Single Electron Transistor

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Abstract- Modern techniques of lithography make it possible to confine electrons to sufficiently small dimensions that the quantization of both their charge and their energy are easily observable. When such confined electrons are allowed to tunnel to metallicle ads a single electron transistor (SET) is created. This transistor turns on and off again every time one electron is added to the isolated region. 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 review, the physics underlying the operation of SETs is explained, a brief history of its invention is presented, and issues of current interest are discussed.

Keywords: single electron transistor, mesoscopic physics, nanostructure

I. THE PHYSICS OF SINGLE ELECTRON TRANSISTORS

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 behaviour 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 tunnelling, 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 behaviour of the device is entirely quantum mechanical.

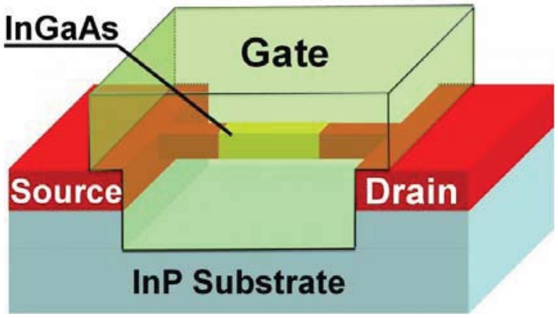

Fig. 1 Schematic drawing of a SET. Wires are connected to source and drain contacts to pass current through the 2DEG at the InGaAs/InP interface. Wires are also connected to the confining electrodes to bias them negatively and to the gate electrode that controls the electrostatic energy of the confined electrons.

A schematic of one kind of SET is shown in Fig. 1. It consists of a semiconductor, in this case InGaAs, separated from metal electrodes by an insulator, in this case InP. The InP is doped with Si, which donates electrons. These fall into the InGaAs, because their energy is lower in the latter material. The resulting positive charge on the Si atoms creates a potential that holds the electrons at the InGaAs/InP interface, creating a two dimensional electron gas (2DEG). The source and drain contacts allow one to drive electrons from an external circuit through the 2DEG. A negative voltage on these electrodes creates a potential similar to the one sketched in Fig. 2; the negative voltage repels electrons from underneath the confinement electrodes and creates saddle point potential barriers under the constrictions.

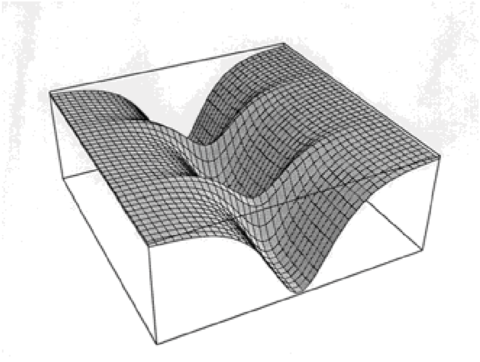

Fig. 2 Sketch of the electrostatic potential energy experienced by an electron moving at the interface between InGaAs and InP in Fig. 1.

Figure 3 shows an electron micrograph of such constriction and gate electrodes for one of the smallest SETs made in this way so far. The region surrounded by electrodes appears to be a few hundred nanometers in diameter. However, the droplet of electrons confined in it is considerably smaller. We estimate that these SETs have about 50 electrons confined to a droplet about 100 nm in diameter. When the voltage on the gate electrode is increased, the potential minimum, in which the electrons are trapped, becomes deeper. This causes the number of trapped electrons to increase. However, unlike a conventional transistor, in which the charge increases continuously, the charge in the trap increases in discrete steps, and this is reflected in the conductance between source and drain.

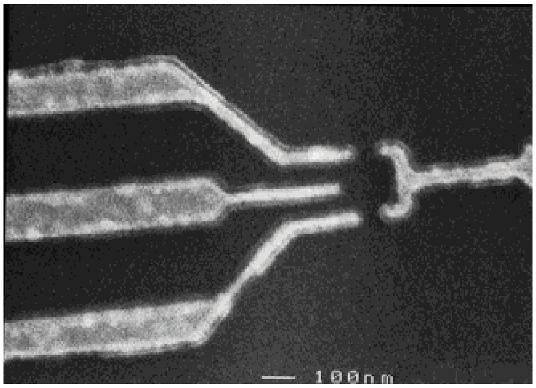

Fig. 3 Electronmicrograph of the top surface of the SET

Figure 4 shows the conductance as a function of gate voltage V_g for a SET. The conductance is measured by applying a very small voltage V_{ds} between drain and source, small enough that the current is proportional to V_{ds}. As seen in the figure, the conductance increases and decreases by several orders of magnitude almost periodically in V_g. A calculation of the capacitance between the gate electrode and the droplet of confined electrons shows that the voltage between two peaks or two valleys is just that necessary to add one electron to the droplet. The name "single electron transistor" comes from the observation that the transistor turns on and off again every time a single electron is added to it.

