

Single Electron Transistors

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Abstract— Nanotechnology is ushering in the era of self-replicating machinery and self-assembling consumer goods made from raw atoms. Utilizing the well understood properties of atoms & molecules, nanotechnology proposes the construction of novel molecular devices possessing extraordinary properties. The single electron transistor or SET is a new type of switching device that uses controlled electron tunnelling to amplify current. It is a key element of current research area of nanotechnology which can offer low power consumption and high operating speed. Single electron transistor [SET] is a new nanoscaled switching device because single-electron transistor retains its scalability even on an atomic scale and besides this; it can control the motion of a single electron. Here, scalability means that the performance of electronic devices increases with a decrease of the device dimensions. By using the “Electron beam lithography” and “Electromigration”, the research leads to the designing of a single atom transistor with the help of the meticulously synthesized semiconductor crystals called “quantum dots”, which embodies the electrons confined in a channel and resembles same in its properties as a real atom. Whereas we can understand conventional transistors using classical concepts, the SET is quantum mechanical in an essential way. In fact, there is a close analogy between the confined electrons inside an SET and an atom. In this paper, the physics underlying the operation of SETs is explained, a brief history of its invention is presented, and issues of current interest are discussed.

Index Terms— Nanoelectronics, single-electron box, Quantum tunnelling, Coulomb blockade, Quantum Dot, Single-electron transistor

1 INTRODUCTION

THE discovery of the transistor has clearly had enormous impact, both intellectually and commercially, upon our lives and work. It led to the microminiaturization of electronics, which has permitted us to have powerful computers on our desktops that communicate easily with each other via the Internet. Over the past 30 years, silicon technology has been dominated by Moore’s law: the number of transistors on a silicon integrated circuit doubles about every 18 months. To continue the increasing levels of integration beyond the limits mentioned above, new approaches and architectures are required. In today’s digital integrated circuit architectures, transistors serve as circuit switches to charge and discharge capacitors to the required logic voltage levels. It is also possible to encode logic states by the positions of individual electrons (in quantum dot single-electron transistors, for example) rather than by voltages. Such structures are scalable to molecular levels, and the performance of the device improves as the size decreases. Artificially structured single electron transistors studied to date operate only at low temperature, but molecular or atomic sized single electron transistors could function at room temperature.

Single-electron transistor (SET) is very popular in the field of nanoelectronics since a decade. 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. Since the technology reaches nano size, the behavior of a nanoelectronic single electron transistor (SET) is controlled by the quantum mechanical effects.

2 END OF MOORE’S LAW

Moore’s law is named after the Intel cofounder Gordon Moore in 1965, who stated that, “the number of transistors on a chip will double approximately every two years”. The term is not an actual law in any scientific rule, similarly to “the rule of

thumb”; however, Intel’s development from Moore’s law has fulfilled the many breakthrough achievements and has made the law widely acceptable.

But physicists predict that in about ten years or so, we will see the collapse of Moore’s Law. In fact, already, we see a slowing down of Moore’s Law. Computer power simply cannot maintain its rapid exponential rise using standard silicon technology. Intel Corporation has admitted this. In fact, Intel Corporation is now working towards three-dimensional chips, chips that compute not just flatly in two dimensions but in the third dimension. But there are problems with that. The two basic problems are heat and leakage. That’s the reason why the age of silicon will eventually come to a close. No one knows when, but we now can see the slowing down of Moore’s Law, and in ten years it could flatten out completely. The problem is that a Pentium chip today has a layer almost down to 20 atoms across. When that layer gets down to about 5 atoms across, it’s all over. You have two effects. Heat--the heat generated will be so intense that the chip will melt and disintegrate, and second of all, leakage--you don’t know where the electron is anymore. The quantum theory takes over. The Heisenberg Uncertainty Principle says you don’t know where that electron is anymore, meaning it could be outside the wire, outside the Pentium chip, or inside the Pentium chip. So there is an ultimate limit set by the laws of thermal dynamics and set by the laws of quantum mechanics as to how much computing power you can do with silicon.

Moore’s law could “flatten out completely” in the next few decades because sooner or later the silicon transistors will not get any smaller and no more could be squeezed onto a chip, and there needs to be a post-silicon era. Going beyond silicon, there have been a number of proposals. SET is one such proposed candidate.

