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Non-stationary spin-filtering effects in correlated quantum dot

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ABSTRACT

The influence of external magnetic field switching "on" and "off" on the non-stationary spin-polarized currents in the system of correlated single-level quantum dot coupled to non-magnetic electronic reservoirs has been analyzed. It was shown that considered system can be used for the effective spin filtering by analyzing its non-stationary characteristics in particular range of applied bias voltage.

1. Introduction

One of the key issues of spintronics is the control and generation of spin-polarized currents. Nowadays generation and detection of spin-polarized currents in semiconductor nanostructures has attracted great attention since this is the key problem in developing semiconductor spintronic devices [1–4]. To generate tunable highly spin-polarized stationary currents the variety of systems has been already proposed ranging from semiconductor heterostructures to low-dimensional mesoscopic samples [5–8]. Significant progress has been achieved in experimental and theoretical investigation of stationary spin-polarized transport in magnetic tunneling junctions [9–12]. Nevertheless spin-polarized current sources based on the non-magnetic materials are attractable as one could avoid the presence of accidental magnetic fields that may result in the existence of undesirable effects on the spin currents. It was demonstrated recently that stationary tunneling current could be spin dependent in the case of non-magnetic leads [13,14]. There have been several proposals to generate stationary spin-polarized currents using non-magnetic materials: small quantum dots [15,16] and coupled quantum dots [5,17] built in semiconducting nanostructures in the presence of external magnetic field. Moreover, quantum dots systems based on the non-magnetic materials were proposed as a spin filter prototypes [18,19]. Effective spin filtering in such systems requires to have many quantum dots with the Coulomb correlations inside each dot [20–22] and also between the dots [5].

To the best of our knowledge usually stationary spin-polarized currents are analyzed. However, creation, diagnostics and controllable manipulation of charge and spin states in the single and coupled quantum dots (QDs), applicable for ultra small size electronic devices design requires analysis of non-stationary effects and transient processes [23–28]. Consequently, non-stationary evolution of initially prepared spin and charge configurations in correlated quantum dots is of great interest both from fundamental and technological point of view.

In this paper we analyze non-stationary spin polarized currents through the correlated single-level QD localized in the tunnel junction in the presence of applied bias voltage and external magnetic field, which can be switched "on" or "off" at a particular time moment. We demonstrate that single biased QD in the external magnetic field can be considered as an effective spin filter based on the analysis of non-stationary spin-polarized currents, which can flow in the both leads. Currents direction can be tuned by the external magnetic field switching "on" or "off".

2. Theoretical model

We consider non-stationary processes in the single-level quantum dot with Coulomb correlations of localized electrons situated between two non-magnetic electronic reservoirs in the presence of external magnetic field **B** switched "on"/"off" at $t = t_0$. We are interested in the influence of magnetic field directly on the quantum dot [5]. Modern experimental scanning probe technique provides possibility of applying magnetic field to various subsystems: directly to the dot, to the reservoirs or both to the dot and reservoir with the controllable field direction [29–32]. Moreover, when the uniform magnetic field in the dot and in the lead is applied to the system the situation when g-factor in the leads is much smaller than in the dots can be realized due to the materials properties (strongly different effective masses of electrons in the reservoir and in the dot). So only the effect of external magnetic field on the dot states was considered. The Hamiltonian of the system

$$\hat{H} = \hat{H}_{QD} + \hat{H}_R + \hat{H}_T \quad (1)$$

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can be written as a sum of the single-level quantum dot part

$$\widehat{H}_{QD}=\sum_{\sigma}\varepsilon_1\widehat{n}_1^{\sigma}+U\widehat{n}_1^{\sigma}\widehat{n}_1^{-\sigma}, \tag{2}$$

non-magnetic electronic reservoirs Hamiltonian

$$\widehat{H}_R=\sum_{k\sigma}\varepsilon_k\widehat{c}_{k\sigma}^{+}\widehat{c}_{k\sigma}+\sum_{p\sigma}(\varepsilon_p-eV)\widehat{c}_{p\sigma}^{+}\widehat{c}_{p\sigma} \tag{3}$$

and the tunneling part

$$\widehat{H}_T=\sum_{k\sigma}t_k(\widehat{c}_{k\sigma}^{+}\widehat{c}_{1\sigma}+\widehat{c}_{1\sigma}^{+}\widehat{c}_{k\sigma})+\sum_{p\sigma}t_p(\widehat{c}_{p\sigma}^{+}\widehat{c}_{1\sigma}+\widehat{c}_{1\sigma}^{+}\widehat{c}_{p\sigma}). \tag{4}$$

