

The Transport Properties of the Coupled Quantum Dot – Quantum Well – Quantum Dot (QD – QW – QD) system

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Abstract

We study the electron transport through nano device with " hetro dimension quantum confinement system ". The system is coupled quantum dot – quantum well – quantum dot, embedded between two leads. We derive a theoretical model for the coherent tunneling from one quantum dot to the other one through quantum well based on the transition – probability formulation. The transport properties of this system, (QD – QW – QD) system, are calculated and discussed, which are found to be depend on the electronic properties of the sub – systems. The device parameters that assist the electron tunneling are investigated. We find that two features are functional, the Coulomb blockade and the linear relation for $I - eV_{\text{bias}}$ characteristic.

Keywords: Transport Properties, QD – QW – QD system, nanostructure.

1 – Introduction

Nano – technology has stimulated much interest in the study of quantum transport in mesoscopic structures. Among these various structures, devices based on quantum dot (QD) which have drawn particular attention⁽¹⁾, since the electron transport is shown to be affected by the confined electrons in the dot.

Novel tunable Kondo effect has been experimentally found in a single electron transistor^(2,3), where the level position of the quantum dot and the tunneling rate were controlled by the external gate voltages, via Coulomb blockade.

Experimental study, based on a configuration of a quantum dot coupled to normal metal leads (N), has been reported^(4 – 7). When the quantum dot is coupled to a

super conductor (S), the resonant tunneling current is strongly affected by the singular BCS density of states, they⁽⁸⁾ was found that the singularity of BCS density of states plays an important role in the electron transport. If the coupling between the leads and the QD is sufficiently weak, the sub gap transport is suppressed in the case of small dc bias. Also investigated the many – body resonance by an ac applied voltage in the N – QD – S system as an application of the derived current formula.

Artificially grown low – dimensional semiconductor systems, such as GaAs – (Ga , Al)As super lattices (SL's), quantum wells (QW's) , quantum well – wires (QWW's), quantum dots (QD's), and so on, have become the object of extensive research activity due not only to their interesting

physical properties but also to their importance for potential applications in a wide range of semiconductor devices.

The electronic properties, that calculated theoretically for the coupled quantum dot – quantum well QD – QW which are presented in our pervious paper ⁽⁹⁾, will be used to study and investigate the transport properties of the device considered in our study which is coupled quantum dot – quantum well – quantum dot (QD_L–QW–QD_R) system. The device is embedded between two leads (see fig.(1)).

The model analysis the tunneling probability from a 3D quantum confinement nanostructure (QD) to 1D quantum confinement nanostructure (QW) then to a 3D quantum confinement nanostructure (QD) in terms of the initial state in the quantum dot to final state in the second quantum dot via transfer Hamiltonian. However, the symmetric case will be studied only.

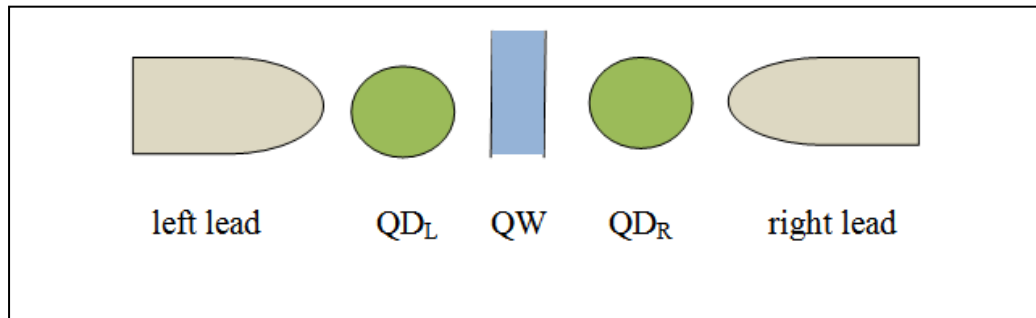


Fig.(1) : Schematic illustration for the device under consideration .

