SINGLE ELECTRON TRANSISTOR (SET): OPERATION AND APPLICATION PERSPECTIVES

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ABSTRACT

The concept of miniaturization originated after the deliberation of a talk given by physicist Richard Feynman on 29th December 1959, led to the development of quantum dot (QD), which is the basic building block of single electron transistor (SET). SET is a new type of switching device used controlled tunneling of electron to amplify current. According to Moor's law, SET may be alternative of complemented metal oxide semiconductor (CMOS) device for the next generation electronic devices and sensors. This is a review article intended to consolidate the knowledge on the working principle of SET along with relevant other aspects and also highlighting the promising applications with limitation of implementations in the 21st century in order to reduce power dissipation.

Key Words: SET, QD, FET, CMOS

1.0 INTRODUCTION

The concept of miniaturization of devices is date back, which originated from the classic talk entitled "There's Plenty of Room at the Bottom" given by physicist Richard Feynman in an annual meeting of American Physical Society on 29th December 1959[1]. In his talk, he challenges the miniaturization and focuses idea on how to manipulate and control the matter in atomic and molecular levels. Finally his dream came into reality with the discovery of carbon nanotube by Sumio Ijima in 1991 at the NEC laboratory, Tsukuba, Japan. This discovery became the launching pad of Today's nanoscience and nanotechnology [2]. Since then worldwide, scientists, researchers, engineers and technologists have started to investigate a variety of ways to synthesize materials in the size of nanometer and finally led to the development of quantum dots (QD). This QD is a nanoparticle having all the dimensions reduced to below 100 nm, which is the main building block of Single Electron Transistor (SET). This SET is actually a new type of switching device that uses controlled electron tunneling to amplify current [3]. According to Moor's law every after 18 months the density of transistor in integrated circuit is becoming almost double [4-7]. The resulting fact of size reduction and power dissipation may limit the scope of further miniaturization of integrated circuit using the existing semiconductor technology (silicon based) and leads to evolve alternatives using nanoscience and technology [8]. As such, SET is expected to be an option to replace normal transistor either bipolar transistor (BJT) or field effect transistor (FET), the building block of computers, for the next generation of electronic devices like optical computers etc. However, the SET is yet in its infancy because of complexity in cost effective fabrications but still having promising applications in the next generation electronic devices and sensors. The objective of this paper is to review the fundamental understanding on operation of SET and its promising applications in the alternative devices to meet the upcoming challenges for further miniaturization and reducing the power dissipation.

2.0 TRANSISTOR

Transistor was first invented by Shockley, Brattain and Barden in 1948 [9]. Then it was integrated in a chip as integrated circuit in 1961. In 2003, it was reduced to processor consisting of millions of transistors in a chip to be used in the computer. Finally, the processor size became 22 nm by the year of 2013. As such, miniaturization of transistor has made the complemented metal oxide semiconductor (CMOS) as the workhorse of modern electronics. By the forecast of Moor's law as shown in figure-1, CMOS has attained its least most possible size and likely ending the regime of semiconductor technology.

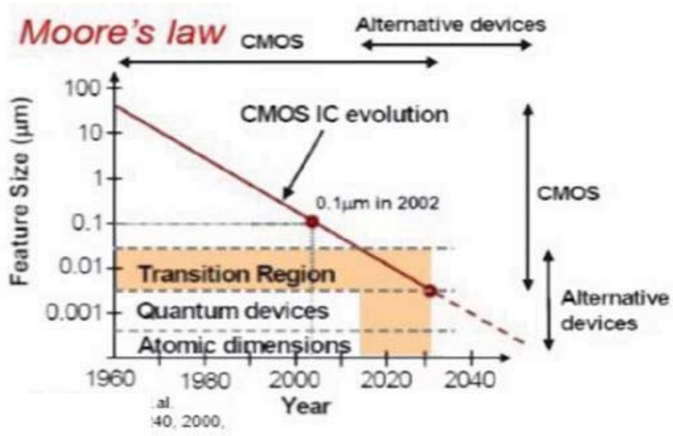

Fig-1: Graphical presentation of Moor's forecast [10]

