External field induced switching of tunneling current in the coupled quantum dots

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We investigated the tunneling current peculiarities in the system of two coupled by means of the external field quantum dots (QDs) weakly connected to the electrodes in the presence of Coulomb correlations. It was found that tuning of the Rabi frequency induces fast multiple tunneling current switching and leads to the negative tunneling conductivity. Special role of multi-electrons states was demonstrated. Moreover we revealed conditions for bistable behavior of the tunneling current in the coupled QDs with Coulomb correlations.

1. Introduction. Electron tunneling through the system of coupled quantum dots in the presence of strong Coulomb correlations seems to be one of the most interesting and important problems in the physics of nanostructures. Tunneling current changes localized states electron filling numbers, consequently, the spectrum and electron density of states are also modified due to Coulomb interaction of localized electrons.

The present day experimental technique gives possibility to create QDs with a given set of parameters and to produce coupled QDs with different spatial geometries [1, 2], which give an opportunity to analyze non-equilibrium and non-stationary effects in the small size correlated structures [3–9]. Thereby the main effort in the physics of QDs is devoted to the investigation of non-equilibrium charge states and different spin configurations due to the electrons tunneling [10–12] through the system of coupled QDs in the presence of strong Coulomb interaction.

Double QDs systems behavior is recently under careful investigation because of the variable inter-dot tunneling coupling [13, 14], which is the physical reason for non-linearity formation and consequently for existence of such phenomena as bifurcations [15, 16] and bistability [11, 17]. That's why double QDs can be applied for logic gates fabrication based on the effect of ultra-fast switching between intrinsic stable states.

In the present paper we consider electron tunneling through the QDs with Coulomb correlations in the regime when coupling between the dots is carried out by means of the external field with Rabi frequency Ω. We

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analyzed tunneling current behavior in terms of pseudo operators with constraint on possible physical states [18–20, 12]. For large values of applied bias Kondo effect is not essential so we neglect any correlations between electron states in the QDs and in the leads. This approximation allows to describe correctly non-equilibrium occupation of any single- and multi-electron state due to the tunneling processes.

We revealed the presence of negative tunneling conductivity in certain ranges of the applied bias voltage and analyzed the multiple tunneling current switching caused by the Rabi frequency tuning.

2. Suggested model. We consider a system of coupled QDs with the single particle levels $\widetilde{\varepsilon}_1$, $\widetilde{\varepsilon}_2$ connected to the two leads. The Hamiltonian can be written as:

$$\hat{H} = \sum_\sigma c_{1\sigma}^+ c_{1\sigma} \widetilde{\varepsilon}_1 + \sum_\sigma c_{2\sigma}^+ c_{2\sigma} \widetilde{\varepsilon}_2 + U_1 \widehat{n}_{1\sigma} \widehat{n}_{1-\sigma} +$$
$$+ U_2 \widehat{n}_{2\sigma} \widehat{n}_{2-\sigma} + \sum_\sigma \frac{\Omega}{2} (c_{1\sigma}^+ c_{2\sigma} + c_{2\sigma}^+ c_{1\sigma}), \qquad (1)$$

where operator $c_{l\sigma}$ creates an electron in the dot l with spin σ, $\widetilde{\varepsilon}_l$ is the energy of the single electron level in the dot l and inter-dot coupling is realized by means of the external field with Rabi frequency Ω, $n_{l\sigma} = c_{l\sigma}^+ c_{l\sigma}$, and $U_{1(2)}$ is the on-site Coulomb repulsion of localized electrons. When the coupling between QDs exceeds the value of interaction with the leads, one has to use the basis of exact eigenfunctions and eigenvalues of the coupled QDs without interaction with the leads. In this case all energies of single- and multi-electron states are well known.

● one electron in the system: two single electron states with the wave function

$$\psi_i^\sigma = \mu_i \cdot |0\uparrow\rangle|00\rangle + \nu_i \cdot |00\rangle|0\uparrow\rangle. \tag{2}$$

Single electron energies and coefficients μ_i and ν_i can be found as an eigenvalues and eigenvectors of matrix:

$$\begin{pmatrix} \varepsilon_1 & -\Omega/2 \\ -\Omega/2 & \varepsilon_2 \end{pmatrix}; \tag{3}$$

