The effect of spin-orbit coupling on magnetoresistance in nonmagnetic organic semiconductors*

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We investigated the effect of spin-orbit coupling on magnetoresistance in nonmagnetic organic semiconductors. A Lorentz-type magnetoresistance is obtained from spin-orbit coupling-dependent spin precession under the condition of a space-charge-limited current. The magnetoresistance depends on the initial spin orientation of the electron with respect to the hole in electron–hole pairs, and the increasing spin-orbit coupling slows down the change in magnetoresistance with magnetic field. The field dependence, the sign and the saturation value of the magnetoresistance are composite effects of recombination and dissociation rate constants of singlet and triplet electron–hole pairs. The simulated magnetoresistance shows good consistency with the experimental results.

Keywords: organic magnetoresistance, spin-orbit coupling, recombination, spin precession

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1. Introduction

There has been growing interest in spin and magnetic field effects in organic semiconductors (OSCs).[1−6] The ability to manipulate electron spin in OSCs offers an alternative route to conventional spintronics, both from fundamental and technological points of view. The crucial point for spintronics is spin-charge coupling. The electrical field does not interact directly with the electron spin. By spin-orbit interaction, however, charge and spin transport can be interconnected.[7] For semiconductors with different energy gaps, their spin-orbit coupling strengths vary across six orders of magnitude, thereby making possible the electrical manipulation of electron spins.[8] Generally, spin-orbit coupling is weak in OSC, but significant for OSCs containing heavy atoms.

The effect of magnetic field on the current across OSCs presents dubbed organic magnetoresistance (OMAR). Much work has been done on the exploration of OMAR.[2,3,9−18] An OMAR exceeding 10% at low fields for several OSCs was reported in Refs. [2], [3], [9] and [10]. However, the origin of the large OMAR effect in organic devices is still under argument. Various models have been proposed to explain the observed effects,[11,14−18] but differences between the theoretical calculations and the experimental results still exist.

OMAR is now considered to be an intrinsic property that is universal across OSCs. Despite considerable discussions about the fine mechanism responsible for OMAR, almost all the potential models rely to some degree on spin dynamics involving spin configuration, spin correlation and spin flip.[19,20] Spin-orbit coupling is an important component in organic spin dynamics. It has been found that the excited states can contribute significantly to OMAR,[13,14] and the modification of spin-orbit coupling can lead to a tuning of OMAR in OLED.[13,21] In the present work, we give a physical description to demonstrate the effect of a magnetic field combined with spin-orbit coupling on exciton generation and recombination, with the aim of presenting the mechanisms behind the response of OMARs to magnetic field.

2. Model and method

2.1. Evolution of electron spin with time

Spin-orbit coupling is an important interaction between the spin angular momentum of the carrier

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and the orbital angular momentum of the nuclear centre. When a magnetic field, $B = B\boldsymbol{k}$, is applied to the OSC, the spin Hamiltonian including spin-orbit coupling is expressed as

$$H = \omega_0 \left(\frac{1}{2}L_z + S_z\right) + \frac{b}{\hbar}\boldsymbol{L}\cdot\boldsymbol{S}, \tag{1}$$

where $\omega_0 = 2\mu_{\rm B}B/\hbar$, with $\mu_{\rm B}$ being the Bohr magneton, $\boldsymbol{L}$ the orbital momentum, $\boldsymbol{S}$ the electron spin, and b the spin-orbit coupling constant. Assuming $B_{\rm SO}$ to be an effective spin-orbit coupling field, we have $b/\omega_0 = B_{\rm SO}/B$ for $L_z = \hbar$. The spin-orbit coupling results in $[\boldsymbol{S}, \boldsymbol{S}\cdot\boldsymbol{L}] \neq 0$ and $[\boldsymbol{L}, \boldsymbol{S}\cdot\boldsymbol{L}] \neq 0$, therefore $\boldsymbol{L}$ and $\boldsymbol{S}$ are no longer conserved separately, whereas the total angular momentum $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$ is still conserved. Accordingly, S_z may change with time.

