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A Brief Review Towards Single Electron Transistor

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***Abstract*— Recent research in SET gives new ideas which are going to revolutionize the random access memory and digital data storage technologies. The goal of this paper is to discuss about the basic physics and applications of nano electronic device 'Single electron transistor [SET]' which is capable of controlling the transport of only one electron. Single-electron transistor (SET) is a key element of current research area of nanotechnology which can offer low power consumption and high operating speed. The single electron transistor is a new type of switching device that uses controlled electron tunnelling to amplify current.**

Keywords- Theory of single electronics, Operation principle of SET, Thesis associated with SET: Orthodox theory, Kondo effect, tunnelling effect, Application of SET: logic, Supersensitive electrometer etc, MOSFET's and SET's, Limitations of SET's, Scope of SET's.

I. INTRODUCTION

The semiconductor transistor has been one of the most remarkable inventions of all time. It has become the main component of all modern electronics. The miniaturization trend has been very rapid, leading to ever decreasing device sizes and opening endless opportunities to realize things which were considered impossible. To keep up with the pace of large scale integration, the idea of single electron transistors (SETs) has been conceived. The most outstanding property of SETs is the possibility to switch the device from the insulating to the conducting state by adding only one electron to the gate electrode, whereas a common MOSFET needs about 1000–10,000 electrons. The Coulomb blockade or single-electron charging effect, which allows for the precise control of small numbers of electrons, provides an alternative operating principle for nanometre-scale devices. In addition, the reduction in the number of electrons in a switching transition greatly reduces circuit power dissipation, raising the possibility of even higher levels of circuit integration.

II. OPERATION PRINCIPLE

The basic principle of operation of single electron devices is completely discrete in nature since only one single electron is tunneled through a nanoscale junction unlike MOSFET which involves more than one electron transfer. The electron transfer takes between the two tunneling junctions, forming *quantum dots*, one by one. [1]

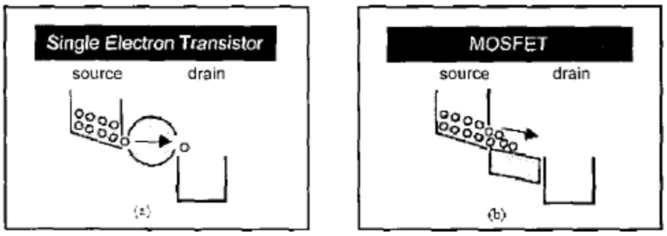


Figure 1 - Transfer of electrons is one by one in SET shown in (a) which is completely in contrast with the conventional working of MOSFET shown in (b)

[7] Let us consider N and N^1 be the number of electron to be transferred between the two tunneling junction, where n = N - N^1 and p be the charge flow index where, p= $N+N^1/2$. As, the electrostatic energies remains constant, let us consider n and $(n)^*$ for the initial and next stages. It is thus observed that the transport voltage for $(n)^{*\ \text{stage}}$ is less than *eV* volts when compared to n stage, hence has no absolute stable states. But for the electron to get transferred from n to $(n)^*$ it needs to attain pre – level as (n-1) and next level (n+1) since tunnel effects takes place one at a time. This is where the single electron *Coulomb energy* $E_c = \frac{e^2}{2C_\Sigma}$ where $C_\Sigma = C+C^1+C_g$, where C and C^1 are two junction capacitances. Now we need to consider the following cases for studying the transfer of electrons between the two tunneling junctions:

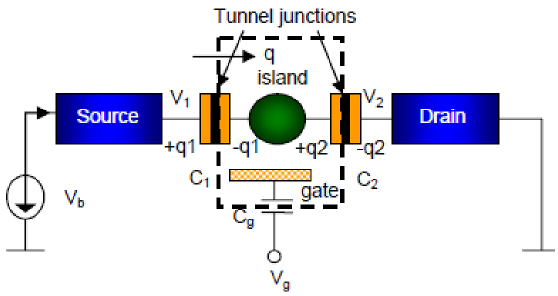


Figure 2 - Schematic Diagram for a Single electron transistor circuit

Case I: When gate voltage U is to ZERO

During this state the state levels (n-1) and (n+1) levels, i.e. (-1) and 1 that are the energy state levels above and below the state level 0, have approximately same E_c which can be defined as, $E_c - eV/2 \sim E_c$. At low temperatures this will provide *Coulomb Barrier*, wherein the current *I* is zero. This condition is referred to as *Coulomb blockade effect.* Reference [15]

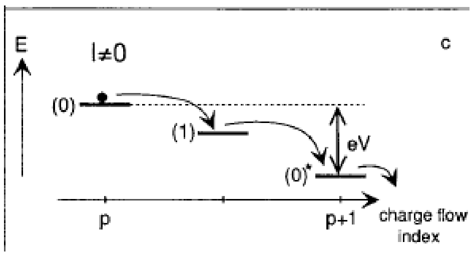


Figure 3 -- Energy transfer when *(CASE I)* U=0 and (*CASE II*) U=e/2C_g

Case II: When the control voltage is U=e/2C_g

When the control voltage is U=e/2C_g, the energy states of the levels 0 and 1 become nearly equal as shown in fig(2). Hence, when the energy of state 1 is lowered than the energy at state 0, the transition 0 → 1 becomes possible, and the electron transfer is achieved from the first junction. This condition can be referred to as *Coulomb Oscillations*. Reference [15]

Therefore, a series of transition is received for n state levels for further working.