• two electrons in the system: two states with the same spin $\sigma\sigma$ and $-\sigma-\sigma$ and four two-electron states with the opposite spins $\sigma - \sigma$ with the wave function:

$$\psi_j^{\sigma-\sigma} = \alpha_j \cdot |\uparrow\downarrow\rangle|00\rangle + \beta_j \cdot |\downarrow 0\rangle|0\uparrow\rangle + $$
$$+ \gamma_j \cdot |0\uparrow\rangle|\downarrow 0\rangle + \delta_j \cdot |00\rangle|\uparrow\downarrow\rangle. \tag{4}$$

Two electron energies and coefficients α_j, β_j, γ_j, and δ_j are the eigenvalues and eigenvectors of matrix:

$$\begin{pmatrix} 2\varepsilon_1 + U_1 & -\Omega/2 & -\Omega/2 & 0 \\ -\Omega/2 & \varepsilon_1 + \varepsilon_2 & 0 & -\Omega/2 \\ -\Omega/2 & 0 & \varepsilon_1 + \varepsilon_2 & 0 \\ 0 & -\Omega/2 & -\Omega/2 & 2\varepsilon_2 + U_2 \end{pmatrix}; \tag{5}$$

• three electrons in the system: two three-electron states with the wave function

$$\psi_m^{\sigma\sigma-\sigma} = p_m|\uparrow\downarrow\rangle|\uparrow\rangle + q_m|\uparrow\rangle|\uparrow\downarrow\rangle,$$
$$m = s, a. \tag{6}$$

Three electron energies and coefficients p_m and Q_m can be found as an eigenvalues and eigenvectors of matrix:

$$\begin{pmatrix} 2\varepsilon_1 + \varepsilon_2 + U_1 & -\Omega/2 \\ -\Omega/2 & 2\varepsilon_2 + \varepsilon_1 + U_2 \end{pmatrix}; \tag{7}$$

• four electrons in the system: one four-electron state with energy $E_{\mathrm{IV}} = 2\varepsilon_1 + 2\varepsilon_2 + U_1 + U_2$ and wave function

$$\psi = |\uparrow\downarrow\rangle|\uparrow\downarrow\rangle. \tag{8}$$

If coupled QDs are connected with the leads of the tunneling contact the number of electrons in the dots changes due to the tunneling processes. Transitions between the states with different number of electrons in the two interacting QDs can be analyzed in terms of pseudo-particle operators with constraint on the physical states (the number of pseudo-particles). Consequently, the electron operator $c_{\sigma l}^+$ $(l = 1, 2)$ can be written in terms of pseudo-particle operators as:

$$c_{\sigma l}^+ = \sum_i X_i^{\sigma l} f_{\sigma i}^+ b + \sum_{j,i} Y_{ji}^{\sigma-\sigma l} d_j^{+\sigma-\sigma} f_{i-\sigma} + $$
$$+ \sum_i Y_i^{\sigma\sigma l} d^{+\sigma\sigma} f_{i\sigma} + \sum_{m,j} Z_{mj}^{\sigma\sigma-\sigma l} \psi_{m-\sigma}^+ d_j^{\sigma-\sigma} + $$
$$+ \sum_m Z_m^{\sigma-\sigma-\sigma l} \psi_{m\sigma}^+ d^{-\sigma-\sigma} + \sum_m W_m^{\sigma-\sigma-\sigma l} \varphi^+ \psi_{m\sigma}, \tag{9}$$

where $f_\sigma^+ (f_\sigma)$ and $\psi_\sigma^+ (\psi_\sigma)$ are pseudo-fermion creation (annihilation) operators for the electronic states with one and three electrons correspondingly, $b^+(b)$, $d_\sigma^+(d_\sigma)$, and $\varphi^+(\varphi)$ are slave boson operators, which correspond to the states without any electrons, with two electrons or four electrons. Operators $\psi_{m-\sigma}^+$ describe system configuration with two spin up electrons σ and one spin down electron $-\sigma$ in the symmetric and asymmetric states.

