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Spin-polarized transport through a coupled double-dot

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Abstract. We investigate the quantum transport through a mesoscopic device consisting of an open, lateral double-quantum-dot coupled by time oscillating and spin-polarization dependent tunneling which results from a static magnetic field applied in the tunneling junction. In the presence of a non-vanishing bias voltage applied to two attached macroscopic leads both spin and charge currents are driven through the device. We demonstrate that the spin and charge currents are controllable by adjusting the gate voltage, the frequency of driving field and the magnitude of the magnetic field as well. An interesting resonance phenomenon is observed.

PACS. 72.10.Bg General formulation of transport theory – 72.25.-b Spin polarized transport – 73.23.-b Electronic transport in mesoscopic systems

1 Introduction

Traditional electronics is based on the charge transport and the spin degree of electrons does not play a role. The idea of electronic devices that exploit both the charge and spin degrees of electrons has led to a new field known as spintronics. In the devices consisting of open quantum dots electrons can freely enter and exit the dots via leads that support one or more propagating modes. Spin-polarized transports in open quantum dots have attracted considerable attentions recently since these devices not only exhibit the new fundamental physics but also are of promising applications in the emerging technologies of spintronics and quantum information [1,2]. Thus it is of great importance to generate and control the spin-dependent current. Recent experimental advances in spintronics have stimulated an impetus to study spin-polarized transport. A spin current is produced by the motion of spin-polarized electrons and the mechanism of realization of spin current relies on spin-orbit coupling to couple the local spin of material to the conduction electrons. Spin-polarized transport occurs naturally in any material with an imbalance of the spin populations at the Fermi level which is the characteristic of ferromagnetic metals [3]. Traditionally, spin injection from a ferromagnetic material to a normal metal or semiconductor material has been used to obtain spin-polarized charge current. More recently, several theoretical proposals of spin-battery were reported for the generation of spin-current [4–7]. In this paper, we present a new type of mechanism for generation of the spin-polarized current based on the Larmor precession of spin in magnetic field which is confined inside the tunneling barrier between two quantum dots. It was demonstrated long ago by Büttiker [8] that the main effect of the magnetic field on the spin of particle which penetrates the barrier is to align the spin with the field since the particle with spin parallel to the magnetic field has lower energy and less decay rate (hence higher tunneling rate) in barrier region than that of particle with spin antiparallel to the magnetic field. The advantage of the device is that both the spin and charge currents are controllable by adjusting of the magnetic field.

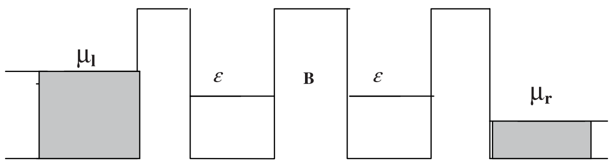

Fig. 1. Schematic diagram for the lateral double-quantum-dot coupled to two leads.

The system we examine is schematically shown in Figure 1 which consists of a double-quantum-dot (DQD) fabricated in two-dimensional electron gas and each quantum dot (QD) is contacted by an electrode. The two electrodes maintain a difference of electrochemical potential $\mu_L - \mu_R = V > 0$ i.e. a bias voltage to generate the charge current. There is no magnetic material involved in our device. We control the QD 's energy levels by an overall gate voltage V_g. A controllable external magnetic field B is applied in the barrier region (perpendicular to the QD plane) between two QDs in order to generate the imbalance tunneling probabilities between spins parallel and antiparallel to the magnetic field as demonstrated earlier. Moreover the

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weak coupling between two QDs is assumed to be time-dependent driven by a time-oscillation microwave field.

2 Model and formulation

Our system of DQD coupled to two leads is described by the following Hamiltonian:

$$H = H_{\rm DQD} + H_T + \sum_{\alpha(\alpha=L,R)} H_\alpha \quad (1)$$

with

$$H_\alpha = \sum_{k\sigma} \varepsilon_{k\alpha} C^+_{k\alpha\sigma} C_{k\alpha\sigma}, \quad (2)$$

$$H_T = \sum_{k\alpha\sigma} (T_{k\alpha} C^+_{k\alpha\sigma} d_{\alpha\sigma} + \text{H.c.}), \quad (3)$$

$$H_{\rm DQD} = \sum_{\alpha\sigma} \varepsilon_{\alpha\sigma} d^+_{\alpha\sigma} d_{\alpha\sigma} + \sum_\sigma \left(g e^{sign\sigma \triangle E} e^{iwt} d^+_{L\sigma} d_{R\sigma} + \text{c.c.} \right). \quad (4)$$

H_α ($\alpha = L, R$) describes the non-interacting left and right leads. $C^+_{k\alpha\sigma}$ (with $\sigma =\uparrow,\downarrow$) is the creation operator of electrons with momentum k and spin index σ in the lead-α. H_T denotes the coupling between one of the DQD and the adjacent lead with coupling matrix elements $T_{k\alpha}$. $H_{\rm DQD}$ models the coupled DQD, in which each QD has a single level $\varepsilon = \varepsilon_0 + eV_g$ which is double degenerate in spin index σ and can be controlled by the gate voltage V_g where e denotes the absolute value of electron charge. $d_{\alpha\sigma}$ denotes the annihilation operator of electron with spin index σ in the dot-α. The coupling between DQD with coupling constant g is modulated by a time-oscillation microwave of frequency w. An external magnetic field B is superposed on the tunnel junction such that the tunnel coupling is modified by a factor $e^{sign\sigma\triangle E}$ (sign$\sigma = \pm 1$, for $\sigma =\uparrow,\downarrow$ respectively). The small parameter $\triangle E$ is proportional to the magnitude of the external magnetic field. It is obviously that the factor leads to a slightly higher tunneling rate for spin parallel to the magnetic field (sign$\sigma = +1$) than antiparallel case (sign$\sigma = -1$).

