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# A Brief Review towards Set and Its Applications

Renu Mehla[1], Bal Krishan[2], Neelam Bedwal[3]

M.Tech. Student, Dept. of Electronics Engg., YMCAUST, Faridabad, India[1,3]

Assistant Professor, Dept. of Electronics Engg., YMCAUST, Faridabad, India[2]

**ABSTRACT:** Single-electron transistor (SET) is a vital element of todays research world of nanotechnology which can offer high operating speed and low power consumption. Scalability implies that the performance of electronic devices increases with a decrease of the device dimensions. Single electron transistor [SET] is a recent nanoscaled switching device as it keeps its scalability even on an atomic scale and can also control the movement of a single electron. As Power consumption is roughly analogous to number of electron transferred from voltage source to the ground in diverse logic operations. Thus, the single- electron transistor [SET] is generally used as an ULSI element to minimize the power consumption of ULSIs. Therefore, the Single electron transistor [SET] can give low power consumption and the controlled tunnelling of a single electron forms its high operating speed. The SET's physical size is quite small and as its size is reduced, its performance, such as ON-OFF current ratio, upgrades. Thus,the SET can be taken as promising device for various large scale and low-power integrated circuits . The theoretical study of single electronics also involves Coulomb Blockade, Kondo Effect that is beneficial in a number of applications are also discussed here. The main objective of this paper is to discuss about the fundamental physics of nano electronic device ‘Single electron transistor [SET] which is able of controlling the transfer of a single electron.
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**KEYWORDS**: SET, structure of SET, Coulomb blockade, single electron tunnelling, Quantum Dot .

## I. INTRODUCTION

Scaling down of electronic device sizes has been the elemental approach for enhancing the performance of ultra-large-scale integrated circuits (ULSIs). Metal-oxide-semiconductor field-effect transistors (MOSFETs) have been the most prevasive electron devices for ULSI applications, and therefore the sizes of MOSFETs has been scaled down and so, it is the basis of the enlargement of the semiconductor industry from the last 30 years. The scaling of CMOSFETs is entering the deep sub-10 nm regime in the early years of the 21st century,. In this deep-nanoscaled regime, fundamental limit of CMOSFETs and technological problems faced with scaling down of CMOSFETs are encountered . On the other side, quantum-mechanical effects are expected to be fruitful in small sized devices. Therefore, in order to enlarge the tremendous progress of LSI performance, it is requisite to introduce a new device having an operation principle which may utilize the quantum- mechanical effects and is effective in smaller dimensions , thus yield a new functionality beyond that obtainable with CMOSFETs.

Single-electron devices are current nanoscaled promising devices because they retain their scalability even on an atomic scale[1] and, additionally , they can control the movement of even a single electron. Consequently, if the single-electron devices are taken as ULSI elements, the ULSI will have the attributes of tremendously high integration and immensely low power consumption. The idea of SET was divulged by Millikan at beginning of the century, but it was not implemented in solid state physics until the late 1980's. The first observation of the Coulomb blockade and hence single electronics was done by Gorter in 1951.

Since a decade , Single-electron transistor (SET) is extremely popular in the research field of nanoelectronics. Single electron transistor (SET) is the most basic three-terminal single electron device (SED) which is capable of offering low power consumption and high Operating speed. As the technology scales down to nano size, the demeanour of a nanoelectronic single electron transistor (SET) is controlled by the quantum mechanical effects.

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## II. CONCEPT OF SINGLE ELECTRONICS

A single electron transistor (SET) may be reviewed as a field effect transistor (FET) whose channel have a small and low capacitance (C), conducting Island [Quantum Dot] which is coupled to the source and drain having two tunnel junctions and capacitively coupled to one or more than one gate which is used to control the transfer of single electron from the source to drain. Here, the tunnel junction acts as a thin insulating barrier between two conducting electrodes. The SET is used in a single electronics regime in which only one electron can move from source to drain via quantum dot by applying constant gate voltage on the island[1]. Single electron device is based on an quantum phenomenon known as the Tunnel effect and this single electron tunnelling technology presents the ability to control the movement of one electron.

