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# A Review towards Single Electron Transistor (SET)

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**Abstract**: Single-electron transistor (SET) is a key element of current research area of nanotechnology. The aim of this paper is to discuss about the basic physics of nano electronic device 'Single electron transistor [SET]' which is capable of controlling the transport of only one electron. The SET's physical size is quite small and its performance, such as ON-OFF current ratio, improves as its size is reduced. The SET is therefore thought to be a promising device for large-scale and low-power integrated circuits. In addition, its current characteristics are unique and much different from those of conventional transistors. The goal of this paper is to review in brief the basic physics of nano-electronic device single-electron Transistor [SET] as well as prospective applications. The most promising applications for SET's are charge-sensing applications.

**Keywords**: SET, structure of SET, Quantum Dot, coulomb blockade, coulomb staircase

## I. INTRODUCTION

In today's digital integrated circuit architectures, transistors serve as circuit switches to charge and discharge capacitors to the required logic voltage levels[1].A transistor is a three terminal semiconductor device used to amplify and switch electronic signals and electrical power. It has been observed that the fabrication technology has reached on its limits for the MOS feature size, beyond which further scaling of the channel is becoming impossible. Due to which SET is considered as the future of the complex IC fabrication by replacing MOS technology, having small quantum dot or island, instead of channel.

Single electron transistor (SET) is the most fundamental three-terminal single electron device (SED) which is capable of offering low power consumption and high Operating speed[2][3]. SET is said to be the tiny transistor with tiniest power consumption. Since the technology reaches nano size, the behavior of a nano-electronic single electron transistor (SET) is controlled by the quantum mechanical effects. Analytical modeling of single electron transistor for hybrid CMOS-SET analog IC design is described in [4]. The rest of this paper is organized as follows. Section 2 states about the need of single electron transistor. Section 3 gives basic description of single electron transistor. Section 4 presents the structure of single electron transistors. Section 5 addresses the physics behind single electron transistor. Section 6 presents the applications of single electron transistor. Finally, Section 7 summarizes the concluding remarks.

## II. NEED OF SET

According to Moore's Law the number of transistors on integrated circuits doubles approximately every two years. With the downsizing of present silicon IC technology, validity of Moore's law has become seemingly limited. The field of nano electronics aims to enable the continued realization of this law by using new methods and materials to build electronic devices with feature sizes on the nanoscale. One of the device introduced to meet this requirement of downsizing is SET.

Advantages Single electron transistor:

- Low energy consumption
- High charge sensitivity
- Compact size
- High operating speed
- Feature of reproducibility
- Simple principle of operation
- Improved working when hybrid with MOS transistor is formed

The biggest limitation single electron transistors face is in the area of digital logic. Because of the difficulty in fabricating atomically identical transistors, there is a huge variation in when they turn on or off. This variation makes the creation of a large array of single electron transistors working together impossible. Advances in our ability to precisely define features in materials with atomic precision have the potential to allow the use of these transistors for computation.

### A. WHAT IS A SET?

The SET is a nano electronic, three-terminal, tunnel junction device, where a capacitively coupled input voltage modulates a drain-source current serving as the amplifier output. A SET is made from two tunnel junctions that share a common electrode. A tunnel junction consists of two pieces of metal separated by a very thin (~1 nm) insulator. The only way for electrons in one of the metal electrodes to travel to the other electrode is to tunnel through the insulator. Since tunneling is a discrete process, the electric charge that flows through the tunnel junction flows in multiples of e, the charge of a single electron.

The idea of SET was demonstrated by Millikan at beginning of the century, but in solid state physics it was not implemented until the late 1980's. The first

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observation of the Coulomb blockade and thus single electronics was made by Gorter in 1951.

## III. STRUCTURE

The single electron transistor is made of a quantum dot connected through two tunneling junctions to a drain and a source electrode, and through a capacitor to a gate electrode.

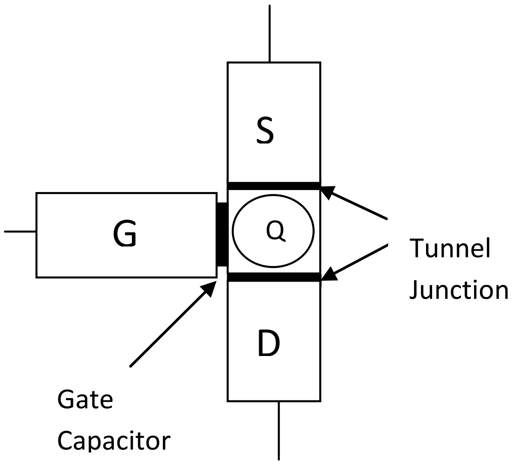


Fig 1. Schematic structure of SET

Quantum dot ,which is less than 10 nm in diameter, in which the electrostatic energy can be changed due to removal or addition of a single electron that is greater than the thermal energy and thus can control the electron transport into and out of the quantum dot. In other words, Quantum dot is a small conducting island that contains a tunable number of electrons occupying discrete orbital.

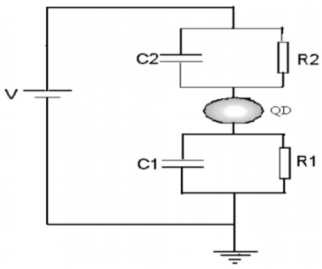


Fig 2. SET circuit

## IV. THEORY OF OPERATION

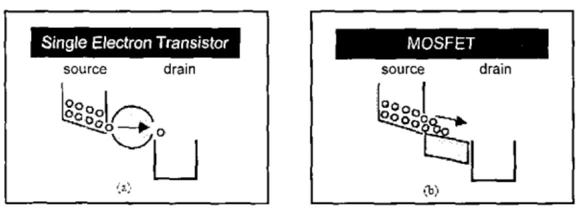


Fig 3. Electron tunneling through the channel (a) one-by-one in SET (b) Transfer of many electrons simultaneously through the channel in MOSFET.

