism has been observed. Here, we study the effect of an electric field on the carrier spin polarization in DMSs (GaAsMn); in particular, emphasis is given to spin-dependent transport phenomena. In our system, the interaction between the carriers and the localized spins in the presence of electric field is taken as the main interaction. Our results show that the electric field plays a major role on the spin polarization of carriers in the system. This is important for spintronics application.

1. Introduction

The presence of both magnetic and semiconductor properties in diluted magnetic semiconductor (DMS) materials provides interesting opportunities for basic research in condensed matter physics and device applications. The manipulation of the spin and charge degrees of freedoms of carriers in the DMS enables the integration of magnetism into existing semiconductor devices, which makes them good candidates for spintronic devices [1, 2].

Diluted Magnetic semiconductors (DMSs) are made artificially by doping appropriate-type magnetic impurity atoms (Mn, Cr, Fe, Ni, etc.) into the host semiconductor. In the DMS, there are two subsystems on which the properties of the material depend. These are the electronic subsystem built out of the itinerant carriers and the magnetic subsystem which constitutes the localized $3d$ or $4f$ electron system [3]. The magnetic properties observed on the DMS are based on the kind of interaction involved in these subsystems. There are different proposed models for understanding the mechanism of ferromagnetism in the DMS and are used for explaining different magnetic phenomena [4]. Regardless of their difference, in most models, charge carriers are considered as itinerant carriers moving in the conduction or valence bands. The density of these carriers is a key factor in terms of the kinetic energy of the system as well as their contribution for assisting coupling of the magnetic ions leading to Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction [5]. In DMSs, there can be a sizable exchange interaction between carrier spin and the magnetic ions. This exchange interaction causes novel spin-dependent phenomena including carrier spin polarization [6] and magnetic polaron formation [7].

Different studies have been conducted on the mechanism of controlling the magnetic properties from internally or externally so far by different scholars. For example, Gomes et al. reported that the spin-polarized charge distributions can be engineered by varying impurity concentration in the magnetic layer in DMS superlattices [8]. Photoinduced [9, 10] and electric-field-controlled magnetic properties [11, 12] of DMSs have been studied by various scholars.

Ohno et al. opened a new way to control ferromagnetism from outside by the use of electric field, and they showed that the electric field amplifies hole-induced ferromagnetism [13]. Since the discovery of Giant Magnetoresistance (GMR) [14], the study of spin-polarized electrons gained more intention to develop a new generation of electronic devices such as spin field effect transistor [15], magnetic sensing, and nonvolatile magnetic memory in which the spin polarization in the device is adjusted by external voltages [16]. This has fundamental importance for modifying the existing semiconductor-based technology. The operation of spin-polarized-electron-based device requires efficient spin injection, manipulation, control, and transport in the semiconductor.

One of the widely known mechanisms of coupling between external electric field and electron spin is through spin-orbit coupling. Since the electric field is not directly coupled to electrons spin, rather it can interact through spin-orbit interaction, which couples the spin dynamics of an electron and its orbital motion in the material. In ferromagnetic semiconductors, the Rashba spin-orbit interaction type is observed [17–19]. Stagraczynski et al. reported that the Rashba spin-orbit interaction significantly modifies the effective spin's magnitude and orientation of two-dimensional GaMnAs magnetic semiconductor [20].

In this work, we investigate the effect of electric field on spin-polarized charge densities in DFMS based on the $s-d$ exchange interaction model. The $s-d$ exchange interaction model is a useful theoretical approach for incorporating carrier spin interaction with the localized spin moments. We use a Green function (GF) formalism for the calculation of the spin-polarized carrier densities.

2. Hamiltonian of the $s-d$ Exchange Model

The system considered here is described by two subsystems. The system of itinerant carriers is built on the s and s-like band carriers, and the system of the localized system comes from the $3d$ electrons of the manganese impurity. Our system is assumed to have large number of itinerant carriers for which the $s-d$ interaction contribution is not negligible. The model Hamiltonian used to describe our system has the following form:

$$H = H_{\mathrm{ee}} + H_{\mathrm{sd}} + H_{\mathrm{ef}}. \quad (1)$$

H_{ee} represents the Hamiltonian of the electronic subsystem and is given by

$$H_{\mathrm{ee}} = \sum_{k,\sigma} \varepsilon_k c^{\dagger}_{k\sigma} c_{k\sigma}, \quad (2)$$

where $c^{\dagger}_{k\sigma}$ ($c_{k\sigma}$) are the fermionic creation (annihilation) operators for carriers. ε_k is the energy of carriers within the system with momentum k.