I. Theory Of Single Electronics:

Recent development in single electron structures in the field of nanotechnology has made it very evident to know the theoretical aspects behind the single electron effects. Thus in the following section the theoretical aspects that helped in the evolution of single electron devices is discussed.

A. Orthodox Theory:

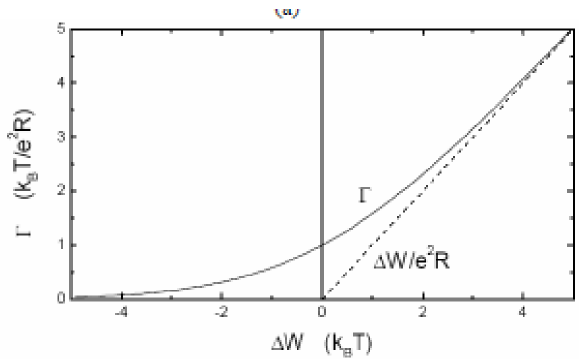
Initially, K.Likharev [1] developed the orthodox theory that marks the history of development of single electronics. According to this theory various assumptions were formulated so as to define the working principles of *Coulomb Blockade* and *Coulomb Oscillations.* Following assumptions were made regarding the same:

1. The electron energy quantization is considered to be continuous.
2. The required time for electron tunneling through the barrier needs to be considered negligibly small compared to all other time including the time interval between the neighboring tunneling events of the order 10^{-15} sec.
3. Cotunneling needs to be ignored. For this purpose following needs to be considered:

$R>>R_Q$, $R_Q=h/e^2 \sim 25.8k\Omega$

Where R=Resistance of the tunnel Barriers and R_Q=Quantum unit of Resistance.

This condition ensures that the electron transfer that takes place is one at a time.



(a)Single electron tunneling rate Vs Energy Loss W where, R is the resistance of the tunnel Barrier, e is the electron charge, k_B is the Boltzmann constant and T is the Temperature.

Even though, the proposed theory meets limitations, it evidently is able to give qualitative description for the same in case of semiconductors. The important conclusion of the orthodox theory is that the rate of tunneling events depends on the charge in free energy in the sequence of events that is discussed in the *reference [2]*.

B. Tunneling Effects:

Reference [16] -The tunneling effects can be completely defined under the phenomenon of *Transmission probability* and *tunnel rate*. *Transmission probability* can be defined as the ratio of the squares of the amplitudes of transmitted and incoming wave packets. Wave packets are nothing but the electrons that hit the potential barrier. It is a derivative of Schrödinger's equation. *Tunnel rate* is defined as the change of rate of tunneling initially till the final state. It is defined by Fermi's equation as:

$$\Gamma_{i\to j}(\Delta F)=\frac{2\pi}{\hbar}\left|T_{ki,kf}\right|^2\delta\left(E_i-E_f-\Delta F\right)$$

Where ΔF is the difference between the initial and final energy state levels. *Reference [17]*

C. Kondo Effects:

The discovery relating the temperature and the resistance of the metal ion helped in embarkment of single electron transistor. This was introduced by scientist Kondo in the late 1964, and hence the name Kondo Effect [18, 19]. It was found out that the resistance of the metal increases logarithmically when the temperature is lowered. This effect is noteworthy only when an impurity atom with an unpaired electron is placed in the metal. In case of single electron transistors, a spin singlet state is formed at lower temperatures between the unpaired electron and delocalized electron at Fermi energy. This thus leads to following consequences:

1. Formation of spin singlet results in the enhancement of zero-bias conductance when the number of electrons on the metal ion is odd and not when it is even.
2. By applying voltage or magnetic field or by increasing the temperature, the singlet gets altered. *Reference[20]*

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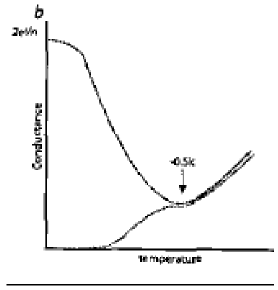