3 BASIC UNDERLYING PHYSICS

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). Furthermore, the behavior of the device is entirely quantum mechanical.

The two main processes that take place in this nano structured electronic device are Coulomb blockade and single electron tunneling

2.1 Quantum tunnelling

Quantum tunnelling or tunneling refers to the quantum mechanical phenomenon where a particle tunnels through a barrier that it classically could not surmount. Quantum tunnelling falls under the domain of quantum mechanics: the study of what happens at the quantum scale. This process cannot be directly perceived, but much of its understanding is shaped by the macroscopic world, which classical mechanics cannot adequately explain.

The reason for this difference comes from the treatment of matter in quantum mechanics as having properties of waves and particles. One interpretation of this duality involves the Heisenberg uncertainty principle, which defines a limit on how precisely the position and the momentum of a particle can be known at the same time. This implies that there are no solutions with a probability of exactly zero (or one), though a solution may approach infinity if, for example, the calculation for its position was taken as a probability of 1, the other, i.e. its speed, would have to be infinity. Hence, the probability of a given particle's existence on the opposite side of an intervening barrier is non-zero, and such particles will appear on the 'other' (a semantically difficult word in this instance) side with a frequency proportional to this probability.

2.2 Coulomb blockade

A Coulomb blockade (abbreviated CB), is the increased resistance at small bias voltages of an electronic device comprising at least one low-capacitance tunnel junction. Because of the CB, the resistances of devices are not constant at low bias voltages, but increase to infinity for zero bias (i.e. no current flows).

According to the laws of classical electrodynamics, no current can flow through an insulating barrier. According to the laws of quantum mechanics, however, there is a non-vanishing (larger than zero) probability for an electron on one side of the barrier to reach the other side (see quantum tunneling). When a bias voltage is applied, this means that there will be a current, and, neglecting additional effects, the tunnelling current will be proportional to the bias voltage. In electrical

terms, the tunnel junction behaves as a resistor with a constant resistance, also known as an ohmic resistor. The resistance depends exponentially on the barrier thickness. Typical barrier thicknesses are on the order of one to several nanometers.

An arrangement of two conductors with an insulating layer in between not only has a resistance, but also a finite capacitance. The insulator is also called dielectric in this context; the tunnel junction behaves as a capacitor.

Due to the discreteness of electrical charge, current through a tunnel junction is a series of events in which exactly one electron passes (*tunnels*) through the tunnel barrier (we neglect cotunneling, in which two electrons tunnel simultaneously). The tunnel junction capacitor is charged with one elementary charge by the tunnelling electron, causing a voltage buildup $V=e/C$, where e is the elementary charge of 1.6×10^{-19} coulomb and C the capacitance of the junction. If the capacitance is very small, the voltage build-up can be large enough to prevent another electron from tunnelling. The electrical current is then suppressed at low bias voltages and the resistance of the device is no longer constant. The increase of the differential resistance around zero bias is called the Coulomb blockade.

4 QUANTUM DOT AND SINGLE ELECTRON DEVICES

The basic building block of the single-electron transistor is a small island of conducting material, sometimes called a quantum dot. When the island is small enough, the energy needed to land an electron on it or take one from it depends on how large it is and how many electrons are already on it. For room temperature operation, an island as small as 1-3 nm is needed. A simple way to get electrons on and off the island is to add an electron source separated from the island by a thin oxide through which electrons can tunnel. A gate over the island changes its energy state, determining the conditions under which electrons tunnel. The result is a structure called a single-electron box (Fig 1).

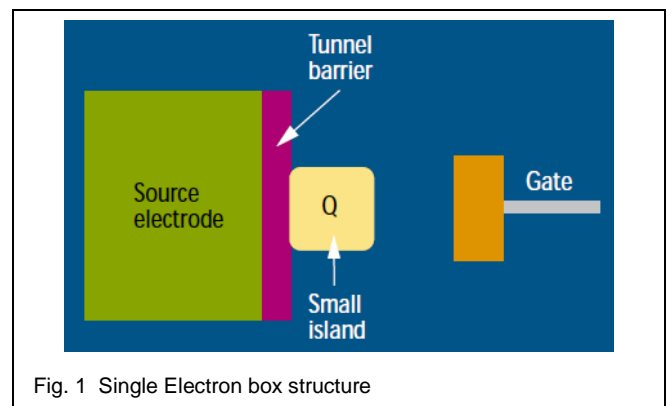


Fig. 1 Single Electron box structure

Electrons are injected/ejected into/from the quantum dot through the tunnelling junction. As the size of the quantum dot decreases, the charging energy W_C of a single excess charge on the dot increases. If the quantum-dot size is sufficiently small and the charging energy W_C is much greater than thermal energy $k_B T$, no electron tunnels to and from the quantum dot. Thus, the electron number in the dot takes a fixed