The Hamiltonian of the magnetic subsystem (H_{sd}) is due to the interaction of the band carriers (holes) and the localized spin Mn^{2+} ions, expressed as Heisenberg-type Hamiltonian. H_{sd} can be expressed in the Zener $s-d$ exchange model [3] as

$$H_{\mathrm{sd}} = -2\frac{J_{\mathrm{sd}}}{\sqrt{N}} \sum_i \sigma_i \cdot S_i, \quad (3)$$

where J_{sd} is the exchange coupling between the carriers and the localized spins S_i and σ_i represents the spin of the carriers in the FMS system.

The term H_{ef} arises from the disturbance on the carriers due to the external electric field (EEF). When an electron with energy k moves over an electric field E, it encounters an effective magnetic field proportional to $B_{\mathrm{eff}} = (\mathbf{E}\times\mathbf{k})/mc^2$ (where m the mass of the electron and c is the speed of light) in its rest frame. This effective magnetic field is due to Rashba spin-orbit interaction (RSOI) which induces momentum-dependent Zeeman-like energy of the form $H_{\mathrm{so}} \sim \mu_\beta (\mathbf{E}\times\mathbf{k})\cdot\sigma/\mathbf{mc}^2$ (where σ is the Pauli spin matrices) [19]. Assuming the mean electric polarization to be proportional to the z-component of the carrier spin, it can be expressed analogous to the Zeeman term ($g\mu_\beta H \sum_i \sigma^z$) in the form $\mu_e E \sum_i \sigma^z$ [21]. The coefficient μ_e is the electric dipole moment. Then, we can write H_{ef} in the form

$$H_{\mathrm{ef}} = -\mu_e E \sum_i \sigma^z_i. \quad (4)$$

σ represents the spin of the carriers in the DMS system and is given by

$$\sigma_\alpha = \frac{1}{2}\sum_{\sigma\sigma'} c^{\dagger}_{m\sigma} \tau_{\sigma\sigma'} c_{m\sigma'}, \quad (5)$$

where ($\alpha = x, y, z$) and τ are the matrix elements of the Pauli spin matrices.

The Hamiltonian (H_{sd} and H_{ef}) in k-space can be written in the form

$$H_{\mathrm{sd}} = -\frac{J_{\mathrm{sd}}}{\sqrt{N}} \sum_{kq} \left(S^{+}_{-q} c^{\dagger}_{k\downarrow} c_{k+q\uparrow} + S^{-}_{-q} c^{\dagger}_{k\uparrow} c_{k+q\downarrow} + S^{z}_{-q} \left(c^{\dagger}_{k\uparrow} c_{k+q\uparrow} - c^{\dagger}_{k\downarrow} c_{k+q\downarrow} \right) \right),$$
$$H_{\mathrm{ef}} = -\frac{\mu_e E}{2N} \sum_q \left(c^{\dagger}_{k\uparrow} c_{k+q\uparrow} - c^{\dagger}_{k\downarrow} c_{k+q\downarrow} \right), \quad (6)$$

where N is the number of unit cells.

In order to find the spin polarization of carriers, we define the following Green function (GF):

$$G_{k,\sigma}(t,t') = \langle\langle c_{k\sigma}(t); c^{\dagger}_{k\sigma}(t') \rangle\rangle. \quad (7)$$

Here, we use $\hbar = 1$ throughout the calculation for simplicity.

$$\omega \langle\langle c_{k\sigma}; c^{\dagger}_{k\sigma} \rangle\rangle_\omega = \frac{1}{2\pi} \langle [c_{k\sigma}; c^{\dagger}_{k\sigma}] \rangle + \langle\langle [c_{k\sigma}, H]; c^{\dagger}_{k\sigma} \rangle\rangle_\omega. \quad (8)$$

Calculating the commutators which appear in equation (8) and plugging the result into it, we get

$$\omega\langle\langle c_{k\sigma};c_{k\sigma}^{\dagger}\rangle\rangle=\frac{1}{2\pi}+\left(\varepsilon_k-\sigma\frac{\mu_e E}{2}\right)\langle\langle c_{k\sigma};c_{k\sigma}^{\dagger}\rangle\rangle-\frac{J_{\text{sd}}}{\sqrt{N}}\sum_{q\sigma}\sigma\langle\langle S_q^z c_{k+q\sigma};c_{k\sigma}^{\dagger}\rangle\rangle$$
$$-\frac{J_{\text{sd}}}{\sqrt{N}}\sum_{q}\left\{\langle\langle S_{-q}^{+}c_{k+q\uparrow};c_{k\sigma}^{\dagger}\rangle\rangle\delta_{\sigma\downarrow}+\langle\langle S_{-q}^{-}c_{k+q\downarrow};c_{k\sigma}^{\dagger}\rangle\rangle\delta_{\sigma\uparrow}\right\}. \quad (9)$$

