

The Electron Transport Properties of Qubit Coupled with SET: The Electrostatic Coupling Effect

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Abstract

In this study, theoretical treatment is presented to study the electron transport in a system consists of two principle coupled parts, these are the qubit and the single electron transistor (SET). Model calculation that includes the derivatives of the time dependent equations of motion for the system under consideration is presented. We find particular relations for the time variation of the occupation numbers of the qubit quantum dots and the single electron transistor quantum dot as well as the current that flows from the left lead. We investigate the electrostatic coupling effect on the electron transport dynamical properties in the system. We conclude that the charge accumulation increases on the far-removed qubit quantum dot from the single electron transistor as the electrostatic coupling increases at relatively low bias voltage, while the charge accumulation increases on the nearest one to the single electron transistor with increasing the electrostatic coupling at relatively high bias voltage.

Keywords: Qubit; Single Electron Transistor; Electron Transport; Quantum Computer.

1. Introduction

To construct a device for treating quantum information (quantum computer) we must firstly have physical system that can store and present information. The simplest system is a quantum system with two states that called "Two level system" or "qubit". In the quantum computing, the qubit is considered as quantum information unit it is quantum equivalent of classical bit. The qubit is quantum mechanical system with two states, for example single photon polarization, since the two states are vertical polarization and horizontal polarization [1]. In the classical system, the bit can be specific state or other state, but in the quantum mechanics it can be also superposition of states at the same time. The states, at which the qubit is measured, are called basis states or basis vectors [2]. The third qubit state is the superposition of states $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$, whereas α and β are the probability amplitudes which can be both complex numbers, with $|\alpha|^2 + |\beta|^2 = 1$. In other word, the qubit is quantum two levels system and that can be obtained by many possible ways. As the required case is two discrete quantum levels that can be controlled practically and in the same time they can be completely isolated from unfavorable reactions [3]. There are two main options for qubit basis these are the spin freedom degree in the single quantum dot and the orbital (charge) degree of freedom in the

double quantum dots. The double quantum dots provides simple and factual system with two energy levels [4, 5]. The charge qubit with the single electron can be defined as a state in which one of the quantum dots or the other is occupied by a single electron. [6]. There is two types of coupling between the quantum dots: the electrostatically coupling which prevents two electron to occupy the same quantum dot and the other is the quantum tunneling which allows the electron to occupy two quantum dots [7]. The single electron tunneling has been discussed using conventional current measuring method [8]. The current measurement has very few sensitivity whereas millions of electrons are required to find current with scientific concept. And conversely, the charge detection measurement in the qubit provides direct detection to electron occupation in quantum dots and provides sensible measurement to the single electron transport. The single electron transistor in which the transport is influenced by the Coulomb interaction in the quantum dot is considered as a sensitive electrical measuring machine. There is another tool for measurement that is the quantum point contact, i. e. semiconductor point contact structure which is sensitive to the charge distribution on contacts [9]. This measurement machines provide detection for the charge in the quantum dots that coupled

electrostatically with the measurement machines. The electrical measurement machine, the single electron transistor is more sensitive than the quantum point contact which exhibits high variation in the transmission probability. It is well known that many studies discuss the qubit problem theoretically and a lot of experimental studies are still required.

The aim of our work is to study the electron transport dynamic and properties in a system consisting of qubit coupling with single electron transistor (see fig. (1)). Where a mathematical model is presented to derive the time dependent equations of motion for the system under consideration in order to find a

special relations for the time dependence of the occupation numbers on the (QDs) of the qubit and the QD of the SET, also to find formula for the current that flows from the left lead passing through the left tunnel barrier to the quantum dot of the single electron transistor. All the system parameters are taken into consideration in our study.

QDS that means to quantum dots, QD that means to quantum dot, SET that means to single electron transistor.

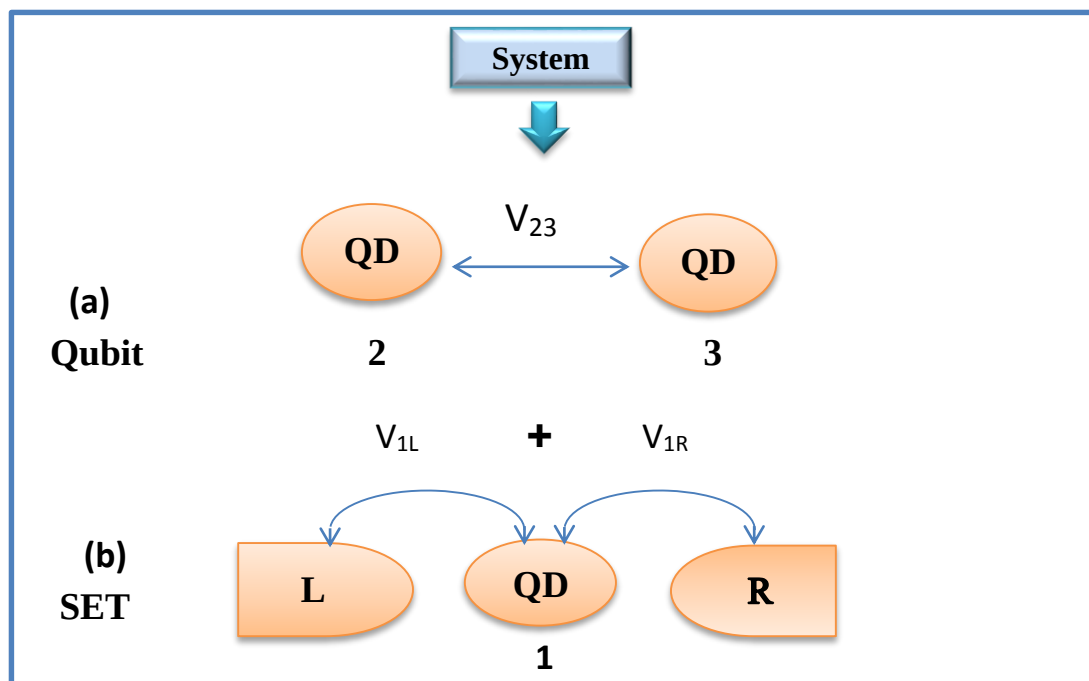


Fig. (1) Represents the subsystems (a) qubit dot (QD) (b) single electron transistor (SET).

2. Model Calculation

The system which is studied in this paper can be described (see fig.(2)) by using the following time dependent Hamiltonian [10]:

$$H(t) = H_{SET}(t) + H_{Qubit}(t) + H'(t) \quad (1)$$

The first term in eq. (1) represents the Hamiltonian that describes the SET,

$$\begin{aligned} H_{SET}(t) = & \sum_{k_L} E_{k_L} n_{k_L} + \sum_{k_R} E_{k_R} n_{k_R} + E_1 n_1(t) \\ & + \sum_{k_L} (V_{1k_L}(t) C_1^+(t) C_{k_L}(t) + h.c.) \\ & + \sum_{k_R} (V_{1k_R}(t) C_1^+(t) C_{k_R}(t) + h.c.) \end{aligned}$$

n_i Represents the occupation number of the level E_i whereas $i = k_L, k_R, 1$ where 1

denotes the (SET) E_1 . k_L And k_R represent the energy levels on the left and right leads respectively. V_{1k_R} and V_{1k_L} Represent the tunnel barriers between the QD of the SET and the right and left leads respectively. μ_L Represents the chemical potential for the lead left, μ_R represents the chemical potential for the lead right.

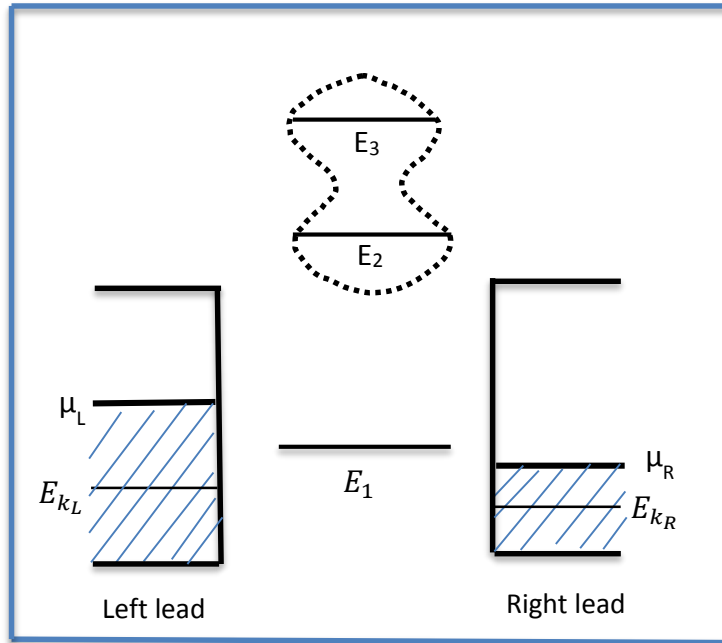


Fig. (2): Schematic representation for the energy scheme that corresponding to the system (qubit + single electron transistor) in presence of bias voltage state.