2 – The Transport Properties Calculation

The current that tunnels through the system considered in our study can be calculated by using the following relation ⁽¹⁰⁾ :-

$$I = \frac{\Delta_L \Delta_R}{\Delta_R + \Delta_L} \int \rho_{Act}(E) (f_L(E, T) - f_R(E, T)) dE \quad (1)$$

$\rho_{Act}(E)$ Represents the density of states of the active region,

$$\rho_{Act}(E) = \rho_{DL}(E) + \rho_W(E) + \rho_{DR}(E) \quad (2)$$

Where, $\rho_{D\alpha}(E)$ ($\alpha = L, R$) is the local density of states of left (right) quantum dot ,

$$\rho_{D\alpha}(E) = \frac{1}{\pi} \frac{\Delta_{C\alpha}}{(E - E_D)^2 + \Delta_{C\alpha}^2} \quad (3)$$

With E_D is the quantum dot eigen energy, $\Delta_{C\alpha}$ is the tunneling rate coupling interaction of the quantum dot with the quantum well and the lead α , and it is given by,

$$\Delta_{c\alpha} = \frac{\Delta_{\alpha} \Delta_{DW}}{\Delta_{\alpha} + \Delta_{DW}} \quad (4)$$

for more details see reference [11] :

The quantum well density of states is given by⁽¹²⁾:

$$\rho_W(E) = \frac{L}{2\pi} \frac{\partial k_z}{\partial E} \quad (5)$$

Where k_z is given by :

$$k_z = \sqrt{\frac{2M_w^*}{\hbar^2} (E_w + \phi)} \quad (6)$$

Where M_w^* , E_w and ϕ is the quantum well effective mass, quantum well eigen energy and work function respectively.

With, $f_\alpha(E, T)$ is the Fermi distribution function at the $\alpha = L, R$ lead, and T is the lead temperature,

$$f_\alpha(E, T) = \frac{1}{1 + \exp\left(\frac{E - \mu_\alpha}{k_B T}\right)} \quad (7)$$

With, μ_α is the lead chemical potential and k_B is the Boltzman constant.

The tunneling current is calculated as a function of bias voltage eV_{bias} , with, $\mu_L = -\mu_R = eV_{bias}$ for different values of well width L and quantum dot radius R_D . While the device is considered to be at thermal equilibrium.

These results are presented in figs.((2) – (7)) for $L = 12nm$ where $E_w = -0.000193eV$ and in figs.((8) – (13)) for $L = 24nm$ where $E_w = -0.243886eV$ for GaAs quantum well⁽¹¹⁾ where $M_w^* = 0.067a.u$. The GaAs quantum dot eigen energies are shown in table (1)⁽¹¹⁾ where $M_D^* = 0.067a.u$.

Table (1): quantum dot eigen energy as function of quantum dot radius

$R_D(nm)$	20	21	23	25	27	29
$E_D(eV)^{(11)}$	-0.078282	-0.098909	-0.132373	-0.158127	-0.178371	-0.194571

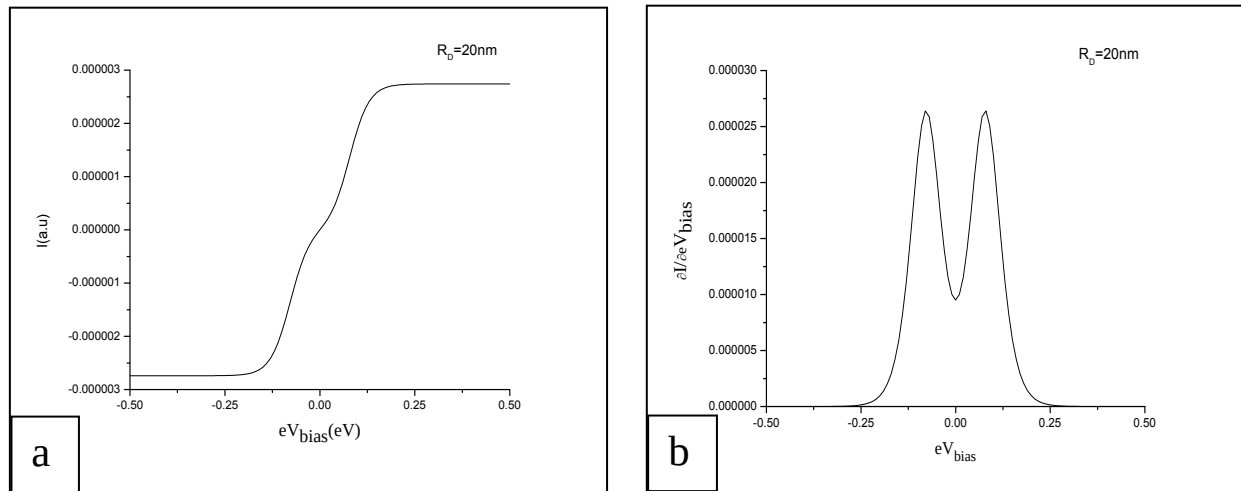


Fig.(2): The tunneling current and the differential conductance as a function of bias voltage with $L = 12nm$ and $R = 20nm$.