In the following, we study the spin-dependent quantum transport using the standard keldysh nonequilibrium Green's function (NEGF) technique [9,10] in terms of which the spin-dependent current can be evaluated explicitly. To this end we define the spin-dependent current operator [5] in the lead-α as

$$J_{\alpha\sigma\sigma'} \equiv \sum_k \frac{d[C^+_{k\alpha\sigma} C_{k\alpha\sigma'}]}{dt} = \frac{1}{i\hbar} \sum_k [C^+_{k\alpha\sigma} C_{k\alpha\sigma'}, H], \quad (5)$$

and then the current operator from the left contact to the left dot is seen to be

$$J_{L\sigma\sigma'} = -i \sum_k [T_{kL} C^+_{kL\sigma} d_{L\sigma'} - T^*_{kL} d^+_{L\sigma} C_{kL\sigma'}]. \quad (6)$$

The electric current operator is defined by [5]

$$J_{Lq} = -e \sum_\sigma J_{L\sigma\sigma} = -e(J_{L\uparrow\uparrow} + J_{L\downarrow\downarrow}), \quad (7)$$

and the spin-current operator with spin component σ is [5]

$$J_{Ls} = \frac{1}{2} \sum_{\sigma\sigma'} J_{L\sigma\sigma'} \boldsymbol{\sigma}^z_{\sigma\sigma'} \quad (8)$$

where $\boldsymbol{\sigma}^z$ is Pauli matrix.

The spin-dependent current can be computed from current operator equation (6)

$$I_{L\sigma\sigma'}(t) \equiv \langle J_{L\sigma\sigma'}(t) \rangle = -\sum_k [T_{kL} G^{\prec}_{Lk,\sigma\sigma'}(t,t) - T^*_{kL} G^{\prec}_{kL,\sigma'\sigma}(t,t)] \quad (9)$$

where the nonequilibrium Green's functions (NEGFs) are defined as

$$G^{\prec}_{Lk,\sigma'\sigma}(t,t') \equiv i\langle C^+_{kL\sigma}(t') d_{L\sigma'}(t) \rangle,$$

$$G^{\prec}_{kL,\sigma'\sigma}(t,t') \equiv i\langle d^+_{L\sigma}(t') C_{kL\sigma'}(t) \rangle.$$

For the case of noninteracting leads, a general relation for the contour-ordered Green functions $G_{Lk,\sigma\sigma'}(t,t')$ between the left dot and left lead can be derived rather easily either with the equation-of-motion technique or by a direct expression of the S matrix [9] and the result is

$$G_{Lk,\sigma\sigma'}(t,t') = \sum_{\underline{\sigma}} \int dt_1 G_{LL,\sigma\underline{\sigma}}(t,t_1) T^*_{kL} g_{kL,\underline{\sigma}\sigma'}(t_1,t'). \quad (10)$$

Using the set of operational rules given by Langreth [11] that if one has an expression for Green functions such that $A = \int BC$ on the contour, the retarded and lesser Green functions are given by

$$A^r(t,t') = \int dt_1 B^r(t,t_1) C^r(t_1,t')$$

and

$$A^{\prec}(t,t') = \int dt_1 [B^r(t,t_1) C^{\prec}(t_1,t') + B^{\prec}(t,t_1) C^a(t_1,t')]$$

respectively, we can write the lesser Green's functions as

$$G^{\prec}_{Lk,\sigma\sigma'}(t,t') = \sum_{\underline{\sigma}} \int dt_1 T^*_{kL} [G^r_{LL,\sigma\underline{\sigma}}(t,t_1) g^{\prec}_{kL,\underline{\sigma}\sigma'}(t_1,t') + G^{\prec}_{LL,\sigma\underline{\sigma}}(t,t_1) g^a_{kL,\underline{\sigma}\sigma'}(t_1,t')] \quad (11)$$

$$G^{\prec}_{kL,\sigma'\sigma}(t,t') = -\left[G^{\prec}_{Lk,\sigma\sigma'}\right]^* = \sum_{\underline{\sigma}} \int dt_1 T_{kL} \left[g^{\prec}_{kL,\sigma'\underline{\sigma}}(t',t_1) G^a_{LL,\underline{\sigma}\sigma}(t_1,t) + g^r_{kL,\sigma'\underline{\sigma}}(t',t_1) G^{\prec}_{LL,\underline{\sigma}\sigma}(t_1,t) \right]. \quad (12)$$

where the superscript a denotes the advanced Green function.