The second term in equation (1) represents the Hamiltonian that describes the qubit;

$$H_{Qubit}(t) = E_2 n_2(t) + E_3 n_3(t) + (V_{23}(t) C_2^+(t) C_3(t) + h.c.) \quad (3)$$

n_2, n_3 are the occupation numbers of the QDs that corresponding to the energy levels E_2, E_3 , respectively. While V_{23} describes the tunnel barrier between QDs of the qubit, h.c. represents the harmonic conjugate. $H'(t)$ in eq. (1) corresponds to the interaction between qubit and the SET,

$$H'(t) = U n_1(t) n_2(t) \quad (4)$$

U represents the electrostatic coupling between these two subsystems, it is important term because it determines the current value

that flowing between the leads in the SET because of electron oscillations between the qubit QDs. In general, the occupation number of the energy levels i can be written as, [11] :

$$n_i(t) = C_i^+(t) C_i(t) \quad (5)$$

Where as $C_i^+(t)(C_i(t))$ is the creation (annihilation) operators of electrons localized on the i th QD, $i=1,2,3$ and on the two leads when $i = k_L, k_R$. Our main goal is to derive the equations of motion for the system under consideration. For this purpose we use Heisenberg representation to write the time evolution of the occupation numbers [12]. By using atomic units we write the following relations:

$$\frac{dC_1(t)}{dt} = -i \left[E_1 C_1(t) + \sum_{k_L} V_{1k_L} C_{k_L}(t) + \sum_{k_R} V_{1k_R} C_{k_R}(t) + U C_1(t) n_2(t) \right] \quad (6)$$

$$\frac{dC_1^+(t)}{dt} = i \left[E_1 C_1^+(t) + \sum_{k_L} V_{1k_L}^* C_{k_L}^+(t) + \sum_{k_R} V_{1k_R}^* C_{k_R}^+(t) + U C_1^+(t) n_2(t) \right] \quad (7)$$

By taking the quantum-mechanical average to both sides of equation (5), we get,

$$\frac{d}{dt} \langle n_1(t) \rangle = 2Im \left[\sum_{k_L} V_{1k_L} \langle C_1^+(t) C_{k_L}(t) \rangle + \sum_{k_R} V_{1k_R} \langle C_1^+(t) C_{k_R}(t) \rangle \right] \quad (8)$$

We can also simplify eq. (8) by finding $\frac{dC_{k_\alpha}(t)}{dt}$, as follows:

$$\frac{dC_{k_\alpha}(t)}{dt} = -i [E_{k_\alpha} C_{k_\alpha}(t) + V_{1k_\alpha}^* C_1(t)] \quad , \quad \alpha = L, R \quad (9)$$

Then by solving eq. (9) analytically one can get,

$$C_{k_L}(t) = C_{k_L}(t_0)e^{-iE_{k_L}(t-t_0)} - i \int_{t_0}^t dt' V_{1k_L}^* e^{-iE_{k_L}(t-t')} C_1(t') \quad (10)$$

$$C_{k_R}(t) = C_{k_R}(t_0)e^{-iE_{k_R}(t-t_0)} - i \int_{t_0}^t dt' V_{1k_R}^* e^{-iE_{k_R}(t-t')} C_1(t') \quad (11)$$

t_0 is the initial time. Then by getting use of the following equation [11],

$$\Gamma_\alpha(E) = 2\pi \sum_{k_\alpha} V_{1k_\alpha} V_{1k_\alpha}^* \delta(E - E_{k_\alpha}) \quad , \quad (12)$$

Whereas $\Gamma_\alpha(E)$ represents the tunnel barrier between the QD of the SET and the lead α , by using the following definitions [13],

$$V_{1k_\alpha} = v_{k_\alpha} V_{1\alpha} \quad , \quad C_{k_\alpha}(t_0) = v_{k_\alpha} \tilde{C}_{k_\alpha}(t_0) \quad (13)$$

For simplicity we will not write the sign. The lead density of states is given by[11],

$$\rho_L(E) = \sum_{k_L} |v_{k_L}|^2 \delta(E - E_{k_L}) \quad (14)$$

We also use the so- called wide band approximation [11], then $\Gamma_\alpha(E)$ be independent on energy, so one can write the tunneling rates and the lead density of states as follows,

$$\Gamma = \Gamma_L + \Gamma_R \quad , \quad \rho_\alpha(E) = \rho_\alpha = \frac{1}{4\beta} \quad (15)$$

Where β is a factor related to the band width ($=4\beta$) . Eq. (8) becomes;

$$\frac{d}{dt} \langle n_1(t) \rangle = 2\text{Im} \left[I_1(t) + I_2(t) - i \frac{\Gamma}{2} \langle n_1 \rangle \right] \quad (16)$$

$I_1(t)$, $I_2(t)$ are given by the following equations,

$$I_1(t) = \frac{V_{1L}}{4\beta} \int_L e^{-iE_{k_L}(t-t_0)} \langle C_1^+(t) C_{k_L}(t_0) \rangle dE_{k_L} \quad (17)$$

$$I_2(t) = \frac{V_{1R}}{4\beta} \int_R e^{-iE_{k_R}(t-t_0)} \langle C_1^+(t) C_{k_R}(t_0) \rangle dE_{k_R} \quad (18)$$

Following the same procedure, we get,

$$\frac{d}{dt} \langle n_2(t) \rangle = 2\text{Im} \{ V_{23} \langle C_2^+(t) C_3(t) \rangle \} \quad (19)$$

$$\frac{d}{dt} \langle n_3(t) \rangle = -2\text{Im} \{ V_{23} \langle C_2^+(t) C_3(t) \rangle \} \quad (20)$$

In order to find the occupation numbers $n_1(t)$, $n_2(t)$ and $n_3(t)$ we must find the equations of motion for the correlation functions. The correlation functions are

$\langle C_1^+ C_{k'_L}(t_0) \rangle$, $\langle C_1^+ C_{k'_R}(t_0) \rangle$ and $C_2^+(t) C_3(t)$. where k'_L is one of k_L values. By getting use of eq. (5)

we write;

$$C_{k_\alpha}^+(t_0) C_{k'_\alpha}(t_0) = n_{k_\alpha}(t_0) \delta_{k_\alpha k'_\alpha} \quad (21)$$

Accordingly, we find the following equation of motion for the correlation function $\langle C_1^+ C_{k'_\alpha}(t_0) \rangle$,

$$\frac{d}{dt} \langle C_1^+ C_{k'_\alpha}(t_0) \rangle = \left(iE_1 - \frac{\Gamma}{2} \right) \langle C_1^+ C_{k'_\alpha}(t_0) \rangle + iV_{1k'_\alpha}^* n_{k'_\alpha}(t_0) e^{iE_{k'_\alpha}(t-t_0)} + iU \langle C_1^+ n_2(t) C_{k'_\alpha}(t_0) \rangle \quad (22)$$

Where $n_{k_\alpha}(t_0)$ is Fermi distribution function of the lead α :

$$n_{k_\alpha}(t_0) = f(E_{k_\alpha}, T) = \frac{1}{1 + \exp\left(\frac{E_{k_\alpha} - \mu_\alpha}{k_B T}\right)} \quad (23)$$

μ_α Represents the chemical potential for the lead α , while T represents the lead temperature and k_B is Boltzmann constant, since the system is in thermal equilibrium . Now in order to get the differential equation for the correlation function $\langle C_2^+(t) C_3(t) n_1 \rangle$ we write,

$$\frac{d}{dt} \langle C_2^+(t) C_3(t) n_1 \rangle = \langle C_2^+(t) C_3(t) \rangle \frac{d\langle n_1 \rangle}{dt} + \frac{d\langle C_2^+(t) C_3(t) \rangle}{dt} \langle n_1 \rangle \quad (24)$$

