COMPARATIVE STUDY OF SINGLE ELECTRON DEVICES

by

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A comprehensive project report has been submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology

in

ELECTRONICS & COMMUNICATION ENGINEERING

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CERTIFICATE OF APPROVAL

This is to certify that the project titled "**COMPARATIVE STUDY OF SINGLE ELECTRON DEVICES**" carried out by

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for the partial fulfillment of the requirements for B.Tech degree in **Electronics and Communication Engineering** from **Maulana Abul Kalam Azad University of Technology, West Bengal** is absolutely based on his own work under the supervision of Mrs**. Arpita Ghosh**. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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CERTIFICATE of ACCEPTANCE

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ABSTRACT

With acing nanotechnology, and the constant miniaturization of circuit elements, Single Electron Devices have come into being, offering us both the characteristics that we are in need of- reduced size and lesser power consumption. These devices are based on Quantum Mechanical tunneling principle and a single (or few) electrons are used to switch the devices from conducting to non-conducting state. In this paper, first we have understood the general operating principle of Single Electron Devices, and then studied the principles of operation of four Single Electron Devices- Single Electron Box, Double Tunnel Junction, Single Electron Transistor and Single Electron Turnstile. Thereafter, we have done a comparative study of these devices based on certain properties.

CONTENTS

LIST OF ABBREVIATIONS

CNTFET	**Carbon Nano Tube Field Effect Transistor**
DIBL	**Drain Induced Barrier Lowering**
DTJ	**Double Tunnel Junction**
MOSFET	**Metal Oxide Semiconductor Field Effect Transistor**
MTJ	**Multi Tunnel Junction**
RTD	**Resonant Tunneling Diode**
SEB	**Serial Electron Box**
SED	**Single Electron Devices**
VLSI	**Very Large Scale Integration**
ULSI	**Ultra Large Scale Integration**

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OBJECTIVE OF THE PROJECT

The transistors are one of the most important circuit components in the field of electronics. Since the invention of transistors, there has been continuous efforts to reduce its size and power. Now, with acing nanotechnology, and the constant miniaturization of circuit elements, Single Electron Devices have come into being, offering us both the characteristics that we are in need of- reduced size and lesser power consumption. These devices are based on Quantum Mechanical tunneling principle and a single (or few) electrons are used to switch the devices from conducting to non-conducting state. In our project, first we have attempted to understand the general operating principle of Single Electron Devices, and how they can suitably match our area and power requirements and then studied the principles of operation of four Single Electron Devices- Single Electron Box, Double Tunnel Junction, Single Electron Transistor and Single Electron Turnstile. Thereafter, we have done a comparative study of these devices based on certain properties.

INTRODUCTION

The transistors have been one of the most important inventions in the history of technology. Since the invention of transistors continuous efforts have been made to reduce the size and power consumption of transistors. The main reason behind scaling is that our memory requirement is increasing day by day. We have no option other than increasing package density and accommodating more number of components in a smaller space. With the invention of Integrated Circuits in 1960s, it became possible to accommodate as many as 10-100 transistors in a single chip. Since then, the number of transistors that could be fabricated in a single chip has increased exponentially, indicating the proportional decrease in the size and power consumption of transistors. In 1965, Gordon Moore, co-founder of Intel observed that the number of transistors per square inch on the integrated circuits has doubled since their invention. Moore predicted that this trend will continue in the foreseeable future, and the number of transistor in each chip will double every 1.5 years [1]. Our world has sustained itself to Moore's law. With the invention VLSI (Very Large Scale Integration) around 1980s, it became possible to accommodate as many as 10 million transistors in a single chip. Further still, with the advent of ULSI (Ultra Large Scale Integration), the number of transistors in a single chip increased to a 1 billion. The transistors used were the MOSFETs (Metal Oxide Semiconductor Field Effect Transistor). The channel length (distance between the source and drain) of a MOSFET in ULSI was very small, near 100nm [2].

PROBLEMS DUE TO SCALING DOWN OF MOSFETs

When the channel length was reduced below 100nm, several problems showed up. Till then, the charge transfer in these devices was based on classical physics, but reduction in length beyond 100nm introduced several problems, one of the most important being quantum effects. The problems are collectively known as short channel effects [3], which are introduced when the channel length becomes comparable to the depletion layer width of the source and drain regions. These effects make the transistors behave differently which impacts performance, modellingand reliability. The following are the types of short channel effects-

i. **Drain Induced Barrier Lowering (DIBL):** Normally, under zero gate voltage, there is a potential barrier that stops the electrons from flowing to the source and drain. But as the channel becomes shorter, the drain depletion region is widened to a point that reduces the potential barrier, leading to unwanted flow of electrons from source to drain. In this condition, the drain voltage itself lowers the potential barrier, allowing electrons to flow, and thus turning on the transistor just as a gate would. This is essentially similar to reducing the threshold voltage of the transistor, which leads to leakage current.

ii. **Surface Scattering:** The velocity of the charge carriers is given by $v = \mu E$, along the channel, where is the mobility of the carriers and is the applied electric field. When the carriers travel, they are attracted by the electric field created by the gate voltage and hence they keep crashing and bouncing against the surface as they travel. Thus the surface mobility of the carriers is much reduced, in comparison to bulk mobility. Now, as the length of the channel is reduced, the electric field created by the drain becomes stronger, and thus the electric field created by the gate has to be increased proportionally. The stronger electric field of the gate increases the surface scattering. So increased surface scattering impacts the I-V characteristics of the transistor.

iii. **Velocity Saturation:** Above a critical electric field, the velocity of the charge carriers do not follow the $v = \mu E$ relationship anymore, they tend to saturate. As we have already discussed, there is a higher electric field due to short channel effects, so velocity saturation is more prominent.

iv. **Impact Ionization:** The strong electric fields in short channel MOSFETs endows the carriers with high velocity and hence high energy. They are known as "*hot carriers*". When they travel through the channel, these can collide with an atom of the silicon lattice and knock out one electron from the valence band to conduction band creating an electron hole pair. This in turn, can have two effects-

   a. Creation of a parasitic Bipolar Transistor.
   b. Newly generated electrons can themselves become hot carriers and knock out other electrons, creating an avalanche effect, ultimately damaging the device due to an excessive current.

v. **Hot Carrier Injection:** The hot carriers created by the high electric field may also enter the gate oxide layer and be trapped there. The trapped electrons produce an effect of increased threshold voltage. Also, over time the accumulation of the charges in the gate oxide layer causes "*ageing*" of the transistors.

LOW DIMENSIONAL DEVICES

To overcome these problems, some other low dimensional devices came into being. Some of them have been discussed below.

CNTFET (Carbon Nano Tube Field Effect Transistor): Carbon nanotube is essentially rolled up graphene. The CNTFET uses a single carbon nanotube or an array of nanotubes and produces 6 times more current than MOS by application of the same gate voltage. It has high electron mobility, high current density and high trans-conductance. It could overcome the problems like short channels and thin insulator films, the associated leakage currents, passive power dissipation, short channel effects, and variations in device structure and doping to some extent and facilitate further scaling down of device dimensions by modifying the channel material in the traditional bulk MOSFET structure with a single carbon nanotube or an array of carbon nanotubes [4]. It possessed some major advantages like better control over channel formation, better threshold voltage, better subthreshold slope, high electron mobility, high current density, high trans-conductance, high linearity compared to MOSFETs. But, they also suffered from some major disadvantages-

a) Degradation in a few days, when exposed to oxygen.
b) Reliability issues under high electric field and temperature gradients [5]
c) Difficulties in mass production [6]

RTD (Resonant Tunelling Diode): All types of tunneling diodes make use of quantum mechanical tunneling. Characteristic to the current–voltage relationship of a tunneling diode is the presence of one or more negative differential resistance regions, which enables many unique applications. Tunneling diodes can be very compact and are also capable of ultra-high-speed operation because the quantum tunneling effect through the very thin layers is a very fast process. A resonant-tunneling diode (RTD) is a diode with a resonant-tunneling structure in which electrons can tunnel through some resonant states at certain energy levels .RTDs have allowed us to realize certain applications that will be beyond the capability of CMOS technology. These low-power, high speed, and small devices are especially important as we continue to scale down to the size of atoms where heat and parasitic effects are a major problem [7]. But, resonant tunneling diodes suffer from some disadvantages [7] such as-

a) Fabrication is very difficult. Precise barrier thickness control is very important in order to make these devices fully functional.
b) Output power is very limited.
c) Due to very small output power, RTD circuits cannot be realized without amplifiers or any other driver circuits.