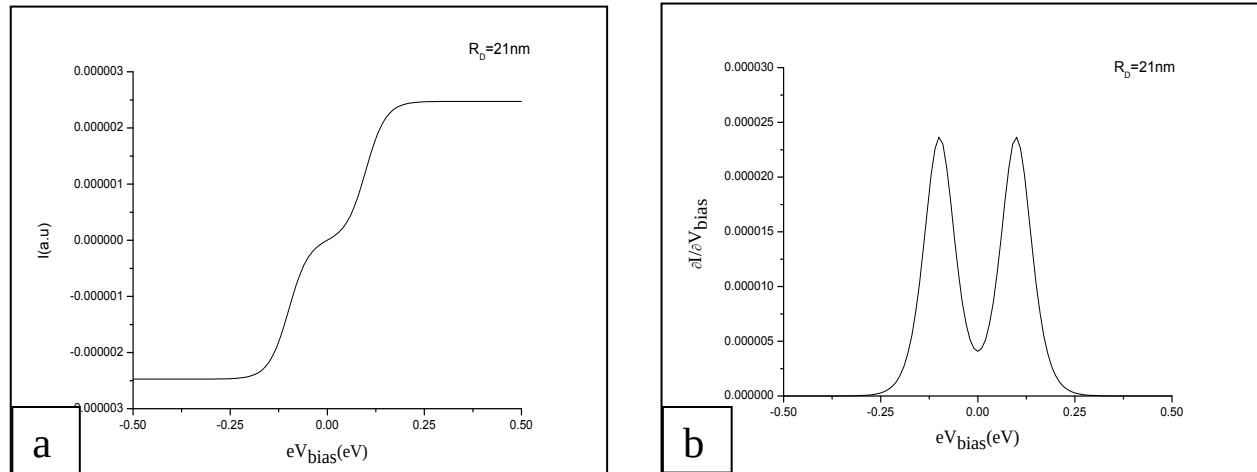


Fig.(3): The tunneling current and the differential conductance as a function of bias voltage with $L = 12\text{nm}$ and $R = 21\text{nm}$.

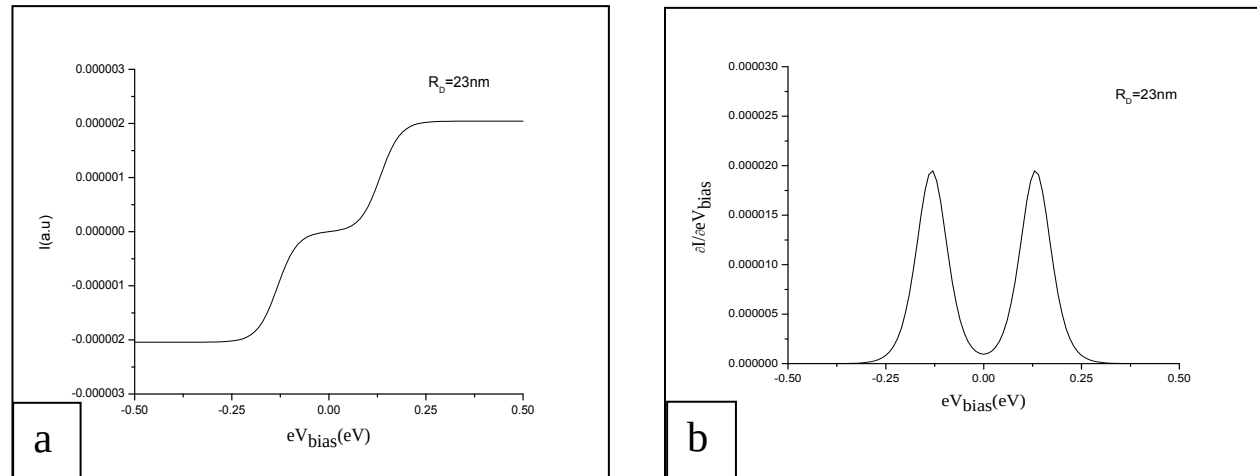


Fig.(4): The tunneling current and the differential conductance as a function of bias voltage with $L = 12\text{nm}$ and $R = 23\text{nm}$.