For simplification we use the following,

$$iUC_2^+(t) C_3(t) C_1^+(t) \{1 - C_1^+(t) C_1(t)\} C_1(t) = iUC_2^+(t) C_3(t) n_1$$

To get the,

$$\begin{aligned} \frac{d}{dt} \langle C_2^+(t) C_3(t) n_1 \rangle = & [iE_2 - iE_3 + iU - \Gamma] \langle C_2^+(t) C_3(t) n_1 \rangle + iV_{23}^* [\langle n_3 n_1 \rangle - \langle n_2 n_1 \rangle] \\ & - i(I_3 + I_4 + I_5 + I_6) \end{aligned} \quad (25)$$

We also derive the differential equation for $\langle n_1 n_3 \rangle$ and $\langle n_1 n_2 \rangle$ which take the following relations:

$$\frac{d}{dt} \langle n_3 n_1 \rangle = -\Gamma \langle n_3 n_1 \rangle + 2Im\{I_7 + I_8 - V_{23} \langle C_2^+(t) C_3(t) n_1 \rangle\} \quad (26)$$

$$\frac{d}{dt} \langle n_2 n_1 \rangle = -\Gamma \langle n_2 n_1 \rangle + 2Im\{I_9 + I_{10} + V_{23} \langle C_2^+(t) C_3(t) n_1 \rangle\} \quad (27)$$

Since I_i represents the following integrals, ($i = 3, 4, 5, \dots, 10$):

$$I_3 = \frac{V_{1L}}{4\beta} \int_L e^{-iE_{k_L}(t-t_0)} \langle C_1^+ C_2^+ C_3 C_{k_L}(t_0) \rangle dE_{k_L}$$

$$\begin{aligned}
I_4 &= \frac{V_{1L}}{4\beta} \int_L e^{+iE_{k_L}(t-t_0)} \langle C_1^+ C_2 C_3^+ C_{k_L}(t_0) \rangle dE_{k_L} \\
I_5 &= \frac{V_{1R}}{4\beta} \int_R e^{-iE_{k_R}(t-t_0)} \langle C_1^+ C_2^+ C_3 C_{k_R}(t_0) \rangle dE_{k_R} \\
I_6 &= \frac{V_{1R}}{4\beta} \int_R e^{+iE_{k_R}(t-t_0)} \langle C_1^+ C_2 C_3^+ C_{k_R}(t_0) \rangle dE_{k_R} \\
I_7 &= \frac{V_{1L}}{4\beta} \int_L e^{-iE_{k_L}(t-t_0)} \langle C_1^+ n_3 C_{k_L}(t_0) \rangle dE_{k_L} \\
I_8 &= \frac{V_{1R}}{4\beta} \int_R e^{-iE_{k_R}(t-t_0)} \langle C_1^+ n_3 C_{k_R}(t_0) \rangle dE_{k_R} \\
I_9 &= \frac{V_{1L}}{4\beta} \int_L e^{-iE_{k_L}(t-t_0)} \langle C_1^+ n_2 C_{k_L}(t_0) \rangle dE_{k_L} \\
I_{10} &= \frac{V_{1R}}{4\beta} \int_R e^{-iE_{k_R}(t-t_0)} \langle C_1^+ n_2 C_{k_R}(t_0) \rangle dE_{k_R}
\end{aligned} \tag{28}$$

Now, to find differential equation for $\langle C_1^+(t) n_2 C_{k'_L}(t_0) \rangle$ we can write,

$$\frac{d}{dt} C_1^+(t) n_2 C_{k'_L}(t_0) = \frac{dC_1^+(t)}{dt} n_2 C_{k'_L}(t_0) + C_1^+(t) \frac{dn_2}{dt} C_{k'_L}(t_0) \tag{29}$$

Then by using the following relations [12],

$$[C_i^+(t), C_j(t)] = \delta_{ij}$$

And,

$$iUC_1^+(t)C_2^+(t)C_2(t)C_3^+(t)C_3(t)C_{k'_L}(t_0) = -iUC_1^+(t)C_2^+(t)C_3^+(t)C_2(t)C_3(t)C_{k'_L}(t_0) = 0$$

we get,

$$\begin{aligned}
\frac{d}{dt} \langle C_1^+(t) n_2 C_{k'_L}(t_0) \rangle &= \left[iE + iU - \frac{\Gamma}{2} \right] \langle C_1^+(t) n_2 C_{k'_L}(t_0) \rangle + iV_{1k'_L}^* e^{iE_{k'_L}(t-t_0)} \langle n_2 \rangle \langle n_{k'_L}(t_0) \rangle \\
&\quad - iV_{23} \langle C_1^+(t) C_2^+(t) C_3(t) C_{k'_L}(t_0) \rangle + iV_{23}^* \langle C_1^+(t) C_2(t) C_3^+(t) C_{k'_L}(t_0) \rangle \tag{30}
\end{aligned}$$

and,

$$\begin{aligned} \frac{d}{dt} \langle C_1^+(t) n_3 C_{k_L'}(t_0) \rangle &= \left(iE_1 - \frac{\Gamma}{2} \right) \langle C_1^+(t) n_3 C_{k_L'}(t_0) \rangle + iV_{1k_L'}^* e^{iE_{k_L'}(t-t_0)} \langle n_3 \rangle \langle n_{k_L'}(t_0) \rangle \\ &\quad + iV_{23} \langle C_1^+(t) C_2^+(t) C_3(t) C_{k_L'}(t_0) \rangle + iV_{23}^* \langle C_1^+(t) C_2(t) C_3^+(t) C_{k_L'}(t_0) \rangle \end{aligned} \quad (31)$$

We also get the corresponding equations to the right lead.

To obtain the differential equation for the $\langle C_1^+(t) C_2^+(t) C_3(t) C_{k_L'}(t_0) \rangle$ we used the same steps to get,

$$\begin{aligned} \frac{d}{dt} \langle C_1^+(t) C_2^+(t) C_3(t) C_{k_L'}(t_0) \rangle &= iV_{1k_L'}^* e^{iE_{k_L'}(t-t_0)} \langle C_2^+(t) C_3(t) \rangle \langle n_{k_L'}(t_0) \rangle \\ &\quad + i \left(E_1 + E_2 - E_3 + U + i \frac{\Gamma}{2} \right) \langle C_1^+(t) C_2^+(t) C_3(t) C_{k_L'}(t_0) \rangle \\ &\quad + iV_{23}^* \langle C_1^+(t) n_3 C_{k_L'}(t_0) \rangle - iV_{23} \langle C_1^+(t) n_2 C_{k_L'}(t_0) \rangle \end{aligned} \quad (32)$$

Where,

$$UC_1^+(t) C_2^+(t) C_2(t) C_2^+(t) C_3(t) C_{k_L'}(t_0) = UC_1^+(t) C_2^+(t) C_3(t) C_{k_L'}(t_0)$$

In the same way we get relations for the right lead.

Following the same procedure, we also obtain,

$$\begin{aligned} \frac{d}{dt} \langle C_1^+(t) C_2(t) C_3^+(t) C_{k_L'}(t_0) \rangle &= -iV_{1k_L'}^* e^{iE_{k_L'}(t-t_0)} \langle C_2(t) C_3^+(t) \rangle^* \langle n_{k_L'}(t_0) \rangle \\ &\quad + i \left(E_1 + E_2 + E_3 + i \frac{\Gamma}{2} \right) \langle C_1^+(t) C_2(t) C_3^+(t) C_{k_L'}(t_0) \rangle \\ &\quad + iV_{23} \langle C_1^+(t) n_3 C_{k_L'}(t_0) \rangle - iV_{23} \langle C_1^+(t) n_2 C_{k_L'}(t_0) \rangle \end{aligned} \quad (33)$$

and also for the correlation function $\langle C_1^+(t) C_2(t) C_3^+(t) C_{k_R'}(t_0) \rangle$.