WHY SINGLE ELECTRON DEVICES?

Failure in the scaling down of MOSFETs to sub 50nm ranges, opened a new door of possibility- the Single Electron devices. These devices seemed to overcome the problems faced in scaling down of MOSFETs and also offer better prospective as follows-

i. **Reduced size:** The channel is replaced by an island, which us a nanostructure. This provides a significant reduction in size.

ii. **Reduced current and power consumption:** As a single (or very few) number of electrons which are used to switch on any Single Electron device, constitute a much smaller current than a stream of few thousands of electrons used to switch on a MOSFET. Hence, power consumption also reduced proportionately.

iii. **Greater levels of circuit integration:** With such a major reduction in the number of electrons, comes reduction in device size thus promising greater levels of circuit integration.

Failure of the traditional method, shifted the focus to Quantum Mechanics based devices, and Single Electron Devices came into consideration. They are based on the principle that a single or few number of electrons are necessary to switch a device from conducting to non-conducting state, making them ideal for our area and power requirements.

BASIC OPERATING PRINCIPLE OF SINGLE ELECTRON DEVICES

Single Electron Devices are totally based on the principle of Quantum Mechanical Tunneling. The basic principle is that, when the channel length or device size is reduced to sub nanometer ranges, quantum effects are introduced and the behavior of the electrons does not remain deterministic and becomes probabilistic. In classical physics, electrons move from a region to another only if a potential gradient is present. But quantum mechanics takes into account the wave nature of electrons and also says that an electron can move from one region to another even in the presence of a potential barrier. Every single electron device has an island, also known as quantum dot. Also, there are metallic tunnel junctions present. Tunnel junctions consists of parallel metal plates separated by a very small distance. Coulomb blockade is a phenomenon that precisely controls the movement of electrons in Single Electron Devices. It can be defined as the increased resistance in electronic devices containing low capacitance tunnel junctions at low bias voltages.

Let E_{total} be the total energy of an electron present in the left tunnel junction. It can be expressed as –

$E_{total} = E_c + E_F + E_N$ [8]

Where, $E_c = \frac{e^2}{2C}$ is the electron charging energy, E_F is the change in Fermi Energy and $E_N = \frac{1}{2m^*}\left(\frac{hN}{2d}\right)^2$ is the quantum confinement energy [9]. If the work done by voltage sources is W, then the difference between E_{total} and W measures the probability of a tunneling event. When an electron tunnels from the left junction to the island, the electrostatic energy of the system increases by $\frac{e^2}{2C}$. The removal of an electron from the tunnel junction endows it with a positive charge. At very low temperatures (near absolute zero) when the thermal fluctuations are very less, this phenomenon lowers conduction and the charging energy opposes the outflow of electrons. This phenomenon is called Coulomb Blockade. [10]

There are two conditions that must be satisfied for Coulomb Blockade to take place-

i. Resistance Condition: $R_T > \frac{h}{e^2} = 25813\Omega$. [11]

ii. Temperature Condition: $kT < E_C$. [12]

The tunnel junctions, being parallel metallic plates separated by a dielectric has a resistance and capacitance. In the simplest model, they can be considered as a resistance and capacitance connected in parallel [13].

SOME SINGLE ELECRON DEVICES

There can be various types of single electron devices like Single Electron Box, Double Tunnel Junction, Multi tunnel junction, Single Electron Pump, Single Electron Transistor, Single Electron Turnstile.

i. **Single Electron Box-** It consists of a single tunnel junction along with a low value capacitance. The arrangement is biased using a DC voltage source.

ii. **Double tunnel junction-** The double tunnel junction has an island and two electrodes, basically source and drain electrodes. They are coupled with the island through tunnel junctions

iii. **Multi Tunnel Junctions-** It consists of an array of Double Tunnel Junctions.

iv. **Single Electron Transistor-** It consists of a two tunnel junctions, each on either side of a central metallic island. The island is capacitively coupled to an ac voltage source, one electron is transferred from source to drain in one complete cycle of the ac voltage.

v. **Single Electron Turnstile-** It consists of a total of four tunnel junctions, two each on either side of a central metallic island. The island is capacitively coupled to an ac voltage source, one electron is transferred from source to drain in one complete cycle of the ac voltage.

In our paper, we have studied 4 devices in detail- Single Electron Box, Double Tunnel Junction, Single Electron Transistor and Single Electron Turnstile and then done a comparative study of the four devices based on certain properties.

SINGLE ELECTRON BOX

Single Electron Box or SEB is the simplest single electron device. It is the least complex one with least power consumption and also is minimum in case of size as there is only one tunnel junction is existing in this device.

Structure

The single electron box consists of an isolated metallic island or box which is coupled via a tunnel junction with a capacitance (C_J) to an electrode and via another capacitance (C_G) to a voltage source (V_G).

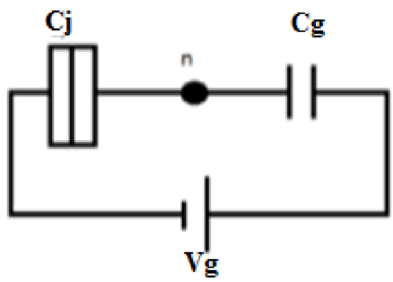


Fig.1 depicts the standard single electron box.

As the name implies, SEB consists of only one tunnel junction. This makes the device conceptually the simplest among all the other SEDs [14].

Equivalent Circuit

A capacitance and a resistance connected in parallel with each other replaces the tunnel junction in the equivalent circuit of the SEB. Also, a DC gate voltage is applied. The equivalent circuit of a SEB is shown in Fig.2. Transportation of electrons in this device is governed by quantum mechanics and only one electron is allowed to pass through the tunnel junction at a time.

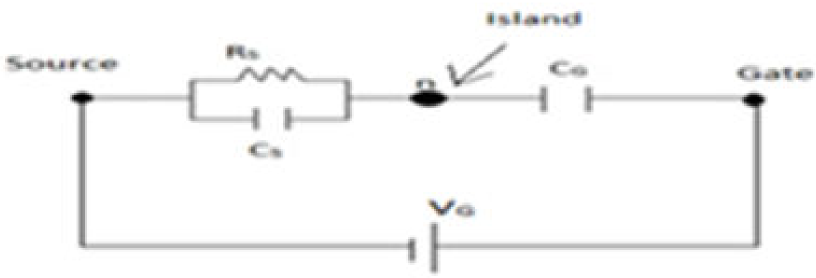


Fig 2: Equivalent circuit of a SEB

Working Principle

When the applied gate voltage V_G=0, number of excess electrons, n=0 on the island. But as the gate voltage is increased the number of excess electrons on the island changes in discrete steps to n=±1, ±2, due to tunneling across the junction, and this is generally shifted to the positive background as the net charge on island is integer and is spatially distributed. When a voltage is applied, the charges on the capacitor plates which are generally non-quantized and are of equal magnitude but opposite signs on the either sides of the junction are determined by the number of excess electrons on the island (i.e., an integer) and the applied voltage that is non-quantized. The net excess charge is divided into two parts on the either sides of the capacitor, i.e. $ne = Q_l + Q_r$.