For simplicity we assume $l = 1$, then its projection on the applied magnetic field is $m_l = 1$, 0, -1. Using the uninteracted basis vectors $|L_z, S_z\rangle$, i.e. $\psi_1 = |1, 1/2\rangle$, $\psi_2 = |0, 1/2\rangle$, $\psi_3 = |-1, 1/2\rangle$, $\psi_4 = |1, -1/2\rangle$, $\psi_5 = |0, -1/2\rangle$, and $\psi_6 = |-1, -1/2\rangle$, we write the Hamiltonian in matrix form as[22]

$$H = \hbar \begin{pmatrix} \omega_0 + b/2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \omega_0/2 & 0 & \sqrt{2}b/2 & 0 & 0 \\ 0 & 0 & -b/2 & 0 & \sqrt{2}b/2 & 0 \\ 0 & \sqrt{2}b/2 & 0 & -b/2 & 0 & 0 \\ 0 & 0 & \sqrt{2}b/2 & 0 & -\omega_0/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega_0 + b/2 \end{pmatrix}. \tag{2}$$

The nondiagonalized matrix implies that $\psi_{1,6}$ are eigenstates and therefore evolve not with time but through a trivial phase factor. However, ψ_{2-5} are mixed through the off-diagonal matrix elements and therefore will change with time. By solving the Schrödinger equation $\mathrm{i}\hbar\partial\psi(t)/\partial t = H\psi(t)$, the time-dependent wavefunction $\psi(t)$ can be obtained. Then we have the expectation value S_z as a function of time.

The six-dimensional uninteraction spaces could be divided into four subspaces: $\{\psi_1\}(j = l + s = 3/2)$, $\{\psi_2, \psi_4\}(j = 1/2)$, $\{\psi_3, \psi_5\}(j = -1/2)$ and $\{\psi_6\}(j = -3/2)$. For the subspaces of $j = \pm 3/2$, S_z does not change with time; for the subspaces of $j = \pm 1/2$, the expected value of S_z varying with time is expressed as

$$S_z(t) = \left(\psi(t), \hat{S}_z\psi(t)\right) = S_z(0)\frac{(\omega_0 \pm b)^2 + 8b^2\cos\left(\sqrt{\left(\frac{\omega_0 \pm b}{2}\right)^2 + \left(\sqrt{2}b\right)^2}\,t\right)}{(\omega_0 \pm b)^2 + 8b^2}, \tag{3}$$

where $S_z(0) = \pm\hbar/2$ are the initial spins of the electron, with the sign '$\pm$' corresponding to the subspace of $j = \pm 1/2$.

2.2. Interconversion of singlet and triplet e–h pairs

Now we consider the electron–hole (e–h) pairs, where the electron and the hole are subject to a separate Hamiltonian of Eq. (1). For the initial state $|\psi_1\rangle_{\rm h}|\psi_2\rangle_{\rm e}$ or $|\psi_1\rangle_{\rm h}|\psi_3\rangle_{\rm e}$ of the e–h pair, the hole spin is in an eigenstate ψ_1 and therefore will not evolve with time, whereas the electron spin is time-dependent (Eq. (3)). Then we obtain the total spin of the e–h pair as

$$\begin{aligned} S_z^{\rm e-h}(t) &= S_z^{\rm h}(t) + S_z^{\rm e}(t) \\ &= \frac{\hbar}{2} + \frac{\hbar}{2}\frac{(\omega_0 \pm b)^2 + 8b^2\cos\sqrt{\left(\frac{\omega_0 \pm b}{2}\right)^2 + 2b^2}\,t}{(\omega_0 \pm b)^2 + 8b^2}. \end{aligned} \tag{4}$$

Writing the probability for finding the e–h pair in a parallel (antiparallel) state as $p_{\rm P}$ ($p_{\rm AP}$), we can also express the spin as

$$S_z^{\rm e-h}(t) = S_z^{\rm h}(t) + S_z^{\rm e}(t) = \frac{\hbar}{2} + \frac{\hbar}{2}(p_{\rm P} - p_{\rm AP}). \tag{5}$$

