Single Electron Transistor

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1.Abstract

The evolution of silicon technology today impacts all our lives, and this trend is expected to continue beyond obstacles that have not yet even been seen. When Jack Kilby created the first integrated circuit in 1959, he was probably not imagining that 50 years later, these small silicon chips of a few cm2 would be able to contain more than 100 million quasi-invisible components scaled to the limits of known physics. Today, this aggressive scaling has resulted in extremely small volumes, dramatically reducing the number of elementary charge carriers (electrons and holes) that create the basic conduction in transistors. The effects of charge and energy quantization on such extremely small scales were explored by many physicists in the mid-1980s, and the concept of single electron devices emerged [1]

Single-electron devices provide a means to control electronic charge at the level of one electron, by means of the single-electron charging or 'Coulomb blockade' effect. These devices operate by controlling the transfer of charge across tunnel barriers onto nanometer-scale conducting regions or islands. In such a process, the energy needed to charge an island with even one electron can be large enough to influence the tunnelling process. This energy, the 'single-electron charging energy', must be overcome to allow current to flow across the island, preventing current flow at low applied voltage and temperature. .[5]

2.Introduction

Since the 1970s, the speed and performance of LSI circuits has improved dramatically, associated with a continuous reduction in the size of semiconductor devices. The minimum feature size in an integrated circuit has reduced from >1 μm in 1970 to ~50 nm in 2008, and it is expected that by 2011, it may be possible to define features smaller than ~20 nm[7]. At present, the physical gate length in high-performance metal-oxide semiconductor field-effect transistors (MOSFETs) may be as small as ~35 nm (Mistry et al., 2007). At least with respect to the channel length, we may regard LSI MOSFETs as nanoscale devices, i.e. with dimensions in the range 1–100 nm.

The possibility that the single-electron charging energy of a nanostructure could influence the tunnelling of even one electron onto the nanostructure was identified as early as the 1950s. In 1951, C.J. Gorter proposed that the observed increase in resistance in thin, granular metal films at low electric fields and temperatures was associated with the need to overcome the single-electron charging energy of the nanometer-scale grains in the film. In the mid-1980s, K.K. Likharev and co-workers predicted, in great detail, effects relating to single-electron charging in nanometer-scale tunnel junctions. By this stage, advances in nanofabrication techniques had led to the ability to fabricate well-defined, nanometer-scale, islands and tunnel junctions. In 1987, this led to the first demonstration, at low temperature, of a designed single-electron device, the single-electron transistor (SET) of Fulton and Dolan.[5]

The single-electron transistor (SET) is a nanodevice that can control the transport of single elementary charges on and off a metallic island. It can also function as transistor similarly to a nowadays FET. The principles of the operation of the SET is determined by the Coulomb blockade, an energy barrier that determines the current flow through the device and the charge placed on the metallic island. Regulating the gate charge of the device can modify the Coulomb blockade. The SET can also be used as an ultra-sensitive electrometer in DC ad RF mode. Theoretical calculations show a charge sensitivity h values lower than 1.7 10 e / Hz −6 × for the SET and experimental research gives values of 1.2 10 e / Hz −5 × . The experimental value for the SET is 1000 times better than the field-effect transistor used as an electrometer. The SET can thus be used as ultrasensitive electrometer and will be used in the future in the study of charged nanoscale systems [2]

The discovery of periodic conductance oscillations as a function of charge density in very small transistors has led to a new understanding of the behavior of electrons in such small structures. It has been demonstrated that, whereas a conventional transistor turns on only once as electrons are added to it, submicron size transistors, isolated from their leads by tunnel junctions, turn on and off again every time an electron is added. This unusual behavior is primarily the result of the quantization of charge and the Coulomb interaction between electrons on the small transistor. However, recent experiments demonstrate that the quantization of energy is important as well [4]

This basis of synchronous manipulation of individual electrons in solid-state devices was laid by the rise of single electronics about two decades ago. Ultrasmall structures in a low-temperature environment form an ideal domain for addressing electrons one by one. In the so-called metrological triangle, voltage from the Josephson effect and resistance from the quantum Hall effect would be tested against current via Ohm’s law for a consistency check of the fundamental constants of nature, Several attempts to create a metrological current source that would comply with the demanding criteria of extreme accuracy, high yield and implementation with not too many control parameters have been reported[5]. Here, we propose and prove the unexpected concept of a hybrid normal-metal–superconductor turnstile in the form of a one-island single-electron transistor with one gate, which demonstrates robust current plateau at multiple levels of *e f* at frequency *f*. [3]