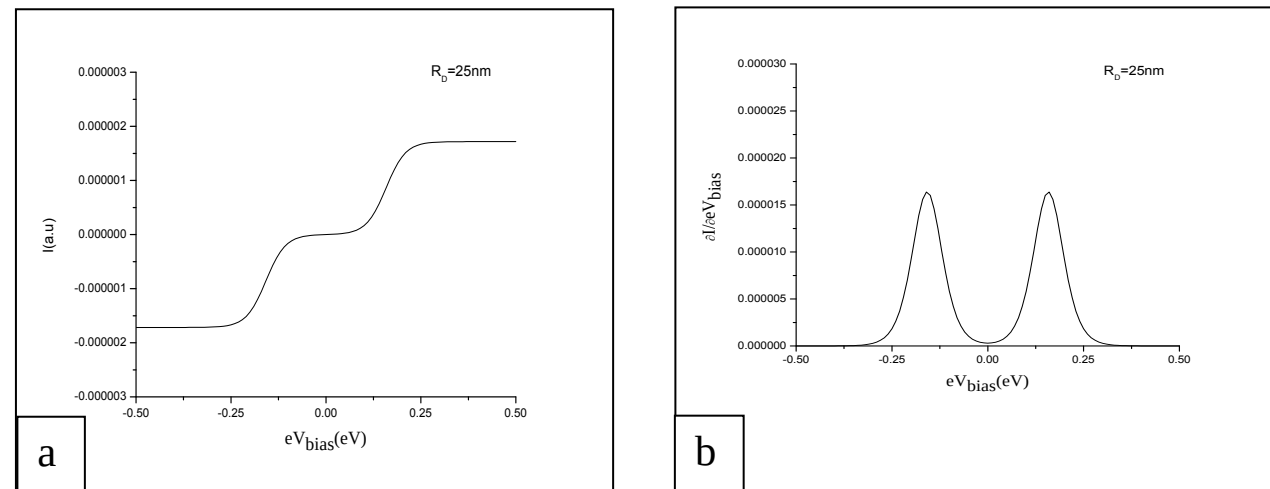


Fig.(5): The tunneling current and the differential conductance as a function of bias voltage with $L = 12\text{nm}$ and $R = 25\text{nm}$.

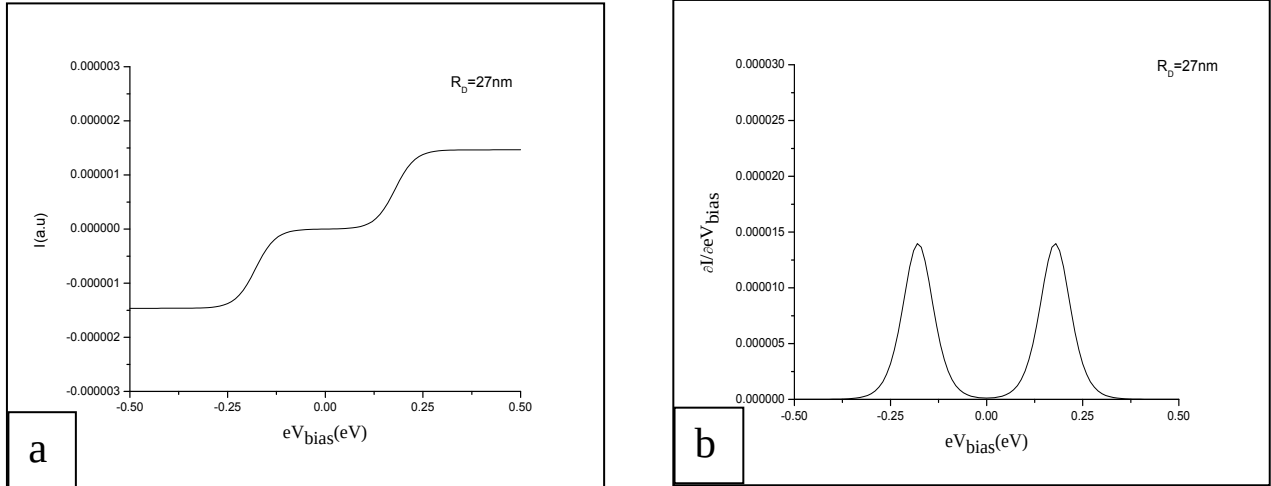


Fig.(6): The tunneling current and the differential conductance as a function of bias voltage with $L = 12\text{nm}$ and $R = 27\text{nm}$.

