The effects of electric and magnetic fields on the current spin polarization and magnetoresistance in a ferromagnetic/organic semiconductor/ferromagnetic (FM/OSC/FM) system*

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From experimental results of spin polarized injection and transport in organic semiconductors (OSCs), we theoretically study the current spin polarization and magnetoresistance under an electric and a magnetic field in a ferromagnetic/organic semiconductor/ferromagnetic (FM/OSC/FM) sandwich structure according to the spin drift-diffusion theory and Ohm's law. From the calculations, it is found that the interfacial current spin polarization is enhanced by several orders of magnitude through tuning the magnetic and electric fields by taking into account the specific characteristics of OSC. Furthermore, the effects of the electric and magnetic fields on the magnetoresistance are also discussed in the sandwich structure.

Keywords: organic spintronics, spin diffusion and drift, current spin polarization, magnetoresistance

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1. Introduction

Organic semiconductor spintronics, which is based on the control and manipulation of electron spin, has attracted considerable attention recently.[1−3] Organic semiconductors (OSCs) have very important technological applications in large-area electrics, and have some unique features such as easy synchronization at low temperature, little toxic waste, etc. compared with conventional semiconductors.[4−6] OSCs are characterized by a low spin–orbit interaction and weak hyperfine interaction, so that the electron spin diffusion length is expected to be much longer than that of the inorganic semiconductor. These properties make OSC an ideal material for spin-polarized injection and transport applications, which is considered to be the next interesting topic in spintronics.

The current spin polarizations (CSPs) in organic spintronic devices under different conditions have been studied experimentally and theoretically. In 2002, Dediu *et al.*[7] first observed spin injection into thin films of conjugated organic material sexithieny. Xiong *et al.*[8] obtained a negative magnetoresistance (MR) under a magnetic field in a $La_{0.7}Sr_{0.3}MnO_3$/Alq_3/Co system. In 2008, Dediu *et al.*[9] further reported that the efficiency of spin injection into OSCs could be improved by the interface between an OSC and FM electrode. In 2010, Barraud *et al.*[10] fabricated a nanometre-scale (La,Sr)MnO_3/Alq_3/Co magnetic tunnel junction and also described the role of spin-dependent interfaces on spin injection. Theoretically, Ren *et al.*[11] constructed a model of spin injection and transport in OSC devices and studied the properties of CSP according to the spin diffusion theory and Ohm's law by supposing a constant polaron ratio in OSC, but they did not mention the effects of the external electric and magnetic field. Yu and Flatté[12] derived a drift-diffusion equation for spin polarized injection and transport in a nonmagnetic semiconductor by taking into account the electric field effects and found that the injection efficiency was enhanced by

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several orders of magnitude in the high-field regime. Yu *et al.*[13] also found that even a weak magnetic field could significantly modify spin transport in a polymer through spin precession, however, they did not consider the effects of the special carriers in the OSC in their work. Bobbert *et al.*[14] presented a theory for spin diffusion in a disordered OSC with hyperfine coupling and found that the spin-diffusion length depended rather weakly on temperature, but considerably more on the applied magnetic field. From the above investigations, one can find that different carriers and the external electric and magnetic fields are important factors which influence the CSP and MR in an organic spintronic device.

The carriers in an OSC are instinctively different from those in inorganic ones. Carriers are extended electrons or holes with a 1/2 spin in an inorganic semiconductor. However, carriers are spin polarons or spinless bipolarons in an OSC. Effects of these different carriers on the spin polarized injection and transport in an organic spintronic device are important.[15,16] In the present paper, we do not consider the exact transfer mechanism and just suppose that the fully injected spin polarized electrons will be converted into polarons and bipolarons in an OSC respectively, and then we study the CSP and MR in the FM/OSC/FM system under an external electric and a magnetic field. We provide a description of the model and the relevant formulae in Section 2, and the results and discussion are given in Section 3. In Section 4 we draw some conclusions from the present study.

2. FM/OSC/FM model

Here we consider a simple one-dimensional spin injection and transport sandwich structure that is comprised of two semi-infinite FM layers ($x < 0$ and $x \geq x_0$) and one layer of an OSC with a length x_0. The two FM layers are in parallel or anti-parallel magnetization alignment. Spin-polarized electrons in the left FM layer are injected into the OSC layer and they will completely convert into spin polarons and spinless bipolarons. When they are injected out and enter into the right FM layer, these carriers (spin polarons and spinless bipolarons) would completely convert into spin-polarized electrons. The electric field is anti-parallel to the x axis, while correspondingly the magnetic field is anti-parallel to the y axis. The whole transport picture is shown schematically in Fig. 1.