Matrix elements $X_i^{\sigma l}$, $Y_{ji}^{\sigma-\sigma l}$, $Y_{ji}^{\sigma\sigma l}$, $Z_{mj}^{\sigma\sigma-\sigma l}$, $Z_m^{\sigma-\sigma-\sigma l}$, and $W_m^{\sigma-\sigma-\sigma l}$ can be evaluated as:

$$X_i^{\sigma l} = \langle \psi_i^\sigma | c_{\sigma l}^+ | 0 \rangle,$$
$$Y_{ji}^{\sigma-\sigma l} = \langle \psi_j^{\sigma-\sigma} | c_{\sigma l}^+ | \psi_i^{-\sigma} \rangle,$$
$$Y_{ji}^{\sigma\sigma l} = \langle \psi_j^{\sigma\sigma} | c_{\sigma l}^+ | \psi_i^\sigma \rangle,$$
$$Z_{mj}^{\sigma\sigma-\sigma l} = \langle \psi_m^{\sigma\sigma-\sigma} | c_{\sigma l}^+ | \psi_j^{\sigma-\sigma} \rangle,$$
$$Z_m^{\sigma-\sigma-\sigma l} = \langle \psi_m^{\sigma-\sigma-\sigma} | c_{\sigma l}^+ | \psi^{-\sigma-\sigma} \rangle,$$
$$W_m^{\sigma-\sigma-\sigma l} = \langle \psi^{\sigma\sigma-\sigma-\sigma} | c_{\sigma l}^+ | \psi_m^{\sigma-\sigma-\sigma} \rangle. \tag{10}$$

Finally one can easily express matrix elements through the matrixes (3), (5), (7) eigenvectors elements:

$$X_i^{\sigma 1} = \mu_i; \quad X_i^{\sigma 2} = \nu_i,$$
$$Y_{ji}^{\sigma-\sigma 1} = \alpha_j\mu_i + \beta_j\nu_i,$$
$$Y_{ji}^{\sigma-\sigma 2} = \delta_j\nu_i + \gamma_j\mu_i,$$
$$Y_{ji}^{\sigma\sigma 1} = \nu_i; \quad Y_{ji}^{\sigma\sigma 2} = \mu_i,$$
$$Z_{mj}^{\sigma\sigma-\sigma 1} = p_m\gamma_j + q_m\delta_j,$$
$$Z_{mj}^{\sigma\sigma-\sigma 2} = p_m\alpha_j + q_m\beta_j,$$
$$Z_{mj}^{\sigma-\sigma-\sigma 1} = p_m; \quad Z_{mj}^{\sigma-\sigma-\sigma 1} = q_m,$$
$$W_m^{\sigma-\sigma-\sigma 1} = q_m; \quad W_m^{\sigma-\sigma-\sigma 2} = p_m. \tag{11}$$

The constraint on the space of the possible system states have to be taken into account:

$$\widehat{n}_b + \sum_{i\sigma} \widehat{n}_{fi\sigma} + \sum_{j\sigma\sigma'} \widehat{n}_{dj}^{\sigma\sigma'} + \sum_{m\sigma} \widehat{n}_{\psi m\sigma} + \widehat{n}_\varphi = 1. \tag{12}$$

Condition (12) means that the states with only one pseudo-particle are allowed.

Electron filling numbers in the coupled QDs can be expressed in terms of the pseudo-particles filling numbers:

$$\widehat{n}_\sigma^{el} = \sum_l c_{\sigma l}^+ c_{\sigma l} = \sum_{i,l} |X_i^{\sigma l}|^2 \widehat{n}_{fi\sigma} + \sum_{i,j,l} |Y_{ji}^{\sigma-\sigma l}|^2 \widehat{n}_{dj}^{\sigma-\sigma} + $$
$$+ \sum_{i,l} |Y_{ji}^{\sigma\sigma l}|^2 \widehat{n}_{dj}^{\sigma\sigma} + \sum_{m,j,l} |Z_{mj}^{\sigma\sigma-\sigma l}|^2 \widehat{n}_{\psi m-\sigma} + $$
$$+ \sum_{m,l} |Z_{mj}^{-\sigma-\sigma\sigma l}|^2 \widehat{n}_{\psi m\sigma} + \sum_{m,l} |W_m^{\sigma-\sigma-\sigma l}|^2 \widehat{n}_\varphi. \tag{13}$$