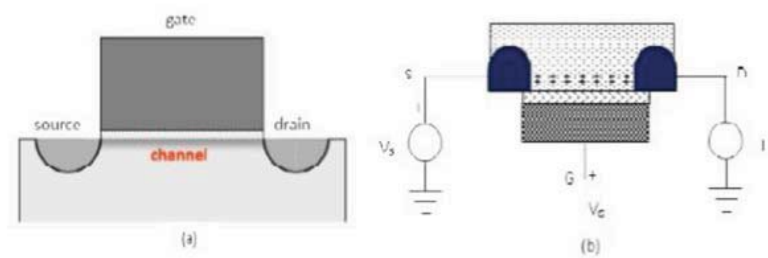

Fig-2: (a) Schematic view of Construction of FET (b) schematic view of operation of FET

Field Effect Transistor (FET) is a three terminal switching device used in computers as well as electronic devices. The three terminals are source (S), drain (D) and gate (G) [11]. It is of two kinds such as n-channel and p-channel depending on the type of material of channel. They are broadly classified as bipolar transistor (BJT) and field effect transistor (FET). Complementary metal–oxide–semiconductor (CMOS) is the latest version of FET [12]. The FET is constructed with n-type (n-channel) or p-type (p-channel) semiconductor as channel and one or two gate consisting of p-type (for n-channel) or n-type (p-channel) semiconductor separated from the channel by insulating layer as shown in figure-2(a).

Principle of Operation

In its operation, the drain-to-source voltage (VDS) provides current through the channel. The gate voltage (VGS) controls the current (electrons) flow through the channel by depleting immobile opposite charge layers as shown in figure-2(b). Notable here, millions of electrons flows through the channel in its operation and maximum of them dissipated as heat, which ultimately heats up the device and radiates out. The resulting effect is therefore power loss. Further miniaturization and power dissipation are the challenges, which may be meeting by the use of SET in the next generation technology. By the time, the fabrication of SET has been possible in the laboratory, wherein QD is the main part, but yet to be publicly available in the market with any devices.

3.0 QUANTUM DOT (QD)

When all the three dimensions of a material reduced to the nanometer range, then this material is called quantum dot (QD). It may have cubical or spherical shape. When the material dimensions reduce then the delocalized electrons become localized and confined with discrete energy levels, which can be called quantized. As such, they behave like an atom and therefore sometimes referred to as artificial atom [13]. Accordingly, its electrical and optical properties depend mostly on its size and geometrical structure of the quantum dot (QD).There is metallic and semiconductor QDs. The metallic QD used in the construction of SET. The density of quantum energy states of localized electrons depend on the size of QD. The smallest QDs have the compressed quantum energy states whereas the biggest QDs have spaced quantum energy states of localized electrons as shown in figure-3.

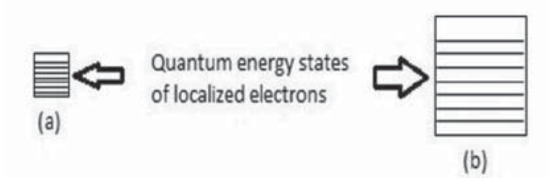

Fig-3: (a) Smallest QD and (b) biggest QD

4.0 SINGLE ELECTRON TRANSISTOR (SET)

A single electron transistor (SET) is a new type of switching device that uses controlled electron tunneling to amplify current. This transistor is constructed based on quantum mechanical principle. The single electron transistor is similar to the normal transistor (FET) except the channel is replaced by QD. The QD is separated by thin insulators from both the source and drain. The thin insulators act as tunnel barrier between source to QD and QD to drain. The gate is connected to the QD by a capacitor, Cg. as shown in figure-4. In SET, electron tunnels in two steps such as source to dot and dot to drain. The gate voltage Vg controls the charge on this capacitor Cg.

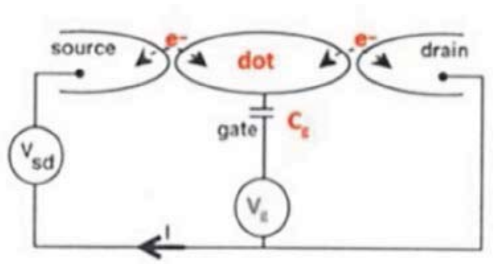

Fig-4: Construction of SET

Working Principle

The metallic QD, which is separated from the source and drain by the thin insulators, is capacitively coupled to the gate as shown in figure-5(a). This gate controls the tunneling current across the tunnel barrier and operates on the principle of coulomb blockade.