The correlation functions needed to find the occupation numbers on the three quantum dots are $\langle C_1^+(t) C_{k_\alpha'}(t_0) \rangle$, $\langle C_2^+(t) C_3(t) \rangle$, $\langle C_2^+(t) C_3(t) n_1 \rangle$, $\langle n_1 n_3 \rangle$, $\langle n_1 n_2 \rangle$, $\langle C_1^+(t) n_2 C_{k_\alpha'}(t_0) \rangle$, $\langle C_1^+(t) n_3 C_{k_\alpha'}(t_0) \rangle$, $\langle C_1^+(t) C_2^+(t) C_3(t) C_{k_\alpha'}(t_0) \rangle$ and $\langle C_1^+(t) C_2(t) C_3^+(t) C_{k_\alpha'}(t_0) \rangle$. Notably the correlation functions number may increase depending on the procedure that followed in the treatment.

Depending on the differential relations that we obtained, we can write formula for the current that tunnels from the left lead,

$$I_L(t) = 2Im \left[\sum_{k_L} V_{1k_L}(t) \langle C_1^+(t) C_{k_L}(t_0) \rangle^* e^{-iE_{k_L}(t-t_0)} - i \sum_{k_L} V_{1k_L} \int_{t_0}^t V_{1k_L}^* \langle C_1^+(t) C_1(t') \rangle e^{-iE_{k_L}(t-t')} dt' \right] \quad (34)$$

By using the definitions (12-15) we obtain,

$$I_L(t) = 2Im \left[I_1(t) - i \frac{\Gamma}{2} \langle n_1(t) \rangle \right] \quad (35)$$

3. Calculations and Results

To study electron transport dynamics in qubit coupled with single electron transistor (SET) we solve the related equations of motion numerically using Rung-Kuta method where the error is calculated in each step of time ($\Delta t = 10^{-2} a.u.$) which is found to be equal to $10^{-9} - 10^{-8}$, while the step in energy integration is equal to 0.024 eV. The program calculates the occupation numbers $n_1(t)$, $n_2(t)$ and $n_3(t)$, as well as the current flows from the left lead as a function of time for all the over mentioned system parameters.

The calculations are accomplished for the initial values $n_1(t_0) = 1$, $n_2(t_0) = 0$ and $n_3(t_0) = 1$, whereas $t_0 (= 0)$ represents the initial time. Also, the quantum dots (QDs) effective energy levels are located at $E_1 = E_2 = E_3 = 0$.

It is well known that the electrostatic coupling between the qubit and the SET is one of the most important parameters that determine the electron transport properties in the system. This coupling determines the dependence of

the current that flows from the left lead to the single electron transistor (SET) quantum dot on the electron oscillations between the qubit quanta dots (QDs).

To study the effect of this coupling on the electron transport properties the electrostatic coupling strength is fixed at 0.5 eV. The occupation numbers on the three quantum dots and the current flows from the left lead are calculated as a function of time for the case of equilibrium (see fig. (3)), as well as in the case of nonequilibrium when the bias voltage is equal to $eV_{bias} = 0.5, 1, 1.5, 2$ eV (see fig. (4)-(7)). Notably, for comparison these calculations are also accomplished and presented in Ref [14] for $U=0.25$ eV while all the other parameters are fixed at the same values. In the case of equilibrium, as the electrostatic coupling increases, the oscillations in the occupation number and current curves do not take certain manner. But the time dependence of the qubit quantum dots occupation numbers curves are completely dissimilar. Also, we notice that

the oscillation amplitude decreases obviously with time and the time spacing between any two peaks in $n_2(t)$ and $n_3(t)$ curves becomes lesser as the electrostatic coupling strength increases. The effect of the electrostatic coupling is dominant, since one cannot write certain notes about the increasing of bias voltage. So, in fig. (8) The occupation numbers $n_1(\infty)$, $n_2(\infty)$ and $n_3(\infty)$ are presented as a function of bias voltage. And according to these results one can write the following,

1. The behavior of $n_1(\infty)$ with the bias voltage coincides with the nearest SET quantum dot behavior, while it is opposite with the behavior of the far - removed one.
2. The accumulation of charge on the far - removed qubit quantum dot is enhanced for $eV_{bias} < 1 \text{ eV}$. While for $eV_{bias} > 1 \text{ eV}$, $n_1(\infty)$, $n_2(\infty)$ and $n_3(\infty)$ are nearly equal to 0.5.

The value of bias voltage, at which the behavior of curves is changed, will be not the same if one performs the calculations for another set of parameters which are considered experimentally in the initialization process that concerned to the device.

To determine the effect of increasing the electrostatic coupling between the qubit and

the SET, we calculate $n_1(\infty)$, $n_2(\infty)$, $n_3(\infty)$ and $I_L(\infty)$ as a function of the electrostatic coupling for two values of bias voltage $eV_{bias} = 0.2 \text{ eV}$, 1.0 eV , these calculations are presented in the figs. (9) and (10) respectively.

In fig. (9a), $n_3(\infty)$, $(n_2(\infty))$ increases (decreases) with increasing U . The behaviors of $n_1(\infty)$ and $n_2(\infty)$ are corresponding and the sum of the occupation numbers $n_1(\infty) + n_2(\infty) + n_3(\infty)$ is less than 2 for all U values. The current (in fig. (9b)) decreases with increasing U because increasing U leads to increase the electron oscillations between the quantum dots QDs qubit. At relatively high bias voltage we note that the behavior $n_2(\infty)$ and $n_3(\infty)$ is exactly opposite (see fig. (10a)). Our calculation confirms the validity of observations about the decrease in the occupation number of the far-removed QD with increasing U at relatively high bias voltage, we also notice that $I_L(\infty)$ decrease noticeably with increasing U at high bias voltage (for comparison see figs. (9b) and (10b)).

Finally, we conclude that the accumulation of the qubit's quantum dots depend on all the parameters that determined in the initialization, manipulation and measurement.