Using equations (11, 12) the particle current defined by equation (9) is seen to be

$$I_{L,\sigma\sigma'}(t) = -\int_{-\infty}^{t} dt_1 \sum_{\underline{\sigma}} \{G^r_{LL,\sigma\underline{\sigma}}(t,t_1)\Sigma^{\prec}_{L,\underline{\sigma}\sigma'}(t_1,t) + G^{\prec}_{LL,\sigma\underline{\sigma}}(t,t_1)\Sigma^a_{L\underline{\sigma}\sigma'}(t_1,t) - \Sigma^{\prec}_{L\sigma'\underline{\sigma}}(t,t_1)G^a_{LL,\underline{\sigma}\sigma}(t_1,t) - \Sigma^r_{L,\sigma'\underline{\sigma}}(t,t_1)G^{\prec}_{LL,\underline{\sigma}\sigma}(t_1,t)\}, \quad (13)$$

where

$$\Sigma^{\gamma}_{L,\underline{\sigma}\sigma'}(t_1,t_2) = \sum_k T_{kL}T^*_{kL} g^{\gamma}_{kL,\underline{\sigma}\sigma'}(t_1,t_2) \quad (14)$$

is the self-energy with $\gamma = r, a, <$ respectively.

The time-average current is

$$I_{L,\sigma\sigma'} = -\frac{1}{2N_\tau}\int_{-N_\tau}^{N_\tau} dt \int_{-\infty}^{t} dt_1 \Big[G^r_{LL,\sigma\underline{\sigma}}(t,t_1)\Sigma^{\prec}_{L,\underline{\sigma}\sigma'}(t_1,t) + G^{\prec}_{LL,\sigma\underline{\sigma}}(t,t_1)\Sigma^a_{L,\underline{\sigma}\sigma'}(t_1,t) + \text{c.c.}\Big] \quad (15)$$

where the integration duration is $[-N_\tau, N_\tau]$ with $N_\tau \to \infty$. With the following double-time Fourier transformation

$$G^{\gamma}(t_1,t_2) = \int \frac{dE_1}{2\pi}\int \frac{dE_2}{2\pi} e^{-iE_1t_1+iE_2t_2} G^{\gamma}(E_1,E_2) \quad (16)$$

the average current equation (15) becomes

$$I_{L,\sigma\sigma'} = -\frac{1}{2N_\tau}\int \frac{dE_1}{2\pi}\int \frac{dE_2}{2\pi}\sum_{\underline{\sigma}}\{[G^r_{LL,\sigma\underline{\sigma}}(E_1,E_2) - G^a_{LL,\sigma\underline{\sigma}}(E_1,E_2)]\Sigma^{\prec}_{L,\underline{\sigma}\sigma'}(E_2,E_1) + G^{\prec}_{LL,\sigma\underline{\sigma}}(E_1,E_2)[\Sigma^a_{L,\underline{\sigma}\sigma'}(E_2,E_1) - \Sigma^r_{L,\underline{\sigma}\sigma'}(E_2,E_1)]\}. \quad (17)$$

Under steady-state conditions the self-energy functions are purely diagonal in energy space and we obtain from equation (14)

$$\Sigma^{\prec}_{L,\underline{\sigma}\sigma'}(E_1,E_2) = 2\pi i\delta(E_1-E_2)\Gamma_L(E_1)f_L(E_1)\delta_{\underline{\sigma}\sigma'}. \quad (18)$$

The matrix $\mathbf{\Gamma_L(E)}$ denotes the line-width function defined by

$$\Gamma_L(E) \equiv 2\pi\rho_L(E)\left|T_{kL}(E)\right|^2, \quad (19)$$

where $\rho_L(E)$ is the density of states in the left lead, and

$$f_\alpha(E) = \{\exp[(E-\mu_\alpha)/kT]+1\}^{-1} \quad (20)$$

is the Fermi distribution of the lead-α.

Substituting the self-energy function $\Sigma^{\prec}_{L\underline{\sigma}\sigma'}(E_1,E_2)$ given by equation (18) into equation (17), the current from the left lead flowing to the DQD is obtained as

$$I_{L,\sigma\sigma'} = \frac{-i}{2N_\tau}\int \frac{dE_1}{2\pi}\{[G^r_{\sigma\sigma'}(E_1,E_1) - G^a_{\sigma\sigma'}(E_1,E_1)]_{LL}\Gamma_L(E_1)f_L(E_1) + G^{\prec}_{LL,\sigma\sigma'}(E_1,E_1)\Gamma_L(E_1)\}. \quad (21)$$

In the steady state [9] the current is uniform such that $I = I_L = -I_R$ and

$$I = \frac{I_L - I_R}{2}$$

where I_R denotes the current from the right dot flowing to the device. The particle current through the device can be written as

$$I_{\sigma\sigma'} = \frac{-i}{4N_\tau}\int \frac{dE_1}{2\pi}[\Gamma_L(E_1)-\Gamma_R(E_1)]G^{\prec}_{LL,\sigma\sigma'}(E_1,E_1) + [f_L(E_1)\Gamma_L(E_1) - f_R(E_1)\Gamma_R(E_1)] \times [G^r_{\sigma\sigma'}(E_1,E_1) - G^a_{\sigma\sigma'}(E_1,E_1)]_{LL}. \quad (22)$$