With $p_{\rm P} + p_{\rm AP} = 1$ we have

$$p_{\rm P} = \frac{(\omega_0 \pm b)^2 + 8b^2\cos^2\frac{1}{2}\sqrt{\left(\frac{\omega_0 \pm b}{2}\right)^2 + 2b^2}\,t}{(\omega_0 \pm b)^2 + 8b^2},$$

$$p_{\rm AP} = \frac{8b^2 \sin^2 \frac{1}{2} \sqrt{\left(\frac{\omega_0 \pm b}{2}\right)^2 + 2b^2 t}}{(\omega_0 \pm b)^2 + 8b^2}. \quad (6)$$

Because the initial spin of the electron is parallel to that of the hole, $p_{\rm AP}(p_{\rm P})$ is in fact the spin-flip (spin-non-flip) probability of the electron. At this point, we represent $p_{\rm AP}(p_{\rm P})$ as $p_{\rm F}(p_{\rm NF})$. For initial state $|\psi_1\rangle_{\rm h}|\psi_4\rangle_{\rm e}$ or $|\psi_1\rangle_{\rm h}|\psi_5\rangle_{\rm e}$ of the e–h pair, a similar deduction proves that $p_{\rm F}(p_{\rm NF})$ does not change with initial spin state. Therefore we easily obtain the time average of $p_{\rm F}(p_{\rm NF})$ as

$$\bar{p}_{\rm NF} = \frac{(\omega_0 \pm b)^2 + 4b^2}{(\omega_0 \pm b)^2 + 8b^2}, \quad \bar{p}_{\rm F} = \frac{4b^2}{(\omega_0 \pm b)^2 + 8b^2}. \quad (7)$$

For b=0 we have $\bar{p}_{\rm F} = 0$ and $\bar{p}_{\rm NF} = 1$, thus no spin-flip occurs under any weak or strong magnetic field. The effect of the magnetic field is only the Zeeman split of the triplet e–h pairs. In the absence of magnetic field ($\omega_0 = 0$) we have $\bar{p}_{\rm NF} = 5/9$ and $\bar{p}_{\rm F} = 4/9$.

2.3. Recombination rate $\Re$ of e–h pairs recombining into excitons

Here we assume that the e–h pair forms with a corresponding formation rate constant denoted by C. The formed e–h pairs may recombine into excitons. The recombination rate depends on the spin state and is described by rate constants $k_{\rm S}$ and $k_{\rm T}$ for singlet and triplet e–h pairs, respectively. The e–h pairs may also dissociate back into free carriers with the rates described by rate constants $q_{\rm S}$ and $q_{\rm T}$. For a weak magnetic field, it is possible for all four spin states to be mixed. As a result, the recombination rate $\Re$ of the e–h pairs is

$$\Re(B) = C\frac{p_{\rm S}k_{\rm S} + \left(p_{\rm T_0} + p_{\rm T_1} + p_{\rm T_{-1}}\right)k_{\rm T}}{p_{\rm S}\left(k_{\rm S} + q_{\rm S}\right) + \left(p_{\rm T_0} + p_{\rm T_1} + p_{\rm T_{-1}}\right)\left(k_{\rm T} + q_{\rm T}\right)}, \quad (8)$$

where $p_{\rm S,T}$ are the formation rates of the e–h pairs with corresponding spin states, and $p_{\rm S} + p_{\rm T_0} = p_{\rm AP}$, $p_{\rm T_1} + p_{\rm T_{-1}} = p_{\rm P}$. Owing to the same energy levels of the S and $\rm T_0$ states, we consider $p_{\rm S} = p_{\rm T_0} = p_{\rm AP}/2$ but generally $p_{\rm T_1} \neq p_{\rm T_{-1}}$. Then we have

$$\Re(B) = C\frac{p_{\rm AP}k_{\rm S} + (p_{\rm AP} + 2p_{\rm P})\,k_{\rm T}}{p_{\rm AP}\,(k_{\rm S} + q_{\rm S}) + (p_{\rm AP} + 2p_{\rm P})\,(k_{\rm T} + q_{\rm T})}. \quad (9)$$