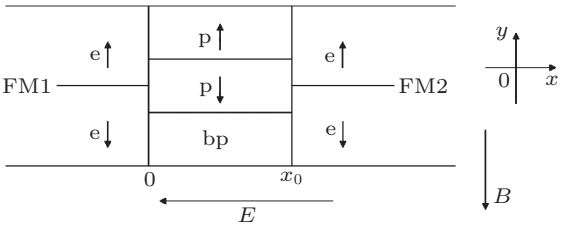


Fig. 1. Schematic diagram of the FM/OSC/FM system with an electric and a magnetic field.

Our theoretical investigation is based on the drift-diffusion model,[12,17] which is applied to the spin-polarized electrons in the FM and spin-polarized polarons in the OSC layer. Here we define the CSP in the FM as $\alpha(x) = (j_\uparrow - j_\downarrow)/(j_\uparrow + j_\downarrow)$, where $j_\uparrow$, $j_\downarrow$ are the currents contributed from the up-spin and down-spin electrons. CSP in the OSC is defined as $\alpha(x) = (j_{\mathrm{p}\uparrow} - j_{\mathrm{p}\downarrow})/(j_{\mathrm{p}\uparrow} + j_{\mathrm{p}\downarrow} + j_{\mathrm{bp}})$, where $j_{\mathrm{p}\uparrow}$, $j_{\mathrm{p}\downarrow}$, and j_{bp} are the currents contributed from the up-spin polarons, down-spin polarons, and the spinless bipolarons respectively. The currents for the up-spin and down-spin carriers (electrons and polarons) can be written respectively as[12]

$$j_\uparrow = \sigma_\uparrow E + eD_\uparrow \nabla n_\uparrow, \quad j_\downarrow = \sigma_\downarrow E + eD_\downarrow \nabla n_\downarrow. \tag{1}$$

Here, $D_{\uparrow(\downarrow)}$ is the up-spin (down-spin) diffusion coefficient, $\sigma_{\uparrow(\downarrow)}$ is the up-spin (down-spin) conductivity of the carriers, and $n_{\uparrow(\downarrow)}$ is the deviation of the up-spin (down-spin) carrier density from its equilibrium value. In a nondegenerate system ν and D are related via Einstein's relationship $\nu/eD = 1/K_{\mathrm{B}}T$. Here the mobility $\nu_{\uparrow(\downarrow)}$ is independent of the external field. For a homogeneous system, there is no space-charge and $(n_\uparrow + n_\downarrow)$ should be balanced by a local change of carrier concentration. In a steady state the spin diffusion-drift equation is[12,13,17,18]

$$\nabla^2(n_\uparrow - n_\downarrow) + \frac{eE}{K_{\mathrm{B}}T}\nabla(n_\uparrow - n_\downarrow) - \frac{n_\uparrow - n_\downarrow}{L_{\mathrm{s}}^2} - \frac{g\mu_{\mathrm{B}}B}{\hbar D}(n_\uparrow - n_\downarrow) = 0, \tag{2}$$

where L_{s} is the intrinsic spin-diffusion length. We define two quantities L_{d} and L_{u} as the down-stream and up-stream spin diffusion lengths respectively, which can be presented as[12]

$$L_{\mathrm{d}}(u) = \left[-(+)\frac{|eE|}{2K_{\mathrm{B}}T} + \sqrt{\left(\frac{eE}{2K_{\mathrm{B}}T}\right)^2 + \frac{1}{L_{\mathrm{s}}^2} + \frac{g\mu_{\mathrm{B}}B}{\hbar D}} \right]^{-1}. \tag{3}$$

It can easily be seen from the above equation that the down-stream diffusion length L_{d} increases while

the up-stream diffusion length $L_{\rm u}$ decreases with the increase of the electric and magnetic fields.

From the relationship between electrochemical potentials and the carrier density in the FM and OSC layers, the electrochemical potential in the FM layer can be obtained as[12]

$$\mu_{\rm FM\uparrow(\downarrow)} = ej\left(\frac{x}{\sigma_{\rm f}} + (-)\frac{c}{\sigma_{\rm f\uparrow(\downarrow)}}\,{\rm e}^{x/L_{\rm f}}\right), \tag{4}$$

where c is a constant, $\sigma_{\rm f\uparrow(\downarrow)}$ is the up-spin (down-spin) electrical conductivity in the FM layer, the total electrical conductivity of the FM is $\sigma_{\rm f} = \sigma_{\rm f\uparrow} + \sigma_{\rm f\downarrow}$, and j is the total current which is a constant throughout the structure in a steady state. The electrochemical potential in the OSC layer is[3]

$$\begin{aligned}\mu_{\rm p\uparrow(\downarrow)} &= K_{\rm B}T\frac{2n_{\rm p\uparrow(\downarrow)}}{n_0} - eEx - D \\ &= K_{\rm B}T\frac{+(-)2A\,{\rm e}^{-x/L_{\rm d}}}{n_0} - eEx - D, \end{aligned}\tag{5}$$

where D is a constant, n_0 is the total polaron density and $n_0 = 2n_{\rm p\uparrow(\downarrow)}$, with $n_{\rm p\uparrow(\downarrow)}$ being the carrier density in the equilibrium state.

