Research Article

Electric Field Controlled Itinerant Carrier Spin Polarization in Ferromagnetic Semiconductors

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Received 4 November 2020; Accepted 27 June 2021; Published 13 July 2021

Academic Editor: Leonid Pryadko

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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 semi-
conductor-based technology. The operation of spin-polar-
ized-electron-based device requires efficient spin injection,
manipulation, control, and transport in the semiconductor.

One of the widely known mechanisms of coupling be-
tween 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 ferro-
magnetic 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-dimen-
sional 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. Iˇhe system considered here is described by two subsystems.

s
H
Hamiltonian of the system of itinerant carriers is built on the
d
system of itinerant carriers, and the system of the localized system comes
d
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:

\begin{equation}
H = H_{ee} + H_{sd} + H_{ef}.
\end{equation}

\(H_{ee}\) represents the Hamiltonian of the electronic sub-

\begin{equation}
H_{ee} = \sum_{k,\sigma} \epsilon_k c_{k\sigma}^+ c_{k\sigma},
\end{equation}

system and is given by

where \(c_{k\sigma}^+\) and \(c_{k\sigma}\) are the fermionic creation (annihilation)
operators for carriers. \(\epsilon_k\) 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 lo-

\begin{equation}
H_{sd} = -\sum_{k,\sigma} \epsilon_k c_{k\sigma}^+ c_{k\sigma},
\end{equation}

calized spin \(S_i\) and \(\sigma_i\) 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 \(B_{eff} = (E \times k)/mc^2\)
(where \(m\) is 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 \(H_{sd} = \mu_s E \sum \sigma^\alpha \cdot \mathbf{S}_i\cdot \mathbf{H}_{sd}\) (where \(\sigma^\alpha\) 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 \((g\mu_s H_S)\sum \sigma^z\) [21]. The coefficient \(g\mu_s\) is the electric dipole
moment. Then, we can write \(H_{ef}\) in the form

\begin{equation}
H_{ef} = -\mu_s E \sum \sigma^z \mathbf{S}_i.
\end{equation}

\(\sigma\) represents the spin of the carriers in the DMS system
and is given by

\begin{equation}
\sigma^\alpha = \frac{1}{2} \sum_{\alpha'} \sigma_{\alpha\alpha'} c_{\alpha} c_{\alpha'},
\end{equation}

where \((\alpha = x, y, z)\) and \(\tau\) 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

\begin{equation}
H_{sd} = \frac{J_{sd}}{\sqrt{N}} \sum_{kq} \left( S_{-q} c_{kq}^+ c_{k+q}^\dagger \right.
+ \left. S_{+q} c_{k+q}^+ c_{kq}^\dagger \right),
\end{equation}

where \(N\) is the number of unit cells.

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

\begin{equation}
G_{k,\sigma} (t, t') = \langle \langle c_{k\sigma}^\dagger (t) ; c_{k\sigma}^\dagger (t') \rangle \rangle.
\end{equation}

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

\begin{equation}
\omega \langle \langle c_{k\sigma}^\dagger (t) ; c_{k\sigma}^\dagger (t') \rangle \rangle_w = \frac{1}{2\pi} \langle \langle c_{k\sigma}^\dagger (t) , c_{k\sigma}^\dagger (t') \rangle \rangle_w
\end{equation}
Calculating the commutators which appear in equation (8) and plugging the result into it, we get

\[ \omega \langle c_{k\sigma}^\dagger c_{ko}\rangle = \frac{1}{2\pi} + (\epsilon_k - \sigma \frac{\mu_s E}{2}) \langle c_{k\sigma}^\dagger c_{ko}\rangle - \frac{J_{sd}}{\sqrt{N}} \sum_{q} \sigma \langle S_q^c c_{k\sigma}^\dagger c_{ko}\rangle \]

\[- \frac{J_{sd}}{\sqrt{N}} \sum_{q} \left\{ \langle S_q^c c_{k\sigma}^\dagger c_{ko}\rangle \delta_{\sigma\uparrow} + \langle S_q^c c_{k\sigma}^\dagger c_{ko}\rangle \delta_{\sigma\downarrow} \right\}.\]

