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The Conditions of Amplification for Nano Quantum Diodes

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Abstract

It is well known that nanomaterials are described by quantum laws. In this work quantum treatment for two metal contacts or diodes on a nanoscale was done. A useful expression for the input and output current is found by using the notion of the current density in quantum mechanics. The conditions required by this contact to act as a rectifier and amplifier are discussed. It found that certain restrictions should be imposed on the potential and the wave number for the metal contact to act as an amplifier. This requires the potential barrier to be positive this requires the region of incident current to have work function less than the transmuted one.

Keywords: Amplification; nano; diode; potential barrier; quantum; work function.

1. Introduction

Diodes and transistors are commonly used in electronic circuits in order to extract the original signal from the carrier wave so as to be displayed on the display unit [1]. The diode act in these circuits as a rectifier for it allows current to flow in a certain direction and prevent it to flow in the opposite direction [2]. The transistor is utilized in these circuits to amplify signals [3]. Diodes are used in electronic circuits for rectification, while transistors are used for amplification [4]. They are widely used in integrated circuits (IC), where they are fabricated in a very small, tiny size [5]. The behavior of diodes and transistors on a micro scale is determined using quantum laws [6].

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However, the voltage current characteristics needs using the ordinary conventional electricity relations which are based on classical Newtonian laws and electromagnetic Maxwell’s equations [7]. However, for super conductors the expression of the current generated was found using quantum laws. The current density is found by using the number of electrons or free carriers which are related to the Schrodinger wave function [8]. The question now is under those conditions quantum laws give more accurate results than classical laws. According to De Broglie hypo thesis the wave nature can be observed when diffraction condition is satisfied. This requires the electron wavelength to be smaller than the distance between two adjacent atoms and crystal planes [9]. Different attempts made by M. Dirar, Rasha A.T and Asma E. to use quantum laws to describe electrical and magnetic properties of bulk matter [10]. Also, Asim M. Fadol uses quantum laws for rectification [11]. Anew transistor fabrication technique was proposed by Raghvendra k. Pandey and other researchers [12]. In this work single crystal of an oxide semiconductor in the family of $Fe_2\,TiO_5$ has been used as a substrate for the varistor. The varistor behavior was modified by superimposing a bias voltage in the current path of the varistor. This rivets the existence of embedded transistors that can act as an amplifier. This work opens a new horizon in fabricating new transistor types which can tribute to nano transistors. The work done by Michel H. Devoret and his colleagues shows that the so-called single electron transistor (SET) which obeys quantum laws can act on the nano scale [13]. It is also useful in retro low noise applications. This SET transistor can act as orange amplifying device, with sensitivity in the radio frequency (r.f) domain limited by quantum shot noise. This single electron transistor together with silicon germanium heterojunction bipolar transistor HBT which was used for orgy genic pre- amplification of SET shows very interesting properties, as shown by M. J Curry and others [14]. In their work the SET current modulates the base current of HBT. When immersed in helium liquid, the frequency response become very brad. The signal noise ratio is improved by a factor of 10 – 100 lagers than without the HBT. The transition frequency has been extended by as much as a factor of compared to without the HBT. This work shows possibility of manufacturing and improving quantum SET. Anew trend of current amplification was adopted by J. Smedley, etal [15]. In their work using hydrogenation preparation technique for diamond, it is possible to amplify the incident electron beam by a factor over 300. This comes from the fact that the number of secondary electrons emitted from diamond is more than the primary one by a factor of more than 300. E. Tafa Tulu, and others showed in their work on a photocathode unit [16] that introducing periodic rectangular groves on the cathodes surface perturb the trajectories of the secondary electrons. PIC simulation shows that most of the secondary electrons eliminate at the bottom of the grove. Thus, one can change amplification. The successes of these models motivate in using quantum laws to study amplification. This is done in section 2. Diodes are used in electronic circuits for rectification, while transistors are used for amplification. They are widely used in integrated circuits (IC), where they are fabricated in a very small tiny size. To improve the performance of IC manufacturers, tend to reduce the size of the electronic components to become smaller and smaller. The size of these components becomes now very small, in the limits where quantum effects become dominant. In this case the classical treatment of the behavior of diodes and transistors is no longer valid. An alternative approach based on quantum mechanics is needed in this case. The goal of this chapter is to find a full quantum mechanical expression for the current in diode and transistor to see the condition under which rectification and amplification is achieved.