Using the identity of the Green functions between two dots

$$(G^r - G^a)_{ij} = -iG^r_{iL}\Gamma_L G^a_{Lj} - iG^r_{iR}\Gamma_R G^a_{Rj} \quad (23)$$

where $i, j = L, R$ and keldysh equation

$$G^{\prec}_{jk} = G^r_{jL}\Sigma^{\prec}_L G^a_{Lk} + G^r_{jR}\Sigma^{\prec}_R G^a_{Rk} \quad (24)$$

we obtain spin-dependent current

$$I_{\sigma\sigma'} = \frac{-i}{4N_\tau}\int \frac{dE_1}{2\pi}\int \frac{dE_2}{2\pi}(\Gamma_L(E_1)-\Gamma_R(E_1)) \times [G^r_{LL,\sigma\sigma_1}(E_1,E_2)\Gamma_L(E_2)if_L(E_2)G^a_{LL,\sigma_1\sigma'}(E_2,E_1) + G^r_{LR,\sigma\sigma_1}(E_1,E_2)\Gamma_R(E_2)if_R(E_2) \times G^a_{RL,\sigma_1\sigma'}(E_2,E_1)] + [\Gamma_L(E_1)f_L(E_1) - \Gamma_R(E_1)f_R(E_1)][-iG^r_{LL,\sigma\sigma_1}(E_1,E_2)\Gamma_L(E_2) \times G^a_{LL,\sigma_1\sigma'}(E_2,E_1) - iG^r_{LR,\sigma\sigma_1}(E_1,E_2)\Gamma_R(E_2) \times G^a_{RL,\sigma_1\sigma'}(E_2,E_1)]. \quad (25)$$

Thus the current of spin parallel to the magnetic field is

$$I_{\uparrow\uparrow} = \frac{1}{4N_\tau}\int \frac{dE_1}{2\pi}\int \frac{dE_2}{2\pi}\Gamma_L^2[f_L(E_2) - f_L(E_1)][G^r_{LL,\uparrow\uparrow}(E_1,E_2)G^a_{LL,\uparrow\uparrow}(E_2,E_1) + G^r_{LL,\uparrow\downarrow}(E_1,E_2)G^a_{LL,\downarrow\uparrow}(E_2,E_1)] + \Gamma_R^2[f_R(E_1) - f_R(E_2)][G^r_{LR,\uparrow\uparrow}(E_1,E_2)G^a_{RL,\uparrow\uparrow}(E_2,E_1) + G^r_{LR,\uparrow\downarrow}(E_1,E_2)G^a_{RL,\downarrow\uparrow}(E_2,E_1)] + \Gamma_L\Gamma_R[f_R(E_2) - f_L(E_1)][G^r_{LR,\uparrow\uparrow}(E_1,E_2)G^a_{RL,\uparrow\uparrow}(E_2,E_1) + G^r_{LR,\uparrow\downarrow}(E_1,E_2)G^a_{RL,\downarrow\uparrow}(E_2,E_1)] + \Gamma_L\Gamma_R[f_R(E_1) - f_L(E_2)][G^r_{LL,\uparrow\uparrow}(E_1,E_2)G^a_{LL,\uparrow\uparrow}(E_2,E_1) + G^r_{LL,\uparrow\downarrow}(E_1,E_2)G^a_{LL,\downarrow\uparrow}(E_2,E_1)], \quad (26)$$

and current of spin antiparallel to the magnetic field is

$$I_{\downarrow\downarrow} = \frac{1}{4N_\tau}\int\frac{dE_1}{2\pi}\int\frac{dE_2}{2\pi}\Gamma_L^2[f_L(E_2) - f_L(E_1)][G^r_{LL,\downarrow\downarrow}(E_1,E_2)G^a_{LL,\downarrow\downarrow}(E_2,E_1) + G^r_{LL,\downarrow\uparrow}(E_1,E_2)G^a_{LL,\uparrow\downarrow}(E_2,E_1)] + \Gamma_R^2[f_R(E_1) - f_R(E_2)][G^r_{LR,\downarrow\downarrow}(E_1,E_2)G^a_{RL,\downarrow\downarrow}(E_2,E_1) + G^r_{LR,\downarrow\uparrow}(E_1,E_2)G^a_{RL,\uparrow\downarrow}(E_2,E_1)] + \Gamma_L\Gamma_R[f_R(E_2) - f_L(E_1)][G^r_{LR,\downarrow\downarrow}(E_1,E_2)G^a_{RL,\downarrow\downarrow}(E_2,E_1) + G^r_{LR,\downarrow\uparrow}(E_1,E_2)G^a_{RL,\uparrow\downarrow}(E_2,E_1)] + \Gamma_L\Gamma_R[f_R(E_1) - f_L(E_2)][G^r_{LL,\downarrow\downarrow}(E_1,E_2)G^a_{LL,\downarrow\downarrow}(E_2,E_1) + G^r_{LL,\downarrow\uparrow}(E_1,E_2)G^a_{LL,\uparrow\downarrow}(E_2,E_1)]. \quad (27)$$