2.4. Space-charge-limited current and magnetoresistance

Since OMAR is a bulk effect, rather than an effect on carrier injection,[2] the only way to change the carrier concentration is through recombination. The current–voltage characteristics are usually interpreted using a space-charge limited current model. Parmenter and Ruppel[23] found the exact solution as

$$J = \frac{3}{2}\sqrt{\frac{\pi\varepsilon {\rm e}\mu_{\rm e}\mu_{\rm h}(\mu_{\rm e} + \mu_{\rm h})}{\Re}}\frac{V^2}{d^3}, \quad (10)$$

where J is the electric current density, V is the voltage drop across the OSC film of thickness d, ε is the dielectric constant of the OSC, and $\mu_{\rm e}$ and $\mu_{\rm h}$ are the effective mobilities of the electrons and holes. Prigodin *et al.*[11] suggested that of the parameters influencing J, $\Re$ is the most sensitive to changes in magnetic field B. Assuming a trivial change in the relative modulation of $\Re(B)$ to the relative modulation of $J(B)$ with magnetic field, i.e. $[{\rm d}\ln J(\Re)/{\rm d}\ln\Re(B)]_B \approx [{\rm d}\ln J(\Re)/{\rm d}\ln\Re(B)]_0 = c_0$, we obtain the magnetoresistance as

$$\frac{\Delta R}{R} = \frac{R(B) - R(0)}{R(0)} = \frac{J(0) - J(B)}{J(B)} = -c_0\frac{\Re(B) - \Re(0)}{\Re(B)}. \quad (11)$$

For the current given by Eq. (10) the factor $c_0 = 1/2$. Then combining Eq. (9) with Eq. (11) we can obtain magnetoresistance $\Delta R/R$. For a spin precession frequency much larger than the pair recombination rate, the time averages $\bar{p}_{\rm F}$ and $\bar{p}_{\rm NF}$ enter into the recombination rate to calculate the magnetoresistance. Then we have

$$\frac{\Delta R}{R} = -c_0\frac{\Re(B) - \Re(0)}{\Re(B)} = -c_0\begin{cases} \dfrac{(\omega_0 \pm b)^2 - b^2}{(\omega_0 \pm b)^2 + 4b^2\dfrac{k_{\rm S} + 3k_{\rm T}}{2k_{\rm T}}} \cdot \dfrac{4\,(k_{\rm T}q_{\rm S} - k_{\rm S}q_{\rm T})}{2k_{\rm T}\,(2k_{\rm S} + 2q_{\rm S} + 7k_{\rm T} + 7q_{\rm T})}, & \text{Ini.}\uparrow\uparrow, \\ \dfrac{(\omega_0 \pm b)^2 - b^2}{(\omega_0 \pm b)^2 + 4b^2\dfrac{k_{\rm S} + 3k_{\rm T}}{k_{\rm S} + k_{\rm T}}} \cdot \dfrac{-4\,(k_{\rm T}q_{\rm S} - k_{\rm S}q_{\rm T})}{(k_{\rm S} + k_{\rm T})\left(\dfrac{5}{2}k_{\rm S} + \dfrac{5}{2}q_{\rm S} + \dfrac{13}{2}k_{\rm T} + \dfrac{13}{2}q_{\rm T}\right)}, & \text{Ini.}\uparrow\downarrow, \end{cases} \quad (12)$$

where Ini.↑↑ (↑↓) denotes the parallel (antiparallel) initial spin orientation of the electron with respect to the hole.

3. Results and discussion

Even though the mechanism causing OMAR is currently not well known, OMAR most commonly obeys a Lorentzian empirical law $\Delta R/R \propto B^2/(B^2 + B_0^2)$.[9,10,16] As an essential admittance of our model, Eq. (12) suggests a Lorentzian magnetoresistance where B_0 is caused by spin-orbit coupling and modulated by $k_{\rm S}$ and $k_{\rm T}$. The value and the magnetoresistance sign vary according to the relation among constants $q_{\rm S,T}$, $k_{\rm S,T}$ and the initial spin state.

Figure 1 shows the magnetic field dependent spin flip (non-flip) probability $\bar{p}_{\rm F}(\bar{p}_{\rm NF})$ and magnetoresistance with spin-orbit coupling. From Fig. 1(a) we can see a left ($j = 1/2$) or right ($j = -1/2$) shifted $\bar{p}_{\rm F}(\bar{p}_{\rm NF})$ maximum (minimum) from zero field. The shift depends on the spin-orbit coupling. They cause a difference in $\bar{p}_{\rm F}(\bar{p}_{\rm NF})$ between the total momentums of $j = 1/2$ and $j = -1/2$ under a definite magnetic field. This result implies different probabilities of singlet and triplet e–h pairs in different subspaces.