2. Amplification Properties of Diodes for Nanomaterials

Another alternative can enable using quantum laws. This can be done if one form two metal contacts or diodes or transistors completely isolated nano particles instead of bulk matter. In this case quantum laws can complete explain their behavior. The diode is usually made from n-type and p-type semiconductor, when these are fused together a potential hill is formed. In this work a potential hill can alternatively be formed by bringing two metals of different work functions $\emptyset_1$ and $\emptyset_2$ in direct contact. The height of the potential hill (or step) becomes:

$$V_o = \phi_2 - \phi_1 \tag{1}$$

By appropriately choosing the origin of the x-axis to be at the junction of the two contacts, and choosing the origin of the potential axis to be at ϕ_1 level, Schrödinger equation for the two metal contacts become:

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E - V)\psi = 0 \tag{2}$$

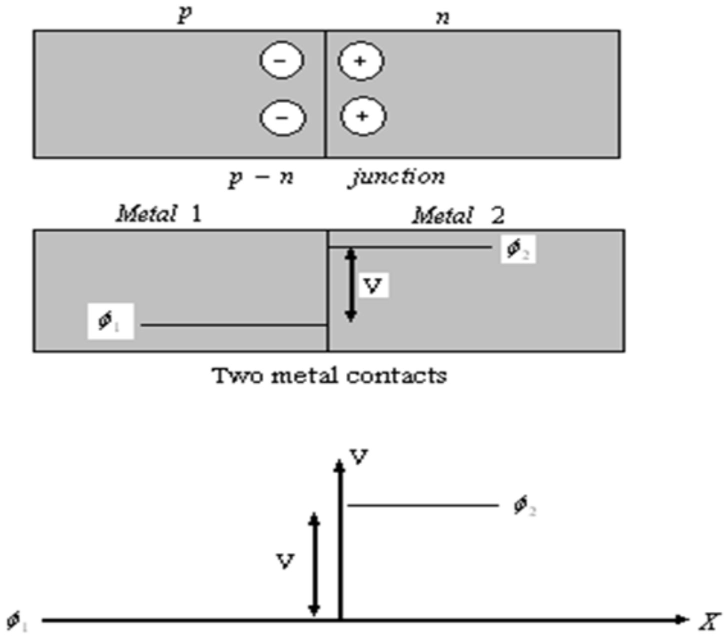

Figure 1: the potential step of p-n junction and two metal contacts.

But since the potential is described by the function

$$\begin{aligned} V(x) &= 0 \quad for \quad x < 0 \\ V(x) &= V_o \quad for \quad x > 0 \\ V(x) &= \phi_2 - \phi_1 \end{aligned} \tag{3}$$

Therefore, Schrödinger equation for metal one, where $x < 0,$ become

$$\frac{d^2\psi}{dx^2} + k^2\psi = 0 \tag{4}$$

Where $$k^2 = \frac{2m}{\hbar^2}E \tag{5}$$

For metal two, where $x > 0,$ Schrödinger equation takes the form

$$\frac{d^2\psi}{dx^2} + k_1^{\ 2}\psi = 0 \tag{6}$$

Where $$k^2{}_1 = \left[\frac{2m}{\hbar^2}\left(E - V_o\right)\right] \tag{7}$$

The general solutions are

$$\begin{aligned} \psi &= Ae^{ikx} + Be^{-ikx} \qquad for \qquad x < 0 \\ \psi &= Ce^{ik_1x} + De^{-ik_1x} \qquad for \qquad x > 0 \end{aligned} \tag{8}$$

