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Spin-dependent quantum transport through an Aharonov–Bohm structure spin splitter*

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Using the tight-binding model approximation, this paper investigates theoretically spin-dependent quantum transport through an Aharonov–Bohm (AB) interferometer. An external magnetic field is applied to produce the spin-polarization and spin current. The AB interferometer, acting as a spin splitter, separates the opposite spin polarization current. By adjusting the energy and the direction of the magnetic field, large spin-polarized current can be obtained.

Keywords: Aharonov–Bohm interferometer, magnetic field, spin splitter
PACC: 7225, 7335A, 7215G

1. Introduction

Spin dependent transport through nanodevices has been a subject of intense experimental and theoretical investigation.[1−5] It is of fundamental importance to study the mechanism to generate and control the spin-polarized currents in these spintronic devices which has a potential applications in quantum computing and information. However, because of the large conductivity mismatch between the ferromagnet and the conductor, the efficiency of spin injection through ideal ferromagnet/semiconductor interfaces is very small. In order to obtain high spin polarization (SP), a lot of nanodevices are investigated. Wu *et al*[6] proposed an Aharonov–Bohm (AB) ring structure with periodic magnetic modulation, and predicted large spin polarized current. Another method to obtain spin polarized current is the spin–orbit coupling.[7,8] Using the effect of spin precessions due to the spin–orbit coupling, Datta and Das studied a sandwich structure spin-transistor.[9] Földi *et al*[10] investigated the quantum interference and spin–orbit interaction in a semiconductor ring with one input and two output leads acted as a spin beam splitter.

Recently, Wang and Liang[11] investigated the spin polarized transport through a T-shaped quantum dot-array, SP can be modulated by adjusting the direction of the magnetic field. In this paper, we propose an AB ring structure with two electrodes, the magnetic field was applied on the certain quantum dots, which is explained schematically in Fig.1. The system is described in terms of discrete lattice sites. The first magnetic field in the z direction is assumed to be applied, without loss of generality, on site 0, and the second magnetic field on the site 9 is along a direction of angle θ with z axis. The angle between the two magnetic field results in the spin-flip effect, which is the mechanism generating the in the AB structure. We remark that it is not necessary to apply the two magnetic fields on the certain quantum dot. In this model choosing the two quantum dots is only for the convenience of analysis and it is easier in experiment to superpose the magnetic fields on the two electrodes of this AB structure.

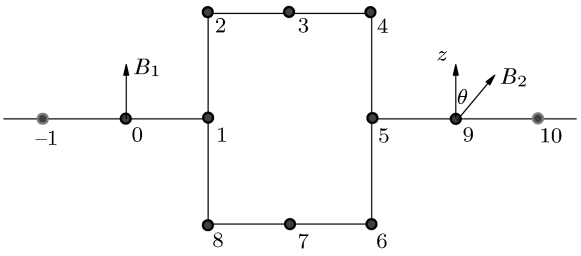


Fig.1. The model of the AB ring spin splitter.

2. Model and formulae

The system is described by a tight-binding Hamiltonian with the nearest-neighbour approximation,[11,12]

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$$
\begin{aligned}
H = & \sum_{n=1,\sigma}^{8} \epsilon_{n\sigma} a_{n\sigma}^{+} a_{n\sigma} + (\epsilon_{0\sigma} + \sigma g \mu_{\mathrm{B}} B) a_{0\sigma}^{+} a_{0\sigma} \\
& + (\epsilon_{9\sigma} + \sigma g \mu_{\mathrm{B}} B \cos\theta) a_{9\sigma}^{+} a_{9\sigma} \\
& + g \mu_{\mathrm{B}} B \sin\theta (a_{9\sigma}^{+} a_{9-\sigma} + \mathrm{H.c.}) \\
& - \sum_{n=1,\sigma}^{7} (t a_{n+1\sigma}^{+} a_{n\sigma} + \mathrm{H.c.}) - (t a_{1\sigma}^{+} a_{8\sigma} + \mathrm{H.c.}) \\
& - (t' a_{0\sigma}^{+} a_{1\sigma} + \mathrm{H.c.}) - (t' a_{5\sigma}^{+} a_{9\sigma} + \mathrm{H.c.}) \\
& + \sum_{n\leq -1,\sigma} \epsilon_{n\sigma} a_{n\sigma}^{+} a_{n\sigma} - \sum_{n\leq -2,\sigma} (t a_{n+1\sigma}^{+} a_{n\sigma} + \mathrm{H.c.}) \\
& + \sum_{n\geq 10,\sigma} \epsilon_{n\sigma} a_{n\sigma}^{+} a_{n\sigma} - \sum_{n\geq 10,\sigma} (t a_{n+1\sigma}^{+} a_{n\sigma} + \mathrm{H.c.}) \\
& - (V_{\mathrm{L}} a_{-1\sigma}^{+} a_{0\sigma} + \mathrm{H.c.}) - (V_{\mathrm{R}} a_{9\sigma}^{+} a_{10\sigma} + \mathrm{H.c.}). \quad (1)
\end{aligned}
$$

