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# Single Electron Transistor: Applications and Limitations

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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 tunneling to amplify current.

**Keywords**: Single-electron transistor, Nanoelectronics, Single-electron tunnelling, Coulomb blockade, Coulomb oscillation, Quantum dot.

## 1. Introduction: The Physics of Single Electron Transistor

The single electron transistor is made of an island connected through two tunneling junctions to a drain and a source electrode, and through a capacitor to a gate electrode (Figure 1). When there is no bias on any electrode, electrons in the system do not have enough energy to tunnel through the junctions.

A conventional field-effect transistor, the kind that makes all modern electronics work, is a switch that turns on when electrons are added to a semiconductor and turns off when they are removed. These on and off states give the ones and zeros that digital computers need for calculation. Interestingly, these transistors are almost completely classical in their physics. Only a few numbers that characterize their behavior are affected by quantum mechanics. However, if one makes a new kind of transistor, in which the electrons are confined within a small volume and communicate with the electrical leads by tunneling, all this changes. One then has a transistor that turns on and off again every time one electron is added to it, we call it a single electron transistor (SET).

In a single electron transistor, a drain and source electrode are connected through a tunneling junction to an island, which is also capacitively connected to a gate.

When all the biases are zero, electrons do not have enough energy to tunnel through the junction. However, if you increase the bias, but keep it less than the coulomb gap voltage, increasing the gate bias above the point of maximum slope on the coulomb staircase causes the state with one or zero excess electrons on the island to have the same energy, resulting in the coulomb barrier being removed and allowing electrons to tunnel through the junctions and between the source and the drain.

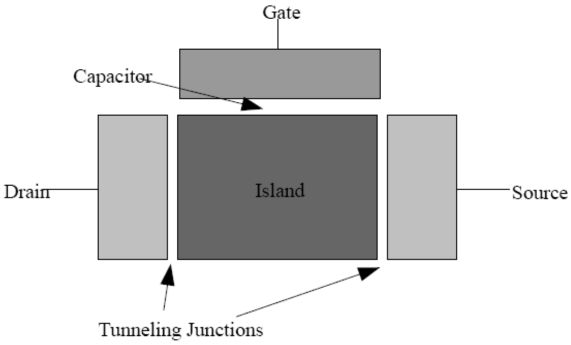

**Figure 1**: Single Electron Transistor.

The Coulomb energy is given by $E_c = e^2/ 2C$

Where e is the charge on an electron and C is the total capacitance of the source and drain junctions and the gate capacitor. When the bias between the source and drain is greater than e/C (e/2C across each junction), called the Coulomb gap voltage, electrons actively tunnel across the junctions, resulting in a current through the transistor independent of the gate bias.

In quantization of electron flow, known as the Coulomb staircase, the thermal energy of the system must be much less than the Coulomb energy. As the gate voltage increases, current increases in quantized chunks.This means that in order for a single electron transistor to operate at room temperature,

$kT \ll e2/2C$

$C \ll e2/2\,kT \approx 3.09\times10-18F$

The capacitance C must be much less than 3.09x10-18 Farads. The capacitance is related to the distance between the two sides of the junction, giving that $C \ll 3.09\times10-18F \Rightarrow d<10$ nm

The diameter of the island, d, must be less than 10 nanometers.

The transistor mode of operation occurs when the bias between the source and drain is less than the coulomb gap voltage. In this regime, when the gate bias is increased to the point corresponding to the maximum slope on the coulomb staircase (i.e. right before a jump in current), the configurations on the island with zero or one excess electron have equal energies, removing the coulomb barrier and allowing tunneling to occur. This maximum point occurs when the gate is charged with exactly minus half an electron. When another minus half an electron charge is put on the gate, the coulomb barrier is reinstated, resulting in an oscillation in conductance of the transistor with maxima at half integer multiples of e and minima at integer multiples of e. This conductance oscillation allows the single electron transistor to be used either as a transistor or as an extremely precise device for measuring charge.

There are a variety of materials chosen for single electron transistors based on the particular properties desired in the system. Relevant properties include the capacitance of the material, the ease of fabrication, crystalline structure, electron mobility, and ease of growing oxide layers. There are two classes of single electron transistors used today, “metallic " and “semiconducting”. This refers to the material they are commonly fabricated from as opposed to describing in any way their operation. Both function through the process of tunneling junctions.

## 2. Applications of Set

### 2.1 Charge Sensor

The Single-electron transistors (SETs) are efficient charge sensors for reading out spin or charge qubits confined in quantum dots (QDs). To investigate their capacitive parameters, which are related to the signal-to-noise ratio (SNR) during qubit readout, twin silicon single QDs were fabricated using a lithographic process on a silicon-on-insulator substrate. Since the configuration and dimensions of the QDs could be determined by direct imaging, the theoretical capacitive parameters could be compared to the measured values. Good agreement was found between the calculated and measured value, which confirms the validity of the calculation method. The results indicated that decreasing the SET diameter reduces the capacitive coupling between qubits but increases the signal-to-noise ratio for both dc and radio frequency single-shot measurements. Since these results are independent of the device materials, they are useful for establishing guidelines for the design of SET charge sensors in lateral QD-SET structures based on a two-dimensional electron gas.