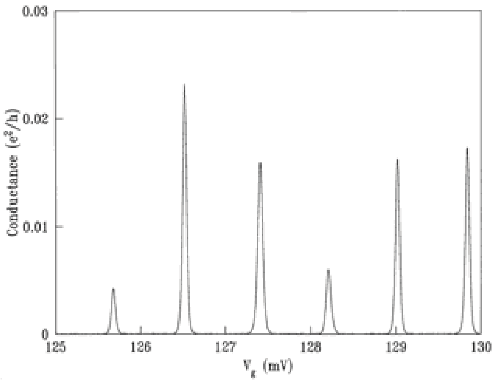

Fig. 4 Conductance of a SET as a function of the gate voltage. The spacing between the peaks is the voltage necessary to add one electron to the artificial atom.

II. QUANTUM DOT STRUCTURE

Quantum dot [QD] is a mesoscopic system in which the addition or removal of a single electron can cause a change in the electrostatic energy or Coulomb energy that is greater than the thermal energy and can control the electron transport into and out of the QD. This sensitivity to individual electrons has led to electronics based on single electrons. When the wave functions between two quantum dots overlap, the coupled quantum dots exhibit the properties of a molecule. To understand the electron transport properties in QD. Let us consider a metal nanoparticle sandwiched between two metal electrodes shown in figure 1. The nanoparticle is separated from the electrodes by vacuum or insulation layer such as oxide or organic molecules so that only tunneling is allowed between them. So we can model each of the nanoparticles-electrode junctions with a resistor in parallel with a capacitor. The resistance is determined by the electron tunneling and the capacitance depends on the size of the particle. We denote the resistors and capacitors by R_1, R_2, C_1 and C_2, and the applied voltage between the electrodes by V. We will discuss how the current, I depends on V. When we start to increase V from zero, no current can flow between the electrodes because movement of an electron onto (charging) or off (discharging) from an initially neutral nanoparticle cost energy by an amount given by equation 1.

$$\mathbf{E = e^2 / 2C} \qquad (1)$$

This suppression of electron flow is called Coulomb blockade. Current start to flow through the nanoparticles only when the applied voltage V is large enough to establish a voltage _ at the nanoparticles. This voltage is called threshold voltage and denoted by V_{th}. So in the I-V curve, we expect a flat zero-current regime with a width of $2V_{th}$. When the applied voltage reaches V_{th}, an electron is added to (removed from) the nanoparticles. Further increasing the voltage, the current does not increase proportionally because it requires us to add (or remove) two electrons onto the nanoparticles, which cost a greater amount of energy. Once the applied voltage is large enough to overcome the Coulomb energy of two electrons, the current starts to increase again. This leads to a stepwise increase in I-V curve, called Coulomb staircase.

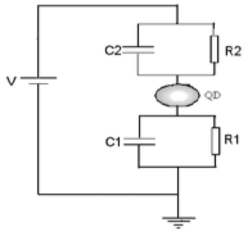

Fig5. Quantum Dot Structure

III. HISTORY OF THE SET

The effects of charge quantization were first observed in tunnel junctions containing metal particles as early as 1968. Later, the idea that the Coulombb lockade can be overcome with a gate electrode was proposed by a number of authors, and Kulik and Shekhter developed the theory of Coulomb-blockade oscillations, the periodic variation of conductance as a function of gate voltage. Their theory was classical, including charge quantization but not energy quantization. However, it was not until 1987 that Fulton and Dolan made the first SET, entirely out of metals, and observed the predicted oscillations. They made a metal particle connected to two metal leads by tunnel junctions, all on top of an insulator with a gate electrode underneath. Since then, the capacitances of such metal SETs have been reduced to produce very precise charge quantization. The first semiconductor SET was fabricated accidentally in 1989 by Scott-Thomas *et al.* In narrow Si field effect transistors. In this case the tunnel barriers were produced by interface charges. Shortly thereafter Meirav *et al.* made controlled devices of the kind depicted in Fig. 1. In these and similar devices the effects of energy quantization were easily observed. Only in the past few years have metal SETs been made small enough to observe energy quantization. In most cases the potential confining the electrons in a SET is of sufficiently low symmetry that one is in the regime of quantum chaos: the only quantity that is quantized is the energy. In this case there is a very sophisticated approach, based in part on random matrix theory, for predicting the distributions of peak spacings and peak heights for data like those in Fig. 4. There are challenging problems in this arena that are still unsolved. In particular, there is great interest in how the interplay of exchange and level spacing determines the spin of a small metal SET. As already mentioned, the data of Fig. 5 are for an SET of sufficiently high symmetry that angular momentum in the plane of the 2DEG is conserved, so shell structure is apparent. Another way to eliminate the scattering that destroys angular momentum conservation is to apply a magnetic field perpendicular to the 2DEG. At sufficiently high fields elegant patterns are seen in the single-electron-peak positions as a function of field.

The future of research on SETs looks very bright. 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.

IV. APPLICATION OF SET

4.1 Supersensitive Electrometer

The high sensitivity of single-electron transistors have 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**.**

4.2 Single-Electron Spectroscopy

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

4.3 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.