Single-electron devices provide a means to precisely control the charging of a small conducting region at the level of one electron. These devices operate using the Coulomb blockade or single-electron charging effect (Devoret and Grabert, 1992; Likharev, 1999), where the energy associated with the addition or subtraction of one electron from a nanometre-scale electrode controls the electrical characteristics of the device. In comparison with conventional semiconductor devices, singleelectron devices such as the single-electron transistor (SET) (Fulton and Dolan, 1987) and the single-electron memory cell (Nakazato et al., 1993) are inherently nanometre-scale and highly scalable. Furthermore, these devices possess the advantages of ultra-low power consumption, associated with the very small amounts of charge they use, and immunity from statistical fluctuations in the charge (Nakazato et al., 1993; Yano et al., 1999). This has led to great interest in these devices for future LSI circuit applications. [5]

Single-electronics implies the possibility to control the movement and position of a single electron or a small number of electrons. It is interesting to see how strong an influence a single electron with the minute charge of 1.6 . 10- 19 As can have, given the right circumstances. Consider an uncharged small metallic sphere with a radius of I nm, something quite possible being produced today. If such a small sphere is charged with a single electron (Fig. I), the electric field on the surface of the sphere in vacuum will become about 1.4GVjm (about 14MVjcm). A remarkably large repelling force for any other electron which wants to approach the sphere. This phenomenon makes it possible to separate a single electron in a solid-state structure. To be more accurate, we have not isolated a single electron, because many other electrons are present in the electron cloud of a metallic grain. But we have added precisely one single electron to the electrically neutral grain. Meaning we have control over single electrons and can manipulate them with single-electron precision.[6]

3. Description and Operation of single electron devices

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It turns out that the capacitance C and the associated charging energy $E_c = e^2/2C$ for a single electron with charge e are the correct measures to quantitatively understand single-electron transfer and related effects. Thus, if the involved capacitances are small enough, charging energies will be dominating.

The simplest circuit which exhibits single-electron charging effects is the single-electron box (see Fig . 2a). The single-electron box is not just easy to understand but it is also relatively simple to manufacture and measure in the laboratory. A metal granule is only on one side connected by a tunnel junction. On this side electrons can tunnel in and out. Imagine for instance a metal grain embedded in oxide, as shown in Fig. 3. The top oxide layer is thin enough for electrons to tunnel through. To transfer one electron onto the granule, the Coulomb energy $E_c = e^2/2C$ has to be "payed". Neglecting thermal and other forms of energy, the only energy source available is the bias voltage V_b . As long as the bias voltage is smal

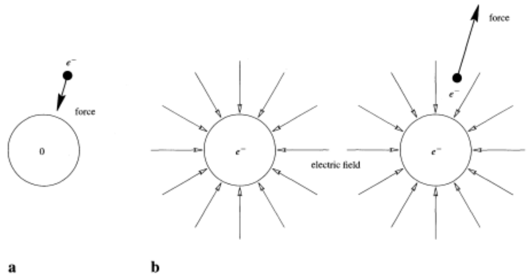

Fig. I. a An electron approaching a small uncharged metallic sphere will feel a small attractive force caused by its own image charge in the sphere. b Once the sphere is charged by a single electron, following electrons will feci a strong repelling Coulomb force

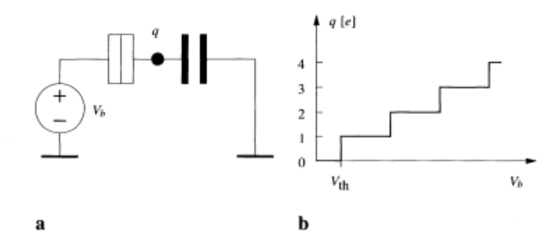

Fig. 2. An electron box (a) can be filled with a precise number of excess electrons by raising the bias voltage Vb above the threshold voltage Vih (b)

enough, smaller than a threshold Vih = ef C, no electron can tunnel because not enough energy is available to charge the island. This behavior is called the Coulomb blockade. Raising the bias voltage will populate the granule with one, then two and so on electrons, leading to a staircase-like characteristic shown in Fig. 2 b [6]