Consequently, the Hamiltonian of the system can be written in terms of the pseudo-particle operators:

$$\hat{H} = \hat{H}_0 + \hat{H}_{tun}, \tag{14}$$

$$\hat{H}_0 = \sum_{i\sigma} \varepsilon_i f_{i\sigma}^+ f_{i\sigma} + \sum_{j\sigma\sigma'} E_{\text{II}j}^{\sigma\sigma'} d_j^{+\sigma\sigma'} d_j^{\sigma\sigma'} +$$

$$+ \sum_{m\sigma} E_{\text{III}}^{m\sigma} \psi_{m\sigma}^+ \psi_{m\sigma} + E_{\text{IV}} \varphi_\sigma^+ \varphi_\sigma +$$

$$+ \sum_{k\sigma} (\varepsilon_{k\sigma} - eV) c_{k\sigma}^+ c_{k\sigma} + \sum_{p\sigma} \varepsilon_{p\sigma} c_{p\sigma}^+ c_{p\sigma},$$

$$\hat{H}_{\text{tun}} = \sum_{k\sigma} T_k (c_{k\sigma}^+ c_{\sigma 1} + c_{\sigma 1}^+ c_{k\sigma}) + (k \leftrightarrow p; 1 \leftrightarrow 2),$$

where ε_i, $E_{\text{II}j}^{\sigma\sigma'}$, $E_{\text{III}}^{m\sigma}$, and E_{IV} are the energies of the single-, double-, triple-, and quadri-electron states, $\varepsilon_{k(p)\sigma}$ is the energy of the conduction electrons in the states k and p correspondingly, $c_{k(p)\sigma}^+/c_{k(p)\sigma}$ are the creation (annihilation) operators in the leads of the tunneling contact, $T_{k(p)}$ are the tunneling amplitudes, which we assume to be independent on momentum and spin. Indexes $k(p)$ mean only that tunneling takes place from the system of coupled QDs to the conduction electrons in the states k and p correspondingly.

Bilinear combinations of pseudo-particle operators are closely connected with the density matrix elements. So, similar expressions can be obtained from equations for the density matrix evolution but method based on the pseudo particle operators is more compact and convenient. The tunneling current through the proposed system written in terms of the pseudo-particle operators has the form:

$$\hat{I}_{k\sigma} = \sum_k \frac{\partial \hat{n}_k}{\partial t} = i \Bigg[\sum_{ik} X_i^{\sigma 1} T_k c_{k\sigma} f_{i\sigma}^+ b +$$

$$+ \sum_{ijk} Y_{ji}^{\sigma-\sigma 1} T_k c_{k\sigma} d_j^{+\sigma-\sigma} f_{i-\sigma} +$$

$$+ \sum_{ijk} Y_{ji}^{\sigma\sigma 1} T_k c_{k\sigma} d_j^{+\sigma\sigma} f_{i\sigma} +$$

$$+ \sum_{mjk} Z_{mj}^{\sigma\sigma-\sigma 1} T_k c_{k\sigma} \psi_{m-\sigma}^+ d_j^{\sigma-\sigma} +$$

$$+ \sum_{mjk} Z_{mj}^{-\sigma-\sigma\sigma 1} T_k c_{k\sigma} \psi_{m\sigma}^+ d_j^{-\sigma-\sigma} +$$

$$+ \sum_{mk} W_m^{\sigma-\sigma-\sigma 1} T_k c_{k\sigma} \varphi^+ \psi_{m\sigma} - \text{h.c.} \Bigg]. \tag{15}$$

We set $\hbar = 1$ and neglect changes in the electron spectrum and local density of states in the tunneling contact leads, caused by the tunneling current. Therefore equations of motion together with the constraint on

the space of the possible system states (pseudo-particles number) (12) give the following equations:

$$\text{Im} \sum_{ik} T_k X_i^{\sigma 1} \cdot \langle c_{k\sigma} f_{i\sigma}^+ b \rangle =$$

$$= \Gamma_k \sum_i \{[1 - n_{k\sigma}(\varepsilon_i)] \cdot n_{fi\sigma} - n_{k\sigma}(\varepsilon_i) \cdot n_b\}(X_i^{\sigma 1})^2,$$

$$\text{Im} \sum_{ijk} Y_{ji}^{\sigma-\sigma 1} T_k \cdot \langle c_{k\sigma} d_j^{+\sigma-\sigma} f_{i-\sigma} \rangle =$$

$$= \Gamma_k \sum_{ij} \{[1 - n_{k\sigma}(E_{\text{II}j}^{\sigma-\sigma} - \varepsilon_{i-\sigma})] \cdot n_{dj}^{\sigma-\sigma} -$$

$$- n_{k\sigma}(E_{\text{II}j}^{\sigma-\sigma} - \varepsilon_{i-\sigma}) \cdot n_{fi-\sigma}\}(Y_{ji}^{\sigma-\sigma 1})^2,$$