Here we take the wide-bandwidth approximation, under which the line-width $\Gamma_L(\Gamma_R)$ is independent of the energy [12,13] ε. Therefore the transport problem is reduced to the calculation of the retarded Green's functions $G^r_{LL,\sigma\sigma'}(E_1,E_2)$, $G^r_{LR,\sigma\sigma'}(E_1,E_2)$. To this end we regard the term, which explicitly depends on time **t**, in the Hamiltonian equation (1) as the interacting part H_I such that $H_0 \equiv H - H_I$. The Green's functions for the Hamiltonian H_0 denoted by $G^{0r}_{LL,\sigma\sigma'}(\varepsilon)$, and $G^{0r}_{RR,\sigma\sigma'}(\varepsilon)$ can be easily obtained in terms of the equation of motion as

$$G^{0r}_{LL,\sigma\sigma'}(\varepsilon) = \frac{\delta_{\sigma\sigma'}}{\varepsilon - \varepsilon_{L\sigma} + \frac{i}{2}\Gamma_L}, \quad (28)$$

$$G^{0r}_{RR,\sigma\sigma'}(\varepsilon) = \frac{\delta_{\sigma\sigma'}}{\varepsilon - \varepsilon_{R\sigma} + \frac{i}{2}\Gamma_R}. \quad (29)$$

The full Green's functions for Hamiltonian equation (1) are then calculated from the Dyson equation

$$G^r_{LL,\sigma\sigma'}(E_1,E_2) = 2\pi G^{0r}_{LL,\sigma\sigma'}(E_1)\delta(E_1-E_2) + \int\frac{dE}{2\pi}G^r_{LR,\sigma\sigma_1}(E_1,E+E_2)\Sigma^r_{RL,\sigma_1\sigma_2}(E)G^{0r}_{LL,\sigma_2\sigma'}(E_2), \quad (30)$$

with

$$G^r_{LR,\sigma\sigma'}(E_1,E_2) = \int\frac{dE}{2\pi}G^r_{LL,\sigma\sigma_1}(E_1,E+E_2) \times \Sigma^r_{LR,\sigma_1\sigma_2}(E)G^{0r}_{RR,\sigma_2\sigma'}(E_2) \quad (31)$$

where the retarded self-energy $\Sigma^r_{LR,\sigma_1\sigma_2}(E)$ is the Fourier transformation of $\Sigma^r_{LR,\sigma_1\sigma_2}(t)$ which is seen to be

$$\Sigma^r_{LR,\sigma_1\sigma_2}(t) = [\Sigma^r_{RL,\sigma_1\sigma_2}(t)]^* = ge^{sign\sigma_1\triangle E}e^{iwt}\delta_{\sigma_1\sigma_2} \quad (32)$$

and

$$\Sigma^r_{LL,\sigma_1\sigma_2}(t) = \Sigma^r_{RR,\sigma_1\sigma_2}(t) = 0. \quad (33)$$

The Fourier transformation is obtained as

$$\Sigma^r_{LR,\sigma_1\sigma_2}(E) = 2\pi\delta(E+w)ge^{sign\sigma_1\triangle E}\delta_{\sigma_1\sigma_2} \quad (34)$$

and

$$\Sigma^r_{RL,\sigma_1\sigma_2}(E) = 2\pi\delta(E-w)ge^{sign\sigma_1\triangle E}\delta_{\sigma_1\sigma_2}. \quad (35)$$

Substituting equations (31, 34, 35) into equation (30) the retarded Green's functions in the left dot can be obtained, after tedious but straightforward algebra, explicitly as

$$G^r_{LL,\uparrow\uparrow}(E_1,E_2) = \frac{2\pi\delta(E_1-E_2)G^{0r}_{LL,\uparrow\uparrow}(E_1)}{1-(ge^{\triangle E})^2G^{0r}_{RR,\uparrow\uparrow}(E_2+w)G^{0r}_{LL,\uparrow\uparrow}(E_2)}, \quad (36)$$

$$G^r_{LL,\downarrow\downarrow}(E_1,E_2) = \frac{2\pi\delta(E_1-E_2)G^{0r}_{LL,\downarrow\downarrow}(E_1)}{1-(ge^{-\triangle E})^2G^{0r}_{RR,\downarrow\downarrow}(E_2+w)G^{0r}_{LL,\downarrow\downarrow}(E_2)}, \quad (37)$$

and

$$G^r_{LL,\uparrow\downarrow}(E_1,E_2) = G^r_{LL,\downarrow\uparrow}(E_1,E_2) = 0.$$