value, say zero, when both the electrodes are grounded. The charging effect, which blocks the injection/ ejection of a single charge into/from a quantum dot, is called Coulomb blockade effect. Therefore, the condition for observing Coulomb blockade effects is expressed as

$$W_c = e^2/2C \gg k_B T$$

where C is the capacitance of the quantum dot and T is the temperature of the system.

Applying a gate voltage polarizes the island. At first, as the voltage is increased from zero, an electron in the source lacks enough energy to charge the island. This Coulomb blockade, as it is called, is the basis of all single- electron transistors. But the greater the voltage, the greater the polarization charge becomes, until it equals one electronic charge, whereupon the energy conditions favour the tunnelling of one electron to the island from the source electrode (Fig 2).

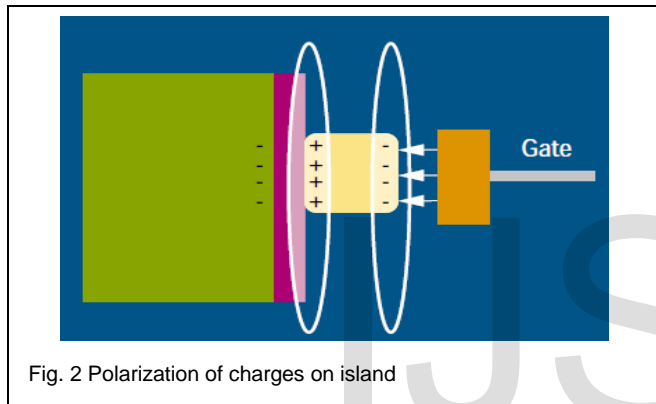


Fig. 2 Polarization of charges on island

However, it should be noted that by applying a positive bias to the gate electrode we could attract an electron to the quantum dot. The increase of the gate voltage attracts an electron more strongly to the quantum dot. When the gate bias exceeds a certain value an electron finally enters the quantum dot and the electron number of the dot becomes one. Further increase of the gate voltage makes it possible to make the electron number two. Thus, in the single-electron box, the electron number of the quantum dot is controlled, one by one, by utilizing the gate electrode.

If a voltage source charges a capacitor, C_g , through an ordinary resistor, the charge on the capacitor is strictly proportional to the voltage and shows no sign of charge quantization (Fig 3). But if the resistance is replaced by a tunnel junction, the metallic area between the capacitor plate and one side of the junction forms a conducting "island" surrounded by insulating materials (Fig 4). In this case the transfer of charge onto the island becomes quantized as the voltage increases, leading to the so called Coulomb staircase (Fig5).

This Coulomb staircase is only seen under certain conditions. Firstly, the energy of the electrons due to thermal fluctuations must be significantly smaller than the Coulomb energy,