$$\text{Im} \sum_{ijk} Y_{ji}^{\sigma\sigma 1} T_k \cdot \langle c_{k\sigma} d_j^{+\sigma\sigma} f_{i\sigma} \rangle =$$

$$= \Gamma_k \sum_{ij} \{[1 - n_{k\sigma}(E_{\text{II}j}^{\sigma\sigma} - \varepsilon_{i\sigma})] \cdot n_{dj}^{\sigma\sigma} -$$

$$- n_{k\sigma}(E_{\text{II}j}^{\sigma\sigma} - \varepsilon_{i\sigma}) \cdot n_{fi\sigma}\}(Y_{ji}^{\sigma\sigma 1})^2,$$

$$\text{Im} \sum_{mjk} Z_{mj}^{\sigma\sigma-\sigma 1} T_k \cdot \langle c_{k\sigma} \psi_{m-\sigma}^+ d_j^{\sigma-\sigma} \rangle =$$

$$= \Gamma_k \sum_{mj} \{[1 - n_{k\sigma}(E_{\text{III}}^{m-\sigma} - E_{IIj}^{\sigma-\sigma})) \cdot n_{\psi m-\sigma} -$$

$$- n_{k\sigma}(E_{\text{III}}^{m-\sigma} - E_{\text{II}j}^{\sigma-\sigma}) \cdot n_{dj}^{\sigma-\sigma}\}(Z_{mj}^{\sigma\sigma-\sigma 1})^2,$$

$$\text{Im} \sum_{mjk} Z_{mj}^{-\sigma-\sigma\sigma 1} T_k \cdot \langle c_{k\sigma} \psi_{m\sigma}^+ d_j^{-\sigma-\sigma} \rangle =$$

$$= \Gamma_k \sum_{mj} \{[1 - n_{k\sigma}(E_{\text{III}}^{m\sigma} - E_{\text{II}j}^{-\sigma-\sigma})] \cdot n_{\psi m\sigma} -$$

$$- n_{k\sigma}(E_{\text{III}}^{m\sigma} - E_{\text{II}j}^{-\sigma-\sigma}) \cdot n_{dj}^{-\sigma-\sigma}\}(Z_{mj}^{-\sigma-\sigma\sigma 1})^2,$$

$$\text{Im} \sum_{mk} W_m^{\sigma-\sigma-\sigma 1} T_k \cdot \langle c_{k\sigma} \varphi_l^+ \psi_{m\sigma} \rangle =$$

$$= \Gamma_k \sum_m \{[1 - n_{k\sigma}(E_{\text{IV}} - E_{\text{III}}^{m\sigma})] \cdot n_\varphi -$$

$$- n_{k\sigma}(E_{\text{IV}} - E_{\text{III}}^{m\sigma}) \cdot n_{\psi m\sigma}\}(W_m^{\sigma-\sigma-1})^2. \tag{16}$$

Tunneling current $I_{k\sigma}$ is determined by the sum of the right hand parts of the Eqs. (16). Pseudo particle filling numbers n_{fi}, $n_{dj}^{\sigma-\sigma}$, $n_d^{\sigma\sigma}$, $n_{\psi m}$, and n_φ can be easily obtained from the stationary linear system of equations [12].

3. Main results and discussion. The behavior of tunneling current with the Rabi frequency tuning for the different values of Coulomb interaction obtained from Eqs. (16) is depicted in Figs. 1–2. The general features of obtained results is tunneling current switching due to the Rabi frequency tuning and formation of negative tunneling conductivity.

