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Non-stationary spin-polarized currents tuning in correlated quantum dot

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1. Introduction. The problem of generation, detection and controlling of spin-polarized currents in low dimensional semiconductor structures attracts recently great attention as it opens the possibility for the semiconductor spintronic devices developing [1, 2]. Essential progress has been attained in the analysis of stationary spin-polarized transport in nanostructures localized within magnetic tunneling leads [3]. However, sources of spin-polarized currents based on the non-magnetic materials are more attractable as they enable to avoid the presence of accidental magnetic fields that may lead to the presence of external uncontrollable effects on the spin currents behavior. Usually stationary spin-polarized currents are analyzed. However, creation, diagnostics and controllable manipulation of charge and spin states in the semiconductor nanostructures, applicable for ultra small size electronic devices design requires analysis of non-stationary effects and transient processes [4–9]. Consequently, the problem of non-stationary evolution of initially prepared spin and charge configurations in correlated quantum dots is really vital. Moreover, non-stationary characteristics provide more information about the properties of nanoscale systems comparing to the stationary ones.

In the present paper we consider non-stationary processes in the correlated single-level quantum dot localized between two non-magnetic electron reservoirs. We are interested in the system response on both the applied bias voltage **eV** polarity switching and changing the direction of the external magnetic field **B**. The Hamiltonian of the system consists of the single-level correlated quantum dot part

$$\hat{H}_{\rm dot} = \sum_{\sigma} \varepsilon_d \hat{n}_d^{\sigma} + U\hat{n}_d^{\sigma}\hat{n}_d^{-\sigma}, \tag{1}$$

non-magnetic electron reservoirs Hamiltonian

$$\hat{H}_{\rm res} = \sum_{k\sigma} \varepsilon_k \hat{c}_{k\sigma}^{+}\hat{c}_{k\sigma} + \sum_{p\sigma}(\varepsilon_p - eV)\hat{c}_{p\sigma}^{+}\hat{c}_{p\sigma} \tag{2}$$

and tunneling part

$$\hat{H}_{\rm tun} = t_k \sum_{k\sigma}(\hat{c}_{k\sigma}^{+}\hat{c}_{d\sigma} + \hat{c}_{d\sigma}^{+}\hat{c}_{k\sigma}) + t_p \sum_{p\sigma}(\hat{c}_{p\sigma}^{+}\hat{c}_{d\sigma} + \hat{c}_{d\sigma}^{+}\hat{c}_{p\sigma}). \tag{3}$$

Here index $k(p)$ labels continuous spectrum states in the leads, $\hat{c}_{k(p)\sigma}^{+}/\hat{c}_{k(p)\sigma}$ are the creation/annihilation operators for the electrons in the continuous spectrum states $k(p)$. $t_{k(p)}$ is the tunneling transfer amplitude between continuous spectrum states and quantum dot which is considered to be independent on momentum and spin. Operator $\hat{n}_d^{\sigma(-\sigma)} = \hat{c}_{d\sigma(-\sigma)}^{+}\hat{c}_{d\sigma(-\sigma)}$ describes localized state electron occupation numbers, where $\hat{c}_{d\sigma(-\sigma)}$ is the annihilation operator for the electron with spin $\sigma(-\sigma)$ for the quantum dot energy level ε_d. U is the on-site Coulomb repulsion for double occupation of the quantum dot.

Following the logic of [10] and considering $\hbar = 1$ and $e = 1$ elsewhere, one can obtain the closed system of kinetic equations for the electron operators products $\hat{n}_d^{\sigma} = \hat{c}_{d\sigma}^{+}\hat{c}_{d\sigma}$, $\hat{n}_{dk(p)}^{\sigma} = \hat{c}_{d\sigma}^{+}\hat{c}_{k(p)\sigma}$ and $\hat{n}_{kk'}^{\sigma} = \hat{c}_{k'(p)\sigma}^{+}\hat{c}_{k(p)\sigma}$, which describes the behavior of localized electrons occupation numbers under the quench: at initial time moment t_0 the polarity and the value of applied bias and the direction of external magnetic field could be changed.

In the considered system non-stationary spin-polarized currents $I_{k(p)}^{\pm}(t)$ could flow in both contact leads:

$$I_{k(p)}^{\pm}(t) = = -2\Gamma_{k(p)}[n_d^{\pm\sigma} - (1-n_d^{\mp\sigma})\Phi_{\varepsilon}^{\pm}(t) - n_d^{\mp\sigma}\Phi_{\varepsilon+U}^{\pm}(t)], \tag{4}$$

where $\Gamma = \Gamma_k + \Gamma_p$ and $\Gamma_{k(p)} = \nu_{k(p)0}\pi t_{k(p)}^2$, $\nu_{k(p)0}$ are the unperturbed densities of states in the left and right leads of the tunneling contact. Functions $\Phi_z^{\pm}(t)$ $(z = \varepsilon, \varepsilon+U)$ read

$$\Phi_z^{\pm}(t) = \frac{1}{2}i \cdot \int d\varepsilon_k \cdot f_k^{\sigma}(\varepsilon_k) \times \times \left[\frac{1 - e^{i(z\pm\mu B + i\Gamma - \varepsilon_k)t}}{z \pm \mu B + i\Gamma - \varepsilon_k} - \frac{1 - e^{-i(z\pm\mu B - i\Gamma - \varepsilon_k)t}}{z \pm \mu B - i\Gamma - \varepsilon_k}\right], \tag{5}$$