In this equation of motion (EOM), there appears a higher-order GF of the form $\langle\langle S_{-q}^{+}c_{k+q\uparrow};c_{k\sigma}^{\dagger}\rangle\rangle$ and $\langle\langle S_{-q}^{-}c_{k+q\downarrow};c_{k\sigma}^{\dagger}\rangle\rangle$. These terms would increase the effective molecular field acting on the carrier spin and the localized spins. But, we ignore such a higher-order GF in order to simplify the theoretical treatment and consider only the molecular field that is of the first order with respect to the exchange parameter J_{sd}. The other higher-order GF appearing in equation (9) are decoupled by the use of Random Phase Approximation (RPA) as follows. Green's functions are of the form

$$\langle\langle S_{-q}^{z}c_{k+q\uparrow};c_{k\sigma}^{+}\rangle\rangle\approx\langle S_0^z\rangle\langle\langle c_{k\sigma};c_{k\sigma}^{\dagger}\rangle\rangle\delta_{\sigma\uparrow}. \quad (10)$$

Substituting equation (10) into (9), the GF becomes

$$\langle\langle c_{k\sigma};c_{k'\sigma}^{\dagger}\rangle\rangle=\frac{1}{2\pi\left(\omega-\widetilde{\varepsilon}_{k\sigma}\right)}, \quad (11)$$

where

$$\widetilde{\varepsilon}_{k\sigma}=\varepsilon_k-z_\sigma\left(\frac{\mu_e E}{2}+J_{\text{sd}}S_z\right), \quad (12)$$

$$z_\sigma=\delta_{\sigma\uparrow}-\delta_{\sigma\downarrow}, \quad (13)$$

and it takes the values ±1 for spin orientation $\uparrow(\downarrow)$, respectively.

The excitation spectrum of the spin-polarized itinerant carriers in the system is obtained from the poles of this GF. Then, it is given by

$$\omega(k)=\varepsilon_k-z_\sigma(\alpha+\Delta), \quad (14)$$

where $\alpha=(\mu_e E/2)$ is the term containing the electric field and is called electric field parameter and $\Delta=J_{\text{sd}}S_z$ is the spin splitting gap.

The number of excited carriers at a temperature T is obtained from the correlation function as

$$\langle c_{k\sigma}^{\dagger}(t')c_{k\sigma}(t)\rangle=\lim_{\varepsilon\longrightarrow0}i\int_{-\infty}^{\infty}\mathrm{d}\omega\frac{e^{-\omega(t-t')}}{e^{\beta\omega}+1}\left(G_{k\sigma}(\omega+i\varepsilon)-G_{k\sigma}(\omega-i\varepsilon)\right). \quad (15)$$

Making use of the Dirac identity

$$\frac{1}{\omega-E\pm i\varepsilon}=P\frac{1}{\omega-E}\mp i\pi\delta(\omega-E), \quad (16)$$

where $\varepsilon\longrightarrow0,\varepsilon>0$ and P denotes the principal value of integral, in the GF, $G_{k\sigma}(\omega\pm\varepsilon)$, and equation (15) becomes

$$\langle c_{k\sigma}^{\dagger}(t')c_{k\sigma}(t)\rangle=\int_{-\infty}^{\infty}\mathrm{d}\omega\frac{e^{-\omega(t-t')}}{e^{\beta\omega}+1}\delta(\omega-\widetilde{\varepsilon}_{k\sigma}). \quad (17)$$

At $t=t'$, the correlation gives the number of excited carriers

$$\langle c_{k\sigma}^{\dagger}(t)c_{k\sigma}(t)\rangle=\frac{1}{\exp\left[\beta\left(\varepsilon_k-z_\sigma(\alpha+\Delta)\right)\right]+1}. \quad (18)$$

The total number of excited carriers at temperature T is

$$\sum_k\langle\nu_{k\sigma}\rangle=\sum_k\frac{1}{\exp\left[\beta\left(\varepsilon_k-z_\sigma(\alpha+\Delta)\right)\right]+1}, \quad (19)$$

where $\langle\nu_{k\sigma}\rangle=\langle c_{k\sigma}^{\dagger}(t)c_{k\sigma}(t)\rangle$ is the Fermionic number operator.