We considered different experimental realizations: both single-electron energy levels are situated between the sample Fermi level ($E_{\text{F}} = 0$) and the value of applied bias voltage ($eV = 1$ for all the figures) (Figs. 1b
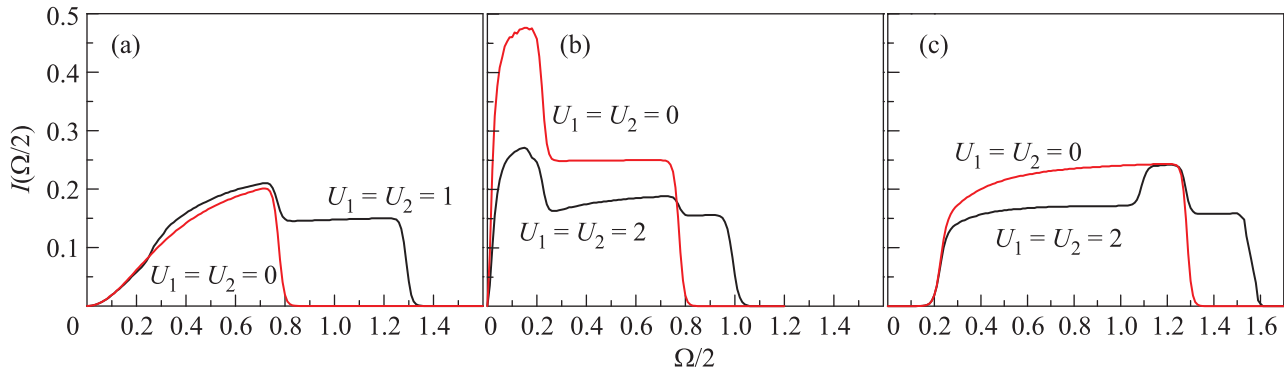
Fig. 1. (Color online) Tunneling current as a functions of Rabi frequency in the case of symmetrical tunneling contact in the presence (black line) and in the absence (red line) of Coulomb interaction: $\varepsilon_1 = 1.20$, $\varepsilon_2 = 0.50$, $eV = 1.00$, $U_1 = U_2 = 1.00$, $\Gamma_k = \Gamma_p = 0.01$ (a), $\varepsilon_1 = 0.25$, $\varepsilon_2 = 0.20$, $eV = 1.00$, $U_1 = U_2 = 2.00$, $\Gamma_k = \Gamma_p = 0.01$ (b), $\varepsilon_1 = 1.50$, $\varepsilon_2 = 1.10$, $eV = 1.00$, $U_1 = U_2 = 2.00$, $\Gamma_k = \Gamma_p = 0.01$(c)

and 2); both levels exceed the sample Fermi level and the value of applied bias voltage (Fig. 1c); one of the energy levels is located between the Fermi level and the value of applied bias voltage and another one exceeds both of them (Fig. 1a).

Rabi frequency tuning results in the single-electron energy levels spacing. When only one of the single-electron energy levels is located between the Fermi level and the value of applied bias voltage in the absence of Coulomb correlations (see red line in Fig. 1a), tunneling current amplitude increases with the increasing of Rabi frequency Ω until the lowest energy level ε_2 continue being localized in the $[E_F; eV]$ energy gap. Further Rabi frequency growth leads to the situation when both energy levels are localized out of the $[E_F; eV]$ energy interval and, consequently, sudden switching "off" of the tunneling current occurs. More complicated system behavior corresponds to the case when Coulomb correlations are considered (see black line in Fig. 1a). The decreasing of tunneling current amplitude with the Rabi frequency increasing is through one more stable state when the tunneling current value continues to differ from zero even when both single electron energy levels are localized out of the $[E_F; eV]$ energy gap. This is the direct manifestation of Coulomb correlations, because due to the presence of Coulomb correlations the multi-electron energy states are located in the $[E_F; eV]$ energy interval. Consequently, tunneling current decreasing reveals more complicated behavior. Moreover, obtained results demonstrate the negative tunneling conductivity, when tunneling current decreases with increasing of the Rabi frequency.

Tunneling current evolution as a function of the Rabi frequency in the case when both single-electron energy levels are initially localized in the $[E_F; eV]$ energy gap is

presented in the Fig. 1b. In the absence of Coulomb interaction one can see the growth of the tunneling current amplitude with the increasing of external field frequency Ω until both single-electron energy levels are localized in the $[E_F; eV]$ energy interval (see red line in Fig. 1b). Rabi frequency increasing leads to the situation when only one energy level is located in the $[E_F; eV]$ energy interval and it corresponds to the sudden decreasing of the tunneling current, which results in the formation of "step-down" in the $I-\Omega$ characteristic. Further increasing of the Rabi frequency leads to the situation when both single electron energy levels are localized out of the $[E_F; eV]$ energy gap, and, consequently, one more "step-down" appears. When Coulomb correlations are taken into account (see black line in Fig. 1b), decreasing of the tunneling current amplitude with the Rabi frequency growth takes place through one more stable state when the tunneling current value continues to differ from zero even when both single electron energy levels are localized out of the $[E_F; eV]$ energy gap due to the multi-electron energy states contribution. Consequently, three "steps-down" are visible in the $I-\Omega$ characteristic.