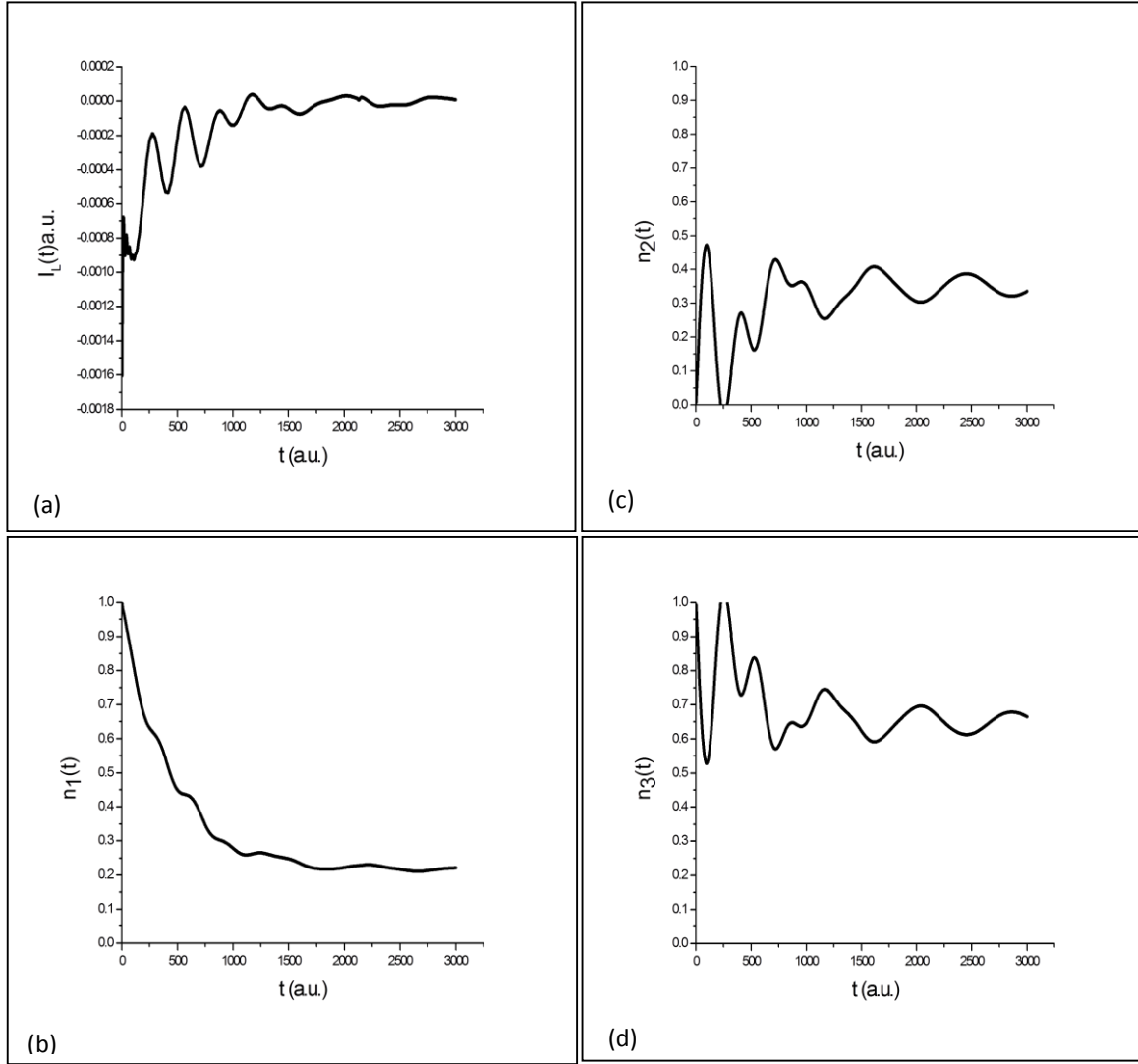


Fig. (3) shows: (a) The current flows from the left lead. (b) The occupation number of the single electron transistor quantum dot. (c) And (d) The occupation numbers of the quantum dots QDs, all as a function of time.

For the parameters: $U = 0.5$ eV , $V_{23} = 0.1$ eV , $eV_{\text{bias}} = 0$, $V_{1\alpha} = 0.3$ eV

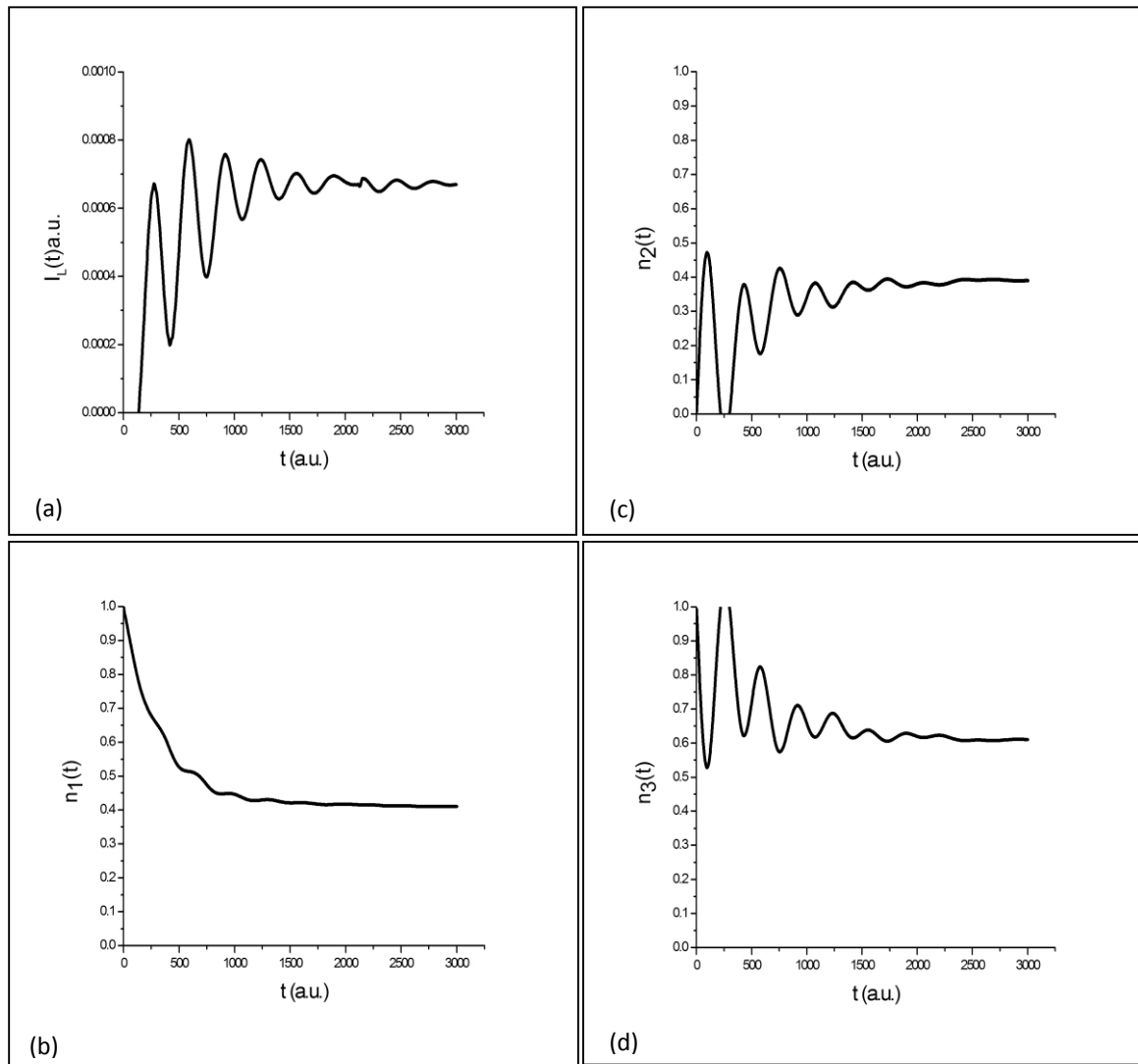


Fig. (4) shows: (a) The current flows from the left lead. (b) The occupation number of the single electron transistor quantum dot. (c) And (d) The occupation numbers of the quantum dots QDs, all as a function of time.

For the parameters: $U = 0.5$ eV , $V_{23} = 0.1$ eV , $eV_{\text{bias}} = 0.5$ eV , $V_{1\alpha} = 0.3$ eV