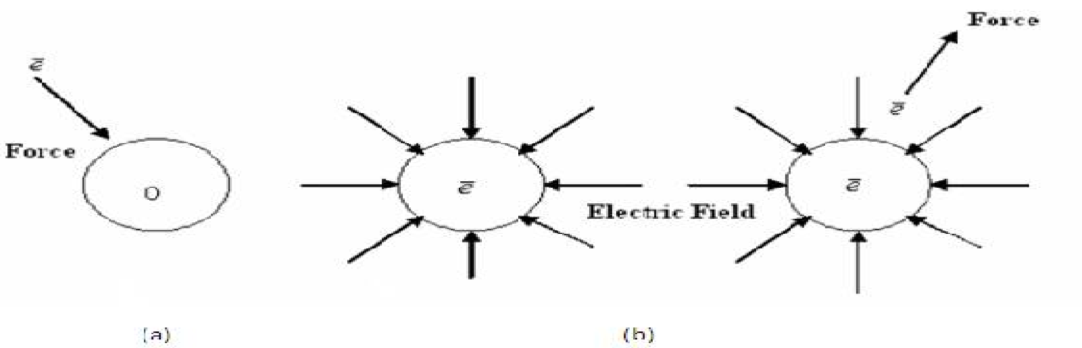

Fig.1. An electron feeling a small attractive force as it comes near to a sphere. b) Once sphere gets charge by a single electron; other electrons will undergo a strong repelling force

Single electronics is the fundamental notion behind devices single electronic likes single electron transistors (SETs) that can be described by assuming a small metallic sphere, as shown in fig 1. , initially it is electro-neutral i.e. the net charge on the sphere is zero because of the same number of electrons and protons in it[1]. Now, assume that a single electron is placed close to the sphere. In this state, that single electron gets attracted by sphere. Thus, it joins the sphere and leaves negative charge of –e on it. Now an electric field is created around the sphere because of the presence of this negative charge so that if any other electron comes close to this sphere, that electron will face a high repulsive force employed by the electric field created around the sphere.

The notion behind the single electronics reveals that charging energy or electrostatic energy, which is given by:

Ec = e2/2c provides the more accurate computation of the strength of this tunnelling effect .

The charge and discharge of tunnel junction and thermal fluctuations are closely associated to each other.

## III. SET SCHAMATIC STRUCTURE

In a single electron transistor, a source and drain electrode are connected via a tunneling junction to an island, which is also capacitively coupled to a gate.. Quantum dot is a very small conducting island that contains a tunable number of electrons occupying discrete orbitals. Quantum dot is having its dimensions less than 100 nm in diameter. When all the biases are zero, electrons do not have sufficient energy to tunnel through the junction[2].

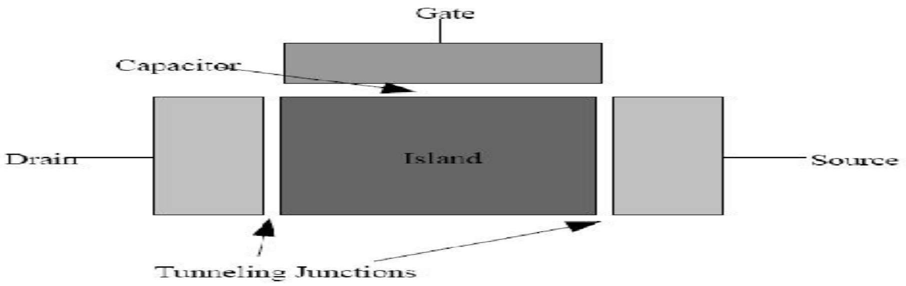

Fig.2. SET structure

When gate electrode is positively biased ,the energy levels of the island electrode get lowered[2]. The electron can tunnel onto the island and occupying a previously vacant energy level. From there it can tunnel onto the drain electrode where it inelastically disperses and reaches the drain electrode Fermi level.