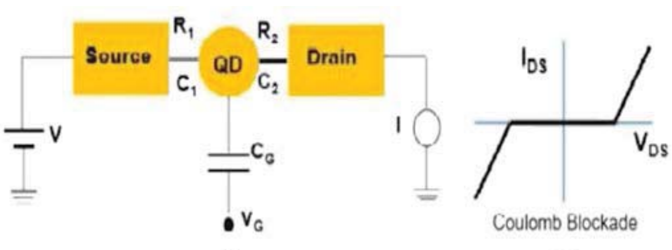

Fig-5: (a) Circuit of SET (b) Coulomb Blockade

The energy needed to charge the capacitor is e^2 /2. It is typically 80 meV [1]. If this energy is not supplied to the system electron transport will be blocked at sufficiently lower temperature, this is known as coulomb blockade (CB) as shown in figure-5(b). The working principle with the help of biasing is discussed below:

Under no bias condition, the transportation of electron from source to drain will not take place because the Fermi levels of both the source and drain will be in the same level and the localized as well as quantized electrons are in quantum mechanically confinement as discrete energy levels and provides coulomb blockade in QD. This situation is shown in figure-6(a).

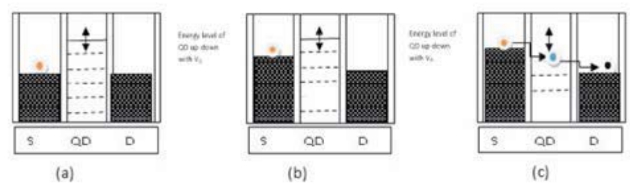

Fig-6: (a) No bias (b) with bias, VDS (c) with gate voltage, VG

Now if a bias voltage applied between drain to source (V_{DS}), then the Fermi level of sources, S will go up and of drain, D go down by the amount of energy /2, which cause off Fermi levels between source and drain. This situation is shown in figure-6(b). In this case, electron may transfer from source to QD but without gate voltage (V_G) it will not happened because for an extra electron, the energy of QD will be increased by the same amount, which is contrary to the principle of conservation of energy of the system. As such, by sweeping the gate voltage for a fixed drain to source voltage, V_{DS}, the tunneling of one electron through the QD in a fashion source to QD and QD to drain is possible to make. In that, when a gate voltage, VG is changed by ΔV_g=e /C_g, then for a certain situation, the whole energy levels of QD go down below the Fermi level of source region but remain above the Fermi level in the drain region as shown in figure-6(c). Under this condition, electron from source will hope to the QD and from QD to drain. Accordingly, the laws of conservation of energy will be maintained inside the QD. By thus gate controls tunneling of one electron from source to drain. This is the working principle of SET.

Now if a curve for drain current, I as a function of gate voltage, V_G is plotted then the current spike will be obtained every after e/C_g volt as shown in figure-

6(a). For different gate voltage, V_G by changing the bias, V_{DS} the current, I will increase, which is shown in figure-6(b). If both the bias is simultaneously changed and plot the data as V_{DS} vs. V_g, then the coulomb diamond will be obtained as shown in figure-6(c).

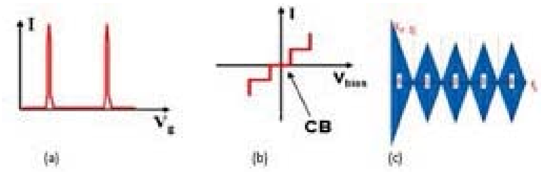

Fig-6: (a) I vs. Vg (b) I vs. VDS (c) VDS vs.Vg

5.0 DISTINCTIONS BETWEEN FET AND SET

Although SET is similar to normal transistor (FET), but there are differences between them in same aspects as given in tabular form:

Table-1: Differences between FET and SET

Aspect	FET	SET
Mode of operation	All electrons move through the channel from source to drain directly, where gate voltage controls the number of electron.	Only one electrons hopes the tunnel barrier and passed through the source to QD and QD to drain
Mode of switching	When electrons ar e added to the semiconductor then switch on which represents logic 1 and when remove them the switch off which represent logic 0 in the computers.	Switch on or off is controlled only by one electron. As such it is faster than FET in its switching operation
Power dissipation	While moving electrons through the channel causes heat to the system or device due to their collisions and the generated heat is dissipated by radiation from the device.	Single electron hopes from the source to QD and QD to drain in its operation, it does not heat up the system or device. So almost no power dissipated by radiation from the device.
Tunnel barrier	It does not have tunnel barrier rather there is depletion region of positive charge inside the channel to control the flow of electrons	It has tunnel barrier which is developed between source and QD, and QD and drain because QD is separated from both the source and drain by a thin insulating materials.
Coulomb blockade	It does not have coulomb blockade (CB)	It has Coulomb blocked, which equals to e^2/C_g
Linking	Normal conductor wire is sufficient enough to outside environment linking.	A quantum cellular automation (GCA)[1] the best option to form a circuit link with the outside environment.
Current Carriers	Millions of electrons are the current carriers in conduction bands in the semiconductor used as channel.	Electrons are densly packed in QD and also localized by quantum mechanical confinement.

[1]The static electronic force is to link up between the basic clusters and QD to form a circuit linked by cluster, which is called quantum cellular automata (QCA).

6.0 PROMISING APPLICATIONS OF SET

The SET used in a variety of applications as describe below:

a. The SET are efficient charge sensors for reading out the spin or charge qbits confined in QD. The SET can be used as an efficient probe of signal-to-noise ratio both for dc and radio frequency single shot measurement [3].

b. The SET can effectively detect infrared signal at the room temperature and therefore can serve as IR sensor in sophisticated device like IR camera.

c. The SET can be used as extremely sensitive and potentially useful detector of microwave wave radiation.

d. The high sensitivity of SETs has enabled them to be used as supersensitive electrometers in unique physical measurements.

e. Another application of single-electron electrometry is the possibility of measuring the electron addition energies (and hence the energy level distribution) in quantum dots and other nanoscale objects [3].

f. The problem of leakage current is solved by the use of another logic device name charge state logic in which single bits of information are presented by the presence/absence of single electrons at certain conducting islands throughout the whole circuit [13]. In these circuits the static currents and power vanish, since there is no dc current in any static state.

g. An SET having nonvolatile memory function is a key for the programmable SET logic.

h. One new avenue toward a new standard of absolute temperature can be developed by the use of 1D single-electron arrays [3].

k. The single-electron transistors can be used in the "voltage state" mode.

7.0 LIMITATIONS OF SET IMPLEMENTATIONS

Despite variety of applications, SET implementation in the device has some limitations as discussed below:

a. The first major limitation with the single electron logic circuits is the randomness of the background charge [13].

b. The another big limitation with all the known types of single electron logic devices is the requirement Ec~100kB T, which in practice means sub-nanometer island size for room temperature operation[14].

c. Outside environment linking with SETs by normal wire connection is another limitation considering the size of SET [3, 14].

d. Lithography technique is another major limitation with single electron devices because of difficulty in fabrication at room temperature [3, 14].

e. The rate of coherent quantum mechanical process is crudely less than that for the single-electron-tunneling.

8.0 CONCLUSION

SET is similar to the normal transistor (FET) only the exception is that QD replaces the channel of FET. QD is separated from both the source and drain by thin insulating material. The insulating layers act tunneling barriers. The tunneling barriers need to overcome to hop electron from source to QD and QD to drain. In SET, QD is capacitively connected with the gate. This gate controls the electron to hop by changing the quantum energy states of electrons those are quantum mechanically confined in the QD. In FET, millions of electrons flow through the channel dissipated as heat due to collision of electrons. But in SET one electron passes the through QD, so no heat generates and does not dissipated as heat radiation.

In QD the delocalized electrons become localized and confined with discrete energy levels, which can be called quantized. This quantized energy states in the QD can move up and down (i.e. varies) according to the voltage applied to it. This variation of quantized electrons gives rise to unique electrical and optical property. SET has numerous promising applications such as, charge sensors, microwave detector, infrared detector, supersensitive electrometer etc. Despite these promising applications, SET has some limitation of its implementations, such as lithography, background charge etc.

ACKNOWLEDGEMENT

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