A Review of Single Electron Transistors

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Abstract – The single electron transistor (SET) is an effectual device to quantize current. It has been highly considered as the most fundamental single-electron device in the research field of nanotechnology. An electron from the single electron transistor (SET) is a pivotal element in the research field of nanotechnology. This type of transistor with very low power consumption and high-performance speed is considered as a nano-scaled switching device that can control the motion of a single electron. The principles of SET and some of its applications are discussed in this paper. In this research paper, we also focus on some basic device characteristics like 'Coulomb blockade', single electron tunneling effect & 'Coulomb staircase' on which this Single electron transistor [SET] works and the basic comparison of SET characteristics and also its [SET] advantages as well as disadvantages to make a clear picture about the reason behind its popularity in the field of nanoelectronics.

Keywords: Single electron Transistor, Electron tunneling, Coulomb blockade, Coulomb staircase.

1. Introduction

A transistor consists of a quantum dot coupled to two electrodes in which the current is generated by single electrons. Hence, it is known as a single-electron transistor. A single-electron transistor is regarded as an electron box that includes two separate junctions for the entrance and exit of electrons. Quantum dot which is less than 100 nm in diameter is a mesoscopic system in which the electrostatic energy or coulomb energy can be changed due to removal or addition of a single electron that is greater than the thermal energy and can control the electron transport into and out of the quantum dot.

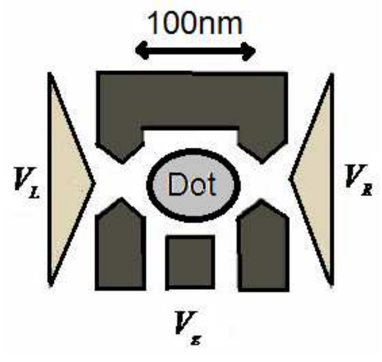

Fig. 1. Quantum dot coupled to two electrodes.

In other words, Quantum dot is a small conducting island that contains a tunable number of electrons occupying discrete orbitals. The single electron tunneling theory depends on the „Orthodox theory" which focuses on charging of the small conducting island of diameter ≤ 100 nm.

A single-electron transistor includes two tunnel junctions and one common electrode, known as the island and exchanges electrons only with the electrodes located on both sides of the tunnel junction called the source and drain. The island capacitance is a function of the QD size, and a QD diameter smaller than 10 nm is preferable when aiming for operation at room temperature. This in turn puts huge restraints on the manufacturability of integrated circuits because of reproducibility issues.

The current passes through the system by applying a bias voltage to the source and drain electrodes and this current result from the tunneling of single electrons in barriers that connect the electrodes and the island (quantum dot). Also, by applying the gate voltage to the island, it controls the opening and closing of the SET or in other words, it controls one-by-one electron transfer. The best advantage of a single-electron transistor is that it can be manufactured in nanometer dimensions [1-3]. In the bias of the single-electron transistor, the drain-source voltage is usually small and about one mili volt, which can reach several volts on the gate voltage. Various materials have successfully been tested when creating single-electron transistors. However, temperature is a huge factor limiting implementation in available electronical devices. Most of the metallic-based SETs only work at extremely low temperatures. The schematic structure of a single-electron transistor is presented in figure 2.

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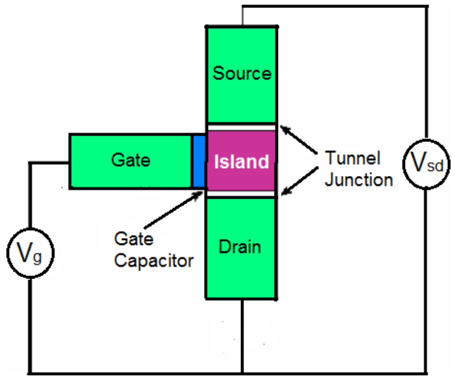

Fig. 2. Schematic structure of a SET. Bias and gate voltage are applied to the electrodes and quantum dot, respectively.