The corresponding voltage drop is $V_G = \frac{Q_l}{C_j} + \frac{Q_r}{C_g}$

And the charging energy is given by $E_{charging} = \frac{Q_l^2}{2C_j} + \frac{Q_r^2}{2C_g}$.

Where e the charge of an electron is, Q_l is the charge on the left of the junction, Q_r is the charge on the right of the junction, C_j is the junction capacitance and C_g is the gate capacitance.

The corresponding free energy is the Legendre transform of this charging energy that contains the work done by the voltage sources too, and is given by $-V_G Q$.

$\therefore E_{charging}(n, Q_G) = (ne - Q_G)^2 / 2C$ Where C denotes the net capacitance on the island and $Q_G = C_g V_G$ is the gate charge.

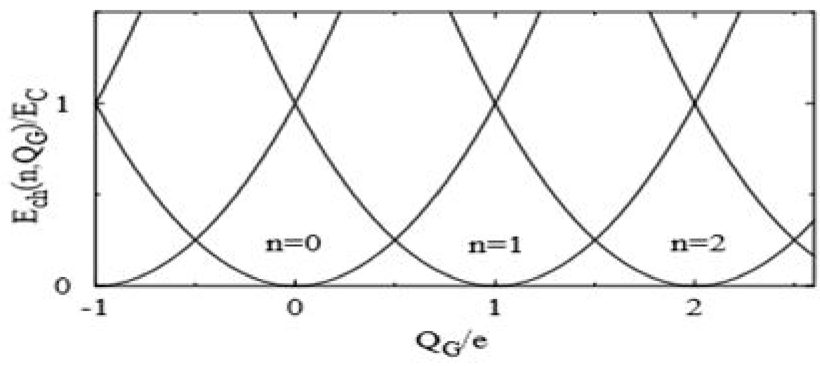


Fig 3: The charging energy is plotted as a function of V_G for different values of excess electrons on the island is plotted

The charging energy is plotted as a function of V_G for different values of excess electrons on the island is plotted in the abovementioned figure (Fig.3). As the gate voltage is increased, number of electrons in the lowest energy state is increased too in discrete steps from n to n+1 at the degeneracy points $Q_G/e = (n+1)/2$.

Also, the voltage of the island or $V_{island} = \partial E_{ch} / \partial Q_G$ displays a saw-tooth dependence on the applied voltage under similar conditions. At certain temperatures these saw-tooth steps are faded and,

$$< n(Q_G) >= \frac{1}{Z_{ch}} \sum_{n=-\infty}^{+\infty} n e^{-E_{ch}(n,Q_G)/kT}$$

Z_{ch}= obvious normalization.

The average number of electron charges <n> on the island of a single-electron box as a function of the gate charge for different temperatures $T/E_C = 0$ is plotted in the below mentioned figure. [1]

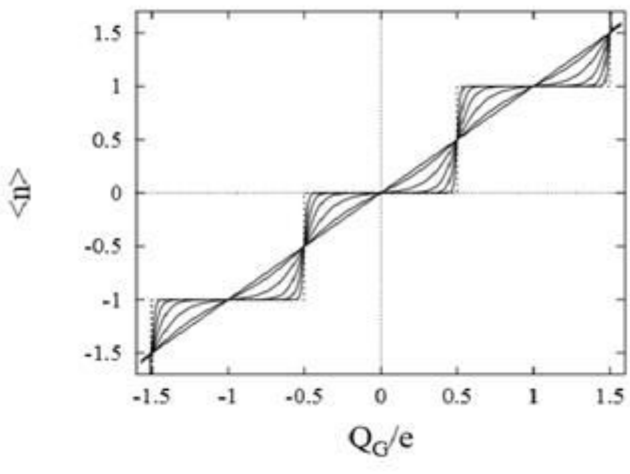


Fig 4: Coulomb Staircase

In mesoscopic and nanoscale systems at low temperatures, charge carriers are typically not in thermal equilibrium with the surrounding lattice. Experimentally the time-dependence of the electron temperature (deviating from the lattice temperature) has been investigated in small metallic islands. Motivated by these experiments the electronic energy and temperature fluctuations in a metallic island in the Coulomb blockade regime, tunnel coupled to a SEB is investigated theoretically. It has been shown that electronic quantum tunneling between the island and the reservoir, in the absence of any net charge or energy transport, induces fluctuations of the island electron temperature [15].

Operating Criterion

The two essential conditions for tunneling are,

a. Tunnel resistance, $R_T > 25813\Omega$. [11]
b. The thermal kinetic energy of the electron must be less than the Coulomb repulsion energy i.e. $KT < E_C$. [12]

Operating Voltage

The operating voltage in the SEB is of purely DC nature. That is why it does not have a current-frequency curve.

Number of Tunnel Junctions

In SEB, number of tunnel junctions present is only one, which means it is the least complex and also least in case of size and is least power consuming among the four devices we have considered here.

Operating Voltage

In the past, SEB was used only in low temperatures but recently a SPICE model has been proposed using SEB to operate in both high and low temperatures [16].

I-V Characteristics

The I-V characteristics of a single tunnel junction has been shown in Fig.5 for increased environment resistance (R_e). Coulomb blockade is only visible for energy fluctuations at the junction much smaller than $e^2/8C$, while the time scale is given by the time constant of the circuit $\delta t \approx \tau = R_e C$.

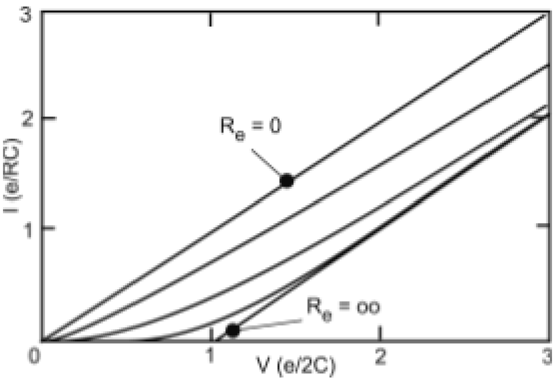


Fig.5

Therefore, Coulomb blockade can be observed on a single tunnel junction only if the environment resistance is of the order of the resistance quantum h/e^2 or higher than that. [8]

Applications

The Single Electron box can have the following applications-

- A majority-logic gate device suitable for use in developing single-electron integrated circuits has been proposed. The device comprises of a capacitor array for input summation and an irreversible single-electron box for threshold operation. This device accepts three binary inputs and produces a corresponding output i.e. a complementary majority-logic output, by using the change in its tunneling threshold caused by the input signals and it produces a logic 1 output if two or three of the inputs are logic 0 and a logic 0 output if two or three of the inputs are logic 1. [17]

- The single electron box along with extra input capacitors is presented with adjusted parameters to get same digital levels for both input and output. Both NOT and NAND gates followed by a double inverter stage is proposed.[18]
- Design of a digital quantizer using SEBs has been proposed. Specifically, this device is made up of two SEBs and one differential amplifier.[19]
- Time-dependent SPICE model for SEB & it's application to logic gates.[16]

Limitations

Two major drawbacks of this device are-

- It cannot store information as the charges stored in the island are a function of applied voltage. So, it cannot be used as a memory device.
- The charge state of this device cannot be determined as no DC current is carried in the box [20].

DOUBLE TUNNEL JUNCTION

The double tunnel junction has an island and two electrodes, basically source and drain electrodes. They are coupled with the island through tunnel junctions

Some basic phenomena related to Double Tunnel Junction

Tunneling

Tunneling or tunneling is a quantum mechanical phenomena where an electron passes through a barrier or lower energy state to higher energy state.

By classical mechanics this phenomena cannot be described, but in quantum mechanics it is possible.

Tunneling is often explained in terms of Heisenberg uncertainty principle and the wave-particle of matter

Back ground charge

It is the amount of charge which is present in island. Due to this stray capacitance is produced.

Coulomb Blockade

The increase of differential resistance around zero bias is called the coulomb blockade.