The summation on the right-hand side (RHS) of equation (19) can be expressed in an integral form, and in the low temperature limit, we can write it as

$$\nu_\sigma\approx e^{\beta\left[-z_\sigma(\alpha+\Delta)\right]}\int_{-\infty}^{\infty}\mathrm{d}^3ke^{-\beta\varepsilon_k}. \quad (20)$$

For the parabolic band of carriers, ε_k is given by

$$\varepsilon_k=\frac{\hbar^2k^2}{2m^*}, \quad (21)$$

where m^* is the electron effective mass. Performing the integration in spherical coordinates and using standard Gauss's probability integrals, one can obtain

$$\nu_\sigma=2\left(\frac{2\pi m^*}{\beta\hbar^2}\right)^{3/2}e^{\beta\left[-z_\sigma(\alpha+\Delta)\right]}. \quad (22)$$

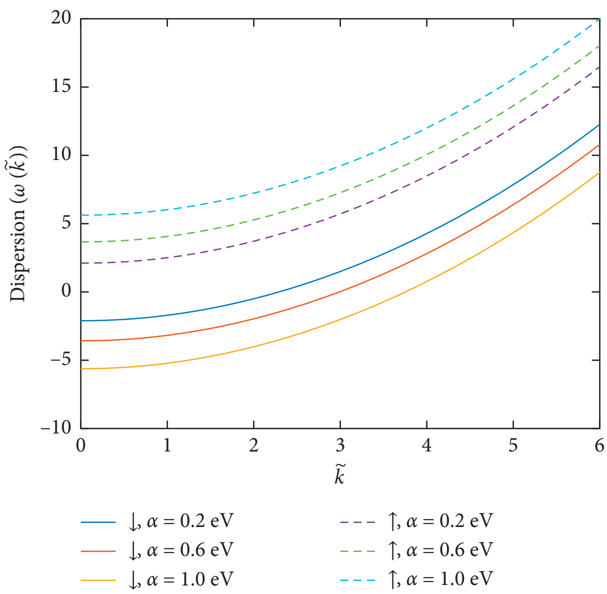

FIGURE 1: Carrier excitation spectrum for spin up and spin down carriers for different values of α.

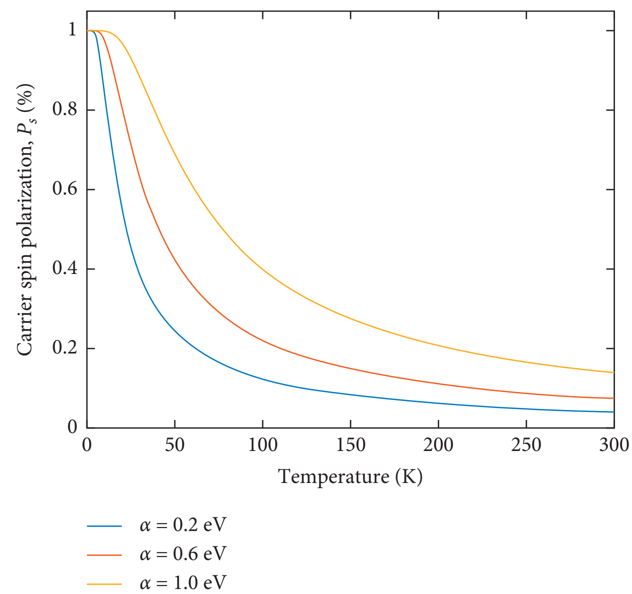

FIGURE 2: Carrier spin polarization as a function of temperature for different values of EEF parameter α.