(9)

In this equation of motion (EOM), there appears a higher-order GF of the form \( \langle S_{-q}^c c_{k\sigma}^\dagger c_{ko}\rangle \) and \( \langle S_{q}^c c_{k\sigma}^\dagger c_{ko}\rangle \). 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

\[ \langle S_{-q}^c c_{k\sigma}^\dagger c_{ko}\rangle = \langle S_{q}^c c_{k\sigma}^\dagger c_{ko}\rangle \delta_{\sigma\uparrow}. \]

(10)

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

\[ \langle c_{k\sigma}^\dagger c_{ko}\rangle = \frac{1}{2\pi(\omega - \tilde{\epsilon}_{k\sigma})}. \]

(11)

Making use of the Dirac identity

\[ \frac{1}{\omega - E + i\epsilon} = P \frac{1}{\omega - E} \tau \Im \delta(\omega - E), \]

(16)

where \( \epsilon \rightarrow 0, \epsilon > 0 \) and \( P \) denotes the principal value of integral, in the GF, \( G_{ka}(\omega + \epsilon) \), and equation (15) becomes

\[ \langle c_{k\sigma}(t')c_{k\sigma}(t) \rangle = \int_{-\infty}^{\infty} dw \frac{e^{-w(t'-t)}}{e^{\omega} + 1} \delta(\omega - \tilde{\epsilon}_{k\sigma}). \]

(17)

At \( t = t' \), the correlation gives the number of excited carriers

\[ \langle c_{k\sigma}(t)c_{k\sigma}(t) \rangle = \frac{1}{\exp[\beta(\tilde{\epsilon}_{k\sigma} - \epsilon_{\sigma}(\alpha + \Delta))] + 1}. \]

(18)

The total number of excited carriers at temperature \( T \) is

\[ \sum_{k} \langle v_{ka} \rangle = \sum_{k} \frac{1}{\exp[\beta(\epsilon_k - \epsilon_{\sigma}(\alpha + \Delta))] + 1}. \]

(19)

where \( \langle v_{ka} \rangle = \langle c_{k\sigma}(t)c_{k\sigma}(t) \rangle \) 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

\[ v_{\sigma} \approx e^{\beta(-z_{\sigma}(\alpha + \Delta))} \int_{-\infty}^{\infty} d^3 k e^{-\beta \epsilon_{k}}. \]

(20)

For the parabolic band of carriers, \( \epsilon_k \) is given by

\[ \epsilon_{k} = \frac{\hbar^2}{2m^*} k^2. \]

(21)

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

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

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

\[
\nu_\uparrow = 2 \left( \frac{2m^*}{\beta h^2} \right)^{3/2} e^{\beta \left( \alpha + \Delta \right)},
\]

\[
\nu_\downarrow = 2 \left( \frac{2m^*}{\beta h^2} \right)^{3/2} e^{-\beta \left( \alpha + \Delta \right)}.
\]

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

\[
P_s = \frac{e^{\beta \left( \alpha + \Delta \right)} - e^{-\beta \left( \alpha + \Delta \right)}}{e^{\beta \left( \alpha + \Delta \right)} + e^{-\beta \left( \alpha + \Delta \right)}}.
\]  

(24)

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

(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 \( 0.1 \text{ eV} \leq \alpha \leq 0.6 \text{ eV}. \) The choice of the electric field parameter \( \alpha \) 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 \((10^{25} \leq n \leq 10^{22})\), \( E_F < J_{sd} S, \) 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 carriers seen in Figure 1 shows that the electric field contributes for the spin splitting.

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.

Acknowledgments

The author acknowledges the discussions with Prof. Hamid K. from the S2N-POEM group, Laboratory PROMES-CNRS, Perpignan, France, and the support from the College of Natural Science, Wollo University, Dessie, Ethiopia.

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