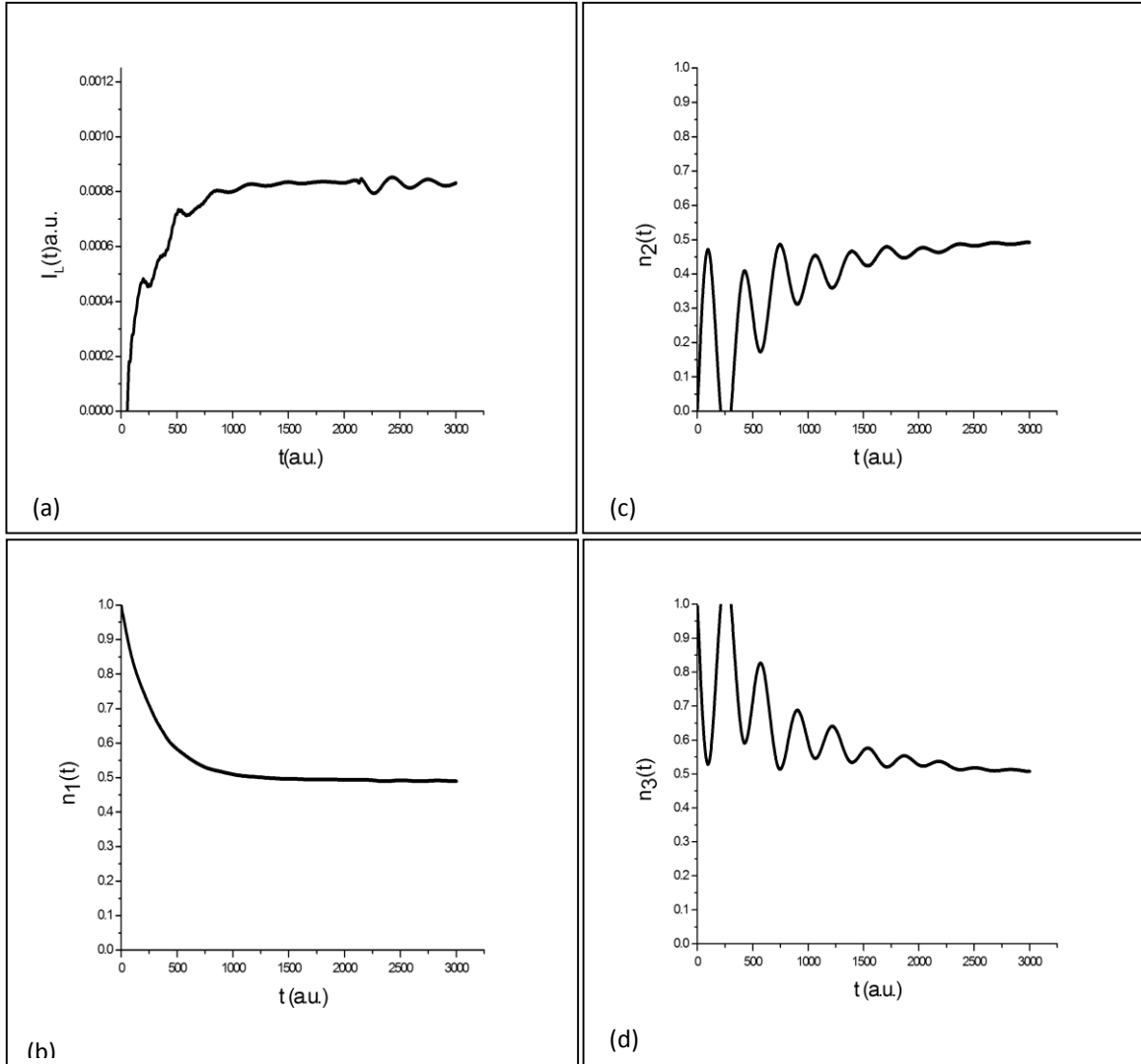


Fig. (5) Shows: (a) The current flows from the left lead. (b) The occupation number of the single electron transistor quantum dot. (c) And (d) The occupation numbers of the quantum dots QDs, all as a function of time.

For the parameters: $U= 0.5$ eV, $V_{23}= 0.1$ eV, $eV_{\text{bias}}= 1$ eV, $V_{1\alpha} = 0.3$ eV

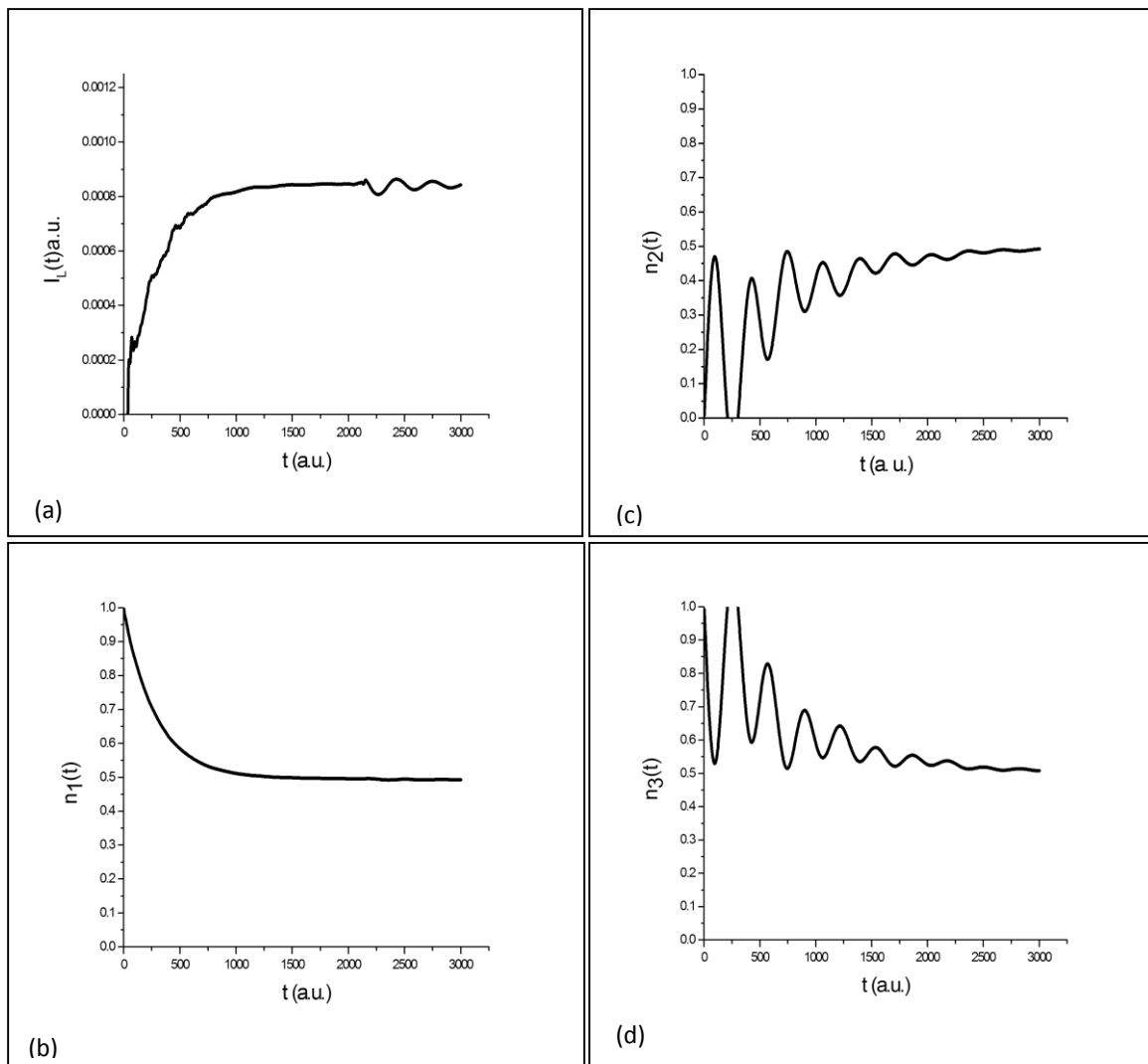


Fig. (6) shows: (a) The current flows from the left lead. (b) The occupation number of the single electron transistor quantum dot. (c) And (d) The occupation numbers of the quantum dots QDs, all as a function of time.

For the parameters: $U = 0.5$ eV, $V_{23} = 0.1$ eV, $eV_{\text{bias}} = 1.5$ eV, $V_{1\alpha} = 0.3$ eV