There are two conditions behind Coulomb Blockade-

A. Tunnel resistance $RT>h/2e^2$
B. The thermal kinetic energy of the electrons must be less than the coulomb repulsion energy which will lead to reduction in current leading to the blockade.

Coulomb Oscillation

If the gate voltage is increased and the bias voltage is kept constant below the Coulomb Blockade, oscillation is produced, which is called Coulomb Oscillation.

To pass through the island, the energy of electron must be equal to the coulomb energy. If gate and biased voltage are zero then no current will flow.

Parasitic capacitance or **stray capacitance**

It is an unwanted capacitance that exists between the parts of an electronic component. When two electrical conductors at different voltages are close together the electric field between them causes electric charge to be stored this effect is parasitic capacitance. This phenomena often called self-capacitance. At low frequencies parasitic capacitance can usually be ignored, but in high frequency circuits it can be a major problem. In amplifier circuits with extended frequency response, parasitic capacitance between the output and the input can act as a feedback path, causing the circuit to oscillate at high frequency. These unwanted oscillations are called parasitic oscillations.

Working principle

The double tunnel junction has an island and two electrodes, basically source and drain electrodes. They are coupled with the island through tunnel junctions or practically insulators. Generally, both the tunnel junctions have same impedance.

Charges on junction 1, junction 2 and the hole or island are

$q_1 = C_1V_1$, $q_2 = C_2V_2$ And $q = q_2 - q_1 + q_0 = -ne + q_{0.}$, where $n = n_1 - n_2$, n_1 is the numbers of electrons tunneling through the junction1 and entering the island, and n_2 is the number of electrons tunneling through the second junction.

The working of single electron devices is governed by quantum mechanics. Classical mechanics does not allow the transfer of electrons through an insulator. But, here the principal is that there is a certain probability of electrons of doing so [21].

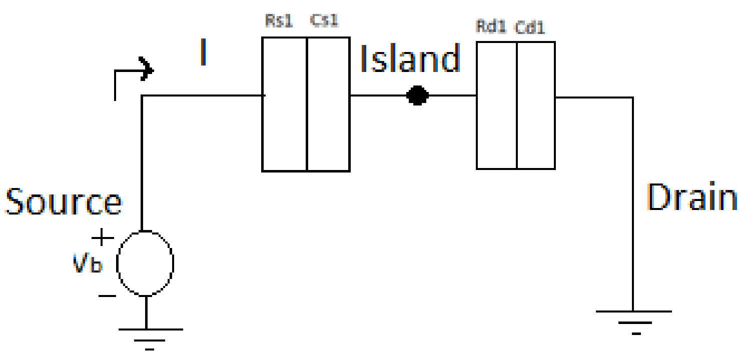


Fig6. Schematic diagram of a Double Tunnel Junction

Electrons accumulate on the tunnel junction. The energy required to cross it is greater than the thermal energy so, the path of the electrons are blocked. This can be termed as Coulomb Blockade. Once an electron reaches that threshold, it gets transferred to the other side. This transfer of electron is known as electron tunneling. When the next electron tries to tunnel through the barrier, the first electron is energetically suitable to leave the island. This is how charge transfer takes place in Double Tunnel Junction. This is the basic working principal of Double Tunnel Junction. [22], [23],[21],[24].

According to Helmholtz's energy the free energy during transport of carriers through tunnel junction (F) is the difference between total energy stored in device and work done by the power source.

Work done by the voltage source in case of electrons tunnel through junction1 and junction2 are accordingly,

$W_1 = -\left(n_1 e V_b C_2\right) / C_\Sigma$ *and* $W_2 = -\left(n_2 e V_b C_2\right) / C_\Sigma$ [24].

Due to Coulomb Blockade, the energy levels of the two tunnel junctions are not at the same level, so at zero biased condition no electron can pass through the island[23],[25].

Equivalent circuit

Two tunnel junctions in series biased with an ideal voltage source. The background charge q_0 is non-integer, and n_1 and n_2 denote the number of tunneled electrons through junction one and junction two, respectively. The tunnel junctions are replaced by a resistor and a capacitor and connect with an ideal dc voltage source.

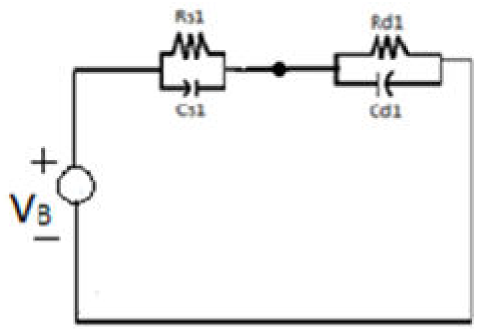


Fig7. Equivalent circuit of Double Tunnel Junction

I-V Characteristics

I-V characteristic of double tunnel junction depends on the impedance of tunnel junction. The no of carriers present in island totally depends on applied voltage.

If the junction1 has less impedance than junction2 then more carriers will present in the island. If the junction2 has less impedance than junction1 then less electron will present in island.

Even if the asymmetry is turned around, the I-V characteristics of Double Tunnel Junction does not change.

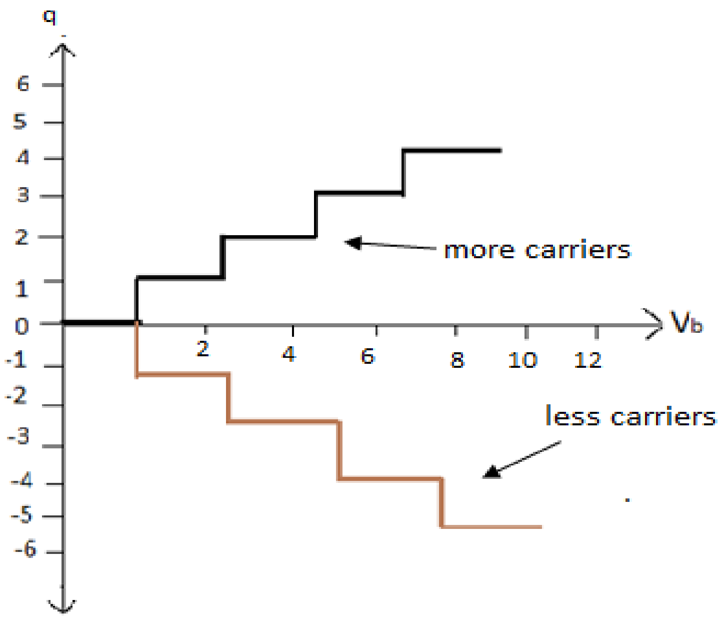


Fig:8 Depending on which tunnel junction is more transparent, and the direction in which the charge carriers will flow, the island will have more carriers or less carries. If the carriers will enter the island through the more transparent junction and leave through opaque one then the island will have more carries. If they enter through the opaque junction and leave through the transparent one then the island will have less carries. [21], [24]

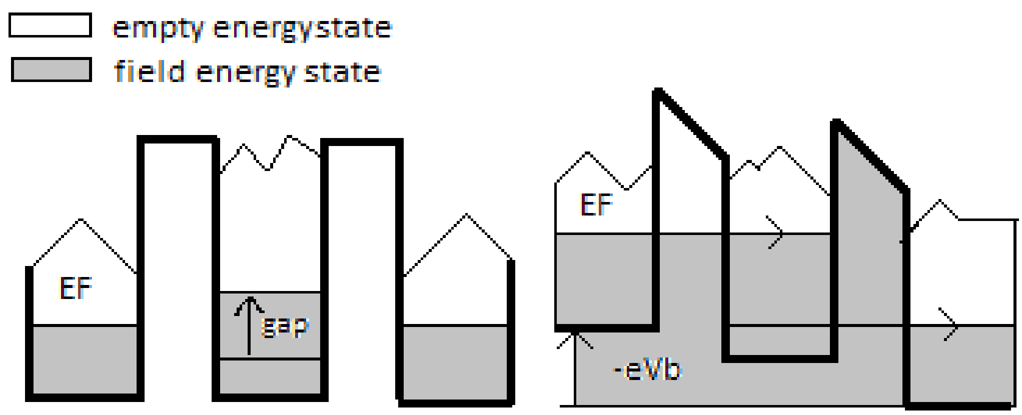


Fig 9: Energy diagram of a double tunnel junction without and with applied bias. The coulomb blockade causes an energy gap where no electron can tunnel through either junction.