The Green function between two dots is evaluated from equation (31) and the result is

$$G^r_{LR,\uparrow\uparrow}(E_1,E_2) = \frac{2\pi\delta(E_1-E_2+w)ge^{\triangle E}G^{0r}_{RR,\uparrow\uparrow}(E_2)G^{0r}_{LL,\uparrow\uparrow}(E_1)}{1-(ge^{\triangle E})^2G^{0r}_{RR,\uparrow\uparrow}(E_2)G^{0r}_{LL,\uparrow\uparrow}(E_2-w)} \quad (38)$$

for the spin parallel to the magnetic field and

$$G^r_{LR,\downarrow\downarrow}(E_1,E_2) = \frac{2\pi\delta(E_1-E_2+w)ge^{-\triangle E}G^{0r}_{RR,\downarrow\downarrow}(E_2)G^{0r}_{LL,\downarrow\downarrow}(E_1)}{1-(ge^{-\triangle E})^2G^{0r}_{RR,\downarrow\downarrow}(E_2)G^{0r}_{LL,\downarrow\downarrow}(E_2-w)}, \quad (39)$$

for the spin antiparallel to the magnetic field. There is no spin flip through the tunnel junction i.e.

$$G^r_{LR,\uparrow\downarrow}(E_1,E_2) = G^r_{LR,\downarrow\uparrow}(E_1,E_2) = 0. \quad (40)$$

We finally obtain the spin-polarized currents from equations (26) and (27) as

$$I_{\uparrow\uparrow} = \frac{1}{2}\int\frac{dE}{2\pi}\Bigg\{\Gamma_R^2[f_R(E)-f_R(E+w)] \times \frac{(ge^{\triangle E})^2\left|G^{0r}_{RR,\uparrow\uparrow}(E+w)\right|^2\left|G^{0r}_{LL,\uparrow\uparrow}(E)\right|^2}{\left|1-(ge^{\triangle E})^2G^{0r}_{RR,\uparrow\uparrow}(E+w)G^{0r}_{LL,\uparrow\uparrow}(E)\right|^2} + \Gamma_L\Gamma_R[f_R(E+w)-f_L(E)] \times \frac{(ge^{\triangle E})^2\left|G^{0r}_{RR,\uparrow\uparrow}(E+w)\right|^2\left|G^{0r}_{LL,\uparrow\uparrow}(E)\right|^2}{\left|1-(ge^{\triangle E})^2G^{0r}_{RR,\uparrow\uparrow}(E+w)G^{0r}_{LL,\uparrow\uparrow}(E)\right|^2} + \Gamma_L\Gamma_R[f_R(E)-f_L(E)] \times \frac{\left|G^{0r}_{LL,\uparrow\uparrow}(E)\right|^2}{\left|1-(ge^{\triangle E})^2G^{0r}_{RR,\uparrow\uparrow}(E+w)G^{0r}_{LL,\uparrow\uparrow}(E)\right|^2}\Bigg\} \quad (41)$$

and

$$I_{\downarrow\downarrow} = \frac{1}{2}\int \frac{dE}{2\pi}\Bigg\{ \Gamma_R^2[f_R(E) - f_R(E+w)] \times \frac{(ge^{-\triangle E})^2 \left|G^{0r}_{RR,\downarrow\downarrow}(E+w)\right|^2 \left|G^{0r}_{LL,\downarrow\downarrow}(E)\right|^2}{\left|1-(ge^{-\triangle E})^2 G^{0r}_{RR,\downarrow\downarrow}(E+w)G^{0r}_{LL,\downarrow\downarrow}(E)\right|^2} + \Gamma_L\Gamma_R[f_R(E+w) - f_L(E)] \times \frac{(ge^{-\triangle E})^2 \left|G^{0r}_{RR,\downarrow\downarrow}(E+w)\right|^2 \left|G^{0r}_{LL,\downarrow\downarrow}(E)\right|^2}{\left|1-(ge^{-\triangle E})^2 G^{0r}_{RR,\downarrow\downarrow}(E+w)G^{0r}_{LL,\downarrow\downarrow}(E)\right|^2} + \Gamma_L\Gamma_R[f_R(E) - f_L(E)] \times \frac{\left|G^{0r}_{LL,\downarrow\downarrow}(E)\right|^2}{\left|1-(ge^{-\triangle E})^2 G^{0r}_{RR,\downarrow\downarrow}(E+w)G^{0r}_{LL,\downarrow\downarrow}(E)\right|^2}\Bigg\} \quad (42)$$

where we have used the identity $2\pi\delta(0) = \int dE = 2N_\tau$. From these two equations (41, 42) one can conclude that the charge current is given by

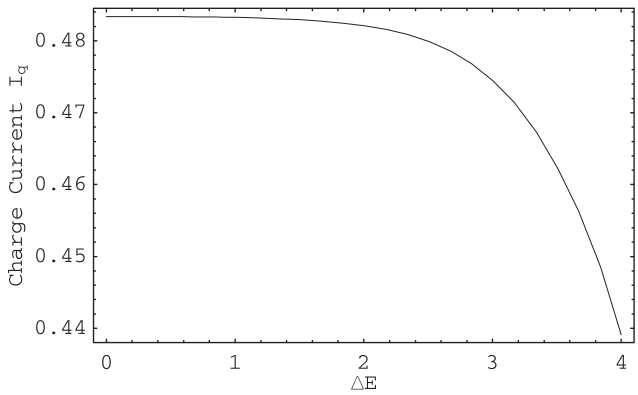
$$I_q = -e(I_{\uparrow\uparrow} + I_{\downarrow\downarrow}) \quad (43)$$