2. Working Principles of Single-Electron Transistor

A simple tunnel junction is viewed as a thin insulating barrier between two conducting electrodes. According to the laws of quantum mechanics, there is a finite probability that an electron will tunnel across the insulating barrier (quantum tunneling) [4-7]. Therefore, tunnel current is established by applying a bias voltage. Ignoring other factors, the tunneling current is proportional to the bias voltage. In other words, the behavior of the tunnel junction is similar to that of a constant value resistor. This is the same as the ohm resistance that its value changes exponentially with the thickness of the barrier and the size of the barrier thickness ranges from one to several nanometers. For the tunnel junctions in SET, not only resistance but also capacitance is considered. So, the equivalent circuit of two tunnel junctions in a SET can be illustrated as the circuit drawn in figure 3.

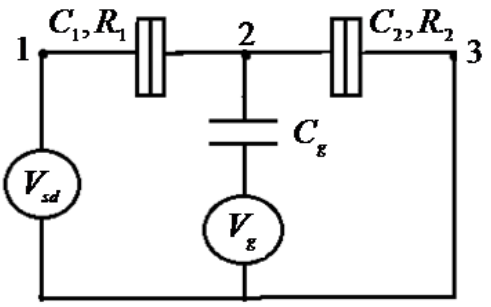

Fig. 3. Single electron transistor circuit.

Each tunnel junction between the island and the source or drain electrode can be modeled with a resistor and capacitor. The resistance value is determined by the tunneling resistance of the electron and the capacitance depends on the dimensions of the island. An island is a quantum dot with a few nanometer dimensions. R_1 / C_1 and R_2 / C_2 are the resistance and capacitor of the source and drain base and the junction of the drain island, respectively. When V_{sd} (bias voltage) increases from zero to higher values, initially no current flows between the source and drain electrodes; since it is necessary to spend energy equal to the energy of the electrostatic charge to transfer an electron to the island or remove the electron from it. This stopping of electron flow is recognized as the Coulomb blockade [5]. The repulsive electron-electron interaction on the island causes the Coulomb blockade. A single-electron transistor applies this phenomenon to control the transfer of single electrons to the island [8-10]. Coulomb charging energy or coulomb blockade energy is equal to:

$$E_C = \frac{e^2}{2C} \tag{1}$$

Where e is the charge on an electron and C is the total capacitance of the source and drain junctions and the gate capacitor. A current between the source and drain electrodes is present only when the bias voltage can establish voltage V in the quantum dot; so that:

$$V \geq \frac{E_C}{e} = \frac{e}{2C} \tag{2}$$

The minimum value of this voltage is called the threshold voltage. Figure 3 shows the I-V Characteristics for the symmetric junction circuit of single electron transistor where $C_1 = C_2$ and $R_1 = R_2$. It is clear from the I-V characteristics of the SET that for $|V|\langle e/C$ $(e/2C$ across each junction), the current is zero. This state is called Coulomb blockade that suppresses the tunneling of single electron in case of low bias condition. Now, if the externally applied junction voltage V is increased up to a level that is above the threshold voltage by charging energy, this effect of Coulomb blockade can be removed and the current flows. In this situation, the junction behaves like a resistor. Or rather, at voltages greater than the threshold voltage, when an electron enters the quantum dot via junction 1, another electron will highly desire to tunnel out of the quantum dot through junction 2. While entering an electron into a quantum dot another electron leaves it almost instantaneously. The sequential entrance and leaving of an electron from one junction to another is generally known as „Correlated tunneling of electrons".

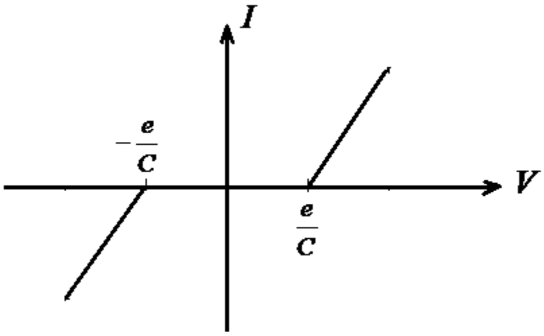

Fig. 4. I-V characteristics of SET for symmetric junction.