## IV. BASIC PHYSICS OF SET OPERATION

Single Electron Transistor [SET] has been made with critical dimensions of just a fewnanometer using metal, semiconductor, carbon nanotubes or individual molecules. A SET comprises of a small conducting island [Quantum Dot] which is coupled to source as well as drain via tunnel junctions and capactively coupled to one or more than one gate. Unlike Field Effect transistor, SET based on an intrinsically quantum phenomenon, the tunnel effect[1].

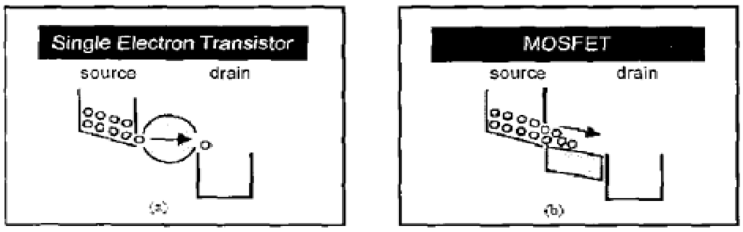

Fig.3. (a) one-byone electron tunneling of electron through channel in SET (b)Transfer of many electrons simultaneously through the channel in MOSFET.

The electrical nature of the tunnel junction depends on how effectually barrier transfer the electron wave, which reduces exponentially with the thickness, which is given as the area of tunnel junction divided by the square of wave length. Quantum dot [QD] as shown in figure 4. is a mesoscopic system in which the insertion or removal of a single electron can effect in electrostatic energy or Coulomb energy that is more as compared to the thermal energy and can control the electron transportation in and out of the QD.

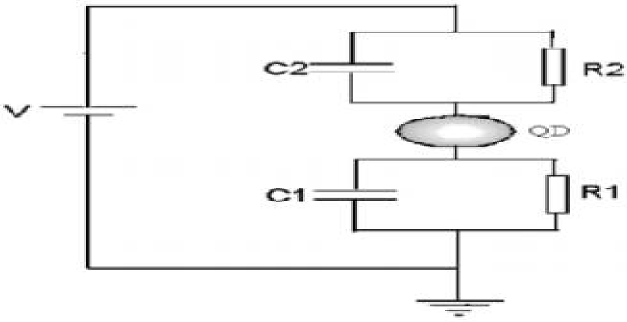

Fig.4. Quantum Dot Structure

The resistance is determined by the tunneling of electron and the capacitance that depends on the size of the particle. We symbolize the resistors and capacitors by R1, R2, C1 and C2, and the applied biased voltage between the electrodes by V. We will study how the current, I depends on V. When we start to increase applied voltage from zero, no current flow between the electrodes. When the voltage applied between the source and drain is greater than e/c (e/2c across each junction), electrons actively tunnel across the junctions, and current starts flows through the transistor independent of the gate bias and this bias voltage is known as Coulomb gap voltage. In quantization of electron flow, noted as the Coulomb staircase, the thermal energy of the system must be much smaller than the Coulomb energy. As the gate voltage grows, current also increases in quantized chunks. This means that in order for a single electron transistor to work at room temperature,

$$Kt << e^2/2c$$

$$C << e^2/2KT \approx 3.09\times10{-}18F$$

The capacitance C must be much less than 3.09x10-18 F. The capacitance is linked to the distance between two sides of the junction, giving that $C << 3.09\times10^{-18}F \Longrightarrow d < 10\ nm$

The diameter of the island(d) must be less than 10 nm. When the bias between the source and drain is less than the coulomb gap voltage, the transistor mode of operation occurs. In this case, when the gate bias is increased to the level corresponding to the maximum slope on the coulomb staircase (i.e. right before a jump in current), the configurations on the island with zero or one extra electron have equal energies, abolishing the coulomb barrier and thus allowing tunneling to occur. This maximum point comes when the gate is charged with exactly minus half an electron. When another minus half an electron charge is set on the gate, the coulomb barrier is rehabilitated, resulting in an oscillation in conductance of the transistor with the maxima at half integer multiples of e and minima at integer multiples of e.