and the spin current is

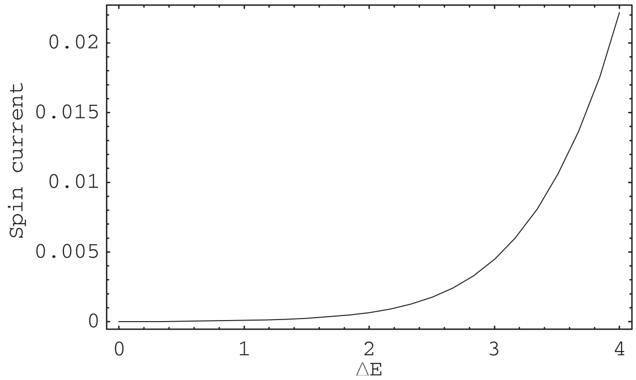
$$I_s = \frac{1}{2}(I_{\uparrow\uparrow} - I_{\downarrow\downarrow}). \quad (44)$$

3 Numerical results

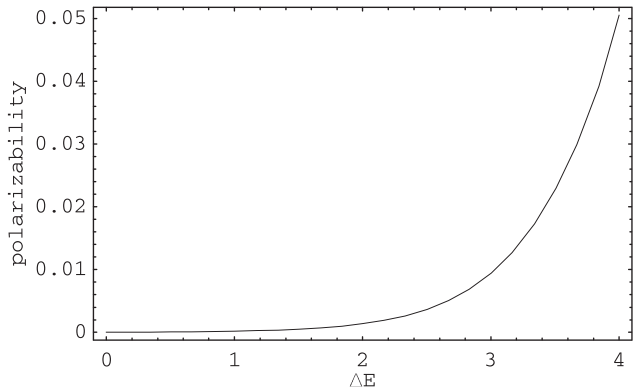
We consider the symmetric coupling barriers for the sake of simplicity i.e. $\Gamma_L(E) = \Gamma_R(E) = \frac{\Gamma}{2}$ and further assume that the gate voltage V_g controls the energy level of the quantum dots such that $\varepsilon_L(V_g) = \varepsilon_R(V_g) = \varepsilon(V_g) = \varepsilon_0 + eV_g$, where ε_0 denotes single-electron energy in the left and right QDs without the gate voltage V_g. The coupling constant Γ is chosen as the energy unit. We also set $\hbar = e = 1$. Figure 2 shows the charge current I_q (Fig. 2a) and the spin current I_s (Fig. 2b) versus the magnetic field-dependent tunneling-parameter $\triangle E$ at zero temperature $T = 0$. Similar results are obtained at low temperatures [14]. Other parameter values used in Figure 2 are such that $\mu_L = 10, \mu_R = 0, V_g = 6, w = 10$ and $g = 0.1$. It is clearly shown that the electron with spin parallel to the magnetic field has lower energy in the barrier region and hence the higher tunneling rate (current). The situation is just opposite for the electron with spin antiparallel to the magnetic field. Therefore, the spin current increases with the magnetic field. The total current I_q decreases slightly with the increase of $\triangle E$. The polarizability I_s/I_q as a function of the parameter $\triangle E$ is shown in Figure 2c.



(a)



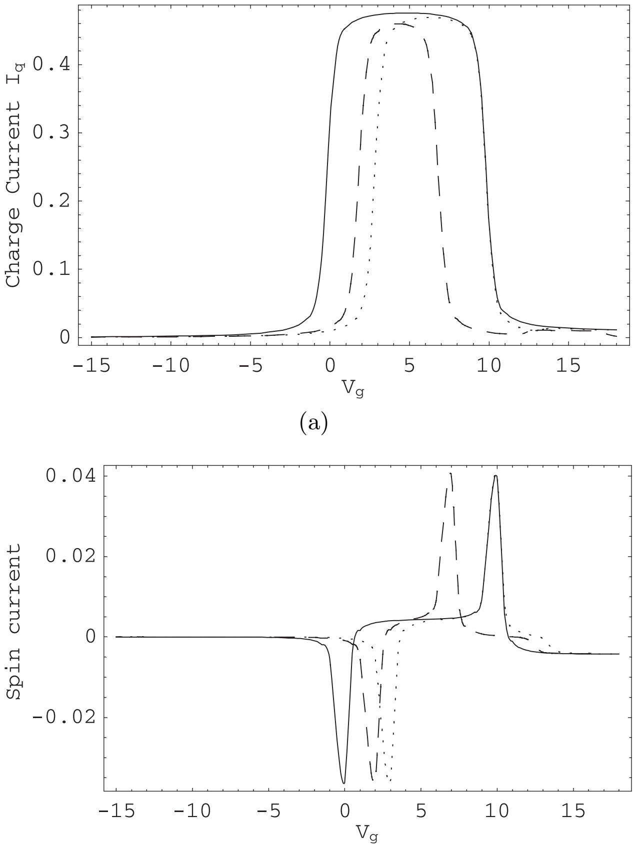
(b)



(c)

Fig. 2. The charge current I_q (a) and spin current I_s (b) versus the coupling $\triangle E$ for a symmetric structure$\Gamma_L = \Gamma_R = \frac{\Gamma}{2}$ with energies measured in unit of Γ ($\mu_L = 10, \mu_R = 0, V_g = 6$, $w = 10$, $g = 0.1$) and polarizability $\frac{I_S}{I_q}$ (c).