If there is no spin-flip scattering at the interface, the current for each spin direction is continuous and is related to the spin-dependent electrochemical potential change across the interface via the Ohm's law $j_{\uparrow(\downarrow)} = \sigma_{\uparrow(\downarrow)}\partial(\mu_{\uparrow(\downarrow)}/e)/\partial x$, so the boundary conditions at the two interfaces should be[12,19]

$$\begin{aligned} ej_{\uparrow}(0^-) &= \left[\mu_{\uparrow}(0^+) - \mu_{\uparrow}(0^-)\right]/R_{1\uparrow},\ ej_{\downarrow}(0^-) \\ &= \left[\mu_{\downarrow}(0^+) - \mu_{\downarrow}(0^-)\right]/R_{1\downarrow}, \\ ej_{\uparrow}(x_0^-) &= \left[\mu_{\uparrow}(x_0^+) - \mu_{\uparrow}(x_0^-)\right]/R_{2\uparrow},\ ej_{\downarrow}(x_0^-) \\ &= \left[\mu_{\downarrow}(x_0^+) - \mu_{\downarrow}(x_0^-)\right]/R_{2\downarrow}, \end{aligned}\tag{6}$$

where $R_{i\uparrow}$ and $R_{i\downarrow}$ are the interfacial resistances of the up-spin and down-spin carriers, $i = 1, 2$, which corresponds to the first and second boundary between the FM and OCS respectively.

From Eqs. (2)–(6), two equations about the interfacial CSP $\alpha(0)$ and $\alpha(x_0)$ can be obtained as

$$\begin{aligned} &\frac{ej}{2}\left[(\alpha(0)+1)\,R_{1\uparrow} + (\alpha(0)+1)\,R_{1\downarrow}\right] \\ &\quad - \frac{4K_{\rm B}T}{n_{\rm p}}\left[A_0 + A_1\,{\rm e}^{-x_0/L_{\rm u}}\right] \\ &\quad + ejc_1\left(\frac{1}{\sigma_{\rm f1\uparrow}} + \frac{1}{\sigma_{\rm f1\downarrow}}\right) = 0, \\ &\frac{ej}{2}\left[(\alpha(x_0)+1)\,R_{2\uparrow} + (\alpha(x_0)+1)\,R_{2\downarrow}\right] \\ &\quad + \frac{4K_{\rm B}T}{n_{\rm p}}\left[A_0 + A_1\,{\rm e}^{-x_0/L_{\rm u}}\right] \\ &\quad + ejc_2\left(\frac{1}{\sigma_{\rm f2\uparrow}} + \frac{1}{\sigma_{\rm f2\downarrow}}\right) = 0, \end{aligned}\tag{7}$$

where $\alpha(0)$ is the CSP at the first interface and $\alpha(x_0)$ is that at the second interface. Coefficients c_1 and c_2 can be obtained from Eqs. (4) and (6) and Ohm's law as $c_1 = L_{\rm f}(\alpha(0) - p_{\rm f1})/2$ and $c_2 = L_{\rm f}(p_{\rm f2} - \alpha(x_0)/2$, the spin polarization of density in the FM is $p_{\rm f} = \left(\sigma_{\rm f\uparrow} - \sigma_{\rm f\downarrow}\right)/\sigma_{\rm f}$. In addition, the relationship between the CSP and the spin polarization of density $p(x)$ in the OSC can be written as $\alpha(x) = p(x) + \frac{D}{\nu E}\cdot\frac{{\rm d}p(x)}{{\rm d}x}$,[12] where $p\,(x) = \left(\sigma_{\rm p\uparrow} - \sigma_{\rm p\downarrow}\right)/\sigma_{\rm s}$, with $\sigma_{\rm p\uparrow(\downarrow)}$ being the conductivity corresponding to the up-spin (down-spin) polarons, and $\sigma_{\rm p} = \sigma_{\rm p\uparrow} + \sigma_{\rm p\downarrow}$, with $\sigma_{\rm p}$ being the conductivity corresponding to all polarons, $\sigma_{\rm p} = \gamma\sigma_{\rm s}$, and $\sigma_{\rm s}$ being the total conductivity of the OSC and γ being the polaron proportion in the OSC. We can obtain the two equations about A_0 and A_1 from the expressions of $\alpha(x)$ as