Applications

- It is very highly sensitive device, so it can be used as sensor.
- It is also used as a multi tunnel junction.

Advantages

The main advantages of Double tunnel junction are

- Power consumption is more than single electron box but less than other two devices.
- Due to narrow channel length, these devices are faster than other electronics components.
- Circuit is simple.

Disadvantages

Some disadvantages of Double tunnel junction are

- The island of a Double Tunnel Junction is highly sensitive to background charges which is basically stray capacitance and impurities. Background charges can reduce and for $q_0=\pm$ (0.5+m) e, coulomb blockade is totally eliminated. This elimination of coulomb blockade due to uncontrollable background charges is the major disadvantage of Double Tunnel Junction.
- Tunnel resistance.
- Difficult to fabricate.
- It cannot be used as storage device.

SINGLE ELECTRON TRANSISTOR

Single Electron Transistor is basically obtained from double tunnel junction by adding a gate electrode which is capacitively coupled to the island. The first experimental SET was fabricated by T.Fulton, G.Dolan, L.Kuzmin and K.Likharev in 1987.

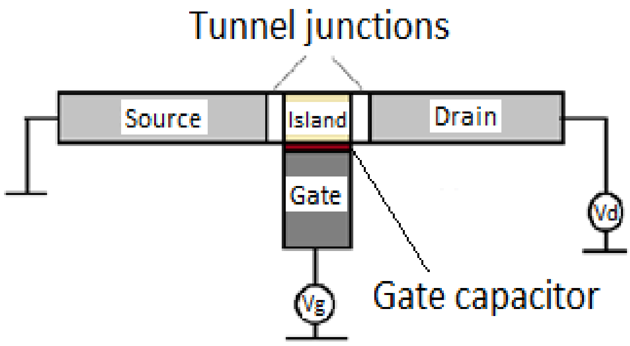


Fig10. Schematic diagram of a Single Electron Transistor [26].

- A single electron transistor consists of an island, where an electron is confined in three spatial dimensions.
- The island is connected through two tunneling junctions or insulating barriers to a source electrode and a drain electrode.
- Then we have the gate terminal which is connected to the island through a capacitor. There can be more than one gate electrodes.

Some basic terms used in SET

Coulomb Blockade [28] - The tunnel junctions can be stated as two thin insulating barriers between conductors. Classical thermodynamics states that no current will flow through the barrier. But, according to quantum mechanics, there is always some probability of the electrons on one side to be transferred to the other side. This will result in the increase of electrostatic energy, which is given by-

$E_c = e^2/2C$

where C is the capacitance of the island. This is also termed as **coulomb blockade energy**. In simple terms, it can be described as the repelling force of an electron in the island, to the next electron coming towards it. In a tiny system, where C is very small, coulomb blockade energy is very large. This energy blocks the simultaneous transfer of electron though the island, and lets the electron pass one by one. This blocking of simultaneous transfer of electrons is known as Coulomb blockade

Coulomb blockade can be removed by:

- When the coulomb blockade energy is overcome by thermal excitations at a temperature T. $T : T_0 = \frac{E_C}{k_B}$.
- When the coulomb blockade energy is overcome by an externally applied voltage V.

Electron tunneling- When an external bias of V=e/C is applied on each of drain and source electrodes, the Coulomb blockade is just lifted. This allows the transfer of an electron from source to drain or vice versa (in case of symmetric junctions). This transfer of electrons is known as electron tunneling.

Working principle of Single Electron Transistor

When there is no biasing provided in any one of the electrodes or in absence of any thermal fluctuations, electrons do not have enough energy to tunnel through the junction.

Charge transfer in Single Electronic Transistor can be explained by simple electronics. If we take a neutral, small metallic sphere. The net charge on it is zero. Now, if a single electron gets close to the sphere, it will get attracted to it. The sphere previously had the same number of electrons and protons but now with the addition of a single electron, it has a negative charge –e on it. Due to this negative charge, an electric field is created around the sphere. This electric field will repeal any other electron coming in close proximity of the sphere. This is the simple understanding behind charge transfer in Single Electronic Transistors.

For further understanding, we will first recall the charge transfer through a simple conductor. The current flowing through a conductor is of continuous because of the number of electrons in it. The current can be calculated by charge transferred per unit time. As, the charge transferred can have any value, therefore it is not quantized. Now, if a tunnel junction is applied, the flow of electrons is restricted. The normal flow of electrons will be restricted due to the insulating barrier. The electrons will flow and accumulate at the junctions or insulating barriers. When a suitable bias is applied across the junction, one electron will get transferred. In this case, the current flow through a conductor may be quantized.

This charging phenomenon is closely related to thermal fluctuations. Thermal fluctuations can alter the motion of electrons and can alter the quantization effects. In refraining it from doing so, we have to maintain a larger coulomb energy than thermal fluctuations. Therefore we can say, $(e^2/2C)>k_BT$.

Here, e=charge on an electron, C=Total charge including the source and drain electrodes and also the gate capacitor($C=C1+C2+C_g$). k_B= Boltzmann constant and T= Temperature in Kelvin. Condition that is to be satisfied to observe the charging effect in room temperature is-

- The electrons should be localized on the islands and the tunnel junctions should be relatively opaque.

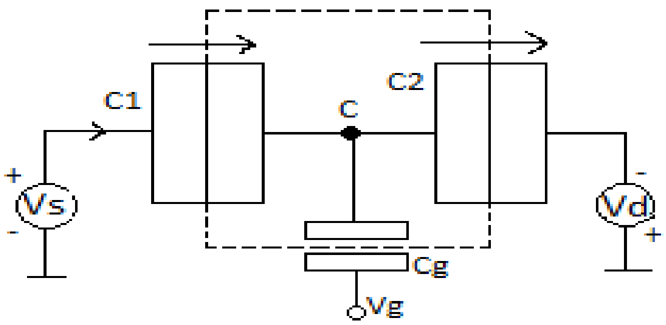


Fig 11.Circuit diagram for Single Electron Transistor [27].

Here, the one-by-one transfer of electrons will take place from the source terminal to the drain terminal when the bias in each terminal is e/C to overcome Coulomb Blockade and with suitable gate bias. C is the capacitance of the island which is equal to the addition of C1= source capacitance, C2= drain capacitance and & C_g= gate capacitance.

The transistor mode of operation takes place when the source and drain bias is kept below the coulomb gap voltage. It is then that the gate bias is increased to a point where the coulomb blockade is lifted and tunneling occurs.

There are two types of SETs used today, "metallic" and "semiconducting", which generally depends on the type of material from which it is fabricated from.

Equivalent circuit of SET

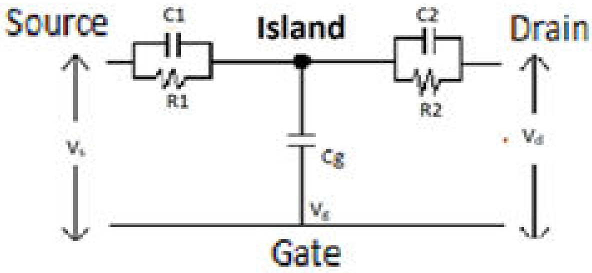


Fig 12. Equivalent circuit of Single Electron Transistor.

In the left hand side of the above figure, we have shown the equivalent circuit of SET. The tunnel junctions can be represented as resistors of constant value, which depends on the thickness of the barrier. A tunnel junction consists of two conductors on either side separated by an insulator. So, it consists of a resistor and a capacitor.