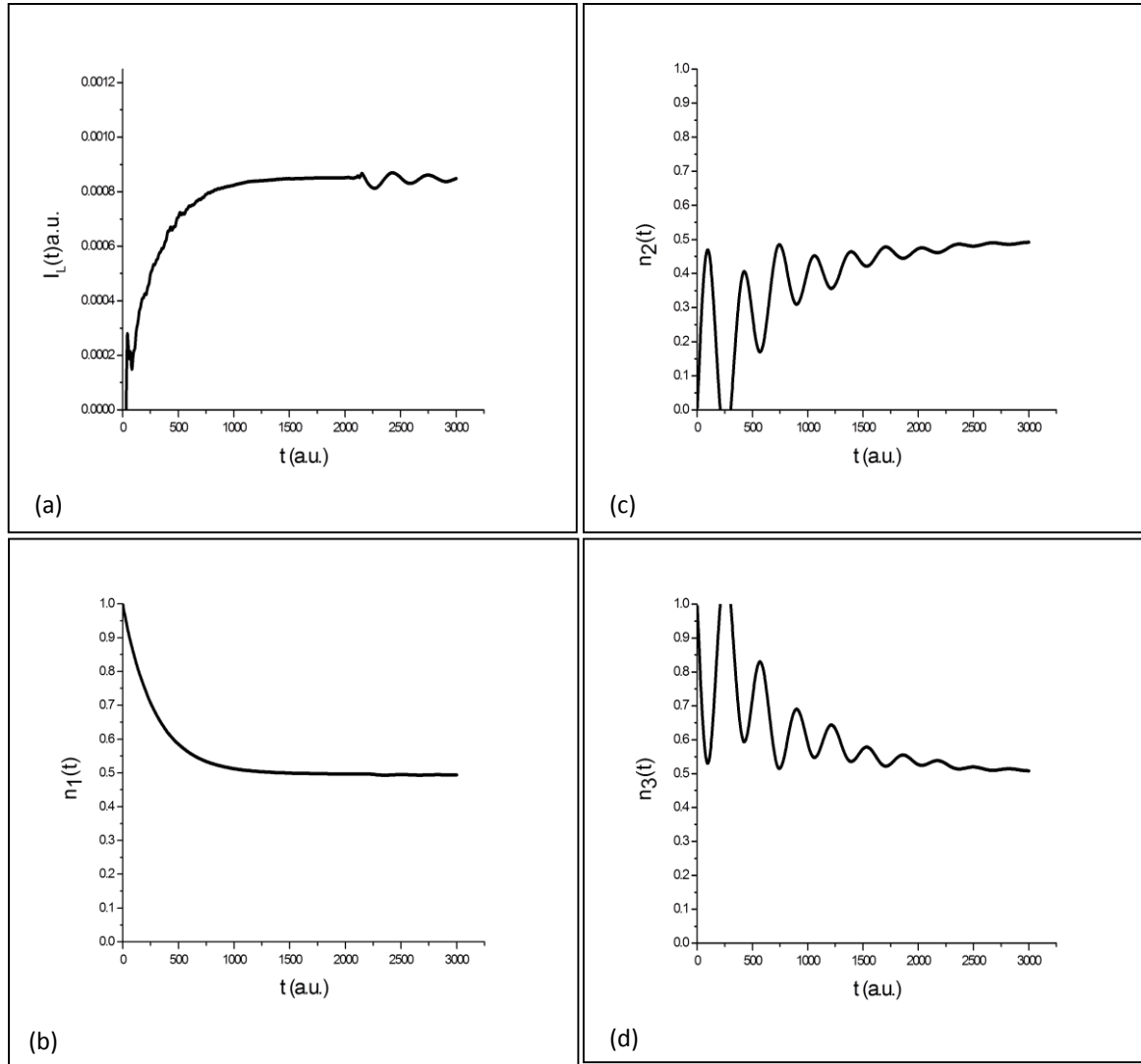


Fig. (7) Shows: (a) The current flows from the left lead. (b) The occupation number of the single electron transistor quantum dot. (c) And (d) The occupation numbers of the quantum dots QDs, all as a function of time.

For the parameters: $U = 0.5$ eV, $V_{23} = 0.1$ eV, $eV_{\text{bias}} = 2$ eV, $V_{1\alpha} = 0.3$ eV

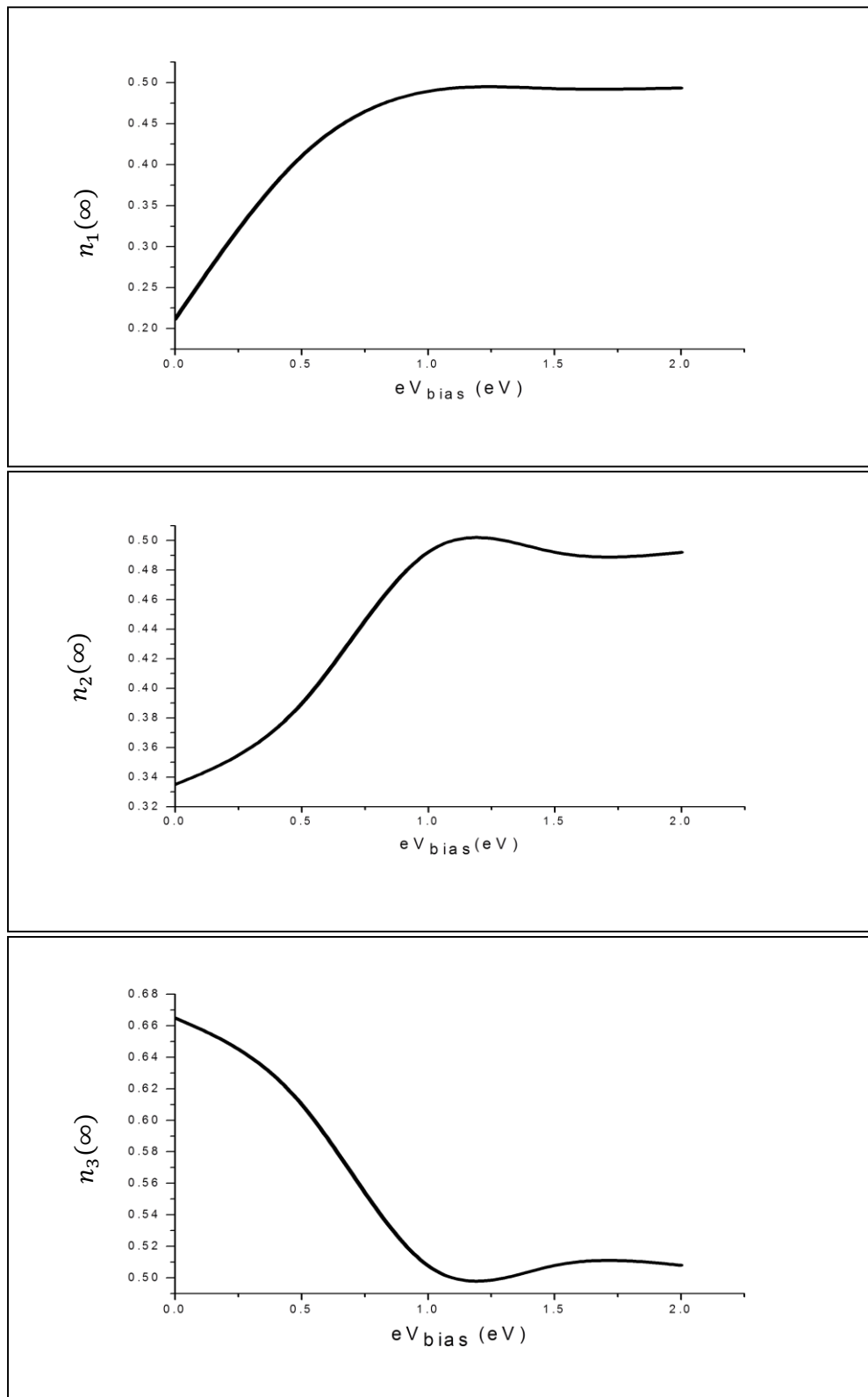


Fig. (8) Shows the occupation numbers $n_1(\infty)$, $n_2(\infty)$ and $n_3(\infty)$ as a function of bias voltage applied to the leads with: $U=0.5$ eV, $V_{23}=0.1$ eV, $V_{1\infty} = 0.3$ eV.