4.4 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 (|V|<Vt) and approaching the linear asymptote V = NRI + constant at (|V|▯ Vt). If the temperature is raised above Ec/kB, thermal fluctuations smear out the Coulomb blockade, and the I-V curve is almost linear at all voltages.

4.5 *Detection of Infrared Radiation*

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 Single electron array have advantages over their SIS counterparts: Firstly lower shot noise and secondly convenient adjustment of the threshold voltage.

4.6 Voltage State Logics

The single-electron transistors can be used in the "voltage state" mode. In this mode, the input gate voltage U 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). 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.

4.7 Charge State Logics

The problem of leakage current is solved by the use of another logic device name 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.

V. PROBLEMS IN SET IMPLEMENTATIONS

5.1. Lithography Techniques

The first biggest problem with all single-electron logic devices is the requirement Ec~100kBT, 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.

5.2. Background Charge

The second major problem with 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 Q0 of the order of e. This charge is effectively subtracted from the external charge Qe.

5.3. Cotunneling

The essence of the effect is that the tunneling of several (N>1) electrons through different barriers at the same time is possible as a single coherent quantum-mechanical process. The rate of this process is crudely (RQ/R)N-1 times less than that for the single-electron tunnelling described by Equation of the orthodox theory □□□*W*) = (1/*e*) *I*(□*W/e*) [1 - exp{-□*W/kBT*}]-1 (4) If the condition expressed by equation (3) is satisfied this ratio is rather small; cotunneling can nevertheless be clearly observed within the Coulomb blockade range where orthodox tunnelling is suppressed.

5.4. Room Temperature Operation

The first big problem with all the known types of single-electron logic devices is the requirement *E*c ~ 100 *kBT*, 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 addition 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 thresholds.

5.5. Linking SETs with the Outside Environment

The individual structures patterns which function as logic circuits must be arranged into larger 2D patterns. There are two ideas. The first is to integrating SET as well as related equipments with the existed 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 clusters, which is called quantum cellular automata (QCA). The advantage of QCA is its fast information transfer velocity between cells (almost near optic velocity) via electrostatic interactions only, no wire is needed between arrays and the size of each cell can be as small as 2.5nm, this made them very suitable for high density memory and the next generation quantum computer.

VI. 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”). : It is a lot like using “Etch a Sketch” except we use a sharp probe from an “atomic force microscope” to charge the top surface of an oxide-based material. Where we place positive charges on the top surface, negatively charged electrons collect directly underneath. One property that we found very interesting was the ability of the transistor to be in the “on” or “off” state in the absence of power. That’s due to the ferroelectric property, which is a lot like magnetism in that you can reverse the properties and they switch the transistor on and off.

One property that we found very interesting was the ability of the transistor to be in the “on” or “off” state in the absence of power. That’s due to the ferroelectric property, which is a lot like magnetism in that you can reverse the properties and they switch the transistor on and off. So it’s like a transistor plus memory. If we can get that to work at room temperature, we wouldn’t need to turn off our computers when we’re not using them. They have properties a lot like semiconductors, but the size that we can control them is much smaller than traditional materials. Also, the interactions between electrons is much stronger. And they have other properties like ferroelectricity and superconductivity.

One favorable aspect of quantum information is security — the data can’t be replicated, promising more secure bank transactions and even improvements in drug design. This is a unique property of quantum states. They can be measured, but not ‘cloned’ or copied. The act of copying them intrinsically changes the original. This might be useful for secure communication, since the person receiving the message would know if it was intercepted and read.

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.

The quantum states encode the information within the bits. Unfortunately, however, they are very fragile. One of the major obstacles is finding ways of preserving them while the computer is running. This is one of the intriguing aspect of quantum physics: the act of observing a state changes the state; to exploit the unique properties of quantum mechanics we need to find new schemes to measure physical properties of matter. These defects within diamond could someday form the individual bits of a quantum computer. They may also form only a specialized part, like memory bits or a way to transform quantum states into light: a type of quantum transducer. The atom-sized diamond defect that we study can absorb light of precisely the right wavelength. If the wavelength is tuned away slightly, it turns out that the photons that pass by the defect can actually interact with the electrons without being absorbed. The experiment provides a method of using light to control and measure the quantum state of diamond defects. It may be also extended to do long-distance communication of quantum states, providing the possibility of building a quantum repeater.

VII. CONCLUSIONS

Single Electronic Transistor (SET) has proved their value as tool in scientific research. Resistance of SET is determined by the electron tunneling and the capacitance depends on the size of the nanoparticle. The current starts to flow through the junction when applied voltage is just sufficient to raise the energy of electron above the coulomb blocked, this is called *threshold voltage V*th and the flat zero current persist for *2V*th. Several applications of nanoscale devices in metrology, including the fundamental standards of current, resistance and temperature also seem quite promising. Another potential application is terahertz radiation detection. The situation is much more complex with digital single electronics. The concept of single electron logic suggested so far face sturdy challenges: either removing background charge or providing continuous charge transfer in nanoscale. The main problem in nanometer era is the fabrication of nanoscale devices. SET provide the potential for low-power, intelligent LSI chips, appropriate for ubiquitous application.

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