Here in SET, the tunnel junctions work as capacitors and the insulating material as a di-electric medium [28].

I-V characteristics of Single Electron Transistor

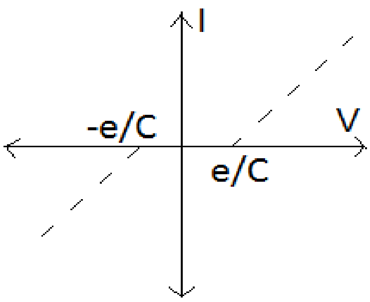


Fig 13.I-V characteristics for Single Electron Transistor for symmetric junction [28].

The above figure shows the I-V characteristics of SET. When the threshold voltage is less than the coulomb voltage, no current flows and we get a straight line. This is where the Coulomb blockade suppresses the tunneling of electrons. Now, as the source and drain bias reaches e/C and a suitable gate bias is applied, Coulomb blockade is lifted in this case and current flows, i.e., the tunneling of electrons occur. This is where the junction behaves like a resistor and there is a linearity between current and voltage.

Advantages of SET

The main advantages of Single Electron Transistors are [28]-

- Low power consumption. This is because small number of electrons are involved in the working of these devices and the low operation voltage.
- It has high operating speed.
- Performance of Single Electron Transistor is better than Field Effect Transistor due to its compact size.
- Simple circuit.
- Simple principal of operation.

Disadvantages of SET

Few disadvantages of SET are [27], [28]-

- To make the SET work at room temperature, island less than 10nm in size has to be fabricated. This fabrication is tough using traditional optical lithography and semiconducting process.
- The Single Electron Island is sensitive to even slight change in the background charge, which generally consists of stray capacitances.
- It is very difficult to fabricate Single Electron Transistors practically.

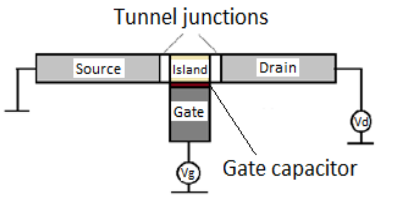
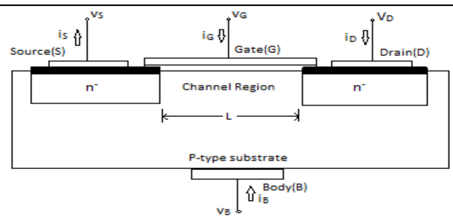
Applications

Among all the Single Electron Devices, Single Electron Transistor is most widely used in applications [27], [28].

- **As charge sensors**- SETs can sense charge efficiently.
- **In the detection of infrared radiations**- SETs can detect infrared radiations in room temperature.

- **As microwave detectors**- During low bias, a quasiparticle maybe introduced in the island. It takes a long time to tunnel off during which electrons can be transported two at a time. This makes the device sensitive to microwave radiations.
- **As electrometers**- Super sensitivity of Single Electron Transistors have made them useful as electrometers. In general, applications like electrometry has two gate electrodes. The bias voltage is to be kept close to the Coulomb Blockade voltage, to enhance the sensitivity of the current to slight changes in the gate voltage.
- **As single electron memory**.
- **As single electron logic systems**- In single electron logic, the transistor turns 'on' and 'off' every time an electron tunnels in or out of the island. This 'on' and 'off' states can give us '1' and '0' for logical circuits design.
- **Nanowires**.

DIFFERENCE BETWEEN SET AND MOSFET [28]

PARAMETER	SET	MOSFET
Structure	 A single electron transistor consists of an island, where an electron is confined in three spatial dimensions. It is connected through two tunneling junctions to a source electrode and a drain electrode. The gate terminal is connected to the island through a capacitor.	 MOSFET is a 3-terminal device which consists of a drain, source and a gate. The source and drain is lightly doped which is indicated by n^-. This is of p-type as the channel is made up of p-type semiconductor material. A thin layer of oxide is sandwiched between the gate terminal and the channel.
Channel	A conducting channel is	MOSFET has channel region.

	present as a quantum dot or island.	
No of carriers passing through channel	The electrons are transferred from source to drain, through the island. They are transferred one by one due to the effect of Coulomb Blockade.	Quite a lot of electrons are transferred through the channel at a given time.
Drain current	Due to Coulomb Blockade, an approaching negative charge experiences an electrostatic repulsion by the previous electron in that region. This regulates the one by one approach of the electrons, and hence the drain current varies accordingly.	In FETs, the drain current depends on the number of electrons passing through the channel. More the electrons, larger is the drain current.

SINGLE ELECTRON TURNSTILE

Among all the single electron devices, one of the most widely discussed is Single Electron Turnstile. The Single Electron turnstile is a device in which the charge transfer is controlled by an RF voltage. A number of electrons are transferred in each cycle of the RF voltage. The device works like a shift register transferring one electron in each cycle of the RF voltage source.

STRUCTURE

The single electron transistor consists of a central island, and two tunnel junctions each on either side of the island [29]. The island is nothing but a quantum dot. Generally metal islands have continuous energy levels, but when they are made as small as a quantum dot, the energy levels are discretized. The discretization in energy level is very essential because otherwise a continuum in energy would have allowed unwanted electrons to pass through the island. The quantum dot allows only single electrons to pass through by virtue of a single energy state. At least two junctions on either side of the island is require to prevent unwanted tunneling. The central island is biased using a gate capacitance cg in series with a voltage source Vg. DC bias voltages are used in either end in order to achieve the Coulomb Blockade.

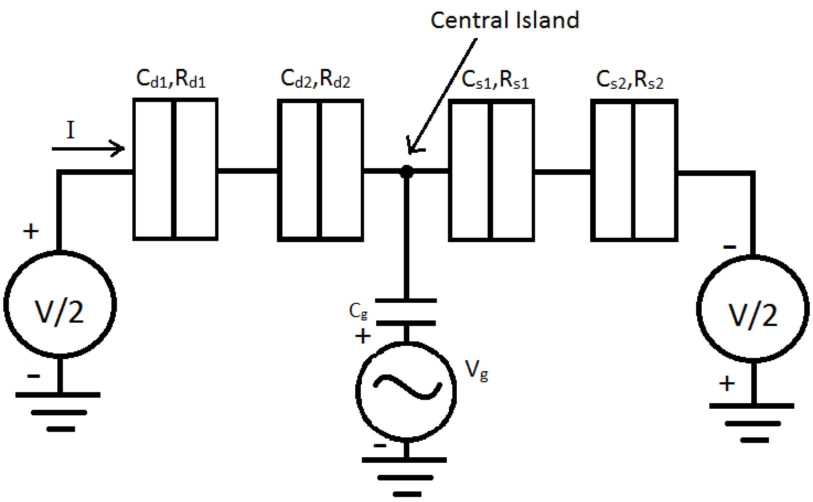


Fig 14: Structure of Single Electron Turnstile

EQUIVALENT CIRCUIT

In the circuit diagram of the Single Electron Turnstile, we find two tunnel junctions on either side of the central island. The tunnel junction consists of two metallic plates separated by air or any other dielectric. So it behaves as a parallel pate capacitor. Again, being made of metal, the tunnel junction also has a finite resistance. According to a paper submitted by DuyMahnLuong and Kazuhiko Honjo in 2013, the simplest modelling of a tunnel junction can be done by considering it to be a resistor and capacitor connected in parallel. The actual realization of this device requires a number of other modelling parameters.