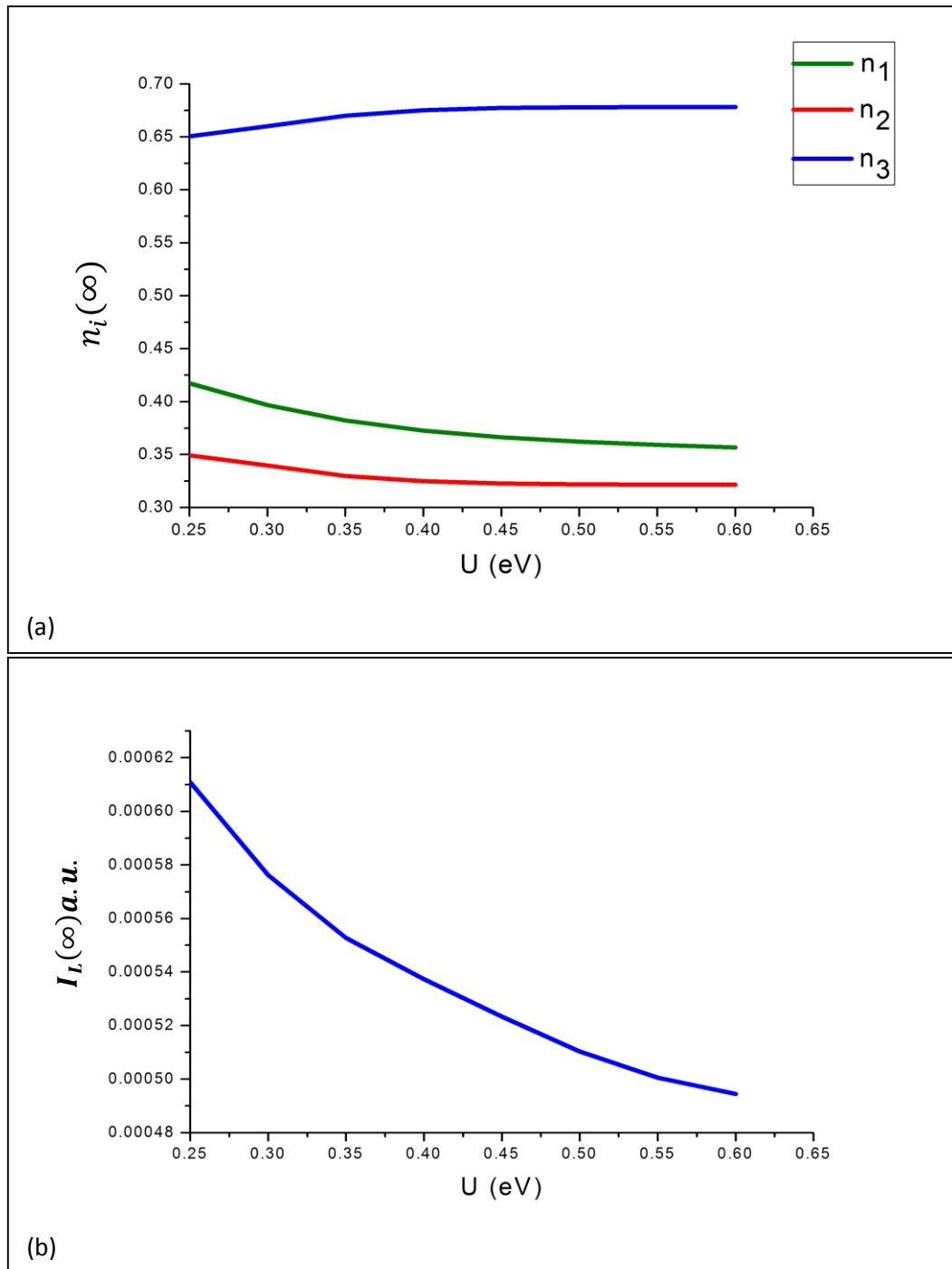


Fig. (9) Shows: (a) The occupation numbers $n_i(\infty)$ as a function of the electrostatic coupling at $i=1,2,3$. (b) The current $I_L(\infty)$ as a function of the electrostatic coupling. To the parameters: $eV_{bias} = 0.2$ eV, $V_{23} = 0.1$ eV, $V_{1\alpha} = 0.3$ eV, $E_i = 0$

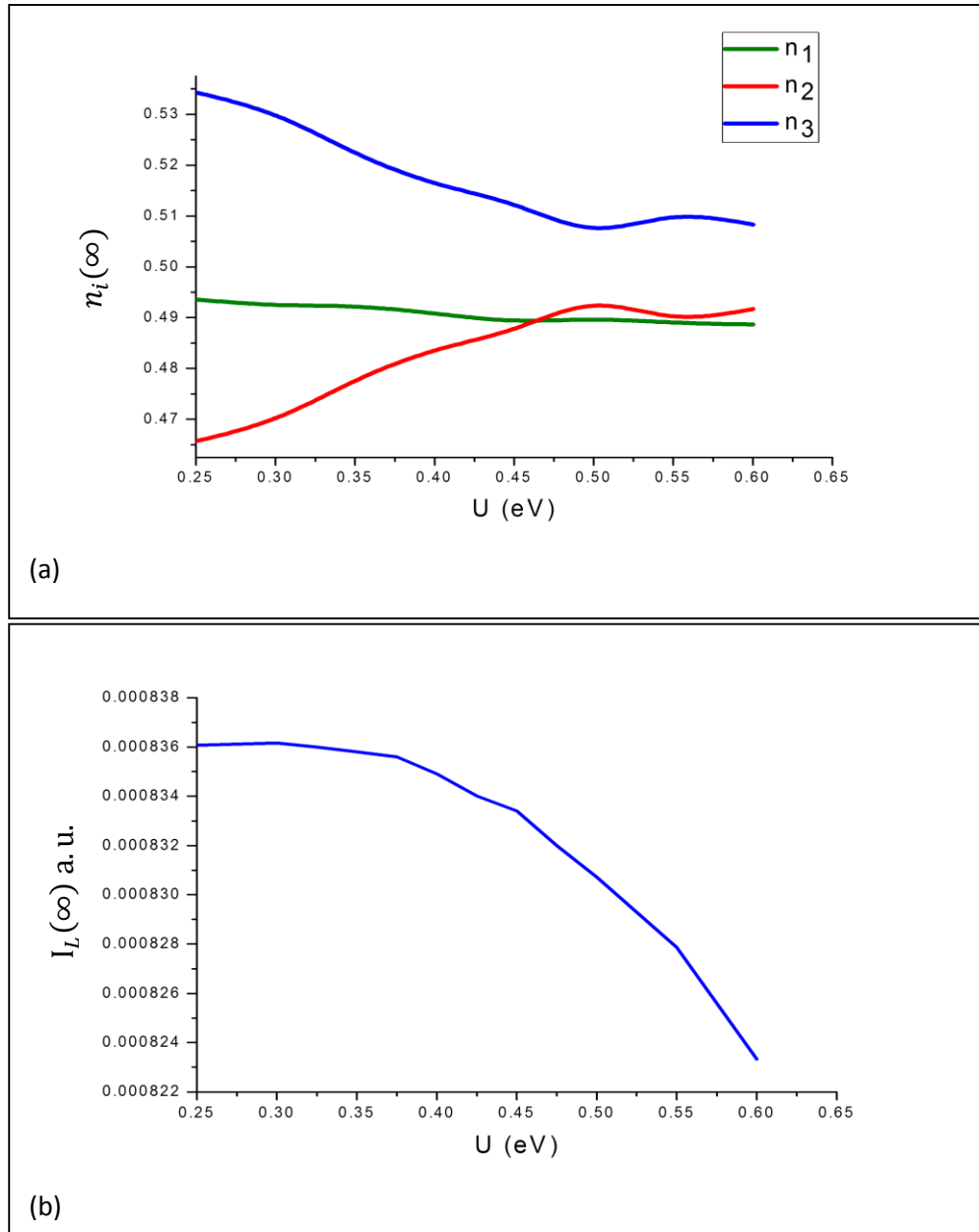


Fig. (10) Shows: (a) The occupation numbers $n_i(\infty)$ as a function of the electrostatic coupling at $i=1,2,3$. (b) The current $I_L(\infty)$ as a function of the electrostatic coupling. To the parameters: $eV_{\text{bias}} = 1$ eV, $V_{23} = 0.1$ eV, $V_{1\alpha} = 0.3$ eV, $E_i = 0$

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خصائص نقل الإلكترون لكيوبت مقترن بترانزستور الإلكترون المفرد: تأثير الإقتران الإلكتروني

آيات طاهر أبراهيم جنان مجيد المخ

قسم الفيزياء/ كلية التربية للعلوم الصرفة / جامعة البصرة

البصرة / العراق

الملخص

في هذا البحث تم تقديم معالجة نظرية لدراسة نقل الإلكترون لنظام مكون من جزئين أساسيين مقترنين هما مفتاح عنصر الحاسبة الكمية المتمثل بالكيوبت والكاشف المتمثل بترانزستور الإلكترون المفرد. الأنموذج الحسابي تضمن اشتقاق لمعادلات الحركة المعتمدة على الزمن للنظام قيد الدراسة. وجدنا علاقات خاصة بتغير اعداد الإشغال لنقطتي الكيوبت والنقطة الكمية التابعة لترانزستور الإلكترون المفرد مع الزمن بالإضافة الى التيار الذي يسري من القطب الايسر. فحصنا تأثير الإقتران الإلكتروني على الخصائص الديناميكية لنقل الإلكترون في النظام. استنتجنا إن تراكم الشحنة يزداد على نقطة الكيوبت الكمية البعيدة عن ترانزستور الإلكترون المفرد بزيادة الإقتران الإلكتروني عند فولتية الانحياز الواطئة نسبياً، بينما يقل تراكم الشحنة على نقطة الكيوبت الكمية البعيدة عن ترانزستور الإلكترون المفرد (ويزداد بالمقابل تراكم الشحنة على نقطة الكيوبت الكمية القريبة من ترانزستور الإلكترون المفرد) بزيادة الاقتران الإلكتروني عند فولتية الانحياز العالية نسبياً.

كلمات مفتاحية: الكيوبت ، ترانزستور الإلكترون المفرد، نقل الإلكترون، الحوسبة الكمية.