The basic element of a SET is the tunnel junction, and hence, unlike MOSFETs, the quantum mechanical tunneling of the electrons through the tunnel barrier controls current conduction in a SET. If we consider a piece of conductor and divide it into two parts by inserting an ultrathin dielectric, the overall structure will behave as a tunnel junction, as shown in Figure 3(a). It should be noted that because it is so thin, the insulator actually acts as a leaky capacitor as electrons tunnel through it. Now the most basic architecture of a single-electron device (SED) can be constructed by placing two such tunnel junctions in series, as shown in Figure 3(b). The piece of the conductor, which is sandwiched between two tunnel junctions, is known as the island (or grain, or dot). This device is called a SED because only one electron can travel from one terminal to another at a time (under some particular assumptions). Therefore, in SEDs, charge transport is discrete in nature, whereas in MOSFETs, it is continuous. Now, if we conceive of a gate terminal, which is coupled to the island via a thick (opaque) dielectric, as shown in Figure 3(c), this three-terminal architecture will act as a SET. One point to be noted is that in SET, the gate term [1]

There are three basic single-electron devices, the single electron transistor (SET) (Fulton and Dolan, 1987), the single-electron box (Lafarge et al., 1991) and the multiple-tunnel junction (MTJ) (Delsing, 1992; Nakazato et al., 1992). These three devices form the most common single-electron systems, and are the basis of more complex single-electron circuits such as single-electron memory (e.g. Yano et al., 1999; Irvine et al., 2000), single-electron logic circuits (Tsukagoshi et al., 1998) and single-electron electron transfer devices such as single-electron pumps and turnstiles (Geerligs et al., 1990; Pothier et al., 1991). Hybrid devices consisting of combinations of the three basic devices may also be fabricated, e.g. the MTJ/single-electron box hybrid (Nakazato et al., 1993) can form a single-electron memory cell, a configuration which has been widely investigated.

Single-electron transistor are made by Adding a third ‘gate’ terminal, electrostatically coupled to the island of the simple double tunnel junction discussed earlier converts the system into an SET (Fulton and Dolan, 1987). The circuit diagram of the SET is shown in Fig. 3(a). Here, a capacitor Cg connects the island to the gate.

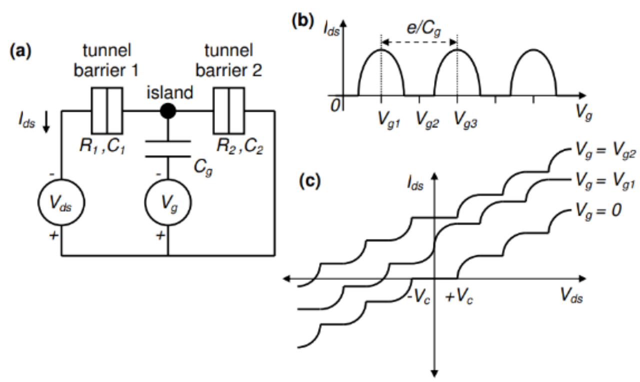

Fig. 3(a) The SET. (b) Periodic single-electron oscillations in the Ids-Vg characteristics, at a constant value of Vds. (c) As Vg is varied, the edges of the Coulomb gap in the Ids-Vds characteristics vary periodically, e.g. from ±Vc at Vg = 0 V, to zero at Vg = Vg1, to ±Vc at Vg = Vg2. Here, for clarity, the three Ids-Vds characteristics are offset in Ids from each other by equal amounts.

The gate voltage Vg may be used to control the Fermi level of the island, and overcome or impose a Coulomb blockade. This leads to the Ids-Vgs characteristics shown schematically in Fig. 3(b), where at a constant value of Vds, Ids oscillates periodically.

These characteristics are known as single-electron current oscillations, or Coulomb blockade oscillations, may be understood as follows. Applying a positive gate voltage Vg lowers the island Fermi energy, and at a value Vg = Vg1, the energy difference between the source and island caused by the single electron charging energy is overcome. Electrons can then transfer from source to drain, across the island and a current is observed. We may view this as a reduction in the Coulomb gap to zero. Increasing Vgs lowers the island Fermi energy further. In Fig. 1.4(b), at Vgs = Vg2, the Coulomb blockade associated with a second electron on the island is yet to be overcome, and the current is very low. Increasing Vgs even further to Vg3 overcomes the Coulomb blockade, and a second electron charges the island.