$$\begin{aligned} A_0 + A_1\,{\rm e}^{-x_0/L_{\rm u}} &= \frac{eE}{K_{\rm B}T}\frac{1}{\gamma}\frac{n_{\rm p}}{2}\frac{\alpha(x_0)(L_{\rm u}+L_{\rm d}) - \alpha(0)(L_{\rm u}\,{\rm e}^{x_0/L_{\rm u}} + L_{\rm d}\,{\rm e}^{-x_0/L_{\rm d}})}{{\rm e}^{x_0/L_{\rm u}} - {\rm e}^{-x_0/L_{\rm d}}}, \\ A_0\,{\rm e}^{-x_0/L_{\rm d}} + A_1 &= \frac{eE}{K_{\rm B}T}\frac{1}{\gamma}\frac{n_{\rm p}}{2}\frac{\alpha(x_0)(L_{\rm u}\,{\rm e}^{-x_0/L_{\rm u}} + L_{\rm d}\,{\rm e}^{x_0/L_{\rm d}}) - \alpha(0)(L_{\rm u}+L_{\rm d})}{{\rm e}^{x_0/L_{\rm d}} - {\rm e}^{-x_0/L_{\rm u}}}. \end{aligned}\tag{8}$$

In addition, CSP in the different interfaces between the FM and OSC layers can be easily obtained from Ohm's law and the boundary conditions as

$$\alpha(0) = \frac{\dfrac{-2ML_{\rm f}p_{\rm f1}}{(1-p_{\rm f1}^2)\sigma_{\rm f1}} - \dfrac{M(R_{1\downarrow}-R_{1\uparrow})}{2} - \dfrac{\dfrac{4}{\gamma\sigma_{\rm s}}\dfrac{L_{\rm f}p_{\rm f2}(L_{\rm u}+L_{\rm d})}{(1-p_{\rm f2}^2)\sigma_{\rm f2}} + \dfrac{(R_{2\downarrow}-R_{2\uparrow})(L_{\rm u}+L_{\rm d})}{\gamma\sigma_{\rm s}}}{\left({\rm e}^{x_0/L_{\rm u}} - {\rm e}^{-x_0/L_{\rm d}}\right)}}{\dfrac{4}{(\gamma\sigma_{\rm s})^2}\dfrac{(L_{\rm u}+L_{\rm d})^2}{\left({\rm e}^{x_0/L_{\rm d}} - {\rm e}^{-x_0/L_{\rm u}}\right)} - MN}, \tag{9}$$

$$\alpha(x_0) = \frac{1}{M}\left[\frac{2L_{\rm f}p_{\rm f2}}{(1-p_{\rm f2}^2)\sigma_{\rm f2}} + \frac{(R_{2\downarrow}-R_{2\uparrow})}{2} + \frac{2}{\gamma\sigma_{\rm s}}\frac{\alpha(0)(L_{\rm u}+L_{\rm d})}{{\rm e}^{x_0/L_{\rm d}} - {\rm e}^{-x_0/L_{\rm u}}}\right], \tag{10}$$

where,

$$M = \frac{(R_{2\uparrow}+R_{2\downarrow})}{2} + \frac{2L_{\rm f}}{(1-p_{\rm f2}^2)\sigma_{\rm f2}} + \frac{2}{\gamma\sigma_{\rm s}}\frac{L_{\rm u}\,{\rm e}^{-x_0/L_{\rm u}} + L_{\rm d}\,{\rm e}^{x_0/L_{\rm d}}}{{\rm e}^{x_0/L_{\rm d}} - {\rm e}^{-x_0/L_{\rm u}}}\Big],$$
$$N = \frac{\frac{2}{\gamma\sigma_{\rm s}}(L_{\rm u}\,{\rm e}^{x_0/L_{\rm u}} + L_{\rm d}\,{\rm e}^{-x_0/L_{\rm d}})}{{\rm e}^{x_0/L_{\rm u}} - {\rm e}^{-x_0/L_{\rm d}}} - \frac{(R_{1\uparrow}+R_{1\downarrow})}{2} - \frac{2L_{\rm f}}{(1-p_{\rm f1}^2)\sigma_{\rm f1}}. \quad (11)$$

From Ohm's law and Eqs. (4) and (5), we can obtain the CSP

$$\alpha(x) = p_{\rm f1} + (\alpha(0) - p_{\rm f1})\,{\rm e}^{x/L_{\rm f}}, \quad x < 0,$$
$$\alpha(x) = \alpha(0)\frac{{\rm e}^{-(x-x_0)/L_{\rm d}} - {\rm e}^{(x-x_0)/L_{\rm u}}}{{\rm e}^{x_0/L_{\rm d}} - {\rm e}^{-x_0/L_{\rm u}}} - \alpha(x_0)\frac{{\rm e}^{-x/L_{\rm d}} - {\rm e}^{x/L_{\rm u}}}{{\rm e}^{x_0/L_{\rm u}} - {\rm e}^{-x_0/L_{\rm d}}}, \quad 0 < x \le x_0,$$
$$\alpha(x) = p_{\rm f2} + (\alpha(x_0) - p_{\rm f2})\,{\rm e}^{-(x-x_0)/L_{\rm f}}, \quad x \ge x_0. \quad (12)$$