(c) Graph of Kondo effect for Quantum Dot

II. APPLICATIONS OF SINGLE ELECTRON TRANSISTORS:

A. *Logic:*

SET's are widely used as a substitute for MOSFET's in conventional Logic gates. The SET's do not have the property of directly generating the currents, even when Coulomb blockade and Coulomb Oscillations are dominant features. SET based logic and Charge state Logic are the two categories of logic for single electron devices [9]. The current in case of SET's is produced because of the tunneling effect. The accumulation of plural electron results in voltage that is used to represent the corresponding bit. SET-based logic circuits, such as Inverter, NAND and XOR gates, have been demonstrated on Si-based researches. In case of charge static logic, the logic is represented by the corresponding elementary charge the bit of the charge state logic is represented by the elementary charge. The representative devices are quantum cellular automation (QCA) and single-electron binary decision Diagram (BDD) [11-14].

B. *Supersensitive electrometer:*

One of the main characteristics of SET is that it is highly sensitive in nature. Hence adopting this characteristic, SET's are widely used as supersensitive electrometer in study of physics. It is thus possible to measure very low DC currents of the order of 10A ~ 20A with the use of this electrometer. Measurements in the study of single electron effects, single – electron box and traps is also possible. The fractional charge excitation incase of fraction Quantum Hall Effect was initially found due to the use of this electrometer. [21-22]

C. *Charge sensors:*

The SET's are capable of analyzing the spin or qubits in case of Quantum Dots. Two silicon quantum dots were fabricated using a lithographic process, on a single – on insulator substrate, where their capacitive parameters that in turn related to signal to noise ratio (SNR ratio) were calculated. The theoretical capacitive parameters that were obtained by direct imaging of the quantum dots were thus compared with the measured values. The analysis was conclusive of the fact that on account of decreasing of SET diameter, it is possible to decrease the capacitive coupling between the qubits but increase the SNR ratio and radio frequency single shot measurement. As these results are independent of the device materials, it was thus possible to establish guidelines for the design of SET charge sensors in lateral QD-SET structures based on a two-dimensional electron gas. [21-22]

D. *Single Electron Spectroscopy:*

It is possible to measure the energy distribution levels in case of quantum dots by the use of single electron spectroscopy where in SET's are used. This can be achieved by capacitive coupling single – electron box wherein the quantum dot is considered as the island to Single electron transistor and measuring the gate voltages which in turn demonstrates sharp increase of source drain conductance.

III. COMPARISON BETWEEN SET'S AND MOSFET'S:

In recent times, the beat alternative for MOSFET's is Single electron transistors. SET's have charge sensitivity much higher than that of the MOSFET'S but have voltage sensitivities less because of the input capacitances of the SET's being less. SET can be considered to be one of the versions of field effect transistors. SET replaces inversion channel with two tunnel barriers embedded in a small conducting island when metal oxide transistors are to be compared with SET's. In case of the single-electron transistor threshold voltage and source-drain current is a periodic function of the gate voltage which is one of the most important feature in case of SET. The effect of V_g which is equivalent to the injection of charge into the island is responsible for periodic dependency as mentioned that in turn changes the balance of the Charges at tunnel barrier capacitance, which helps to determine the Coulomb blockade threshold voltage. [21-22]

IV. LIMITATIONS:

A. *Background charges:*

Due to random charges present in the background, results in polarizing of the corresponding island. This results in the formation of an image charge Q_O of the order e, which gets subsequently subtracted from the external charge $Q_{e...}$ [23-24]

B. *Room temperature:*

The required condition for temperature is given by, $E_c \sim 100 k_B T$, which is equivalent to sub nanometer scale of island size when compared with temperature. The quantum Kinetic energy in these small conductors, will give rise to dominant contribution to electron additional energy. This implies that even when there are minute variations in the dimensions, it may lead to unpredictable changes in the resulting energy spectrums and hence in device switching thresholds. [23-24]

C. *Co – tunneling:*

Due to randomness of electrons, it is possible that at a time multiple tunneling may take place for different barriers as a result of single quantum mechanical process. The resulting phenomenon is referred to as Co- tunneling. This result is the decrease of tunnel rate subsequently when compared to the tunnel rate for single electron tunneling. [23-24]

D. *Lithography techniques:*

It is difficult to fabricate SET's in VLSI circuits. This is because of its sub nanometer scale. Because of its island size, it becomes difficult to implement fabrication technology on the corresponding VLSI circuits. [23-24]

V. CHALLENGES AND CONCLUSION:

This research paper focuses the theoretical discussion of basic principle of Single electron transistor, its applications and limitations with importance of Single electron transistor in the age of nanotechnology to provide low power consumption and high operating speed in the field of VLSI design for the fabrication of various electronic devices. SET has proved its value as tool in scientific research. Resistance of SET is determined by the electron tunneling and the capacitance depends upon the size of the nanoparticle. The main problem in nanometer era is the fabrication of nanoscale devices.

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