Here $a_{n\sigma}(a_{n\sigma}^{+})$ denotes annihilation (creation) operator for electrons in the site n with energy $\epsilon_{n\sigma}$ and spin σ, $-\sigma$ denotes the opposite SP with respect to σ. The Zeeman terms induced by the magnetic field on the sites 0 and 9 result in spin flip, which is the key mechanism of the spin-polarized transport in our model. t is the spin independent hopping matrix, t' is the imbalance of tunnel couplings between spin-up and spin-down electrons due to the magnetic field, V_{L} and V_{R} denote the tunnel couplings between the quantum dots, on which the magnetic field are applied, and corresponding infinite electrodes.

The eigensolutions of the Hamiltonian can be obtained by solving the stationary Shrödinger equation $H|\Psi\rangle = E|\Psi\rangle$, which possesses a general solution of the form

$$
|\Psi\rangle = \sum_{n=-\infty,\sigma}^{\infty} C_{n\sigma} a_{n\sigma}^{+} |0\rangle. \quad (2)
$$

Inserting Eq.(2) into the Shrödinger equation, we get

$$
\begin{aligned}
& (E - \epsilon_{n\sigma}) C_{n\sigma} + t C_{n-1\sigma} + t C_{n+1\sigma} = 0, \\
& n \leq -2, \text{ or } n \geq 11 \text{ or } n = 2, 3, 4, 6, 7, 8, \quad (3) \\
& (E - \epsilon_{-1\sigma}) C_{-1\sigma} + t C_{-2\sigma} + V_{\mathrm{L}} C_{0\sigma} = 0, \quad (4) \\
& (E - \epsilon_{0\sigma} - \sigma g \mu_{\mathrm{B}} B) C_{0\sigma} + V_{\mathrm{L}} C_{-1\sigma} + t' C_{1\sigma} = 0, \quad (5) \\
& (E - \epsilon_{1\sigma}) C_{1\sigma} + t' C_{0\sigma} + t C_{2\sigma} + t C_{8\sigma} = 0, \quad (6) \\
& (E - \epsilon_{5\sigma}) C_{5\sigma} + t C_{4\sigma} + t C_{6\sigma} + t' C_{9\sigma} = 0, \quad (7) \\
& (E - \epsilon_{9\sigma} - \sigma g \mu_{\mathrm{B}} B \cos\theta) C_{9\sigma} - \sigma g \mu_{\mathrm{B}} B \sin\theta C_{9-\sigma} \\
& + t' C_{5\sigma} + V_{\mathrm{R}} C_{10\sigma} = 0, \quad (8) \\
& (E - \epsilon_{10\sigma}) C_{10\sigma} + V_{\mathrm{R}} C_{9\sigma} + t C_{11\sigma} = 0. \quad (9)
\end{aligned}
$$