If are multiplies the wave functions by the time dependent factor $\exp\left(-iEt/\hbar\right),$ one can interpret the terms Ae^{ikx} *and* Ce^{ik_1x} as waves prorogating in the +x direction, and the terms Be^{-ikx} *and* De^{-ik_1x} as waves prorogating in the –x direction. Since the particles is incident from the left on the barrier at $x = 0$, there cannot be a wave prorogating in the –x direction, in region $x > 0$, and hence must put D=0. Therefore, the solution becomes

$$\begin{aligned} \psi_1 &= \psi = Ae^{ikx} + Be^{-ikx} \qquad for \qquad x < 0 \\ \psi_2 &= \psi = Ce^{ik_1x} \qquad for \qquad x > 0 \end{aligned} \tag{9}$$

Where the terms

$$\psi_i = Ae^{ikx}, \quad \psi_r = Be^{-ikx}, \quad \psi_t = Ce^{ik_1x} \tag{10}$$

Represents incident, reflected and transmitted wave respectively. The corresponding current densities can be obtained by using the expression

$$J_{\psi} = nev = evn = ev|\psi|^2$$

$$J_{\psi} = ev\psi^{*}\psi = e\psi^{*}v\psi = e\psi^{*}\frac{p}{m}\psi$$

$$J_{\psi} = e\psi^{*}\frac{\hat{p}}{m}\psi = e\psi^{*}\left(\frac{\hbar}{im}\nabla\psi\right)$$
$$J_{\psi} = e\psi^{*}\left(\frac{\hbar}{im}\frac{d\psi}{dx}\right) \tag{11}$$

Where are takes the real part Re J_{ψ}

$$J = \operatorname{Re} J_{\psi} = \operatorname{Re}\left[e\psi^{*}\frac{\hbar}{im}\frac{d\psi}{dx}\right] \tag{12}$$

But before calculating J, it is important to determine the value of the unknown parameters A, B and C. since ψ is continua at $x = 0$, therefore

$$\psi_1(0) = \psi_2(0)$$
$$A + B = C \tag{13}$$

Applying the continuity of the derivatives at the same point are gets.

$$\left.\frac{d\psi_1}{dx}\right|_{x=0} = \left.\frac{d\psi_2}{dx}\right|_{x=0}$$

$$\left[ikAe^{ikx} - ikBe^{-ikx}\right]_{x=0} = \left[ik_1Ce^{ik_1x}\right]_{x=0}$$
$$ik(A - B) = ik_1C$$
$$A - B = \frac{k_1}{k}C \tag{14}$$

Adding equations (13) and (14) yields

$$2A = \left(1 + \frac{k_1}{k}\right)C$$
$$C = \frac{2k}{k + k_1}A \tag{15}$$

Using (15) in (13) are gets

$$B = C - A$$

$$B = \frac{k - k_1}{k + k_1} A \tag{16}$$

The incident current density can be obtained from (11) and (12) in the from

$$J_i = \mathrm{Re}\left[\frac{e\hbar}{im}\psi_i^* \frac{\partial \psi_i}{\partial x}\right]$$

$$= \mathrm{Re}\left[e\frac{\hbar}{im} A^* e^{-ikx} A \frac{\partial e^{ikx}}{\partial x}\right]$$

$$J_i = \frac{e\hbar k}{m} A^* A = \frac{e\hbar k}{m}|A|^2 \tag{17}$$

Similarly, the reflected current density becomes

$$J_r = \mathrm{Re}\left[\frac{e\hbar}{im}\psi_r^* \frac{\partial \psi_r}{\partial x}\right] = \mathrm{Re}\left[\frac{e\hbar}{im} B^* e^{ikx} B \frac{\partial}{\partial x} e^{-ikx}\right]$$

$$J_r = \mathrm{Re}\left[-\frac{e\hbar k}{m} B^* B\right] = \frac{e\hbar k}{m}|B|^2 \tag{18}$$