Tunneling current evolution in the case when both single-electron energy levels are initially localized above the $[E_F; eV]$ energy gap is shown in the Fig. 1c. The lowest energy level ε_2 is very close to eV. In this case tunneling current value is equal to zero until both single-electron energy levels are located above eV. In the absence of Coulomb interaction one can clearly see one "step-up" and one "step-down" in the $I-\Omega$ characteristic (see red line in Fig. 1c). Switching "on" of the tunneling current ("step-up") takes place when the Rabi frequency has the value, which is enough for the lower energy level to be localized in the $[E_F; eV]$ energy interval. Switching "off" ("step-down") takes place when Rabi frequency

growth leads to the situation when both energy levels are localized out of the $[E_F; eV]$ energy interval. ε_1 is higher than eV and ε_2 is lower than E_F. If one consider Coulomb correlations (see black line in Fig. 1c), two "steps-up" and two "steps-down" are present in the $I-\Omega$ characteristic. This multiple tunneling current switching "on" and "off" is the result of multi-electron energy states contribution caused by the presence of Coulomb correlations.

The other interesting effect associated with Coulomb correlations is the presence of multi-stability in the coupled QDs for the particular value of system parameters (see black line in Fig. 2b). Fig. 2b demonstrates
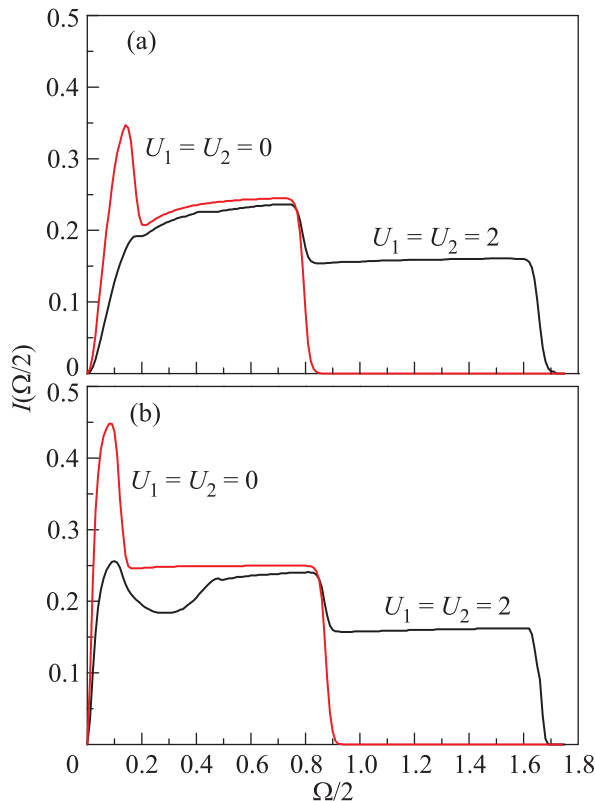

Fig. 2. (Color online) Tunneling current as a functions of Rabi frequency in the case of symmetrical tunneling contact in the presence (black line) and in the absence (red line) of Coulomb interaction: $\varepsilon_1 = 0.90$, $\varepsilon_2 = 0.70$, $eV = 1.00$, $U_1 = U_2 = 2.00$, $\Gamma_k = \Gamma_p = 0.01$ (a), $\varepsilon_1 = 0.90$, $\varepsilon_2 = 0.85$, $eV = 1.00$, $U_1 = U_2 = 2.00$, $\Gamma_k = \Gamma_p = 0.01$ (b)

that when both single-electron energy levels are located slightly above eV and are close to each other, single value of the tunneling current amplitude corresponds to the two values of Rabi frequency Ω (see black line in Fig. 2b). This effect disappears when the single-electron energy levels spacing increases (Fig. 2a).

4. Conclusion. Tunneling through the system of two QDs with strong coupling between localized electron states was analyzed by means of Heisenberg equations for pseudo operators with constraint on possible system states. Various single-electron levels location relative to the sample Fermi level and to the applied bias value in symmetric tunneling contact were investigated.

We revealed the appearance of negative tunneling conductivity and demonstrated multiple switching "on" and "off" of the tunneling current depending on the Coulomb correlations value, external field amplitude and energy levels spacing. We proved that Coulomb correlations strongly influence the system behavior.

We found distable regime in the coupled QDs with Coulomb correlations when single value of the tunneling current amplitude corresponds to the two values of Rabi frequency.

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