Here index $k(p)$ labels continuous spectrum states in the leads, $t_{k(p)}$ is the tunneling transfer amplitude between continuous spectrum states and quantum dot with the energy level ε_1 which is considered to be independent on the momentum and spin. Operators $\widehat{c}_{k(p)\sigma}^{+}/\widehat{c}_{k(p)\sigma}$ are the creation/annihilation operators for the electrons in the continuous spectrum states $k(p)$. $\widehat{n}_1^{\sigma(-\sigma)}=\widehat{c}_{1\sigma(-\sigma)}^{+}\widehat{c}_{1\sigma(-\sigma)}$-localized state electron occupation numbers, where operator $\widehat{c}_{1\sigma(-\sigma)}$ destroys electron with spin $\sigma(-\sigma)$ on the energy level ε_1. U is the on-site Coulomb repulsion for the double occupation of the quantum dot. External magnetic field **B** leads to the Zeeman splitting of the impurity single level ε_1 proportional to the atomic g factor. In the absence of external magnetic field direct exchange and spin-orbit interaction can often lead to the appearance of effective magnetic field acting on electron spins. In the simple mean-field approach electron spin is affected by a mean nuclear spin polarization similar to effective magnetic field and thus hyperfine level splitting appears. The non-negligible value of effective magnetic field averaged value appears due to the finite number of nuclei within the quantum dot. For example, in GaAs this field leads to effective level splitting about 135μeV [36,37]. Consequently, for deep QD's electron levels (about $10-100\ meV$) effective level splitting can be omitted as it doesn't influence opposite spin electron occupation numbers. When quantum dot's energy levels position is comparable to the hyperfine levels splitting two different cases can be distinguished. The first one deals with the value of level splitting can be of the order or smaller then the relaxation rate caused by the coupling to reservoir. In this situation level splitting due to the hyperfine interaction is not important. The second possible situation is when the value of level splitting exceeds the relaxation rate. In this case if the effective magnetic field has the same sign for each spin direction the symmetry between opposite spin states for localized electrons is broken even without external magnetic field. The effects of external magnetic field switching "on" and "off" now should drastically depend on its direction. Another interesting effect can appear in the presence of strong spin-orbit interaction, when the direction of the effective magnetic field is opposite for the two different electron spin projections. This situation is typical for spin-Hall systems and one should expect the appearance of a pair of counter-propagating currents for each spin projection. Further results deal with the case of deep energy levels or correspond to the situation when relaxation rate exceeds hyperfine level splitting (as typical values of relaxation rate can be of order of $1-5\ meV$ [38,39], while hyperfine level splitting is about 135μeV [36,37]).

Further analysis deals with the low temperature regime when the Fermi level is well defined and the temperature is much lower than all the typical energy scales in the system. Consequently, the distribution function of electrons in the leads (band electrons) is close to the Fermi step.

3. Non-stationary electronic transport formalism

Let us further consider $\hbar=1$ and $e=1$ elsewhere, so the motion equations for the electron operators products $\widehat{n}_1^{\sigma}$, $\widehat{n}_{1k}^{\sigma}=\widehat{c}_{1\sigma}^{+}\widehat{c}_{k\sigma}$ and $\widehat{c}_{k'\sigma}^{+}\widehat{c}_{k\sigma}$ can be written as:

$$i\frac{\partial\widehat{n}_1^{\sigma}}{\partial t}=-\sum_{k,\sigma}t_k\cdot(\widehat{n}_{k1}^{\sigma}-\widehat{n}_{1k}^{\sigma}), \tag{5}$$

$$\begin{aligned}i\frac{\partial\widehat{n}_{1k}^{\sigma}}{\partial t}&=-(\varepsilon_1^{\sigma}-\varepsilon_k)\cdot\widehat{n}_{1k}^{\sigma}-U\cdot\widehat{n}_1^{-\sigma}\widehat{n}_{1k}^{\sigma}\\&+t_k\cdot(\widehat{n}_1^{\sigma}-\widehat{n}_k^{\sigma})-\sum_{k'\neq k}t_{k'}\cdot\widehat{c}_{k'\sigma}^{+}\widehat{c}_{k\sigma},\end{aligned} \tag{6}$$

$$\begin{aligned}i\frac{\partial\widehat{c}_{k'\sigma}^{+}\widehat{c}_{k\sigma}}{\partial t}&=-(\varepsilon_{k'}-\varepsilon_k)\cdot\widehat{c}_{k'\sigma}^{+}\widehat{c}_{k\sigma}\\&-t_{k'}\cdot\widehat{c}_{1\sigma}^{+}\widehat{c}_{k\sigma}+t_k\cdot\widehat{c}_{k'\sigma}^{+}\widehat{c}_{1\sigma}.\end{aligned} \tag{7}$$

and

$$\begin{aligned}i\frac{\partial\widehat{c}_{p\sigma}^{+}\widehat{c}_{k\sigma}}{\partial t}&=(\varepsilon_k-\varepsilon_p)\cdot\widehat{c}_{p\sigma}^{+}\widehat{c}_{k\sigma}+\\&+t_k\cdot\widehat{c}_{p\sigma}^{+}\widehat{c}_{1\sigma}-t_p\cdot\widehat{c}_{1\sigma}^{+}\widehat{c}_{k\sigma},\end{aligned} \tag{8}$$

where $\widehat{n}_k^{\sigma}=\widehat{c}_{k\sigma}^{+}\widehat{c}_{k\sigma}$ is an occupation operator for the electrons in the reservoir and $\varepsilon_\sigma=\varepsilon_1+\sigma\mu B$ where $\sigma=\pm1$. Equations of motion for the electron operators products $\widehat{c}_{1\sigma}^{+}\widehat{c}_{p\sigma}$ and $\widehat{c}_{p'\sigma}^{+}\widehat{c}_{p\sigma}$ can be obtained from Eqs. (6) and (7) correspondingly by the indexes substitution $k\leftrightarrow p$ and $k'\leftrightarrow p'$.