Further increase in Vgs causes Ids to oscillate periodically with a period e/Cg, each oscillation corresponding to a change in the electron number on the island by one. Furthermore, in the Ids-Vds characteristics (Fig. 3[c]), adjusting Vgs to a value corresponding to an oscillation peak lead to the Coulomb gap reducing to zero. Varying the gate voltage leads to a periodic oscillation in the Coulomb gap observed in the Ids-Vds characteristics. The SET can then be regarded as a simple switch, controlled by the gate voltage. For small values of Vds, the SET is ‘on’ when the Coulomb blockade is zero and ‘off’ when a Coulomb blockade exists. [5]

3.1 Principles of the Single Electron Transistor

The Coulomb Blockade The single-electron transistor consists of a metallic island, placed between two tunneling junctions connected to a drain and a source and has a gate electrode as in a normal fieldeffect transistor. The tunneling junctions are simply a thin (<10nm) oxide layer between the island of the electrons.

Quantum dots have also been used as islands for the SET. The schematics of the SET are given in figure above. Each tunneling junction in the SET has intrinsic tunneling resistance and capacitance (parallel to each other). Yet, before we can fully understand the working of a SET we must first understand the concept of Coulomb blockade

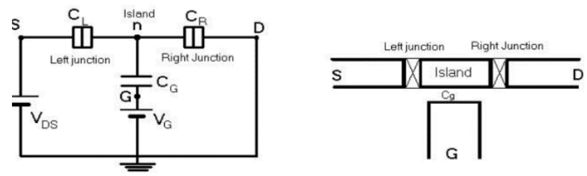

Fig. 4: Left: schematic circuit representation of the single-electron transistor. Right: a more realistic representation of what the ‘core’ of the single-electron transistor looks like

The island of the single-electron transistor, even if very small (nanometric scale) still contains a very large number of electrons (≅109). Yet, through tunneling, one can add or subtract electrons from the island charging it either negatively or positively. The extra electrons that charge the island are called excess electrons and their number is designed by n. The number of excess electrons can also be negative, meaning that electrons have been removed leaving a positive charge on the island (one could talk of excess holes in this case). The presence of excess electrons affects the electrostatic energy of the system, which depends on the charging energy of the SET 0

$$E_{ch} = \frac{1}{2}\frac{{Q_{isl}}^2}{C_\Sigma} = \frac{1}{2}\frac{n^2 e^2}{C_\Sigma}$$

where Qisl is the charge on the island, n the number of excess electrons, e the charge of one electron and CΣ the total capacitance of the island which is equal to: CΣ = CG + CL + CR (CG, CL and CR are the gate capacitance and the intrinsic capacitances of the left and right tunneling junctions respectively). The energy scale applied when working with the SET is usually defined on the charging energy itself and the unit taken is usually: $E= e^2 / C_\Sigma$ The energy does not only depends on Qisl, but also on the charge induced by the gate, the gate charge QG=VGCG where VG is the gate voltage. The electrostatic energy of the system is equal to where n is the number of excess electrons of the island and ng the number of elementary gate charges. The expression for the electrostatic energy of the system then becomes:

$$E_{el} = \frac{1}{2}\frac{Q^2}{C_\Sigma} = \frac{1}{2}\frac{(ne - V_G C_G)2}{C_\Sigma} = \frac{1}{2}\frac{(ne - Q_G)^2}{C_\Sigma}$$

This energy determines if tunneling through a junction is forbidden or allowed: if the adding of an extra excess electron causes the energy of the system to increase then tunneling will be energetically forbidden and the Coulomb charging energy will act as a blockade. This is known as the Coulomb blockade. Two cases are thus possible.

The first case is the one when we consider n excess electrons on the island and tunneling of one electron would cause the energy of the system increases (see also equation (2)). The system having n+1 excess electrons on the island will be then energetically forbidden. No tunneling will occur through the junctions. This is the Coulomb blockade that, in this case, said to be active. In the second case tunneling of an extra electron on the island will lower the energy of the system, hence there will be no Coulomb blockade and tunneling will happen adding an excess electron to the island. The same principle applies if we wish to subtract electrons from the island, charging it positively. The drain-source voltage, VDS, determines the energy of the electrons before the junction. When this energy is higher than the Coulomb blockade, the electrons will overcome the blockade and tunneling will occur. The height of the blockade is determined by the number of excess electrons on the island and the gate charge. [2]

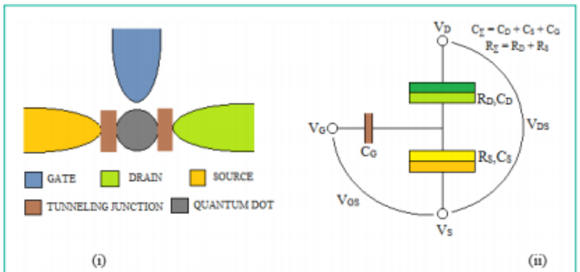

Figure 1: (i) Schematic Structure of SET; (ii) Equivalent Circuit of SET [9].