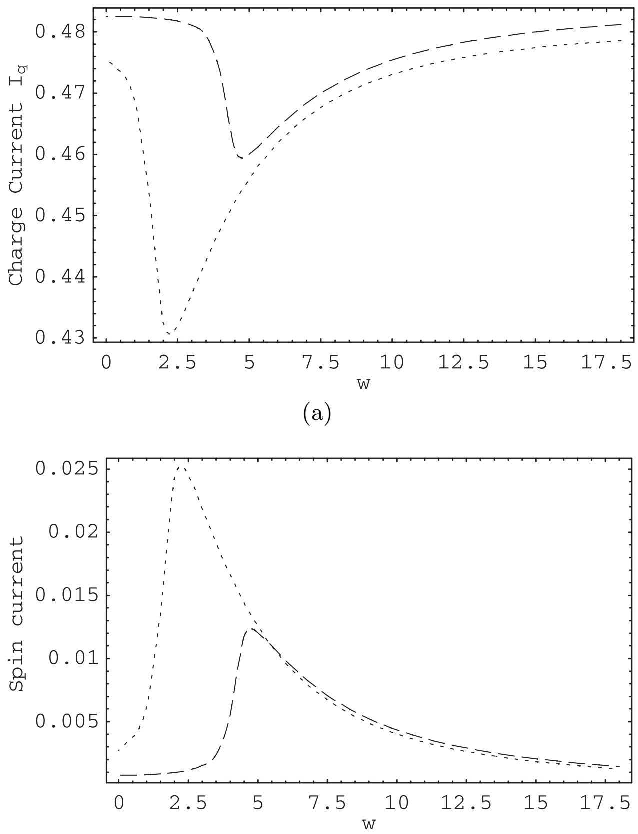
Figure 3 displays I_q (Fig. 3a) and I_s (Fig. 3b) as a function of gate voltage V_g with different external bias $V \equiv \mu_L - \mu_R$. We can see that the resonant charge current I_q varies from zero to large values under the control of the gate voltage V_g. The maximum charge current in the plot extends to a plateau with the corresponding range of gate-voltage values from $V_g = \mu_L$, to $V_g = \mu_R$. While resonant



(a)

(b)

Fig. 3. The charge current I_q(a) and the spin current I_s (b) as a function of gate voltage V_g at different external bias $V \equiv \mu_L - \mu_R$ with $\triangle E = 3.0$; $V = 10$ ($\mu_L = 10, \mu_R = 0$) (solid line), $V = 7$ ($\mu_L = 10, \mu_R = 3$) (dotted line) $V = 4$ ($\mu_L = 6, \mu_R = 2$) (dashed line).



(a)

(b)

Fig. 4. The charge current I_q (a) and the spin current I_s (b) as a function of frequency w at different gate voltage with $\triangle E = 3.0$, $V_g = 3$ (dotted line) $V_g = 5$ (dashed line).

spin current I_s has a peak at gate voltage values $V_g = \mu_L$, μ_R respectively.

Figure 4 depicts the charge current I_q (Fig. 4a) and the spin current I_s (Fig. 4b) as a function of frequency w of driving field at zero temperature [14] with different gate voltages and $g = 0.1$, $\triangle E = 3.0, \mu_L = 10, \mu_R = 0$. We observe, perhaps, a most interesting phenomenon of resonance that both the charge current I_q and the current $I_{\uparrow\uparrow}$ with spin parallel to the magnetic field display a minimum at the certain value of field frequency. We may call this antiresonance as resonance-block since at the resonance frequency the oscillating probability current of electron between two QDs reaches the maximum value [15] and therefore the transport current is suppressed dramatically. The spin current I_s has a maximum value at the resonance frequency due to the imbalance variation of the currents $I_{\uparrow\uparrow}$ and $I_{\downarrow\downarrow}$. This resonance-block phenomenon may have technical applications in electronic devices, for instance, to make an frequency (of driving-field) controlled switch for both spin and charge currents. It may be useful to estimate the practical value of magnetic field for generation of the spin current in our system. For the temperature scale $k_B T = 0.01$ meV [14,16] and coupling constant $\Gamma = 10$ μeV as in typical QD experiments, the magnitude of magnetic field is $B \sim 0.16/g_0$ tesla where g_0 is effective electron g-factor.

4 Conclusion

In summary, we have proposed a new type of device to generate the spin-polarized currents which are controllable by the external field. It is demonstrated that the spin-polarized current can be produced by a static magnetic field applied in the tunneling junction region unlike the usual device where a rotating field is required to cause the spin flip. A general formula for the charge and spin currents flowing through such a device is derived using the NEGF method and the spin polarized currents as functions of gate voltage, the frequency of driving field and the magnitude of the magnetic field are studied explicitly.

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