### 2.2 Detection of Infrared Radiation

The single-electron transistor can also be used to detect infrared signals at room temperature. By exciting electrons over an electrically induced energy barrier, both the range of detectable wavelengths and the sensitivity of the device can be controlled. The sensor works when an infrared signal excites conduction-band electrons in a 25-nm-deep electron reservoir. A silicon insulator channel measuring 40 × 400 nm is placed next to the reservoir to increase the number of excited electrons. A poly-silicon lower gate then turns off the transistor and electrically forms an energy barrier, creating a storage node on the other side. Electrons with energy greater than the height of the barrier are injected into the storage node, where they are read as changes in current flowing through the transistor.

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### 2.4 Ultrasensitive Microwave Detector

Another application of Single Electron Transistor can be as an Ultrasensitive Microwave Detector; island is weakly coupled to a bias circuit through two small-capacitance tunnel junctions and a capacitive gate. At low bias voltages and temperatures, a single quasiparticle may only be introduced to the island through photon-assisted tunneling. Once this occurs, the quasiparticle is trapped on the island because it takes a relatively long time for this specific quasiparticle to tunnel off. While it is trapped, charge is transported through the system two electrons at a time. Since the photon-assisted transition merely switches the detector current on, this device is not limited to one electron tunneled through the system per absorbed photon. This makes the device an extremely sensitive and potentially useful detector of microwave radiation.

### 2.5 Temperature Standards

Theoretical analysis based on the orthodox theory has shown that $\Delta V = 5.44 N k_B T/e$ is surprisingly stable with respect to almost any variations of the array parameters (with the important exception of a substantial spread in the junctions' resistances), providing a remarkable opportunity to use the arrays for absolute thermometry, since the fundamental constants are known with high accuracy. Each particular array may give high (1%) accuracy of within less than one decade of temperature variations, but for arrays with different island size (and hence different), these ranges may be shifted and overlap. Thus, it is possible to have an absolute standard of temperature with a very broad (say, two-decade) total range from several circuits fabricated on a single chip.

This development is very encouraging, but since all this work is recent, some time is needed to see whether these new devices will be able to compete with (or even replace) the established temperature standards.

### 2.6 Supersensitive Electrometer

The technology of fabrication of tunnel barriers for single-electron devices is still in its infancy, they apparently contain many electron trapping centers and other two-level systems capable of producing "telegraph noise"- random low-frequency variations of the barrier conductance.

The high sensitivity of single-electron transistors have enabled to use them as electrometers in unique physical experiments. For example, they have made possible unambiguous observations of the parity effects in superconductors. Absolute measurements of extremely low dc currents (~10-20 A) have been demonstrated. The transistors have also been used in the first measurements of single-electron effects in single-electron boxes and traps. A modified version of the transistor has been used for the first proof of the existence of fractional-charge excitations in the fractional quantum hall effect.

### 2.7 Single-Electron Spectroscopy

Another application of single-electron electrometry is the possibility of measuring the electron addition energies (and hence the energy level distribution) in quantum dots and other nanoscale objects. There are two natural ways to carry out such measurements. The first is to use the quantum dot as the island of the single-electron box, capacitively coupled to the single electron transistor or other sensitive electrometer. The second is to use the quantum dot directly as the island of a weakly biased single-electron transistor and measure the gate voltages providing the sharp increase of the source-drain conductance.

## 3. Limitations in Set Implementations

### 3.1 Back Ground Charge

The first major problem with the single electron logic circuits is the infamous randomness of the background charge. A single charged impurity trapped in the insulating environment polarizes the island, creating on its surface an image charge $Q_0$ of the order of e. This charge is effectively subtracted from the external charge $Q_{e.}$

### 3.2 Room Temperature

The another big problem with all the known types of single electron logic devices is the requirement $E_c$~$100k_B$ T, which in practice means sub-nanometer island size for room temperature operation. In such small conductors the quantum kinetic energy gives a dominant contribution to the electron additional energy even small variations in island shape will lead to unpredictable and rather substantial variations in the spectrum of energy levels and hence in the device switching threshold.

### 3.3 Out Side Environment Linking with SETs

The individual structures patterns which function as logic circuits must be arranged in to larger 2D patterns. There are two ideas, first is to integrate SET as well as related equipments with the existing MOSFET, this is attractive because it can increase the integrating density. The second option is to give up linking by wire, instead utilizing the static electronic force between the basic clusters to form a circuit linked by cluster, which is called quantum cellular automata (QCA). The advantage of QCA is its first information transfer velocity between cells via electrostatic interaction only, no wire is needed between arrays and the size of each cell can be as small as 2.5 nm, this made them very suitable for high density memory and next generation quantum computer.

### 3.4 Lithography Technique

Another major problem with single electron devices is the requirement $E_c \sim 100k_B$ T, which in practice means sub-nanometer island size for room temperature operation. In VLSI circuits, this fabrication technology level is very difficult. Moreover, even if these islands are fabricated by any sort of nanolithography, their shape will hardly be absolutely regular.

### 3.5 Co-tunneling

The pressure essence of the effect is that the tunneling of several electrons through different barriers at the same time is possible as a single coherent quantam mechanical process. The rate of the process is crudely less than that for the single electron tunneling.

## 4. 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 tunnelling 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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