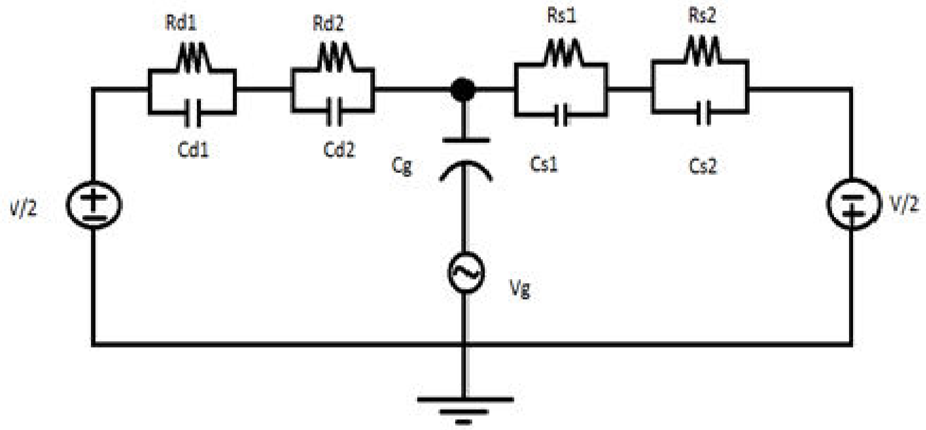


Fig 15: Equivalent circuit of Single Electron Turnstile

In the equivalent circuit, we have taken the simplest model and considered as a capacitor and resistor connected in series. The central island is biased using a gate capacitance and an AC voltage source. This AC biasing simply acts like a revolving door allowing one electron to pass through the island at a single time instant. DC bias voltages are used in either end in order to bias the circuit asymmetrically. The device requires at least two tunnel junctions on either side of the island so that unwanted tunneling of charges across the junction do not take place. The number of tunnel junctions on either side of the gate can be increased above 2 as long as the symmetrical T shape is maintained.

OPERATING PRINCIPLE

The working principle can be explained as follows.

There is a critical charge in each of the junction given by

$Q_{cm} = \frac{e}{2}(1 + \frac{C_{em}}{C_m})$ where C_m is the junction capacitance of the junction and C_{em} is the equivalent capacitance of the rest of the circuit.

If the absolute value of charge in any junction exceeds the critical charge Q_{cm}, an electron tunnels across a specific tunnel junction. By proper choice of the bias voltages V and V_g, this condition can be achieved.

In the positive half cycle of the applied ac voltage, as V_g increases from 0V, the critical charge is exceeded in the tunnel junctions to the left of the circuit but not to the right because of the biasing voltage V. So a single electron tunnels from the left junction to the central island. As a result, C_g is polarized and the charge across each junction is reduced to below the critical charge. Thus, a single electron is trapped in the central island.

In the negative half cycle of the applied ac voltage the charge in the tunnel junctions to the right of the central island exceeds the value of critical charge so now the electron which was previously trapped in the central island now tunnels across the right junction. So we see, that in one full cycle of the ac voltage an electron is transferred. The resulting current in one full cycle is given by

$I = ef$.

For n number of complete cycles, the current is given by $I = nef$.

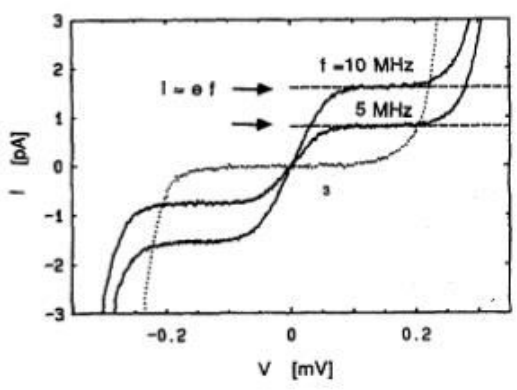


Fig 16: The current voltage characteristics of the single electron turnstile. The dotted line shows characteristics without application of ac voltage.

Research and studies reveal that the tunneling event is a stochastic process. If the energy condition is satisfied for the tunneling event to take place, i.e. the tunneling is favorable energetically, then the tunneling occurs within the time interval given by $t = RC$, where R is the tunnel resistance and C is the tunnel capacitance. Hence, from this fact, we find that there is a restriction on timing and henceforth a restriction on frequencies that we can possibly use. In order to make sure that no cycle is lost the following relationship must hold true.

$f < \frac{1}{RC}$. This is the first restriction on frequency.

Also it has been found that, at finite temperatures there is a probability of thermal activation out of the middle island and the probability is higher for lower frequencies. So that imposes another restriction on frequency.

Following the above two conditions it has been found that for junctions having capacitance of the order 10^{16} F, and for T <=75mK and f <=30MHz, the error in the current expression is expected to be of the order 10^{-8}. [29]

The primary advantage of this device is that there is only one available energy level in the dot is available for the electrons to pass. The access is restricted. So this kind of restricted access makes sure that the electrons that do flow have a single energy, thus making the device ideal for quantum metrology applications. [30]

<u>**CHARACTERISTICS OF SINGLE ELECTRON TURNSTILE**</u>

1. Tunnel junctions- There are a total of 4 tunnel junctions, two each on either side of the island in a Single Electron Turnstile. However the number of tunnel junctions can be increased on either side of the junction, as long as the symmetric T shape of the device is maintained.

2. Size- Each tunnel junction is measures about 10 A in length. This device consists of 4 tunnel junctions, so the device size can be estimated accordingly.

3. Complexity- the device has four tunnel junctions. So, in terms of complexity, it is the most complex structure.

4. I-V Characteristics- In 1990, V.F. ANDEREGG, L.J. GEERLIGS, J.E. MOOIJ fabricated a Single Electron Turnstile using a gate capacitance C_g=0.3 fF , junction capacitances ($C_{s1}, C_{s2}, C_{d1}, C_{d2}$) having a value of 0.5 fF and the tunnel junction Resistances ($R_{s1}, R_{s2}, R_{d1}, R_{d2}$) having a value of 340KΩ. They applied two ac gate voltages, one of 5MHz and the other of 10 MHz, and got the following I-V Characteristics curve.

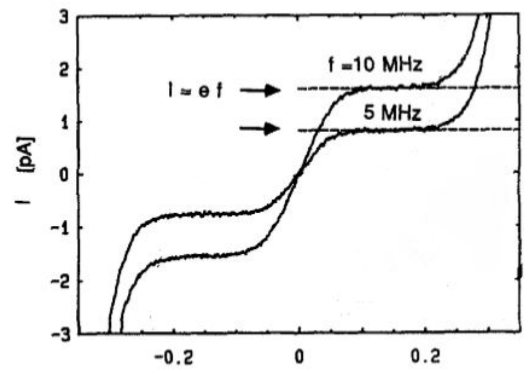


Fig 17: I-V Characteristics of Single electron turnstile

From the graph we can see that at the coulomb gap region, current plateaus have developed, having a value of $I = ef$. The height of the plateau is independent of the amplitude of ac gate voltage, whereas the width of the plateau can be changed by varying the amplitude of the gate voltage.

5. I-f Characteristics- The current expression of a Single Electron Turnstile is given by $I = ef$, for one cycle of the applied ac gate voltage, where e is the charge of an electron. For n number of complete cycles the current is given by $I = nef$. Hence we see, that the current and frequency has a linear relationship, the magnitude of current increases as the frequency is increased.

6. Operating temperature- One of the pre-requisites of operation of single electron Turnstile is that the Coulomb Blockade must take place. So, for Coulomb Blockade to take place, the following condition must be satisfied- $kT < E_C , k$ where is the Boltzmann's constant, T is the operating temperature in Kelvin scale and $E_C = \frac{E^2}{2C}$ is the charging energy of an electron [11], [12].

7. Operating Voltage- The single Electron Turnstile requires an AC gate voltage operating in the RF range, and two DC voltage sources for biasing, in the mV range for achieving the Coulomb Blockade.

8. Restrictions- Thereis imposed two restrictions on the operating frequency (of ac gate voltage) of the Single electron Turnstile. Research and studies reveal that the tunneling event is a stochastic process. If the energy condition is satisfied for the tunneling event to take place, i.e. the tunneling is favorable energetically, then the tunneling occurs within the time interval given by $t = RC$, where R is the tunnel resistance and C is the tunnel capacitance. Hence, from this fact, we find that there is a restriction on timing and henceforth a restriction on frequencies that we can possibly use. In order to make sure that no cycle is lost the following relationship must hold true.