To obtain the MR ratio, we need to calculate the individual electrochemical potential across the system. Substituting $\alpha(x)$ of Eq. (12) into $j_{\rm s}$ of Ohm's law and then integrating it over the three regions, we obtain

$$\mu_{\rm FM1\uparrow} = -\frac{ej}{\sigma_{\rm f1}}x - \frac{ej}{\sigma_{\rm f1}}L_{\rm f} \times \frac{\alpha(0)-p_{\rm f1}}{1+p_{\rm f1}}({\rm e}^{x/L_{\rm f}} - 1), \quad x < 0,$$
$$\mu_{\rm p\uparrow}(x) = -\frac{ej}{\sigma_{\rm s}} + \frac{ej}{\gamma\sigma_{\rm s}} \times \frac{(L_{\rm d}\,{\rm e}^{-(x-x_0)/L_{\rm d}} + L_{\rm u}\,{\rm e}^{(x-x_0)/L_{\rm u}})\alpha(0)}{{\rm e}^{x_0/L_{\rm d}} - {\rm e}^{-x_0/L_{\rm u}}} - \frac{ej}{\gamma\sigma_{\rm s}}\frac{(L_{\rm d}\,{\rm e}^{-x/L_{\rm d}} + L_{\rm u}\,{\rm e}^{x/L_{\rm u}})\alpha(x_0)}{{\rm e}^{x_0/L_{\rm u}} - {\rm e}^{-x_0/L_{\rm d}}} + F_1, \quad 0 \le x < x_0,$$
$$\mu_{\rm FM2\uparrow}(x) = -\frac{ej}{\sigma_{\rm f2}} + \frac{ej}{\sigma_{\rm f2}}L_{\rm f}\frac{\alpha(x_0)-p_{\rm f2}}{1+p_{\rm f2}} \times {\rm e}^{-(x-x_0)/L_{\rm f}} + F_2, \quad x \ge x_0. \quad (13)$$

Here, constants F_1 and F_2 can be obtained from the electrochemical potential by the two interface discontinuity conditions. The corresponding electrochemical potentials for the down-spin carriers (electrons in the FM layer and polarons in the OSC layer) can be obtained in a similar way.

The MR ratio of the FM/OSC/FM system is defined as

$${\rm MR} = \Delta R/R_{\rm ap} = (R_{\rm ap} - R_{\rm p})/R_{\rm ap}, \quad (14)$$

where $R_{\rm ap}$ and $R_{\rm p}$ are the resistances for the antiparallel and parallel magnetization alignment of the two FM layers. The resistance is expressed as

$$R_{\rm ap(p)} = \frac{\mu_{0\rm ap(p)}(-L_{\rm f}) - \mu_{0\rm ap(p)}(x_0 + L_{\rm f})}{ej}. \quad (15)$$

Here μ_0 is the spin-independent component of the electrochemical potential, which is related to the measured voltage drop across the system. In order to obtain the electrochemical potential μ_0, we take the linear part of Eq. (13).

3. Results and discussion

The spin-diffusion length in the FM layer is taken as $L_{\rm f} = 100$ nm and the spin diffusion length in the OSC layer is taken from Dediu's experimental value, i.e., $L_{\rm s} = 200$ nm.[7] In our calculation, the conductivity of the OSC layer is smaller than that of the FM, which has been set as $\sigma_{\rm f} = 100\ (\Omega{\cdot}{\rm cm})^{-1}$ and $\sigma_{\rm s} = 1\ (\Omega{\cdot}{\rm cm})^{-1}$, and the spin polarization in the FM bulk is $p_{\rm f} = 0.9$. The two FM layers are assumed to be identical except for the different magnetization alignments, which are parallel or antiparallel to each other. The calculations of $\alpha(x)$ as a function of position under different electric fields in the parallel magnetization alignment are shown in Fig. 2. Parameters of the two FM layers are $\sigma_{\rm f1} = \sigma_{\rm f2} = \sigma_{\rm f}$, $\lambda_{\rm f1} = \lambda_{\rm f2} = \lambda_{\rm f}$, $p_{\rm f1} = p_{\rm f2} = p_{\rm f}$, $R_1 = R_2 = R$. The polaron proportion is $\gamma = 0.5$, the OSC layer thickness is $x_0 = 100$ nm, and the spin-dependent interfacial resistance is $R_\downarrow = 10R_\uparrow = 10^{-5}\ \Omega{\cdot}{\rm cm}^2$. From Fig. 2 one can see that $\alpha(x)$ no longer shows a symmetric distribution because of the electric field. Furthermore, it is important to note that $\alpha(x)$ improves a lot in the presence of an electric field. For example, when the electric field $E = 15.5$ kV/cm, i.e. $eE/K_{\rm B}T = 0.06\ {\rm nm}^{-1}$ corresponding to $T = 300$ K, $\alpha(0)$ reaches around 0.414, while when the electric field is zero, it is 0.208. This may be interpreted that the electric-field may enhance the CSP for the parallel magnetization alignment of the two FM layers in the FM/OSC/FM system.