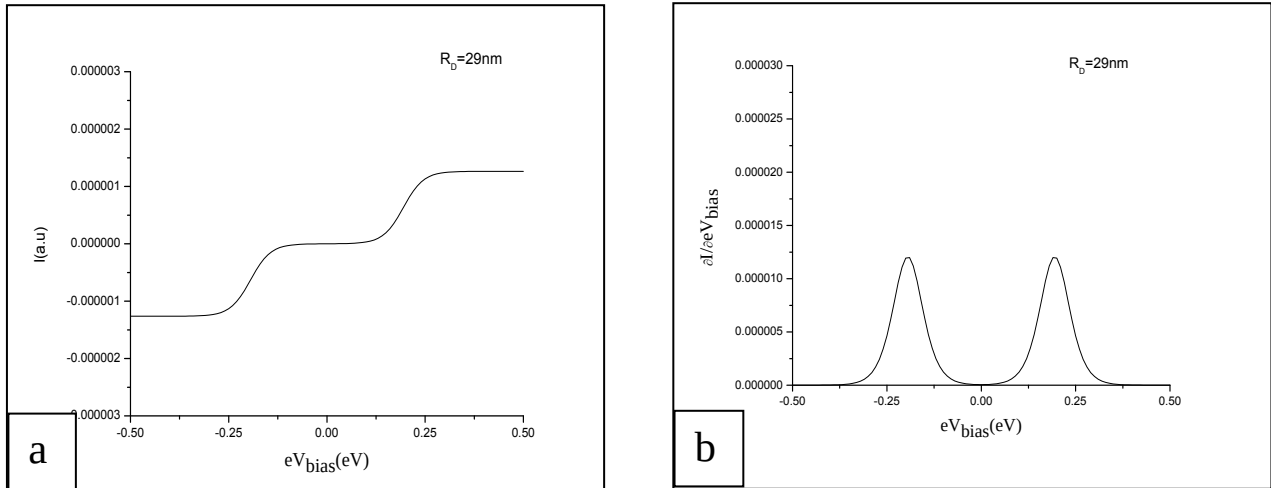


Fig.(7): The tunneling current and the differential conductance as a function of bias voltage with $L = 12\text{nm}$ and $R = 29\text{nm}$.

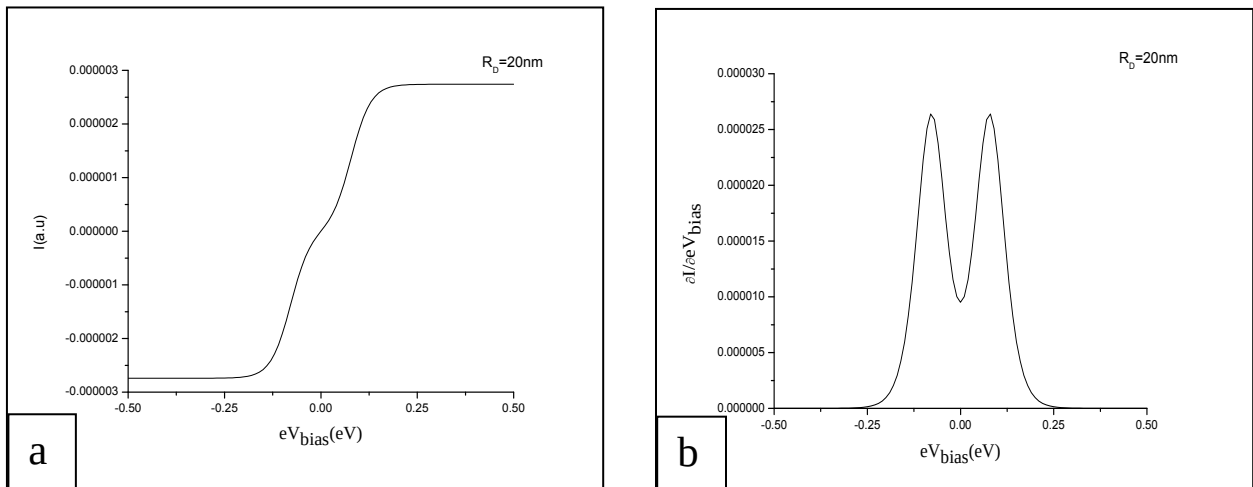


Fig.(8): The tunneling current and the differential conductance as a function of bias voltage with $L = 24\text{nm}$ and $R = 20\text{nm}$.