The corresponding magnetoresistances under the same condition ($B_{\rm SO} = 5$ mT, $k_{\rm S} = 0.1$, $k_{\rm T} = 0.9$, $q_{\rm S} = 0.9$, and $q_{\rm T} = 0.1$) are shown in Fig. 1(b). The slopes of the magnetoresistances are steep in the weak magnetic field, and seem to saturate with the increase in magnetic field. The saturation values vary with the combination of $k_{\rm S}$, $k_{\rm T}$, $q_{\rm S}$ and $q_{\rm T}$, and present a difference between parallel antiparallel original spin orientation. Within the MIST mechanism,[15] if all the singlet and triplet levels in the OSC are degenerate at zero field, then once a magnetic field has lifted this degeneracy beyond the reach of the spin-orbit coupling, mixing will reach a steady state between the $m = 0$ levels and transport should not be affected by larger magnetic fields. In essence the effect should be saturate.

The magnetoresistances in Fig. 1(b) have sign transitions around the extreme points. The sign of $R_{\rm M}$ varies with the combination of $k_{\rm S}$, $k_{\rm T}$, $q_{\rm S}$ and $q_{\rm T}$ as shown in Eq.(12). As is well known, the presence of positive and negative OMAR is an important characteristic widely supported by experiments.[3,9,11,19] The reasonable forecasting of the magnetoresistance sign is a valuable highlight of our model.

The magnetoresistance curve in Fig. 1(b) with the right shifted top value ($j = -1/2$) and positive low-field magnetoresistance (↑↑) is in accordance with Sheng *et al.*'s experimental results.[20,22,24] Sheng *et al.* studied magnetic field effects in Alq_3 and $Ir(ppy)_3$ OLEDs using conductivity measurements. The two materials have similar chemical structures, except that the latter contains the heavy Ir-atom to enhance spin-orbit coupling. The measured OMAR traces in $Ir(ppy)_3$ comprise a low-field effect and a high-field effect of the opposite sign, in contrast to Alq_3 where only a single sign is evident. Sheng *et al.* attributed the behaviour in $Ir(ppy)_3$ to the superposition of two relevant interactions, hyperfine and spin-orbit coupling. According to the above theoretical treatment of spin dynamics induced by spin-orbit coupling, however, we guess that the spin-orbit coupling may be the major origin. Depending on the relative initial spins and momentum subspace of electrons and holes, the combination of the spin-orbit coupling effects shapes the final magnetoresistance.

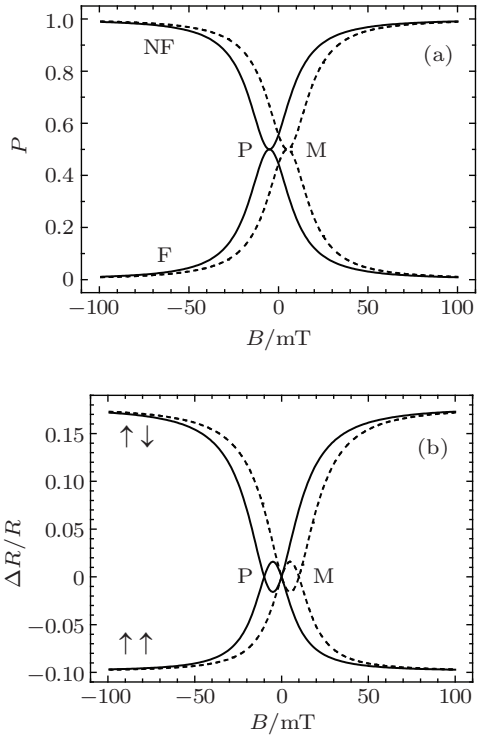


Fig. 1. (a) Flip (F) and non-flip (NF) probabilities of the initial spin orientation of the electron with respect to the hole in the e–h pairs, and (b) magnetoresistance versus magnetic field. P (M) is a mark of plus (minus) corresponding to the left (right) two lines, denoting subspaces of $j = \pm 1/2$. Symbols ↑↑ (↑↓) denote the parallel (antiparallel) initial spin orientation of the electron with respect to the hole, under the condition of $B_{\rm SO} = 5$ mT, $k_{\rm S} = 0.1$, $k_{\rm T} = 0.9$, $q_{\rm S} = 0.9$, and $q_{\rm T} = 0.1$.