The effect of the magnetic filed on the CSP in the FM/OSC/FM system is shown in Fig 3. Here we adopt the electric field to be 15.5 kV/cm, corresponding to $eE/K_{\rm B}T = 0.06\ {\rm nm}^{-1}$ and the spin-dependent resistances are $R_\downarrow = 10R_\uparrow = 10^{-5}\ \Omega{\cdot}{\rm cm}^2$. $\alpha(x)$ has the same trend as that in Fig. 2. It is also clearly seen from Fig. 3 that the values of $\alpha(x)$ in the two FM layers are greatly improved with the increase of

the magnetic field. However, $\alpha(x)$ decreases rapidly into the OSC and nearly to zero in the middle region of the OSC. So an apparent interfacial CSP can be obtained under the parallel magnetization alignment of the FM/OSC/FM system.

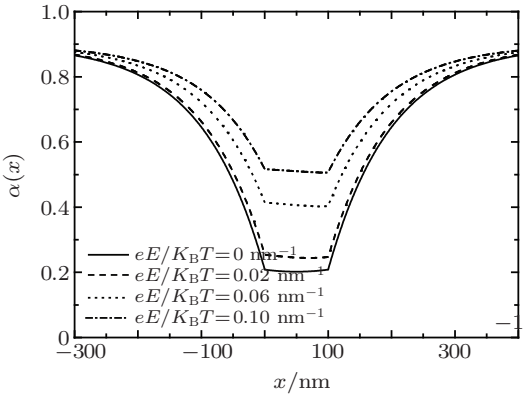


Fig. 2. Position dependences of CSP for various values of an electric field with parallel magnetization alignment of the two FM layers.

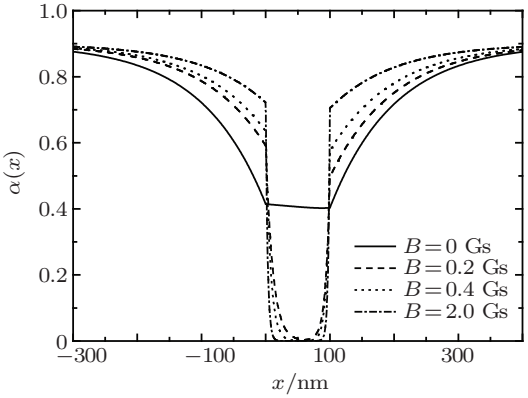


Fig. 3. Position dependences of the CSP for various values of the magnetic field with parallel magnetization alignment of the two FM layers, 1 Gs=10^{-4} T.

Next, we calculate the antiparallel magnetization alignment of the two FM layers. All corresponding parameters are $\sigma_{f1} = \sigma_{f2} = \sigma_f$, $\lambda_{f1} = \lambda_{f2} = \lambda_f$, $p_{f1} = -p_{f2} = p_f$, $R_{1\uparrow} = R_{2\downarrow} = R_\uparrow$, $R_{1\downarrow} = R_{2\uparrow} = R_\downarrow$, and these values in the first FM are kept the same as those in the parallel magnetization alignment. The position dependences of $\alpha(x)$ for various values of the electric field are shown in Fig. 4. It is clear that $\alpha(x)$ decreases exponentially from the FM1 layer into the OSC layer, then decreases slowly in the OSC layer, but increases exponentially in the FM2 layer with reverse sign. For the case of a zero electric field there is nearly zero CSP across the OSC layer. It is also clear that the electric field is helpful for spin injection and transport in antiparallel magnetization alignment.

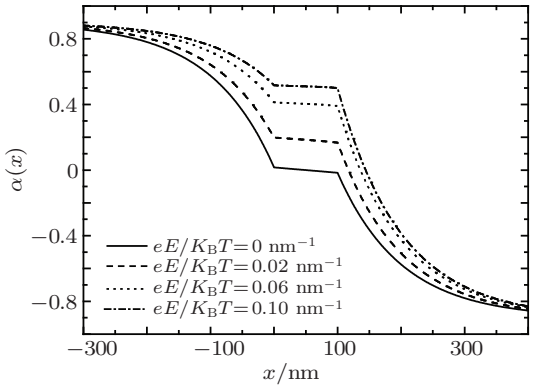


Fig. 4. Position dependences of CSP for various values of an electric field with antiparallel magnetization alignment of the two FM layers.