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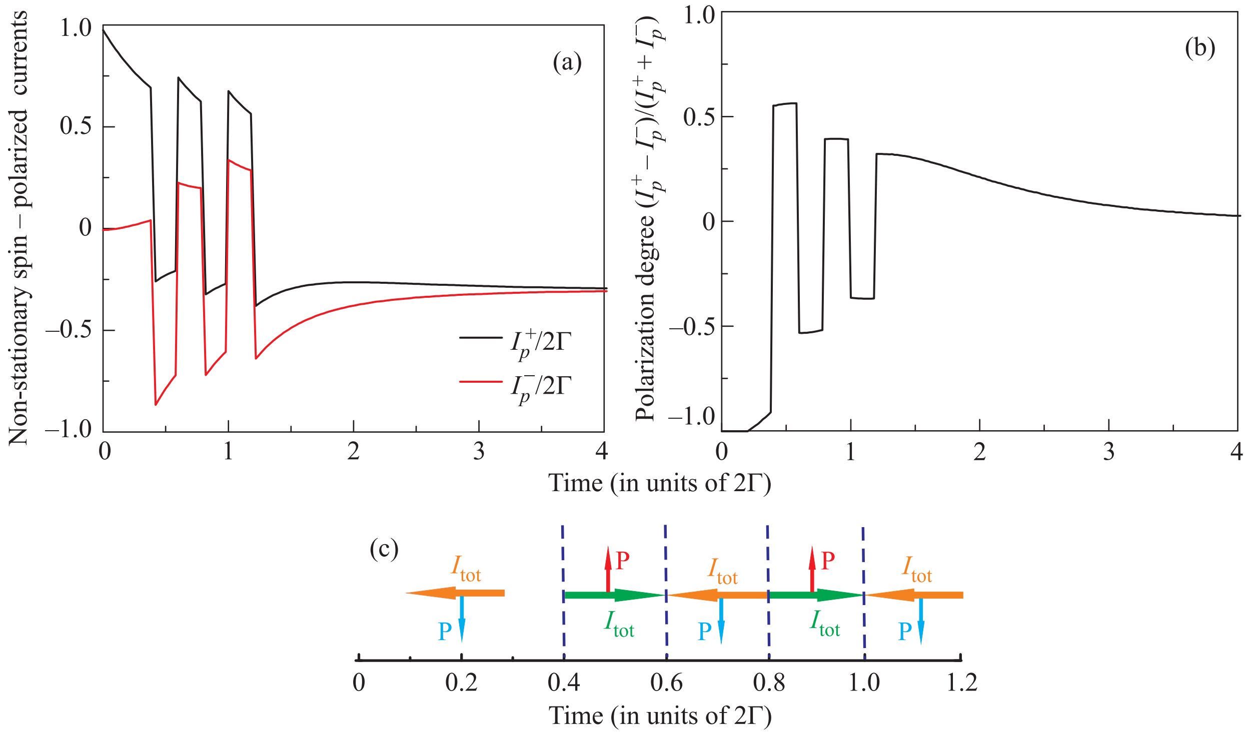

Fig. 1. (Color online) (a) – Multiple switching of the normalized non-stationary spin-polarized tunneling currents. (b) – Polarization degree time evolution for the multiple switching of applied bias voltage between $eV/2\Gamma = 7.5$ and $eV/2\Gamma = -7.5$. (c) – Scheme of the total current direction switching (green and grey horizontal arrows) and spin polarization degree sign changing (red and blue vertical arrows). Black line depicts $I_p^+(t)/2\Gamma$, red line corresponds to $I_p^-(t)/2\Gamma$. Parameters $U/2\Gamma = 7.5$; $\varepsilon/2\Gamma = -2.5$ and $\Gamma = 1$ are the same for all the figures. $n_d^{\sigma}(0) = 1$, $n_d^{-\sigma}(0) = 0$

Direction and polarization of the non-stationary spin-polarized currents depend on the value of applied bias (see Fig. 1a). Panel a demonstrate multiple switching of spin polarization and direction of the non-stationary tunneling currents which occurs due to the fast changing of the applied bias polarity. We now would like to introduce the polarization degree $P(t)$ of the total non-stationary tunneling current, which is also a time dependent variable and it could be measured experimentally:

$$P(t) = \frac{I_p^+(t) - I_p^-(t)}{I_p^+(t) + I_p^-(t)}. \quad (6)$$

Polarization degree time evolution for different initial values of applied bias is shown in Fig. 1b. The degree of spin polarization changes the sign following the applied bias polarity. This fact makes it possible to generate spin-polarized train pulses with the opposite degree of polarization. The scheme of the total current direction changing and corresponding switching of polarization for different initial polarities of applied bias voltage is demonstrated in Fig. 1c. This effect opens the possibility for the spin-polarized train pulses generation with the opposite degree of polarization.

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