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BASIC INTRODUCTION TO SINGLE ELECTRON TRANSISTOR

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Abstract-*The goal of this paper is to review in brief the basic physics of nanoelectronic device single-electron transistor [SET] as well as prospective applications and problems in their applications. The principles followed by SET device i.e. Coulomb Blockade, Kondo Effect that is helpful in a number of applications. SET functioning based on the controllable transfer of single electrons between small conducting "islands". The device properties dominated by the quantum mechanical properties of matter and provide new characteristics coulomb oscillation. SET is able to shear domain with silicon transistor in near future and enhance the device density. Recent research in SET gives new ideas which are going to revolutionize the random access memory and digital data storage technologies.*

Keywords*- Kondo Effect, Coulomb Blockade, SET, Quantum Dot*

I. INTRODUCTION

The discovery of the transistor has clearly had enormous impact, both intellectually and commercially, upon our lives and work. A major vein in the corpus of condensed matter physics, quite literally, owes its existence to this breakthrough. It also led to the microminiaturization of electronics, which has permitted human to have powerful computers that communicate easily with each other via the Internet.

Over the past 30 years, silicon technology has been dominated by Moore's law: the density 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. 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.

II. HISTORY OF SET

The effects of charge quantization were first observed in tunnel junctions containing metal particles as early as 1968. Than the idea that the Coulomb blockade can be overcome with a gate electrode was proposed by a number of researchers, 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.[1]

The first semiconductor SET was fabricated accidentally in 1989 by Scott-Thomas in narrow Si field effect transistors. In this case the tunnel barriers were produced by interface charges. Albeit with an unusual heterostructure with AlGaAs on the bottom instead of the top. In these and similar devices the effects of ener quantization were easily observed. Only in the past few years have metal SETs been made small enough to observe energy quantization. Foxman also measured the level width Γ and showed how the energy and charge quantization are lost as the resistance decreases toward h/e2.

III. KONDO EFFECT IN SET

The Kondo effect can be defined as when a droplet of electrons is enclosed to a small region of space , the number of electrons and their energy become quantized. So, the droplet behaves like an artificial atom is coupled to conducting leads ,the Anderson Model, adesigned to explainthe coupling of naturalatoms to metals.[2]

The Anderson Model defined the behaviour of a metal containing amagnetic impurity. At high temperatures the spin of the impurity is independent of the spins of the electrons in the metal, but at low temperature a spin singlet state state is formed between the unpaired localized electron and delocalized electrons at the fermi energy; in which the spin of the impurity is screened by those of the conduction electrons. The formation of this singlet as the temperature is lowered results in strong scattering of the conduction electrons near the fermi energy and aconsequent increase in the resistance. How the singlet state envoles with temperature and the result of this evolution for magnetization and conductivity is called the kondo problem.

A magnetic field also alters the kondo effect applying a magnetic field splits separates the unpaired localized electron state into a zeeman doublet separated by the energy $g\mu_B B$. This also separates the enhanced density of states at the fermi level into two peaks with enegies $g\mu_B B$ above and below the fermi level.

Beginning in the late 1980_s , theorists proposed that the kondo effect should also arise in nanometer – sized structures that allow tunneling between localized states and metal leads.[3]

It was predicted that because scattering would increase rather than reduce transport for tunneling , the kondo effect would increase the conductance instead of the resistance at low temperature.

IV. COULOMB BLOCKADE

A tunnel junction is, in its simplest form, a thin insulating barrier between two conducting electrodes. If the electrodes are superconducting, Cooper pairs (with a charge of two elementary charges) carry the current. In the case that the electrodes are normal conducting, i.e. neither superconducting nor semiconducting, electrons (with a charge of one elementary charge) carry the current. The following reasoning is for the case of tunnel junctions with an insulating barrier between two normal conducting electrodes (NIN junctions).

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 nonvanishing (larger than zero) probability for an electron on one side of the barrier to reach the other side (see quantum tunnelling). When a bias voltage is applied, this means that there will be a current, 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

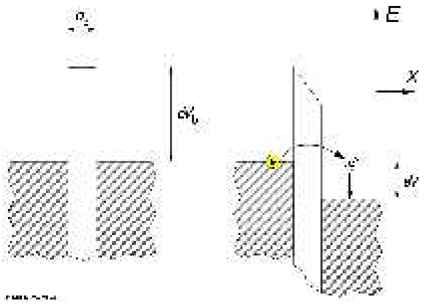

Figure.1. Schematic diagram showing the transport of electrons and tunneling in SET.[10]

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.