Figure 5 represent the I-V Characteristics for a highly asymmetric junction circuit for $R_1 \langle\langle R_2$. In this case, a stepped behavior is observed in the current-voltage characteristic. While by applying a voltage equal to the threshold voltage, an electron enters the quantum dot via junction 1 and the current flows. However, due to the high tunneling resistance over junction 2, the electron does not tunnel out the quantum dot quickly and it requires applying a higher voltage. Thus, most of the time, an excess charge is on the quantum dot. Therefore, to overcome the larger electrostatic energy, applying a voltage is required to increase more current. Accordingly, the current does not change proportionally with the voltage and increases only when enough voltage is applied to overcome the Coulomb energy of two electrons. This behavior results in a stepwise increase of the current relative to voltage and is known as the Coulomb staircase [11-13].

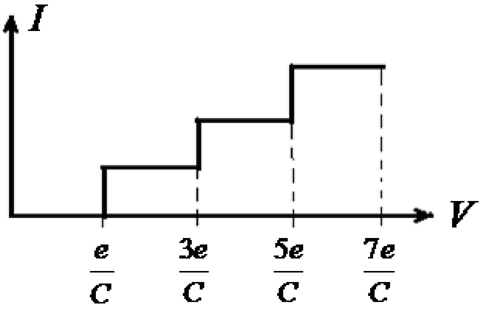

Fig. 5. I-V Characteristics of the SET for asymmetric junction representing „coulomb Staircase‟ state.

Evidently, the initial charge on the quantum dot plays a significant role in transferring electrons in this system. One of the most important problems of the single-electron transistor is the stoppage of the Coulomb barrier function due to the presence of charge on the quantum dot. To establish a current in tunneling junctions, a sufficiently large voltage must be applied to overcome the coulomb blockade and electron tunnel or tunnel out the quantum dot.

The island in the single-electron transistor is capacitively coupled to the third electrode called the gate electrode (figure 2) and a voltage (V_g) is applied to the gate. Transferring the electrons is individually controlled by the gate voltage and hence, it is a controller of connecting or disconnecting the transistor. In disconnecting state, there is no energy level in the quantum dot for tunneling electrons from the source to the island and all energy levels are occupied with energy less than the energy of the electron in the source. When a positive voltage is applied to the gate electrode the energy levels of the island are at a lower level and thus, electrons can tunnel from the source to the island and from there to the drain electrode [8].

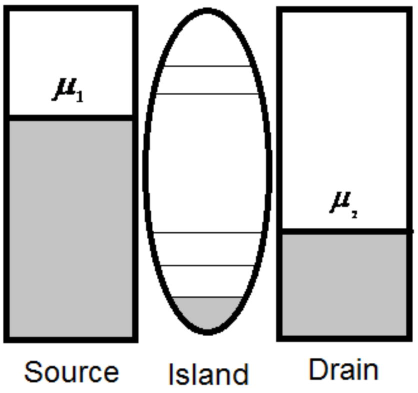

Fig. 6. The bias voltage applied to the system which reduces the chemical potential in the drain relative to the source.

In figure 6, μ_1 and μ_2 are the chemical potentials of the source and drain, respectively. The gate voltage applied to the island is also responsible for adjusting its levels. Despite the continuous movement of electrons in a normal transistor, the energy of the transistor is quantized by decreasing the dimensions of the island in a single-electron transistor about the nanoscale, and as a result, the charge and discharge phenomenon will be discrete. A tunnel junction-related charge and discharge are sensitive to thermal fluctuations. Thermal fluctuations can disrupt the movement of electrons and eliminate the discontinuity effects on electron transfer [14-16]. The Coulomb energy must be more than the thermal fluctuations to avoid this problem. Therefore, an essential condition to observe the single electron phenomenon is as follows:

$$\frac{e^2}{2C}\rangle\rangle K_B T \tag{3}$$

Where, K_B denotes the Boltzmann constant and T is the temperature in Kelvin. This condition explains that the capacitance must be much lower than 3.09×10^{-18} Farads to observe the discontinuity effect of electron transfer through the tunnel barrier at room temperature:

$$C\langle\langle \frac{e^2}{2K_B T} = 3.09\times10^{-18} F \tag{4}$$

Therefore, the island size must be smaller than 10 nanometers to have a tunnel junction with this capacitance. The specific time required for charging or discharging the island through the tunnel resistance is equal to:

$$\Delta t = R_T C \tag{5}$$

The Tunneling resistance (R_T) should be greater than $h/2\pi e^2$, where h is planks constant and e is electronic charge, which is derived from Heisenberg's uncertainty principle.

$$\Delta E \Delta t \rangle \frac{h}{4\pi} \tag{6}$$

$$R_T \rangle \frac{h}{2\pi e^2} = 25813\Omega \tag{7}$$

This condition is required for tunnel resistance.

3. Applications of Set

3.1. Supersensitive Electrometer

The single-electron transistors can be used to make highly sensitive electrometers for the use in some physics experiments. This electrometer, for example, can be used to accurately observe the parity effects in superconductors. Currents of 10^{-20} amperes can be measured using this electrometer. Then it can be used to measure quantities in quantum.

3.2. Single-Electron Spectroscopy

One of the most important application of single-electron electrometry is the possibility of measuring the electron addition energies (and hence the energy level distribution) in quantum dots and other nanoscale objects.

3.3. Logic gates

Power consumption in common elements-based logic circuits is significant. This issue is due to the dimensions and the current drawn by the control bases. In addition to reducing the dimensions of the circuit, the gate can be controlled by only passing a limited number of electrons and the power consumption is as low as possible by using the single-electron transistors-based logic gates.

3.4. Power Electronic Convertors

In recent years, the application of single-electron transistors in integrated electronic circuits and power electronics has been increased more than ever. This is due to the high sensitivity to electric charge, their low energy consumption and high density relative to electric charge, low energy consumption and high density of the integration. Due to the high switching speed of dingle-electron transistors, they are very appropriate for high-frequency switching applications. The dimensions of the circuit elements and accordingly, the conduction losses of the circuit are reduced by increasing the working frequency of power electronic circuits. Nano-invertors and nano-choppers for the drive micro-robots, MEMS, and NEMS are among the applications of single-electron transistors in power electronics.

3.5. Detection of Infrared Radiation

The single electron transistor can also be applied to detect infrared signals at room temperature. The calculations of the optical response of the single-electron systems to electromagnetic waves have been represented with a frequency of about E_c/h that, overall; the response to these waves differs from what is proposed as photon-based tunneling in the Tingarden theory. Indeed, this theory is based on independent (non-correlated) tunneling while the electron transfer is generally correlated in single-electron devices. Therefore, single-electron devices, especially one-dimensional multi-junction arrays with a slow synchronous tunneling rate, seem to be used to detect high-frequency electromagnetic waves.

3.6. Ultrasensitive Microwave Detector

Another application of the single-electron transistor is for a highly sensitive microwave sensor. The island in the single-electron transistor is weakly coupled to a bias circuit through two tunnel junctions with very low capacitance and gate capacitance. At low bias voltages and low temperatures, it is only possible to induce a small quasi-particle to the island via photon-guided tunneling. Since it takes a long time to tunnel this quasi-particle out of the island, it is practically trapped inside the island; however, the charge is transferred through this system. Since the sensor can only be turned on by photon-guided transfer, this instrument can be used to detect microwaves.

4. Conclusion

The importance and unique capabilities of the single electron resistor as a device that controls the movement of single electrons are well-known. These capabilities have drawn the attention of researchers to this type of transistor and made them try to overcome the limitations of its manufacturing. The difficulty of providing the required resolution and controlling the interaction between transistors at very close distances from each other are considered as the most important problems in making single electron transistors. On the other hand, simulating the single electron transistor is of particular importance as it greatly contributes to understanding its behavior and characteristics and also predicts the behavior of the device before its design and construction.

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