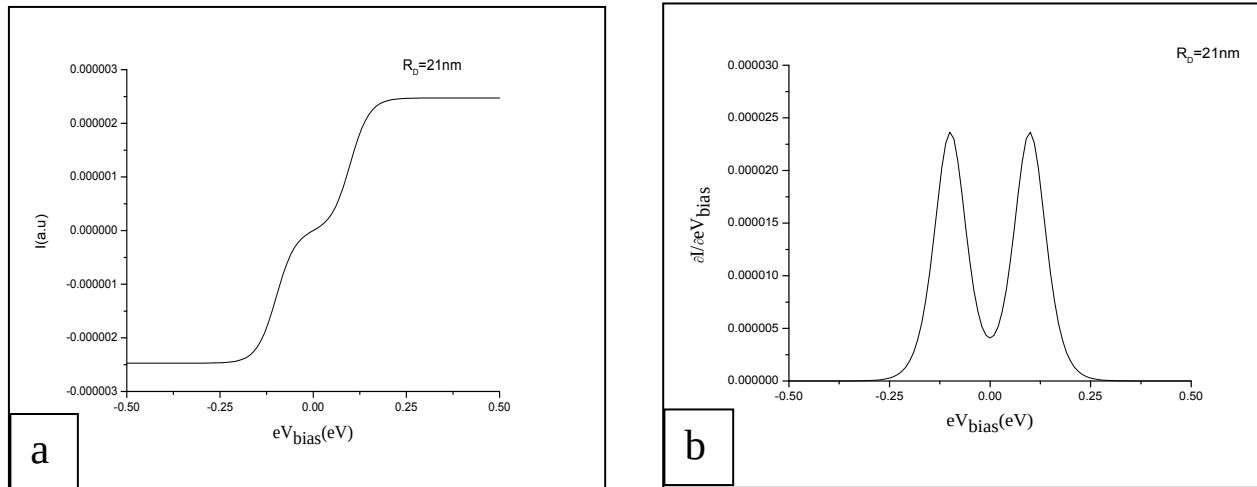


Fig.(9): The tunneling current and the differential conductance as a function of bias voltage with $L = 24\text{nm}$ and $R = 21\text{nm}$.

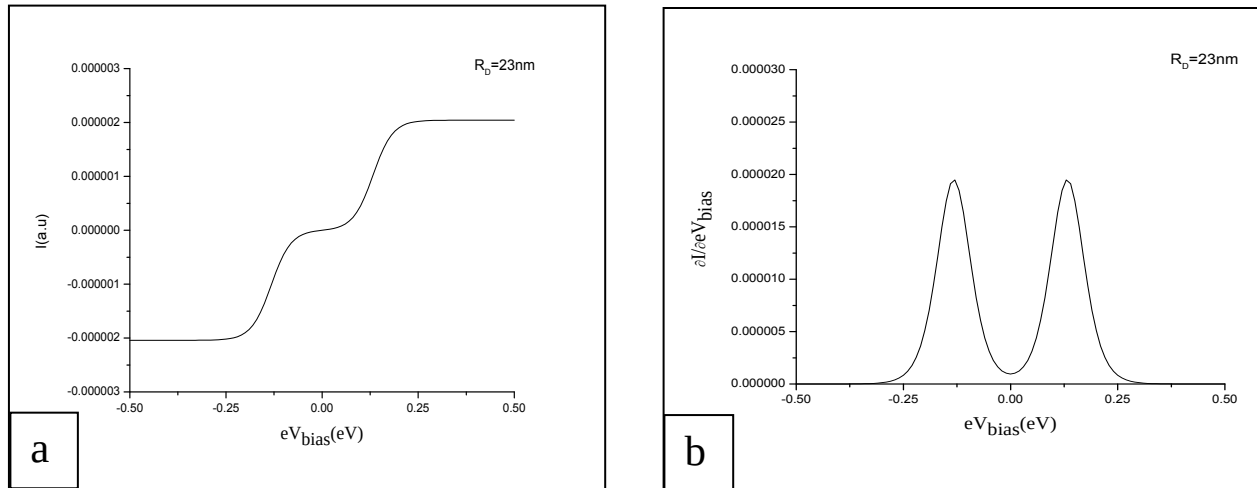


Fig.(10): The tunneling current and the differential conductance as a function of bias voltage with $L = 24\text{nm}$ and $R = 23\text{nm}$.