Figure 2 shows the effects of spin-orbit coupling on magnetoresistance change with magnetic field for parallel initial spins. The increase in spin-orbit coupling enhances the extreme point shift, enlarges the

magnetoresistance difference between $j = 1/2$ and $j = -1/2$ subspaces under a definite magnetic field, and slows down the magnetoresistance saturation with magnetic field. Prigodin *et al.*,[11] Xu *et al.*,[12] and Wu and Hu[13] reported on the influence of spin-orbit coupling in diminishing the OMAR in OSC devices. The decrease in magnetoresistance with the increase in spin-orbit coupling is qualitatively accordant with the experimental results. It also supplies a primary reason why the magnetoresistance occurs at room temperature in carbon-based semiconductors but does not occur in their inorganic counterparts, III–V or II–VI semiconductors, which are composed of much heavier elements resulting in very high spin-orbit coupling.

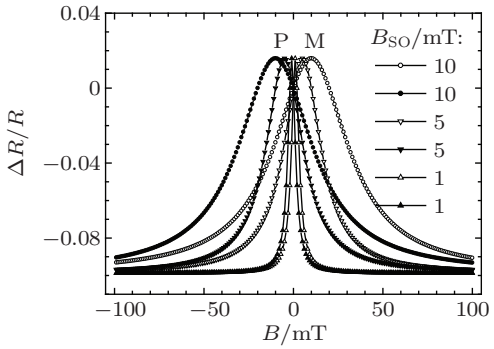


Fig. 2. Magnetoresistance versus magnetic field curves at different spin-orbit couplings under the condition of $k_S = 0.1$, $k_T = 0.9$, $q_S = 0.9$, and $q_T = 0.1$. P (M) is a mark of plus (minus) corresponding to a subspace of $j = \pm 1/2$.

The variation in triplet recombination and dissociation rate induces the variation in the sign and saturation values of the magnetoresistance, as shown in Figs. 3 and 4. If the rate constants for recombination and dissociation of singlet and triplet bound pairs are equal, then regardless of any interconversion, electrical transport will have no dependence on magnetic field, as shown in Eq. (12). However, these rate constants are very different for singlet and triplet e–h pairs. The singlet recombination lifetime is of the order of nanoseconds, whereas for the triplet it may be three or more orders of magnitude longer.[25] The dissociation of triplets into free carriers is typically higher than that of singlets. In the absence of mixing, singlets recombine quickly, triplets are long-lived and an applied magnetic field has no effect. When spin interconversion is operative and no magnetic field is applied, a given e–h pair will intermix between the spin states and may be found in any one of the four states with equal probability. Upon the application of a magnetic field, the interconversion of states is reduced to mixing between the singlet and only the T_0 triplet level, and a pair that initially forms as a singlet has a lower probability of becoming a triplet and dissociating. Conversely, at zero magnetic field, the singlet mixes with the whole triplet manifold and therefore the probability of becoming a triplet and dissociating is higher.

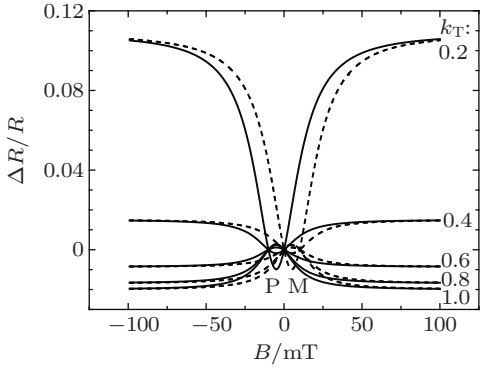


Fig. 3. Magnetoresistance versus magnetic field plots at different values of recombination rate constant k_T for triplet e–h pairs under the condition of $B_{SO} = 5$ mT, $k_S = q_S = q_T = 0.5$. P (M) is a mark of plus (minus) corresponding to a subspace of $j = \pm 1/2$.