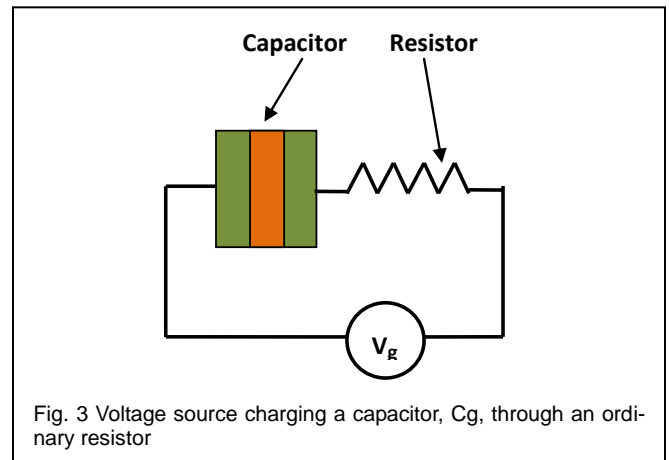


Fig. 3 Voltage source charging a capacitor, C_g , through an ordinary resistor

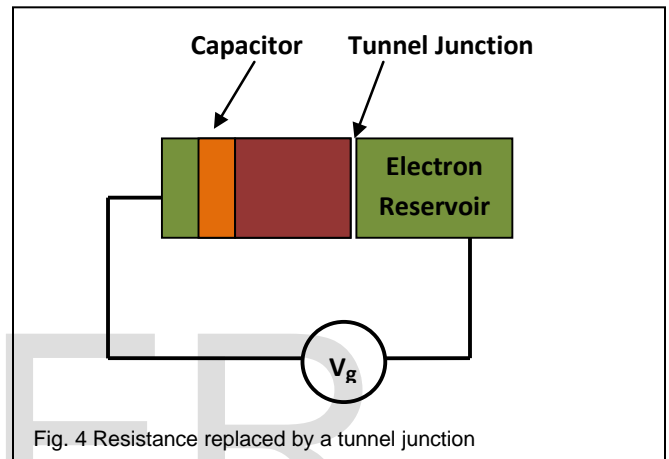
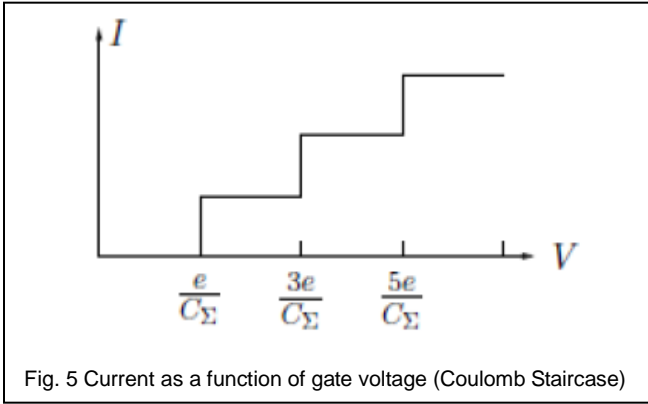


Fig. 4 Resistance replaced by a tunnel junction

which is the energy needed to transfer a single electron onto the island when the applied voltage is zero. This Coulomb energy is given by $e^2/2 C$, where e is the charge of an electron and C is the total capacitance of the gate capacitor, C_g , and the tunnel junctions. Secondly, the tunnel effect itself should be weak enough to prevent the charge of the tunneling electrons from becoming delocalized over the two electrodes of the junction, as happens in chemical bonds. The conductance of the tunnel junction should be much less than the quantum of conductance, $2e^2/h$, where h is Planck's constant. When both these conditions are met, the steps observed in the charge are somewhat analogous to the quantization of charge on oil droplets observed by Millikan in 1911. In a single-electron box, however, the charge on the island is not random but is controlled by the applied voltage. As the temperature or the conductance of the barrier is increased, the steps become rounded and eventually merge into the straight line typical of an ordinary resistor.

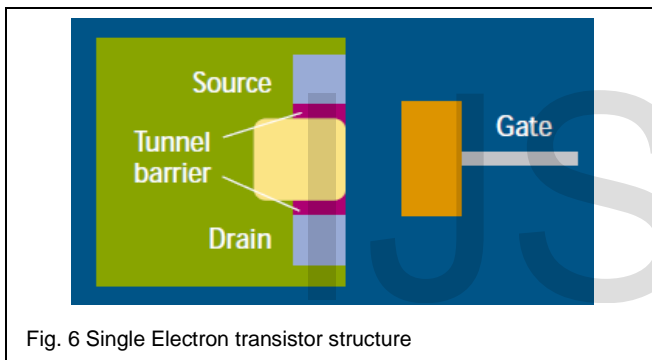
However, two major drawbacks prevent single-electron box from being an electronic circuit component-

- (1) This structure cannot store information, because the charges stored in the island are a function of applied voltage
- (2) It is hard to measure its charge state, due to no dc current carried in the box.



5 SET SCHEMATIC

The single electron-box device can be turned into a transistor. One possibility is to replace the channel of an FET by an island and separate it from the source and drain by tunnelling barriers (Fig 6).