By assuming a plane wave with unity amplitude and spin σ injected from the left electrode, we have

$$
C_{n\sigma} = \mathrm{e}^{\mathrm{i}kn} + r_{\sigma\sigma'} \mathrm{e}^{-\mathrm{i}kn}, \quad n \leq -1, \quad (10)
$$

and

$$
C_{n\sigma} = t_{\sigma\sigma'} \mathrm{e}^{\mathrm{i}kn}, \quad n \geq 10, \quad (11)
$$

with $r_{\sigma\sigma'}$ and $t_{\sigma\sigma'}$ standing for the reflection and transmission amplitudes respectively, k is the wave vector. The lattice constant, in our model, is unity. Eqs.(10) and (11) close the set of Eqs.(3)–(9) and allows one to find a solution for $r_{\sigma\sigma'}$ and $t_{\sigma\sigma'}$. The transmission probability incoming from the left electrode with spin state σ' tunnelling through the right electrode with spin state σ can be obtained

$$
T(\sigma\sigma') = \frac{1}{2} \frac{V_{\mathrm{R}}}{V_{\mathrm{L}}} |t_{\sigma\sigma'}|^2. \quad (12)
$$

With the help of the Landauer–Bütticker formula,[13] the spin dependent conductance reads $G^{\sigma\sigma'} = (e^2/h) T(\sigma\sigma')$.

3. Result and discussion

In our calculation, we set temperature to zero. In fact, a finite temperature only makes the transmission curve smoother and does not affect the main features. The lattice constant is chosen as an unit of length and t as the unit of energy. The onsite energy $\epsilon_{n\sigma} = 2t$, $t' = 0.8t$, the coupling parameters $V_{\mathrm{L}} = V_{\mathrm{R}} = 0.5t$, and the magnetic field $g\mu_{\mathrm{B}} B_1 = g\mu_{\mathrm{B}} B_2 = t$, respectively.[11]

We calculate the spin dependent conductance as a function of Fermi energy with different angles of the magnetic field, the results are indicated in Fig.2. We can see from Fig.2 that in the presence of the external magnetic fields, the transmitted electrons split into spin-up and spin-down components with different spectra. When the two magnetic fields have the same directions, see in Fig.2(a), the maximum of the conductance for $G^{\uparrow\uparrow}$ and $G^{\downarrow\downarrow}$ is e^2/h, but with $G^{\uparrow\downarrow} = G^{\downarrow\uparrow} = 0$. The electrons tunnel through the AB structure without spin flip scattering. Since the potential symmetry results from the applied magnetic field, the conductance for spin-up electrons with energy E is the same as that for spin-down ones with the energy $4t - E$. From the point of view of resonance tunnelling through two barriers, parallel magnetic field directions mean that the two barrier heights are the same, therefore the resonance tunnelling probability is unity, thus, the spin-dependent conductance peak is e^2/h.

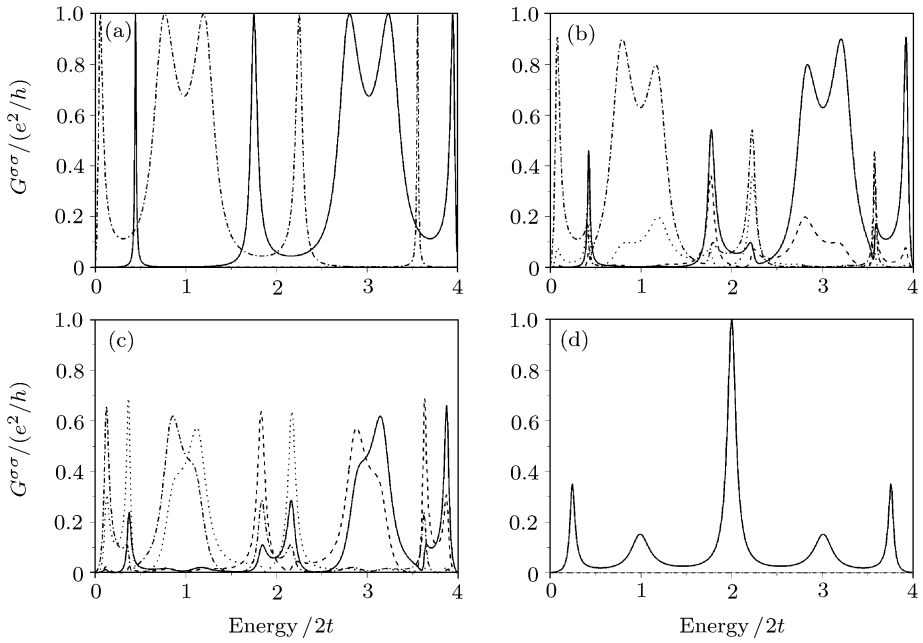


Fig.2. Spin dependent conductance as a function of the energy. Solid, dashed, dotted, and dash-dotted lines corresponding to $G^{\uparrow\uparrow}$, $G^{\downarrow\uparrow}$, $G^{\uparrow\downarrow}$, and $G^{\downarrow\downarrow}$, respectively.