In SET electrons are confined within a small volume and communicate with the electrical leads by tunneling. SET turns on and off again every time one electron is added to it.The Coulomb energy is given by

$$E_c = \frac{e^2}{2C}$$

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 $\frac{e}{C}$ ( $\frac{e}{2C}$ 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,

$$kT << \frac{e^2}{2C}$$

$$C << \frac{e^2}{2kT} \approx 3.09\times10^{-18}F$$

The capacitance C must be much less than $3.09\text{x}10^{-18}$ F. The capacitance is related to the distance between the two sides of the junction, giving that

$$C << 3.09\times10^{-18}F \Longrightarrow d < 10 \text{ nm}$$

The diameter of the island, d, must be less than 10 nm. The transistor mode of operation occurs when the bias between the source and drain is less than the coulomb gap voltage. In this case, 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.

Fig. 4(a) shows the I-V Characteristics for the symmetric junction circuit of single electron transistor where C1=C2 and R1=R2. It is clear from the IV- characteristics of the SET that for |V|< e/C, 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. The sequential entrance and


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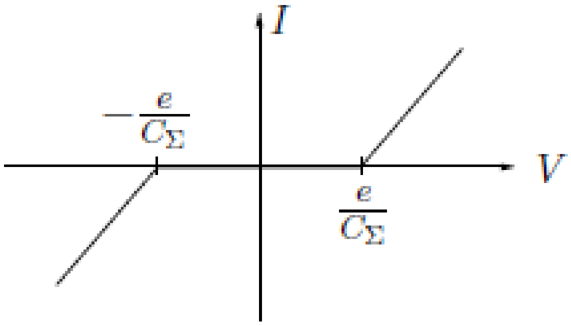
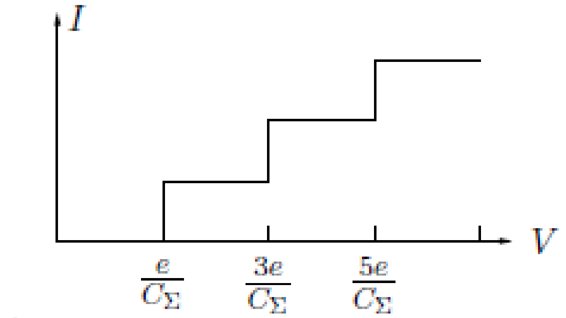
leaving of an electron from one junction to another is generally known as "Correlated tunneling of electrons".




(a)




(b)

Fig 4. I-V Characteristics for (a) Symmetric junction circuit (b) Asymmetric junction circuit

Fig. 4(b) represent the I-V Characteristics for a highly asymmetric junction circuit for R1<<R2.
In this case, the charge carriers i.e. electrons enter through one junction and then escape to second junction due to the presence of high resistance. Now, electrons moves from one junction to another very rapidly. Thus this rapid movement of excess electrons from one junction to another raises the total charge of the island. If the bias is increased, it will tend to increase the population of electrons in the island. In this case the IV- Curve represents Stair-like characteristics, which are commonly referred to as the "Coulomb Staircase".[5]

## V. APPLICATIONS

### A. CHARGE SENSOR

The Single-electron transistors (SETs) are efficient charge sensors for reading out spin. To investigate their capacitive parameters, which are related to the signal-to-noise ratio (SNR) during quantum bits 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 quantum bits 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.

### B. DETECTION OF INFRARED RADIATION

The single-electron transistor can also be used to detect infrared signals at room temperature. Generally, the response differs from that the well-known Tien-Gordon theory of photon-assisted tunneling. In fact, this is based on the assumption of uncorrelated tunneling events, while in single-electron systems the electron transfer is typically correlated [6].

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.

### C.ULTRASENSITIVE MICROWAVEDETECTOR

Single Electron Transistor can work 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 quasi-particle may only be introduced to the island through photon-assisted tunneling. Once this occurs, the quasi particle is trapped on the island because it takes a relatively long time for this specific quasi particle 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.

## VI. TEMPERATURE STANDARDS

Theoretical analysis based on the orthodox theory has shown that ΔV= 5.44NkBT/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.

## VII. PROGRAMMABLE SINGLE ELECTRON TRANSISTOR LOGIC

An SET having non volatile memory function is a key for the programmable SET logic. The half period phase shift makes the function of SET complimentary to the conventional SETs. As a result SETs having non-volatile memory function have the functionality of both the conventional (n-MOS like) SETs and the complementary (p-MOS like) SETs [7]. By utilising this fact the function of SET circuit can be programmed, on the basis of function stored by the memory function. The charged around the QD of the SET namely an SET island shift the phase of coulomb oscillation, the writing/erasing operation of memory function which inject/eject charge to/from the memory node near the SET island, makes it possible to tune the phase of coulomb oscillation. If the injected charge is adequate the phase shift is half period of the coulomb oscillation.

## VIII. CONCLUDING REMARKS

Where single electron transistors go from here will be closely watched over the next ten years. As the first single electron transistor was fabricated just over two decades ago, they are decidedly still in their developmental infancy. Without a doubt, these tiny devices will become a not uncommon part of our daily lives over the next decades, either utilizing their ability to measure with extreme precision the charge on an object, to measure the state of qubits in quantum computers, or using their necessarily atomic size to increase the density and therefore speed of integrated circuits. Many of the advances that will allow single electron transistors to come into common use at room temperature with the switching consistency necessary for integrated circuits will require advances in the materials being used in these devices.

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