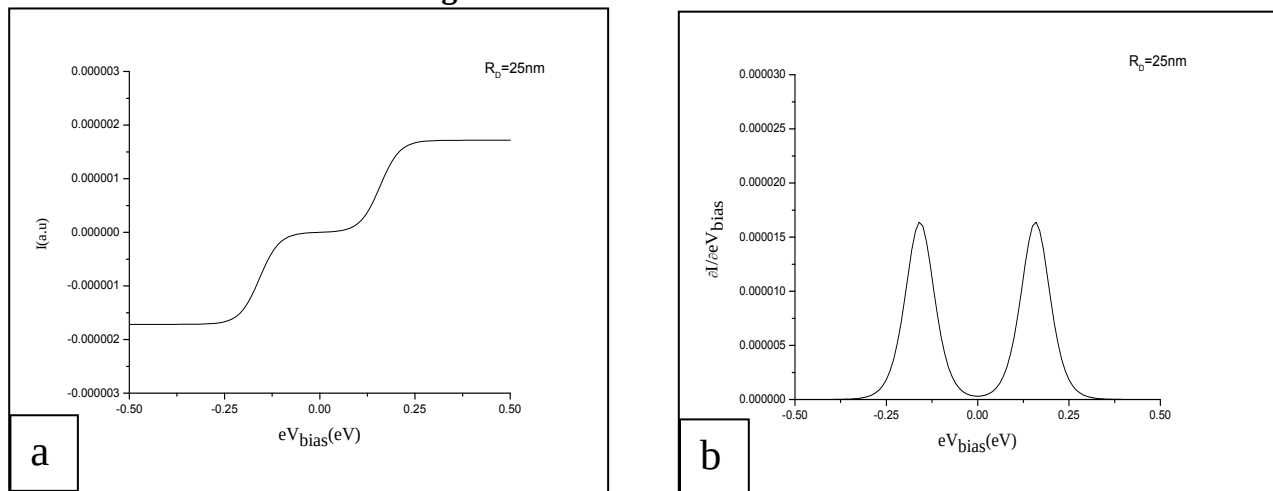


Fig.(11): The tunneling current and the differential conductance as a function of bias voltage with $L = 24\text{nm}$ and $R = 25\text{nm}$.

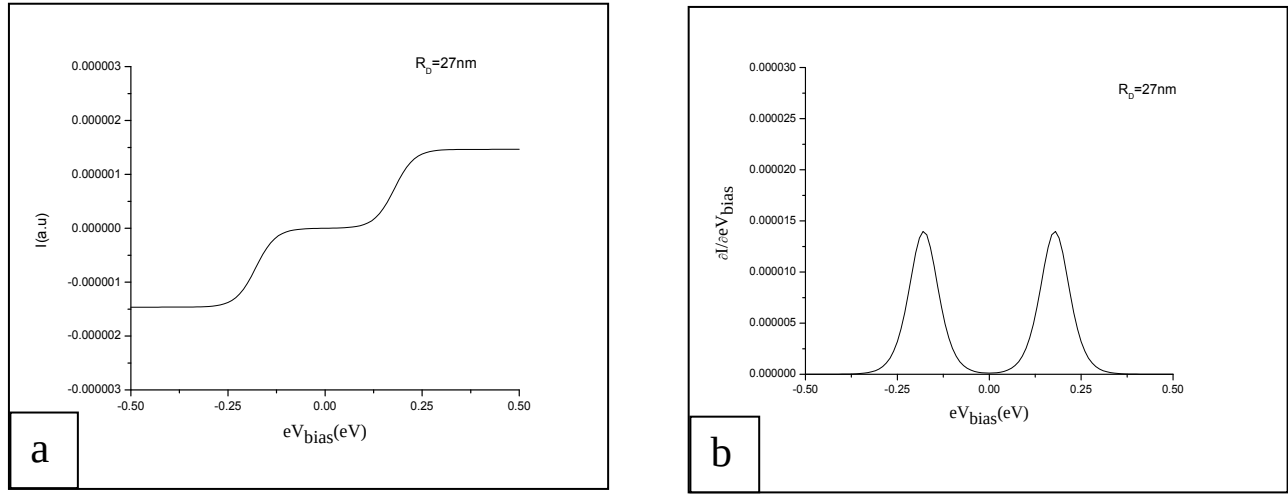


Fig.(12): The tunneling current and the differential conductance as a function of bias voltage with $L = 24\text{nm}$ and $R = 27\text{nm}$.