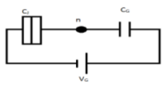
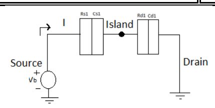
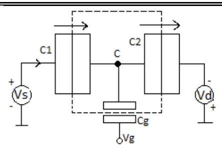
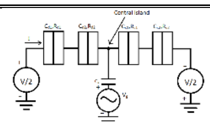
$f < \frac{1}{RC}$. This is the first restriction on frequency.

Also it has been found that, at finite temperatures there is a probability of thermal activation out of the middle island and the probability is higher for lower frequencies. So that imposes another restriction on frequency.

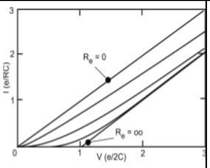
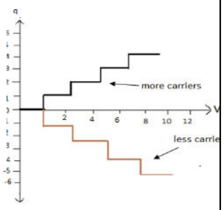
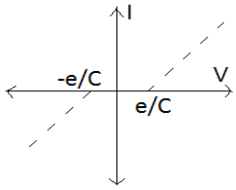
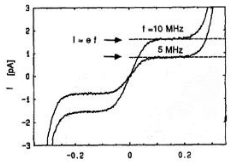
Following the above two conditions it has been found that for junctions having capacitance of the order 10^{16} F, and for T <=75mK and f <=30MHz, the error in the current expression is expected to be of the order 10^{-8}. [31]

9. Power Consumption- As this device contains of maximum number of tunnel junctions, power consumption is obviously the highest in it.

COMPARATIVE STUDY OF VARIOUS SINGLE ELECTRON DEVICES

CHARACTERISTICS	SINGLE ELECTRON BOX	DOUBLE TUNNEL JUNCTION	SINGLE ELECTRON TRANSISTOR	SINGLE ELECTRON TURNSTILE
[1]Structure	 SEB consists of an isolated metallic island which is coupled via a tunnel junction with a capacitance to an electrode and via another capacitance to a voltage source.	 There is a drain and a source terminal which are connected to the island through two tunnel junctions.	 There are two terminals source & drain connected to the island by two tunnel junctions. The gate terminal is connected through a capacitor to the island [28].	 It contains four tunnel junctions, two on either side of the central island [29].
[2]Number of tunnel junctions	This device has only one tunnel junction.	There are two tunnel junctions.	There are two tunnel junctions [28].	There are 4 tunnel junctions.

[3]Size	Least number of tunnel junctions so, the size is minimum.	More than single electron box but less than other two devices because there are only two tunnel junctions.	Two tunnel junctions and an extra gate terminal; therefore, average in size; more than double tunnel junction but less than single electron turnstile.	Maximum number of tunnel junctions, so size is maximum among all the four.
[4]Complexity	This device is conceptually the simplest single electron device.	Less complex structure.	With two tunnel junctions and a gate electrode, its complexity is more than DTJ but less than Single Electron Turnstile.	Most complex structure among all the four due to four tunnel junctions.
[5]Operating Criterion	(i)Tunnel resistance, R_T>25813Ω. (ii) The thermal kinetic energy of the electron must be less than the Coulomb repulsion energy ,i.e. ,$KT<E_C$.	Tunneling depends on barrier quality and pinhole[15]	Has to satisfy: $(e^2/2C)>k_BT$ [19].	Coulomb blockade has to be satisfied. Hence $R_T > \frac{h}{2\pi e^2}$ = 25813Ω and $kT < E_C$

[6] I-V Characteristics	 The I-V curve for a single tunnel junction has been shown for increased environment resistance. Coulomb blockade is only visible for energy fluctuations at the junction much smaller than $e^2/8C$, the time scale is given by $\delta t \approx \tau = ReC$.	 Depending on which tunnel junction is more transparent, and the direction in which the charge carriers will flow, the island will have more carriers or less carries. If the carriers will enter the island through the more transparent junction and leave through opaque one then the island will have more carries. If they	 The above figure shows the I-V characteristics of SET. When the threshold voltage is less than the coulomb voltage, no current flows and we get a straight line. This is where the Coulomb blockade suppresses the tunneling of electrons. Now, as the source and drain bias reaches e/C and a suitable gate bias is applied, Coulomb blockade is lifted in this case and current flows, i.e., the tunneling of electrons occur. This is where the junction behaves	.  I-V Characteristics-. The figure shows the current plateaus at $I = ef$ for both the frequencies signifying the coulomb gap regions.

		enter through the opaque junction and leave through the transparent one then the island will have less carries. [11],[24]	like a resistor and there is a linearity between current and voltage [27].	
[7] I-f Characteristics	None.	None.	None.	$I = nef$, so therefore linear relationship between current and frequency.
[8] Operating Temperature	In the past, SEB was used only in low temperatures but recently a SPICE model has been proposed using SEB to operate in both high and low temperatures.[7]	0.5≤$_{\beta}$Ec≤10[32].		The device was fabricated at T<100mK,[30] , but nowadays fabrication at 0k is also possible.

[9] Operating Voltage	Operating voltage is of purely DC nature.	Ideal dc voltage source.	Two D.C voltage sources are required.	An ac RF voltage and two DC voltage sources required for operation.
[10] Power Consumption	Consists of only one tunnel junctions which implies that it is the least power consuming single electron device.	More than single electron box but less than single electron transistor or single electron turnstile.	Consumes more power than Double Tunnel Junction but less than Single Electron turnstile. It has an extra gate capacitor, whose involvement in the island capacitance will increase the power consumption than DTJ though both has two junctions.	Maximum power consumption because of maximum number of tunnel junctions.

[11] Limitations	Two major drawback of this device is that , (a)It cannot store information and (b)The charge state of this device cannot be determined.[6]	• Background Charges. • Tunnel Resistance.	• Cannot be operated in low frequencies and temperatures which do not satisfy the coulomb blockade criterion. • Island size(<10nm) for room temp, which is hard to achieve with traditional fabrication methods [27].	Cannot be operated in low frequencies and at temperatures which do not satisfy the Coulomb Blockade criterion.

[12] Applications	[i] A majority-logic device suitable for use in developing single-electron integrated circuits has been proposed.[17] [ii] Design of a digital quantizer using SEBs.19] [iii] Logic gates using SEB.[18] [iv] Time-dependent SPICE model for SEB & it's application to logic gates. [16]	• As a multi tunnel junction [25]. • As sensors [25].	• Charge sensors [27]. • Infrared &microwave detection [27]. • As electrometers [27],[28] • As single electron memory and logic system [28]. • As nanowires [28].	This device has not been used in any applications yet. It is still a topic of research.

CONCLUSION

We have studied the basic operating principle of single electron devices and four devices in details. We found from our studies that the single electron devices have can be used in a number of applications. The Single Electron box can be used to fabricate logic gates and digital quantizers. Also, it construction of a majority-logic device suitable for making single electron integrated circuits has been proposed. The Double Tunnel Junction can be used in sensors. The single electron transistor has the maximum number of applications such as nanowires, charge sensors, infrared and microwave detectors, memory and logic systems etc. thus we see the possibility of replacement of traditional MOS based devices by Single Electron Devices in the coming future, and bring along a major reduction in area and power of electronic devices. The major drawback of this device is that fabrication is possible in very low temperatures, in mili Kelvin range. But presently, these devices are being fabricated by hybridization with MOSFETs, through which the area and power can be minimized than using only MOS devices.

FUTURE ASPECTS

In our work we have focused mostly on Single Electron Turnstile. We have studied the working principles, operating conditions and limitations of this device in detail. We wish to continue our work further by trying to make a two port equivalent model of single electron turnstile, computing the impedance and admittance parameters, see the responses with frequency and analyze them. We have already computed the z parameter plots with frequency using MATLAB codes.

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