When the directions of the two magnetic field are not parallel, the results are shown in Figs.2(b) and 2(c). It is interesting to note that, in these two cases, the conductance for $G^{\uparrow\downarrow}$ and $G^{\downarrow\uparrow}$ is not zero, spin flip effect appears due to the term of $g\mu_{\rm B}B\sin\theta(a^{+}_{9\sigma}a_{9-\sigma}+{\rm H.c.})$ in Eq.(1). This spin flip term in Eq.(1) plays an important role, especially the case that the second magnetic field is perpendicular to the first one, in which $G^{\uparrow\downarrow}$ ($G^{\downarrow\uparrow}$) is larger than $0.6e^2/h$, results in a high spin flip effect.

In order to investigate the spin polarized current, we plot SP in Fig.3 with different angles of the magnetic field. The spin polarization can be defined as[14] $P=((G^{\uparrow\uparrow}+G^{\uparrow\downarrow})-(G^{\downarrow\downarrow}+G^{\downarrow\uparrow}))/G$, where $G=G^{\uparrow\uparrow}+G^{\uparrow\downarrow}+G^{\downarrow\downarrow}+G^{\downarrow\uparrow}$. As a function of Fermi energy, the SP experiences different sign. For example, when the two magnetic fields have the same directions, see the solid line in Fig.3, SP oscillated from -1 to 1. In the spectra of SP, many energy windows are opened which give SP. For a certain energy, $E=1.4t$ for example, when the angle between the two magnetic fields varies from 0 to $\pi/2$, SP changes from -1 to 0.6. The SP can be modulated by adjusting the magnetic field. When the second magnetic field is antiparallel to the first one, the electrons for spin-up and spin-down electrons have the same transmission probabilities, see the dot-dashed line in Fig.3 and Fig.2(d), the electrons transport through the structure without SP and spin flip.

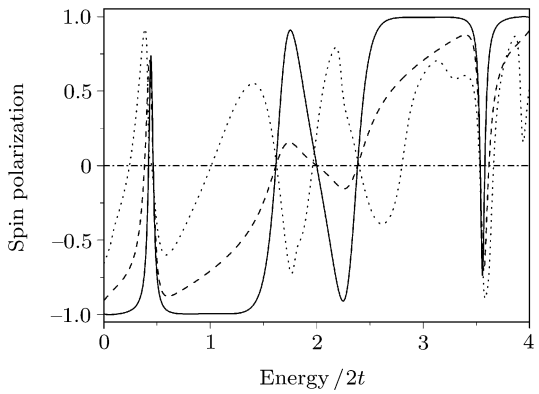


Fig.3. Spin polarization as a function of energy. The solid, dashed, dotted, and dot-dashed curves corresponding to $\theta=0$, $\pi/4$, $\pi/2$, and π, respectively.

In this work, the tight-binding model was only carried out with a single channel, the multichannel model can be obtained directly. It has been shown that a multiple-channel scattering problem can be decomposed into a set of uncoupled single-channel problem.[15] The single-channel model has been widely and successfully used in the study of various nanodevices.[16]

4. Conclusion

In summary, we have investigated the spin dependent electronic transport properties through an AB interferometer with tight binding model approximation. The spin polarized current is tunable by adjusting the directions of the magnetic field. The spin current with opposite SP can be generated. Large SP is predicted and can be accessible with the applied magnetic field. Acting as a spin splitter, the AB interferometer proposed in this work can significantly enhance spin injection efficiencies.

Note added. After the work was completed, we noticed that almost the same AB structure has been studied by Wang *et al.*[17] However, we investigated the SP with different directions of the magnetic field, which is the essential point in this work.

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