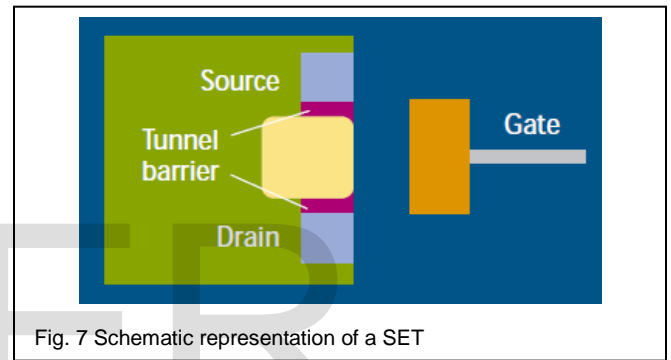


As the source–drain voltage is raised, no current flows until a threshold voltage— high enough to overcome the Coulomb blockade—is reached.

The SET transistor can be viewed as an electron box that has two separate junctions for the entrance and exit of single electrons (Fig 7). It can also be viewed as a field-effect transistor in which the channel is replaced by two tunnel junctions forming a metallic island. The voltage applied to the gate electrode affects the amount of energy needed to change the number of electrons on the island. The SET transistor comes in two versions that have been nicknamed "metallic" and "semiconducting". These names are slightly misleading, however, since the principle of both devices is based on the use of insulating tunnel barriers to separate conducting electrodes. In the original metallic version, a metallic material such as a thin aluminium film is used to make all of the electrodes. The metal is first evaporated through a shadow mask to form the source, drain and gate electrodes. The tunnel junctions are then formed by introducing oxygen into the chamber so that the metal becomes coated by a thin layer of its natural oxide. Finally, a second layer of the metal - shifted from the first by

rotating the sample - is evaporated to form the island. In the semiconducting versions, the source, drain and island are usually obtained by "cutting" regions in a two-dimensional electron gas formed at the interface between two layers of semiconductors such as gallium aluminium arsenide and gallium arsenide. In this case the conducting regions are defined by metallic electrodes patterned on the top semiconducting layer. Negative voltages applied to these electrodes deplete the electron gas just beneath them, and the depleted regions can be made sufficiently narrow to allow tunnelling between the source, island and drain. Moreover, the electrode that shapes the island can be used as the gate electrode.

So, Single-electron transistors (SETs) are three-terminal switching devices, which can transfer electrons from source to drain one by one. The SETs have tunnelling junctions in place of pn-junctions of the MOSFETs and a quantum dot in place of the channel region of the MOSFETs.



6 OPERATION

The key point in the operation of SETs is that charge passes through the island in quantized units. For an electron to hop onto the island, its energy must equal the Coulomb energy $e^2/2C$. When both the gate and bias voltages are zero, electrons do not have enough energy to enter the island and current does not flow. As the bias voltage between the source and drain is increased, an electron can pass through the island when the energy in the system reaches the Coulomb energy. This effect is known as the Coulomb blockade, and the critical voltage needed to transfer an electron onto the island, equal to e/C , is called the Coulomb gap voltage. Now imagine that the bias voltage is kept below the Coulomb gap voltage. If the gate voltage is increased, the energy of the initial system (with no electrons on the island) gradually increases, while the energy of the system with one excess electron on the island gradually decreases. At the gate voltage corresponding to the point of maximum slope on the Coulomb staircase, both of these configurations equally qualify as the lowest energy states of the system. This lifts the Coulomb blockade, allowing electrons to tunnel into and out of the island.

The Coulomb blockade is lifted when the gate capacitance is charged with exactly minus half an electron, which is not as surprising as it may seem. The island is surrounded by insulators, which means that the charge on it must be quantized in units of e , but the gate is a metallic electrode connected to a

plentiful supply of electrons. The charge on the gate capacitor merely represents a displacement of electrons relative to a background of positive ions.

If we further increase the gate voltage so that the gate capacitor becomes charged with $-e$, the island again has only one stable configuration separated from the next-lowest-energy states by the Coulomb energy. The Coulomb blockade is set up again, but the island now contains a single excess electron. The conductance of the SET transistor therefore oscillates between minima for gate charges that are integer multiples of e , and maxima for half-integer multiples of e .

7 APPLICATIONS

7.1 Supersensitive Electrometer

The high sensitivity of single-electron transistors has enabled 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.