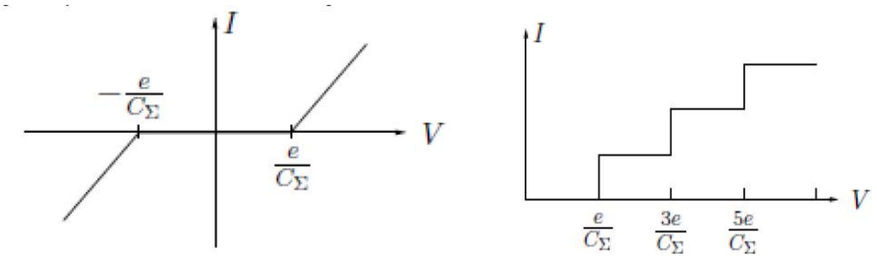

Fig.5. I-V Characteristics for (a) Symmetric junction circuit (b) Asymmetric junction circuit

Fig. 5(a) predicts the I-V Characteristics of the symmetric junction circuit of SET where C1=C2 and R1=R2. It is explicit from the IV- characteristics of the SET that for |V|< e/C, the current doesn't flow. This state is called Coulomb blockade that conceals the tunneling of single electron in state of low bias condition. Now, if the externally applied junction voltage V is enlarged up to a point that is above the threshold voltage by charging energy, this effect of Coulomb blockade can be diminished and the current flows. In this condition , the junction behaves as a resistor. The sequential entrance and leaving of an electron from one junction to another is mainly known as "Correlated tunneling of electrons".

Fig. 5(b) predicts the I-V Characteristics of a highly asymmetric junction for R1<<R2. In this state , the charge carriers i.e. electrons enter through one junction and then escape to second junction due to the existence of high resistance. Now, electrons start moving from one junction to another very speeedly. Thus this speedy movement of excess electrons from one junction to another escalates the total charge of the island. If the bias is raised, it will tend to enlarge the populace of electrons in the island.So, the I-V Curve represents Stair-like characteristics, which are frequently referred to as the "Coulomb Staircase"[1].

## V. PRINCIPLE OF SINGLE-ELECTRON TUNNELING & COULOMB BLOCKADE

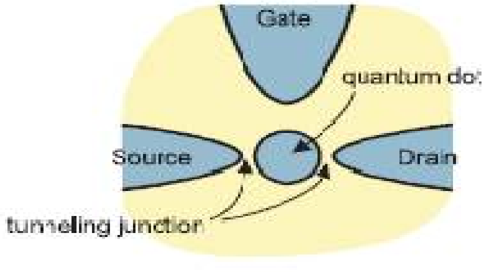

Fig.6. Schematic structure of SET showing tunnel junctions

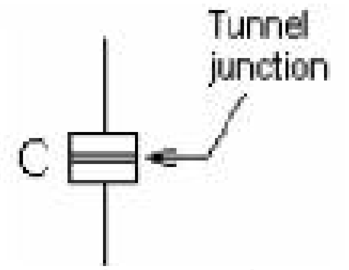

Fig.7. Tunnel junction or Insulating Barrier

As shown in fig 6 & 7, a tunnel junction is referred as a thin insulating barrier between two conducting electrodes source and drain. In theory of classical electrodynamics, zero current flows through an insulating barrier. But according to theory of quantum mechanics , there is some possibility (i.e. more than zero) for an electron positioned at one side of the barrier (tunnel junction) to move the other side. Thus, the transport of electrons through the barriers between the quantum dots would effect in charging of neighboring quantum dots. Now,as a consequence ,there is an increase of the electrostatic energy which is given by:

$$EC=e^2/2c \qquad (1)$$

The coulomb blockade can be obtained only if, in case, when these three conditions meet:

1. The bias voltage must be smaller than the elementary charge divided by the self-capacitance of island.
   i.e. $Vbias < e/C$
2. The thermal energy KBT must be lower than the charging energy i.e. $KBT < e^2/C$; or else the electron will be skilful to cross the quantum dot (QD) via thermal excitation.
3. The tunneling resistance (RT) should be larger than $h/2\pi e2$, which is obtained from „Heisenberg‟s uncertainty principle‟. i.e. $RT > h/2\pi e2 = 25813\Omega$. This is the required condition for tunnel resistance.

## VI. APPLICATIONS

As SET has many advantage like its small size, low energy consumption and high sensitivity, so,it found a large no. of applications in many areas. What's most thrilling is the potential to fabricate them in large scale and use them as common section in modern computer and electronic industry .Various applications of SET are as follows:

### A. *Charge Sensor:*

The Single-electron transistors (SETs) are well organized charge sensors for reading out spin. To scrutinize their capacitive parameters, which are allied to the signal-to-noise ratio (SNR) during quantum bits readout, twin silicon single QDs were designed using a lithographic process on a silicon-on insulator (SOI) substrate. Since the configuration and dimensions of the QDs could be found by direct imaging, measured parameters could be compared to the theoretical capacitive values. Validity of the calculation method was confirmed by good agreement between the calculated and measured value. The results showed that decreasing the SET diameter minimizes the capacitive coupling among quantum bits but increases the signal-to-noise (SNR)ratio for dc and radio frequency both single shot measurements. As these results are independent of the device materials, they are helpful for building guidelines for the designing of SET charge sensors in lateral QD-SET structures based on a 2D electron gas.

### B. *Single-Electron Spectroscopy:*

Another most significant application of single-electron electrometry is the possibility of estimating the electron addition energies (and thus the energy level distribution) in quantum dots and some other nanoscale objects[3].

### C. *DC Current Standards:*

One of the feasible applications of single-electron tunneling is basic standards of dc current for such a standard a phase lock SET oscillations or Bloch oscillations in a standard oscillator with an external RF source of a characterized frequency f. The phase locking would give the transfer of a definite number m of electrons per period of external RF signal and hence generate dc current which is fundamentally linked to frequency as I= mef.Single-electron transistors (SETs) are well organized charge sensors for reading out spin. To scrutinize their capacitive parameters, which are allied to the signal-to-noise ratio (SNR) during quantum bits readout, twin silicon.

### D. *Detection Of Infrared Radiation:*

The measurement of the photo response of single-electron systems to electromagnetic radiation with frequency $\sim EC/\hbar$ have shown that usually the response varies from that the popular Tien-Gordon theory of photon-assisted tunneling. However, this is based on the presumption of independent (uncorrelated) tunnelling events, whereas in single-electron systems the electron transfer is typically correlated. This feature implies that single-electron devices, especially 1D multi-junction array with their low cotunneling rate, can be utilized for ultra-sensitive video- and heterodyne detection of high frequency electromagnetic radiation, close to the superconductor-insulator superconductor (SIS) junctions and arrays.[4]

E. *Voltage State Logics:*

The single-electron transistors may be used in the "voltage state" mode. In this mode, the input gate voltage U directs the source-drain current of the transistor that is utilized in digital logic circuits, similarly to the usual field-effect transistors (FETs). This implies that the single electron charging effects are restricted to the interior of the transistor, while externally it looks like the standard electronic device switching multi-electron currents, with binary unity/zero given by high/low dc voltage levels (physically not quantized). This idea simplifies the circuit design which may disregard all the single-electron physics particulars[4]. One major disadvantage of voltage state circuits is that neither of the transistors in each corresponding pair is closed too well, so that the static leakage current in these circuits is fairly considerable, of the order of 10-4e/RC. The corresponding static power consumption is insignificant for comparatively large devices working at helium temperatures.