The effect of the magnetic field on $\alpha(x)$ with antiparallel magnetization alignment of the two FM layers is shown in Fig. 5. All corresponding parameters are kept the same as those used in Fig. 4. In the presence of the magnetic field, it is important to note that $\alpha(x)$ has significant changes, especially in the FM/OSC boundary, which may be described by the spin procession with the effect of the magnetic field at the interface. The value of $\alpha(x)$ reaches zero in the middle region and changes slowly in the OSC layer which is the same as that in the case of parallel magnetization alignment. Furthermore, the absolute value of interfacial $\alpha(x)$ increases exponentially with the increase in the magnetic field.

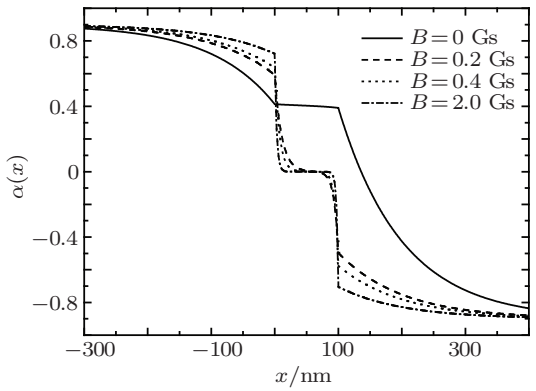


Fig. 5. Position dependences of CSP for various values of magnetic field with antiparallel magnetization alignment of the two FM layers.

The choice of specific carriers is a crucial factor affecting the spin polarized injection into OSCs. The dependence of interfacial CSP on the polaron proportion γ for different electric and magnetic fields is shown in Fig. 6. From the calculation, it is found that when $\gamma = 0$, which corresponds to the case where all the carriers in OSC are spinless bipolarons, CSP is nearly

zero. The maximum CSP is obtained at $\gamma = 1$ which corresponds to the case where all the carriers are spin polarons. In addition, from the figure one finds that the CSP improves by several orders of magnitude in the presence of the electric and magnetic fields. On the other hand, the trends of the curves are sharper in the small polaron proportion under electric and magnetic fields than under a zero field. So it is helpful to obtain a remarkable CSP under the electric and magnetic fields even in the case of a few polarons in the OSC.

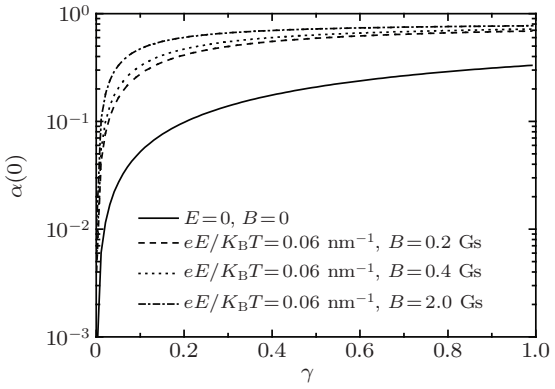


Fig. 6. Dependences of interfacial CSP on polaron proportion for various values of the electric and magnetic fields.

Figure 7 shows the dependences of the MR on electric field for various values of the interfacial resistances in the FM/OSC/FM system. It is clearly seen that when the electric field is 15.5 kV/cm, corresponding to $eE/K_BT = 0.06$ nm^{-1}, the MR reaches around 0.27 in the case of the spin-dependent interfacial resistances $R_\downarrow = 10R_\uparrow = 10^{-5}$ Ω·cm^2, while the MR is 0.063 with a zero electric field. This is interpreted as that the electric field can enhance the MR. Furthermore, the MR increases significantly with the increase of the spin-dependent interfacial resistance, which is consistent with the results from our previous work.[11]

Figure 8 shows the variations of MR with a magnetic field for various values of electric field. The corresponding parameters are kept the same as those used above. It is worthy to mention that we add the magnetic field after the magnetization alignments of the two FM layers have been parallel or antiparallel. From the figure, it is found that MR decreases when the magnetic field increases from zero to 2.0 Gs; for example, MR is 0.275 at zero magnetic field and 0.036 at $B = 0.4$ Gs with $E = 15.5$ kV/cm. The magnetic field is not conducive to obtaining a significant MR under the premise of a system that has had parallel and antiparallel magnetization alignment of the two FM layers.