Equation (22) is the spin-dependent total number of carriers of the system. Evaluating it at different spin orientations, we get

$$\nu_{\uparrow} = 2\left(\frac{2\pi m^*}{\beta \hbar^2}\right)^{3/2} e^{\beta[(\alpha+\Delta)]},$$
$$\nu_{\downarrow} = 2\left(\frac{2\pi m^*}{\beta \hbar^2}\right)^{3/2} e^{-\beta[(\alpha+\Delta)]}. \quad (23)$$

Defining the spin polarization (P_s) of the carriers in the system as $P_s = ((\nu_{\uparrow} - \nu_{\downarrow})/\nu_{\uparrow} + \nu_{\downarrow})$, we get

$$P_s = \frac{e^{\beta(\alpha+\Delta)} - e^{-\beta(\alpha+\Delta)}}{e^{\beta(\alpha+\Delta)} + e^{-\beta(\alpha+\Delta)}}, \quad (24)$$

$$P_s = \tanh[\beta(\alpha + \Delta)]. \quad (25)$$

3. Numerical Results and Discussions

Based on equations (14) and (25), we discuss the effect of the electric field on the carrier spin polarization of the FMS system (EuO). The relevant parameters used for GaAsMn DMS are $J_{sd}S = 0.6\,\text{eV}$, $E_F = 0.4\,\text{eV}$, and $S = 5/2$ [17] and $0.1\,\text{eV} \le \alpha \le 0.6\,\text{eV}$. The choice of the electric field parameter α is made with reference to the value of Fermi energy (E_F) and $\Delta = J_{sd}S$.

For FMS at low temperature with large electron density ($10^{15} \le n \le 10^{22}$), $E_F < J_{sd}S$, the contribution of the spin of the charge carriers is not negligible. The electric field enhances the splitting of spin-polarized carriers, as shown in equation (14). The gap in the dispersion between the spin up and the spin down carries seen in Figure 1 shows that the electric field contributes for the spin splitting.

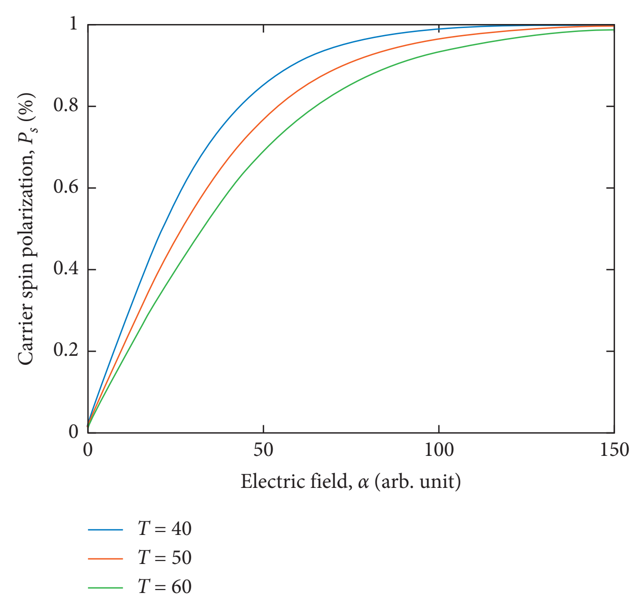

FIGURE 3: Electric field dependence of carrier spin polarization for $T = 40\,\text{K}, 50\,\text{K}$ and $60\,\text{K}$.

Figure 2 shows the dependence of the carrier spin polarization on the EEF. Even though strong spin polarization is seen at low temperature, at all temperatures, there is an increase in carrier spin polarization with increasing external electric field; i.e., at a given temperature, it is seen from the figure that high carrier spin polarization is observed for higher values of electric field. This is an indication of the action of the electric field on the magnetic subsystem via its action on the itinerant carriers. Our result is in agreement with the work of by Ciftja et al. [18]. In their study, they showed that the electric field increases the current spin polarization in ferromagnetic/organic semiconductor systems.

The dependence of the spin polarization on the electric field is shown in Figure 3. It is found that the spin polarization increases with the increase of the electric field. It can be seen from the figure that the spin polarization tends to saturate as the electric field increases.

4. Conclusions

The spin polarization of carriers may be obtained in nonmagnetic materials usually by applying very strong magnetic fields. In the case of FMS, the Zeeman effect allows one to obtain spin polarization by applying relatively small magnetic fields. In both cases, the spin polarization has been achieved through the application of magnetic field from external sources, which brings some limitations on the device technology. In our case, the carrier spin polarization is obtained by the application of EEF and can be used to generate spin-polarized current for the microelectronic device application. The dependence of the carrier spin polarization on the EEF will facilitate external manipulation of the spin state which is very important for the new spin-based devices. Even though the total spin polarization of carriers is small as compared to the localized moments, the presence of these spin-polarized carriers is important for the observed magnetic properties as well as for generating spin-polarized current which is essential for spintronic application.

Data Availability

The data which were used to support this study are included within the article.

Conflicts of Interest

The author declares no conflicts of interest.

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