F. *Charge State Logics:*

The main issue of leakage current is resolved by using another logic device name charge state logic in which single bits of information are given by the presence/absence of only one electron at certain conducting islands all over the whole circuit. In these circuits the static currents and power disperse, since there is no dc current in any static state.[5]

## VII. PROBLEMS IN THE SET IMPLEMENTATION

A. *Back Ground Charge:*

The first crucial issue regarded to the single electron logic circuits is the unscrupulous randomness of the background charge. A single charged impurity confined in the insulating environment polarizes the island, creates an image of charge Q0 on its surface of the order of an e. This charge is effectively deducted from external charge Qe.

*B. Out Side Environment Linking With SETs:*

The descrets structures patterns which perform as logic circuits must be oraganised in to larger 2D patterns. There are two ideas, first is to amalgamate SET as well as related equipments with the existing MOSFET, this is agreeable as it can enhance the integrating density. The second one is to give up linking by wire, instead employing the static electronic force among the fundamental clusters to form a circuit linked by cluster,called quantum cellular automata (QCA). The main advantage of QCA is its first information transfer velocity between cells through electrostatic interaction only, no wire is required between arrays and the size of each cell may be as short as 2.5 nm, it makes them very acceptable for high density memory and next generation quantum computer.

*C. Room Temperature:*

The another major issue with all known types of the single electron logic devices is the demand of Ec~100kB T, which generally means sub-nanometer island size for room temperature operation. In such small size conductors the quantum kinetic energy provides a supreme contribution to the electron additional energy even small alterations in island shape will results to dubious and rather significant variations in the spectrum of energy levels and hence in the device switching threshold.

*D. Lithography Technique:*

Another big issue with single electron devices is the demand of Ec~100kB T, which generally means sub-nanometer island size for room temperature operation. In the VLSI circuits, this fabrication technology level is very tough. Additionally , even if these nano sized islands are fabricated by any kind of nanolithography, their structure will hardly be absolutely in defined pattern.

*E. Co-Tunneling:*

The pressure abstraction of the effect is that the tunneling of various electrons through disparate barriers at the same time is realizable as a single coherent quantam mechanical process. The rate of the process is crudely less than that for the single electron tunnelling.

## VIII. CONCLUSION

This research paper focuses on the theoretical discussion of fundamental principle of Single electron transistor and its significance in the age of nanotechnology to yield low power consumption and high operating speed in the area of ULSI design for the fabrication of several electronic devices. SET has evinced its value as tool in scientific research area. Resistance of SET is measured by the electron tunnelling and the capacitance depends upon the size of the nanoparticle. The main issue in nanometer era is the fabricating nanoscale devices. The current starts flowing through the junction when applied voltage is just adequate to enhance the energy of electron above the coulomb blocked, this is said to be threshold voltage Vth.and the flat zero current continue for 2Vth.

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## BIOGRAPHY

**Renu Mehla** is a M.Tech. Student (VLSI Design) in Electronics Engineering Department, YMCA University of Science and Technology, Faridabad. Her research interests are VLSI Design , Electronics Engineering.

**Bal krishan ,**Assistant Professor, Electronics Engineering Department, YMCA University of Science and Technology, Faridabad,Haryana-121006, India; B.E. (Electronics & Communication Engineering), M. Tech, (Nanotechnology), Ph. D. (pursuing). He has published 28 numbers of papers in various International & National Journals & conferences. His research area: Nanoelectronics & Devices, VLSI Design , Electronics Engineering.

**Neelam Bedwal** is a M.Tech. Student (C&I) in Electronics Engineering Department, YMCA University of Science and Technology, Faridabad. Her research interests are Control engineering and Electronics Engineering.