Also, the transmitted current density can be obtained using the same procedures to get

$$J_t = \mathrm{Re}\left[\frac{e\hbar}{im}\psi_t^* \frac{\partial \psi_t}{\partial x}\right]$$

$$J_t = \frac{e\hbar k_1}{m}|C|^2 \tag{19}$$

3. Current Amplification

The current J can be amplified in this contact when it flows from left to right if

$$J_t > J_i \tag{20}$$

Where the current amplification factor A_i is defined by:

$$A_i = \frac{J_t}{J_i} \tag{21}$$

In view of equations (17), (19), and (15) one obtains

$$A_i = \frac{k_1|C|^2}{k|A|^2} = \frac{k_1(2k)^2}{k(k+k_1)^2} = \frac{4kk_1}{(k+k_1)^2} \tag{22}$$

Current can be amplified if

$$\begin{aligned} &A_i = \frac{4kk_1}{(k+k_1)^2} > 1 \\ &4kk_1 > (k+k_1)^2 \\ &4kk_1 > k^2 + k_1^2 + 2kk_1 \\ &2kk_1 - k^2 - k_1^2 > 0 \\ &(k-k_1)^2 < 0 \end{aligned} \tag{23}$$

This requires that either

$$k - k_1 < 0 \qquad k < k_1 \qquad k^2 < k_1^2 \tag{24}$$

Or

$$-(k-k_1) < 0 \qquad k_1 - k < 0 \qquad k_1 < k, \quad k_1^2 < k^2 \tag{25}$$

Bearing in mind equations (5) and (7), one finds that according to equation (24)

$$\begin{aligned} &\frac{2m}{\hbar^2}(E) < \frac{2m}{\hbar^2}(E - V_o) \\ &E < E - V_o \\ &V_o < 0 \end{aligned} \tag{26}$$

This is not physically acceptable since $V_o > 0$, or according to equation (25)

$$\begin{aligned} &\frac{2m}{\hbar^2}(E - V_o) < \frac{2m}{\hbar^2}E \\ &-V_o < 0 \qquad V_o > 0 \end{aligned} \tag{27}$$

Which is in conformity with the fact that the potential is positive [see equation (3]

Hence current can be amplified if

$$V_o > 0 \tag{28}$$

The physical constraints which determine the conditions which make nano materials having spacing d or atomic spacing d to be described by quantum laws requires the diffraction condition

$$\sin\theta = \frac{\lambda}{a} \le 1$$
$$\lambda \le d$$
$$d \ge \lambda$$

Where the wavelength is related to the momentum

$$p = mv$$

According to the relation

$$d \ge \frac{h}{mv}$$

If the accelerating voltage is v it follows that

$$\frac{m^2v^2}{mv} = \frac{2emv}{\sqrt{2emv}}$$

Thus

$$d \ge \frac{h}{\sqrt{2emv}}$$

Since for electrons

$$h \sim 10^{-34}, m \sim 10^{-31}$$
$$d \ge \frac{10^{-4}}{v}$$

For fast electrons

$$v \sim 10^{5} m/s$$
$$d \ge 10^{-9}$$
$$d \ge 1nm$$

Thus the nano distance should be in the order of $1nm$.

4. Discussion

The amplification condition is related to the input and output currents one must use the incident and transmitted waves as shown by relations (17) and (19). The amplification factor in equation (22) indicates dependence on the incident and transmitted wave numbers, which are in turn, depends on the electrons energy and the height of potential barrier as shown in equations (16), (17) and (19). Equations (23), (24), (25) and (27) show that amplification condition for nano diode or two metal contacts requires positive potential barriers. According to equation (1), the work function of the region of transmitted current should be larger than that of the incident current. This is quite natural as far as this resembles the transistor situation where the base collector potential barrier is positive.

The problem with model is that it needs to give more details about nano materials that can be used to fabricate such quantum amplifiers. The fabrication on a nano scale itself is a formidable task. The trines for quantum electronic devices are bared on using photons rather than electrons. Thus quantum amplification bared on stimulated emission is more preferable. However, the use of single electron transistor (SET) [12, 13] and diamond [14] raiser a hope in fabricating quantum electronic devices using our model.

5. Conclusion

Nano diodes can amplify current without any need for building transistor. Amplification quantum conditions requires positive potential barrier. Additional constrains should be also applied on the potential difference between the two work functions of the two metals.

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