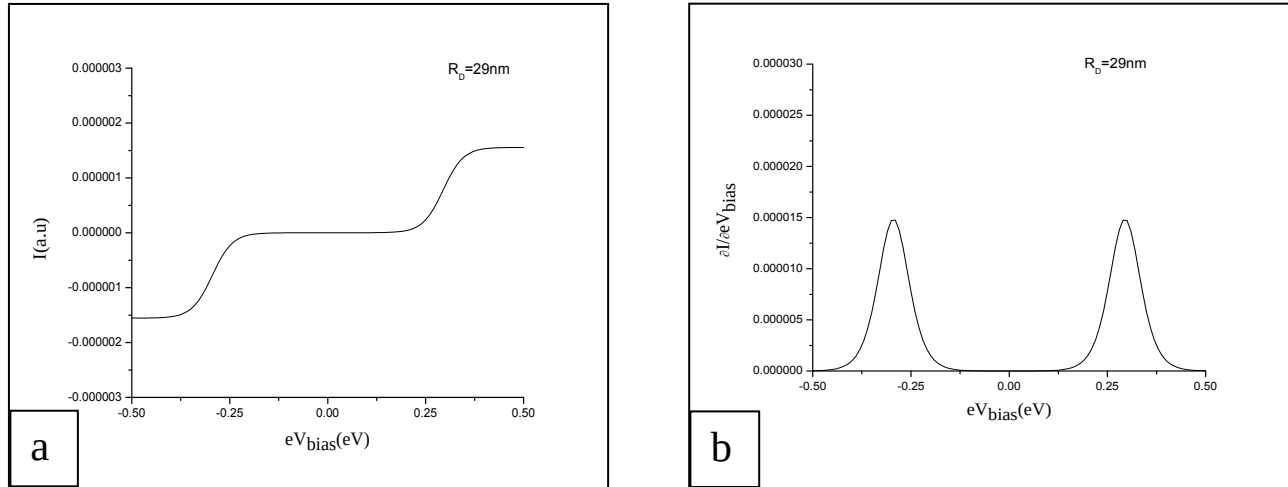


Fig.(13): The tunneling current and the differential conductance as a function of bias voltage with $L = 24\text{nm}$ and $R = 27\text{nm}$.

3 – Conclusions

Results are presented in figs.((2) – (7)) for $L = 12\text{nm}$ and in figs.((8) – (13)) for $L = 24\text{nm}$, from which one can report the following physical features,

- 1 – In general all the current curves show step – stairs like behavior.
- 2 – For $R_D = 20\text{nm}$ and for very low bias voltage, the current – voltage relation is linear.

3 – For $|eV_{\text{bias}}| > 0.25\text{eV}$, the current is bias voltage independent.

4 – When $R_D = 29\text{nm}$, the device shows “bias voltage gap” where the tunneling current equals to zero. This bias voltage gap is equal to 0.16eV , which indicates the Coulomb blockade.

5 – All the differential conductance curves are symmetric with bias voltage polarity.

These curves show obvious maxima at certain values of bias voltage. For certain R_D , this bias voltage is found to be equal to E_D . These results illustrate that the current is tunneling through the quantum dot energy level E_D .

6 – The differential conductance spectrum becomes more broadened with increasing the quantum well width.

7 – The “bias voltage gap” increases as the quantum well width increases.

All the conclusions obtained can be used to control the electronic properties of the device and thus determine its function

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خصائص النقل لنظام نقطة كمية – بئر كمي – نقطة كمية (QD – QW – QD) مقترنة

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الملخص

درسنا نقل الإلكترون خلال جهاز نانوي لنظام ذو حصر كمي بأبعاد مغايرة. النظام هو نقطة كمية – بئر كمي – نقطة كمية مقترنة و وموضوعة بين قطبين. ثم اشتقاق أنموذج رياضي للنفق المتشاكه من نقطة كمية الى النقطة كمية الأخرى خلال البئر الكمي اعتمادا على صياغة احتمالية الانتقال. حسبت ونوقشت خصائص النقل لهذا النظام، نظام (QD – QW – QD) ، ووجد انها تعتمد على الخصائص الالكترونية لأجزاء النظام. فحصت معاملات الجهاز التي تعزز نفق الإلكترون. وجدنا مظهرين وظيفيين حصار كولوم والعلاقة الخطية لمميزة $I - eV_{bias}$.