Figure 5: (i) Schematic Structure of SET.

(ii)Equivalent circuit of SET

Applications in modern electronics

Over the past years metal oxide field effect transistors(MOSFETs) have been basis of major electronics devices. The device allows for scaling dimensions which enabled this progress. Recently, miniaturization is restricted due to quantum effects encountered at sub micron ranges. This pushed researchers to find another alternative for high density integration applications.[8,18] More over, Ultra low power electronic devices are the current emerging topics of research in electronics. The current trend of miniaturized smart devices require more energy conservation.[9,10]. Single electron transistors in this regard are a plausible alternative due to their small energy foot print.

We can classify its applications as digital or analog depending on circuits it is intended to be implemented up on [11]

Analog applications

High sensitivity electron meter

Due to large amplification coefficient an SET based device can be used as electrometer operated by capacitively coupling external charge source to be computed to the gate and then change of current. Experiments showed that if there is a charge change of e/2 on the gate, the current through the Coulomb Island is 10^9 e/sec. This sensitivity is many orders of magnitude better than common electrometer made by MOSFET.[8] SET's have already been used in unambiguous measurement of parity effects in superconductors the device has also been used in the first measurement of single electron effects in single electron boxes and traps.[16]

Single Electron Spectroscopy

Single electron devices enable the possibility of measuring the electron addition energies and the energy level distribution in quantum dots. [8,11]

DC Current Standards

Single-electron tunneling devices have been proposed as standards for DC currents.(especially single-electron turnstiles and pumps). [8,12]

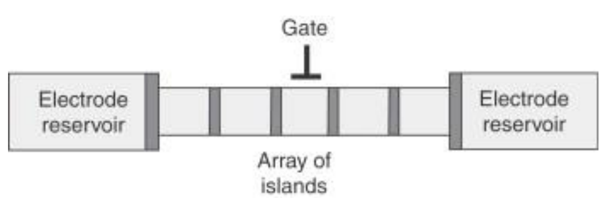

Figure 6 Schematic representation of single electron turnstile image courtesy: sciencedirect.com

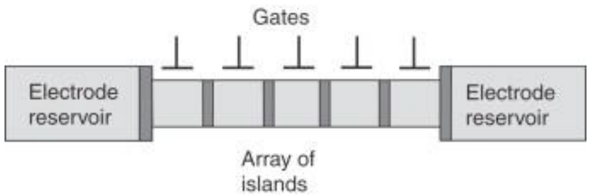

Figure 7 Schematic representation of single electron pump image courtesy: sciencedirect.com

Temperature Standards

One new avenue toward a new standard of absolute temperature can be developed by the use of 1D single-electron arrays. At low temperatures, arrays with N>>1 islands exhibit dc I-V curves generally similar to those of single-electron transistors with a clear Coulomb blockade of tunneling at low voltages [8,11]

Microwave Detection

small amount of radiation will affect the SET device. The sensitivity of this equipment is about 100 times higher than the current best thermal radiation detector.[8] If black body radiation is incident on SET, the photon-aided tunneling will affect the charge transfer of the system. Since the island is coupled weakly to the bias circuit through capacitive and tunnel junctions at low bias voltage and temperature a single quasi particle may be introduced to the island through the photon aided tunneling. Since it takes relatively longer time for the quasi particle to tunnel off the island it becomes trapped off inside it. While the particle is trapped inside the island charge is transmitted two electrons at a time. This makes the device very sensitive detector for microwave radiations.[13,14]

Charge Sensor

Single-electron transistors are efficient charge sensors for reading spin or charge qubits confined in quantum dots. According to investigations in [15] 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.