7.2 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 nano-scale objects.

7.3 DC Current Standards

One of the possible applications of single-electron tunneling is fundamental standards of dc current. For such a standard, a phase lock SET oscillations or Bloch oscillations in a simple oscillator with an external RF source of a well characterized frequency f , the phase locking would provide the transfer of a certain number m of electrons per period of external RF signal and thus generate dc current which is fundamentally related to frequency as $I = mef$. This arrangement have limitation of coherent oscillation that are later overcome by the use of such a stable RF source to drive devices such as single-electron turnstiles and pumps, which do not exhibit coherent oscillations in the autonomous mode.

7.4 Detection of Infrared Radiation

The calculations of the photo response of single-electron systems to electromagnetic radiation with frequency $\sim E_C/h$ have shown that the response generally differs from that the well-known Tien-Gordon theory of photon-assisted tunneling. In fact, this is based on the assumption of independent (uncorrelated) tunneling events, while in single-electron systems the electron transfer is typically correlated. This fact implies that single-electron devices, especially 1D multi-junction array with their low co-tunneling rate, may be used for ultra-sensitive video- and heterodyne detection of high frequency electromagnetic radiation, similar to the superconductor-insulator-superconductor (SIS) junctions and arrays. The Sin-

gle electron array have advantages over their SIS counterparts: Firstly lower shot noise and secondly convenient adjustment of the threshold voltage. This opportunity is especially promising for detection in the few-terahertz frequency region, where no background-radiation-limited detectors are yet available.

7.5 Voltage State Logics

The single-electron transistors can be used in the "voltage state" mode. In this mode, the input gate voltage V controls the source-drain current of the transistor which is used in digital logic circuits, similarly to the usual field-effect transistors (FETs). This means that the single-electron charging effects are confined to the interior of the transistor, while externally it looks like the usual electronic device switching multi-electron currents, with binary unity/zero presented with high/low dc voltage levels (physically not quantized). This concept simplifies the circuit design which may ignore all the single-electron physics particulars. One 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, of the order of 10^{-4} e/RC. The corresponding static power consumption is negligible for relatively large devices operating at helium temperatures. However, at the prospective room-temperature operation this power becomes on the order of 10^{-7} Watt per transistor. Though apparently low, this number gives an unacceptable static power dissipation density (>10 kW/cm²) for the hypothetical circuits which would be dense enough ($>10^{11}$ transistors per cm²) to present a real challenge for the prospective CMOS technology.

7.6 Charge State Logics

The problem of leakage current is solved by the use of another logic device, named charge state logic in which single bits of information are presented by the presence/absence of single electrons at certain conducting islands throughout the whole circuit. In these circuits the static currents and power vanish, since there is no dc current in any static state.

7.7 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 complementary 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. By utilising this fact the function of SET circuit can be programmed, on the basis of function stored by the memory function. The charge around the QD of the SET namely an SET island shifts 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, making 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.

8 QUANTUM COMPUTER

Quantum computers need to be able to control matter at

the most fundamental level. Quantum information is similar to ordinary information in that you have different states of matter representing "0" and "1". For a single electron, that could be the spin orientation ("up" or "down").

The most advanced approaches to quantum computing seek to create qubits—as quantum bits are called—by using ions of cold gas trapped in a confined space, superconducting junctions, or optical systems. However, because of decoherence, these approaches are thought to be hard to scale up to the hundreds of qubits needed to build quantum computers that could rival powerful conventional computers. A type of quantum computer could be implemented in a silicon chip doped with phosphorus, which could be scaled up relatively easily. The idea involved is using the spin of the electron as the qubit. Electron spins in silicon have very long coherence times compared with other comparable solid-state approaches.

Single Electron Transistors (SETs) are nanoscale electrometers of unprecedented sensitivity, and as such have been proposed as read-out devices in a number of quantum computer architectures. It is a device that can act as an exquisitely sensitive electrometer. This sensitivity derives from precise control of the absolute charge state of a small, metallic island, coupled via tunnel junctions to macroscopic leads. SETs have been suggested for a diverse range of applications, from elements for classical logic to single-photon detectors.

The charge of a single electron can be measured single-electron transistors. Sensing the spin of a single electron is much tougher, however, because it is extremely difficult to measure such a minute magnetic moment directly. Instead, it is necessary to convert the spin measurement into a "charge transfer measurement.