Following the logic of Ref. [33] one can get kinetic equations for the electron occupation numbers operators time evolution in the case of external magnetic field **B** switching "on" at the time moment $t=t_0>0$:

$$\begin{aligned}\frac{\partial n_1^{\sigma}}{\partial t}&=-2\Theta(t_0-t)\cdot\gamma\times[n_1^{\sigma}-(1-n_1^{-\sigma})\cdot\Phi_{\varepsilon}^{T}(t)-n_1^{-\sigma}\cdot\Phi_{\varepsilon+U}^{T}(t)]\\&-2\Theta(t-t_0)\cdot\gamma\times[n_1^{\sigma}-(1-n_1^{-\sigma})\cdot\Phi_{\varepsilon}^{+T}(t)-n_1^{-\sigma}\cdot\Phi_{\varepsilon+U}^{+T}(t)],\\\frac{\partial n_1^{-\sigma}}{\partial t}&=-2\Theta(t_0-t)\cdot\gamma\times[n_1^{-\sigma}-(1-n_1^{\sigma})\cdot\Phi_{\varepsilon}^{T}(t)-n_1^{\sigma}\cdot\Phi_{\varepsilon+U}^{T}(t)]\\&-2\Theta(t-t_0)\cdot\gamma\times[n_1^{-\sigma}-(1-n_1^{\sigma})\cdot\Phi_{\varepsilon}^{-T}(t)-n_1^{\sigma}\cdot\Phi_{\varepsilon+U}^{-T}(t)],\end{aligned} \tag{9}$$

where $\gamma=\gamma_k+\gamma_p$ and $\gamma_{k(p)}=\pi\nu_0t_{k(p)}^2$. ν_0 – is the unperturbed density of states in the leads and

$$\begin{aligned}\widehat{\Phi}_{\varepsilon}^{\pm T}(t)&=\frac{\gamma_k}{\gamma}\cdot\widehat{\Phi}_{k\varepsilon}^{\pm}(t)+\frac{\gamma_p}{\gamma}\cdot\widehat{\Phi}_{p\varepsilon}^{\pm}(t),\\\widehat{\Phi}_{\varepsilon+U}^{\pm T}(t)&=\frac{\gamma_k}{\gamma}\cdot\widehat{\Phi}_{k\varepsilon+U}^{\pm}(t)+\frac{\gamma_p}{\gamma}\cdot\widehat{\Phi}_{p\varepsilon+U}^{\pm}(t),\end{aligned} \tag{10}$$

where

$$\begin{aligned}\widehat{\Phi}_{\varepsilon}^{\pm}(t)&=\frac{1}{2}i\cdot\int d\varepsilon_k\cdot f_k^{\sigma}(\varepsilon_k)\\&\times\left[\frac{1-e^{i(\varepsilon_1\pm\mu B+i\Gamma-\varepsilon_k)t}}{\varepsilon_1\pm\mu B+i\Gamma-\varepsilon_k}-\frac{1-e^{-i(\varepsilon_1\pm\mu B-i\Gamma-\varepsilon_k)t}}{\varepsilon_1\pm\mu B-i\Gamma-\varepsilon_k}\right],\\\widehat{\Phi}_{\varepsilon+U}^{\pm}(t)&=\frac{1}{2}i\cdot\int d\varepsilon_k\cdot f_k^{\sigma}(\varepsilon_k)\\&\times\left[\frac{1-e^{i(\varepsilon_1\pm\mu B+U+i\Gamma-\varepsilon_k)t}}{\varepsilon_1\pm\mu B+U+i\Gamma-\varepsilon_k}-\frac{1-e^{-i(\varepsilon_1\pm\mu B+U-i\Gamma-\varepsilon_k)t}}{\varepsilon_1\pm\mu B+U-i\Gamma-\varepsilon_k}\right].\end{aligned} \tag{11}$$

Initially ($t<t_0$) magnetic field **B** is absent [$\mu B=0$ in Eqs. (9)–(11)] and, consequently, the following relation is valid $\widehat{\Phi}_{\varepsilon}^{\pm}(t)=\widehat{\Phi}_{\varepsilon}(t)$. To analyze system kinetics in the situation when magnetic field was initially present in the system and switched "off" at $t=t_0$ one can easily generalize Eq. (9) by substitution $t\leftrightarrow t_0$.

Equations for the localized electrons occupation numbers $n_{1\pm}^{\sigma}(t)$ can be obtained by averaging Eqs. (9)–(11) for the operators and by decoupling electrons occupation numbers in the leads. Such decoupling procedure is reasonable if one considers that electrons in the macroscopic leads are in the thermal equilibrium [34,35]. After decoupling one has to replace electron occupation numbers operators in the reservoir $\widehat{n}_k^{\sigma}$ in Eqs. (9)–(11) by the Fermi distribution functions f_k^{σ}.