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.[15]

Digital applications

Voltage State Logic

In Voltage State Mode operation the applied potential on gate electrode steers the source to drain current. Thus, the single electron charging effects are within the transistor whereas externally it appears to be a usual electronic device. This concept simplifies the circuit design which may ignore all the single-electron physics issues this presents an advantage and a disadvantage. On the one hand this makes possible a very simple design of complementary circuits using transistors of just one type but on the other hand in order to get acceptable parameters, operating temperatures must be kept very low to avoid thermal fluctuations affecting device behavior.[8,11]

One more substantial disadvantage of voltage state circuits is that neither of the transistors in each complementary pair is closed too well, so that the static leakage current in these circuits is fairly substantial.[11]

Single Electron Memory

The state of the coulomb island can be changed by the existence of one electron. Which enables to use the device as a memory cell based on the presence or absence of an electron. Enhancing the storage capacity of memory devices surpassing the functionality of CMOS with such application.[8] This circuits eliminate the static current and power dissipation. Improving on power efficiency.[16] However, the fabrication process of such devices is complex and difficult which prevented mass fabrication[8]

Programmable Single Electron Transistor Logic

SETs having non-volatile memory function have the functionality of both the conventional (n-MOS like) SETs and the complementary (pMOS like) SETs. By utilizing this the function of SET circuit can be programmed on the basis of function stored by the memory function. The charged around the 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.[14]

Current and future trends According to observation known as Moore's law the number of transistors inside an integrated circuit has been increasing in two folds every two years [19] this means the components of an integrated circuit gets smaller and smaller as mentioned in the previous section. the construction of components especially the MOSFET which is the primary building block of modern integrated circuits have entered into sub micron ranges. Quantum mechanical effects are expected to be effective in this level of miniaturization. As components approach atomic scale ordinary properties may no longer hold, instead quantum properties surface limiting the applicability of further scaling down progress. Single electron transistor devices are considered an alternative leveraging quantum effects which is effective in smaller dimension[17]. this enables scalability even on the atomic scale

Some of The current advantages motivating the research into this technology are [8]

- Compact size
- Low energy consumption
- High sensitivity
- High operating speed
- Simplified circuit

Although uncertain, with miniaturization and small power consumption under consideration the Single electron transistor is a viable alternative for silicon transistors especially MOSFETs for current and prospective applications.[11]

Comparison with the MOSFET

Single electron transistors have charge sensitivity which is much higher than MOSFETs but have lower sensitivity to voltage due to lower gate capacitance as compared to MOS transistors.

Construction wise, SET can be considered to be one of the versions of field effect transistors. SET replaces inversion channel with two tunnel barriers embedded in a small conducting island when metal oxide transistors are to be compared with single electron transistors..

In SET the tunneling electrons are transferred one-by-one through the island from source to drain due to the effect of Coulomb blockade whereas in MOSFET a large number of electrons is transferred through the channel at a time. How ever in SET approaching electron experiences electrostatic repulsive force from the previous electron in the island. This regulates the amount of electrons passing through the tunnel and hence a varying drain current results. The following figure illustrates this phenomenon..y. The I_d-V characteristic of SET is periodic which shows a finite drain current only for the specific gate voltages where the energies for N and N+1 electron in the channel are degenerated.[14]

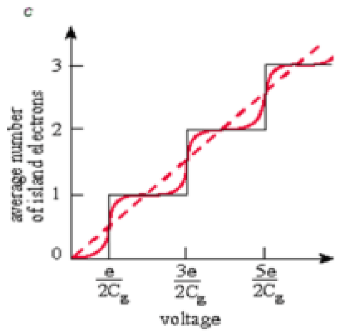

Figure 8 IV characteristics of single electron transistor[image courtesy : IJARCC]

CMOS compatibility

A feasible approach is combining the ultra low power consumption of set devices with the speed and performance of CMOS electronics. The production of This hybrid technology for industrial processes has been aimed by six European partners[18]

Limitations

There are several factors that limit single electron transistor from being a production device.

- Temperature

Temperature is a huge factor limiting implementation in available electronic devices. Most of the metallic-based SETs only work at extremely low temperatures.[10]

- Fabrication

Another factor is fabrication difficulty. The small scale of these devices which is less than 10nm means less reproducibility giving non uniform characteristics hence making large scale integration impractical.[14]

Exposition to the outside environment.[14]

Conclusion

This research paper focused up on the introduction working principles application and trends of single electron transistors. The increasing integration of electronic transistors fundamentally based on MOSFETs are approaching in the nanometre ranges in which quantum effects disrupt normal operations. Single electron transistors use quantum scale to retain scalability to atomic levels. a single electron transistor is made by constructing an "island" connected with two tunneling junctions to a drain and source electrode and through a capacitor to the gate terminal this singe electron tunneling construction enables very low power consumption and ultra low scale which are important for numerous applications we discussed. Even though the results of the experiments is encouraging , we also seen that single electron devices have some draw backs and limitations preventing mass manufacturing. The main limitations currently are in-operability at room temperature and difficulty in manufacturing processes.

Combining set devices with CMOS technology also seems a good approach pushed by European partners

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