SET's helps to get the spin state of the electron to control the flow of charge in a nearby circuit and produce a digital readout. SETs are commonly suggested as readout mechanisms for quantum scale devices and quantum computers (QC), either via direct sensing of charge qubits, or of spin qubits after an initial spin to charge transduction process. Compatibility of SETs with such rigorous demands has been shown often. Merely showing SETs have the required sensitivity for qubit readout is not, however, sufficient for the development of scalable quantum computer architecture. A SET can be used for both qubit control and read-out, reducing the number of electrodes required for operation of the QC. The functionality of a standard SET can be multiplexed so as to operate as both read-out device and control gate for a solid-state qubit. Multiplexing in this way may be critical in lowering overall gate densities in scalable quantum computer architectures.

But reading the spin state of the electron is only one part of quantum computing. You need to be able to write as well. The researchers say the next step they are pursuing is to make a single electron writer and combine it with the reader. Many challenges still remain.

The idea of quantum computing is still a vision. If such a computer could be built, there are certain kinds of computations that it could do much, much faster than regular digital computers. Examples are searching databases, factoring large number and a few others. Some of these problems would take

a lifetime on a conventional computer.

9 ADVANTAGES

Following are the advantages of Single-electron transistors (SETs):

- Low energy consumption
- High sensitivity
- Compact size
- High operating speed
- Simplified circuit
- Feature of reproducibility
- Simple principle of operation
- Straight forward co-integration with traditional CMOS circuits.
- Performance of Single-electron transistors (SETs) is better than the Field-effect transistors (FETs) because of their compact size.

Single electron transistors (SETs) have high input impedances and low voltage gain. Besides this, these are also very sensitive to random background charges. Due to this, SETs have replaced the FETs in many applications where low output impedances and large voltage gain is necessary.

10 DISADVANTAGES

Following are the disadvantage of Single-electron transistors (SETs):

- Integration of SETs in a large scale: To operate SETS at room temperature, large quantities of monodispersed Nano particles less than 10nm in diameter must be synthesized. But, it is very hard to fabricate large quantities of SETs by traditional optical lithography and semiconducting process.
- It is difficult to link SETs with the outside environment.
- Practically difficult to fabricate Single electron transistors (SETs).

11 CONCLUSION

Single-electron devices have already proved their value as tools in scientific research. There are strong efforts around the world to make the artificial atoms in SETs smaller, in order to raise the temperature at which charge quantization can be observed. These involve self-assembly techniques and novel lithographic and oxidation methods whereby artificial atoms can be made nearly as small as natural ones. This is, of course, driven by an interest in using SETs for practical applications. However, as SETs get smaller, all of their energy scales can be larger, so it is very likely that new phenomena will emerge. Transistors are the building blocks of the electronic devices that power the digital world, and much of the growth in computing power over the past many decades has been made possible by increases in the number of transistors that can be packed onto silicon chips.

But that growth, if left to current technology, may soon be coming to an end. Many in the semiconductor field think that the industry is fast approaching the physical limits of transis-

tor miniaturization. The major problem in modern transistors is power leakage leading to the generation of excessive heat from billions of transistors in close proximity.

Only one thing is certain: if the pace of miniaturization continues unabated, the quantum properties of electrons will become crucial in determining the design of electronic devices before the end of the next decade.

It is also one of the key building blocks needed to make quantum computers which promise exponential increases in processing speed over today's computers through their use of the "spin", or magnetic orientation, of individual electrons to represent data in their calculations.

SETs have shown promising applications in metrology, terahertz radiation detection and imaging. Because of natural small dimension, SET is a potential solution for continue silicon scaling. In addition, low power dissipation can be achieved in circuits composed of single-electron devices. Metallic structures can be fabricated with vertical and lateral islands and tunnel barrier structures at temperature up to 77K. GaAs and silicon based SETs have been already demonstrated. However, fabrication is still the most difficult challenge of SET application. Electron beam lithography and scanning probe techniques offer the best prospects for the future. Besides, some more esoteric techniques based on atomic particle deposition and colloid chemistry may also provide some benefits.

The future of research on SETs looks very bright. It now seems that electronics based on individual molecules and single-electron effects will replace conventional circuits based on scaled-down versions of field-effect transistors.

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