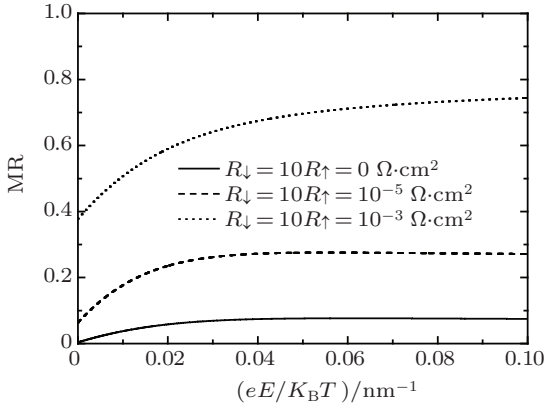


Fig. 7. Dependences of MR on the electric field with various values of spin-dependent interfacial resistances.

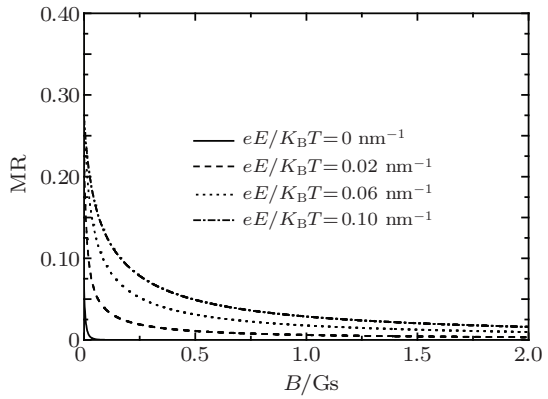


Fig. 8. Dependences of MR on the magnetic field for various values of electric field.

4. Conclusions

The CSP and MR in the system of FM/OSC/FM under electric and magnetic fields are studied based on Ohm's law and the drift-diffusion equation. It is found that the CSP presents different distributions with parallel or antiparallel magnetization alignments of the two FM layers and the interfacial CSP increases significantly with the increase of the electric and magnetic field. On the other hand, the electric and magnetic field make the trends of interfacial CSP on polaron proportion more sensitive. Furthermore, MR increases with the increase in the electric field, while it decreases with the increase in the magnetic field. These findings may be helpful for obtaining remarkable CSP and MR in FM/OSC/FM systems.

References

[1] Wolf S A, Awschalom D D, Buhrman R A, Daughton J M, Molnár S V, Roukes M L, Chtchelkanova A Y and Treger D M 2001 *Science* **294** 1488

[2] Naber W J M, Faez S and Gvan der Wie W 2007 *J. Phys.* D: *Appl. Phys.* **40** R205

[3] Mi Y L, Zhang M and Yan H 2008 *Phys. Lett.* A **372** 6434

[4] Friend R H, Gymer R W, Holmes A B, Burroughes J H, Marks R N, Taliani C, Bradley D D C, Dos Santos D A, Brédas J L, Lögdlund M and Salaneck W R 1999 *Nature* **397** 121

[5] Voss D 2000 *Nature* **407** 442

[6] Dediu V A, Hueso L E, Bergenti I and Taliani C 2009 *Nature Mater.* **8** 707

[7] Dediu V, Murgia M, Matacotta F C, Taliani C and Barbanera S 2002 *Solid State Commun.* **122** 181

[8] Xiong Z H, Wu D, Valy Vardeny Z and Shi J 2004 *Nature* **427** 821

[9] Dediu V, Hueso L E, Bergenti I, Riminucci A, Borgatti F, Graziosi P, Newby C, Casoli F, de Jong M P, Taliani C and Zhan Y 2008 *Phys. Rev.* B **78** 115203

[10] Barraud C, Seneor P, Mattana R, Fusil S, Bouzehouane K, Deranlot C, Graziosi P, Hueso L, Bergenti I, Dediu V, Petroff F and Fert A 2010 *Nature Phys.* **6** 625

[11] Ren J F, Zhang Y B and Xie S J 2008 *Org. Electron.* **9** 1017

[12] Yu Z G and Flatté M E 2002 *Phys. Rev.* B **66** 235302

[13] Yu Z G, Berding M A and Krishnamurthy S K 2005 *Phys. Rev.* B **71** 060408(R)

[14] Bobbert P A, Wagemans W, van Oost F W A, Koopmans B and Wohlgenannt M 2009 *Phy. Rev. Lett.* **102** 156604

[15] Ren J F and Xiu M X 2008 *Chin. Phys. Lett.* **25** 2618

[16] Zhang Y B, Ren J F, Hu G C and Xie S J 2008 *Org. Electron.* **9** 687

[17] Yu Z G and Flatté M E 2002 *Phys. Rev.* B **66** 201202(R)

[18] Yu Z G, Berding M A and Krishnamurthy S 2005 *J. Appl. Phys.* **97** 024510

[19] Ma Y N, Ren J F, Zhang Y B, Liu D S and Xie S J 2007 *Chin. Phys. Lett.* **24** 1697