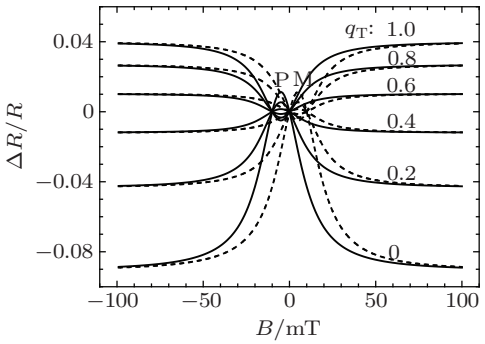


Fig. 4. Magnetoresistance versus magnetic field plots at different values of dissociation rate constant q_T for triplet e–h pairs under the condition of $B_{SO} = 5$ mT, $k_S = k_T = q_S = 0.5$. P (M) is a mark of plus (minus) corresponding to a subspace of $j = \pm 1/2$.

Finally, as a quantitative comparison between the model-based and experimental results, we show a group of magnetoresistances in Fig. 5. The solid and dashed lines show the experimental results of $Ir(ppy)_3$ measured at different voltages.[24] An elemental consistency can be obtained and both the experimental and theoretical results show the most prominent features of OMAR: a right shifted maximum from zero field, and the presence of positive values and negative values. We can see that the theoretical magnetoresistance tends to be saturate faster than the experimental ones, so further detailed theories and more stable

experimental results are needed.

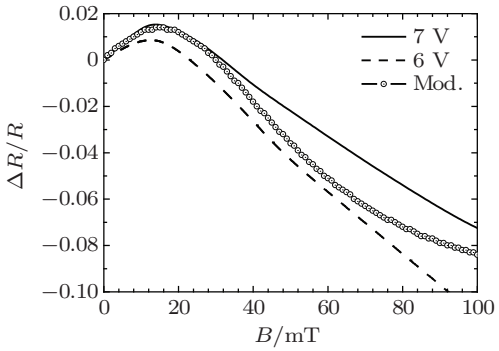


Fig. 5. Comparison between magnetoresistances plots obtained from a model (circle) and experimentally (solid and dashed line, for bias $V = 7$ V, 6 V, respectively) versus magnetic field. The model parameters are chosen as $j = -1/2$, $B_{\rm SO} = 15$ mT, $k_{\rm S} = q_{\rm S} = q_{\rm T} = 0.5$, and $k_{\rm T} = 0.51$. The experimental data are extracted from Fig. 8 in Ref. [24], for ITO/PEDOT/Ir(ppy)$_3$($\sim$ 100 nm)/Ca at room temperature.

4. Conclusions

Along the lines of the space-charge-limited current, we investigate the effects of spin-orbit coupling on OMAR by spin precession. We obtain the Lorentz-type empirical law $\propto B^2/(B^2 + B_0^2)$, where B_0 is caused by spin-orbit coupling and modulated by $k_{\rm S}$ and $k_{\rm T}$. The sign and the saturation value of the magnetoresistance are composite effects of $k_{\rm S}$, $k_{\rm T}$, $q_{\rm S}$, and $q_{\rm T}$. Moreover, the magnetoresistance depends on the initial spin state of the e–h pairs. Even with the universal, evenly distributed spins in nonmagnetic OSCs, the electrons and holes could be spin-polarized by spin precession. Accordingly, the singlet and triplet e–h pairs are modulated, and the magnetoresistance can be controlled. The magnetoresistance characterized by the shifted extreme value, changeable sign and diminishing value with spin-orbit coupling, can be well supported by the experimental results.

Finally, we point out that all the calculations in this work are based on the assumption that the spin precession frequency is much larger than the recombination rate of the electrons and holes. When the assumption does not hold, the time-dependent parallel and antiparallel probability $p_{\rm F}(t)$, $p_{\rm NF}(t)$, rather than their time average, can be used to calculate the magnetoresistance.

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