Electrons move continuously in the conventional transistors, but as the size of the transistors goes down to nanoscale, the transistors energy quantumized, that is the process of charging and discharging is discontinuous i.e.

$$E_c=e^2/2C$$

Where C is the capacitance of this system and E_c is Coulomb Blockade Energy, due to which previous electron repels new electron.[4] For nanoelectronic system capacitance is very small, so Coulomb Blockade Energy(E_c) is very high and due to electrons cannot move simultaneously, but must be passed through one by one. This process is Coulomb Blockade and was first observed in 1980.

V. SINGLE ELECTRON TRANSISTOR

Figure.2.shows the single electron transistor, consists of two tunnel junctions sharing one common electrode with a low self-capacitance, known as the island. The electrical potential of the island can be tuned by a third electrode (the gate), capacitively coupled to the island.

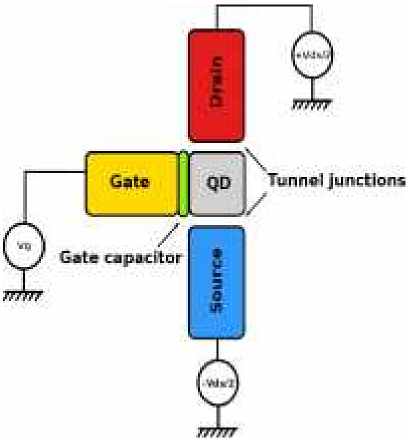

Figure.2. schematic diagram of the Single Electron Transistor

In the blocking state no accessible energy levels are within tunneling range of the electron (red) on the source contact. All energy levels on the island electrode with lower energies are occupied.

When a positive voltage is applied to the gate electrode the energy levels of the island electrode are lowered. The electron can tunnel onto the island, occupying a previously vacant energy level. From there it can tunnel onto the drain electrode where it inelastically scatters and reaches the drain electrode Fermi level.

The energy levels of the island electrode are evenly spaced with a separation of ΔE. ΔE is the energy needed to each subsequent electron to the island, which acts as a self-capacitance C. The lower C the bigger ΔE gets. To achieve the Coulomb blockade, three criteria have to be met:

1. The bias voltage can't exceed the charging energy divided by the capacitance V_{bias} = ;
2. The thermal energy k_BT must be below the charging energy E_C = , or else the electron will be able to pass the QD via thermal excitation; and
3. The tunneling resistance (R_t) should be greater than, which is derived from Heisenberg's Uncertainty principle.

VI. BASIC PHYSICS OF SET OPERATION

Single Electron Transistor [SET] have been made with critical dimensions of just a fewnanometer using metal, semiconductor, carbon nanotubes or individual molecules. A SET consist of a small conducting island [Quantum Dot] coupled to source and drain leads by tunnel junctions and capactively coupled to one or more gate. Unlike Field Effect transistor, Single electron device based on an intrinsically quantum phenomenon, the tunnel effect.[1] The electrical behaviour of the tunnel junction depends on how effectively barrier transmit the electron wave, which decrease exponentially with the thickness, which is given by the area of tunnel junction divided by the square of wave length.

Quantum dot [QD] as shown in figure 3. 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.

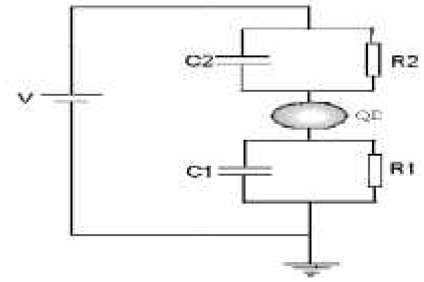

Fig. 3. Quantum Dot Structure

To understand the electron transport properties in QD. Let us consider a metal nanoparticle sandwiched between two metal electrodes shown in figure 4.

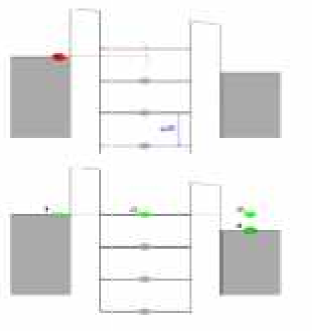

Figure.4 Energylevels of source, island and drain (from left to right) in a single electron transistor for both the blocking state (upper part) and the transmitting state (lower part)[5]

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 R1, R2, C1 and C2, 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.

$E_c = e^2/2c$

VII. APPLICATIONS OF SET

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.

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[6].

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.

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 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 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.[8]

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). This concept simplifies the circuit designwhich may ignore all the single-electron physics particulars[6]. One substantial disadvantage of voltage state circuits is that neither of the transistors in each complementary pair is closed toowell, so that the static leakage current in these circuits is fairly substantial, of the order of 10-4e/RC. The corresponding static power consumption is negligible for relatively large devices operating at helium temperatures.

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.[9]

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.[9]. 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. PROBLEMS IN THE SET IMPLEMENTATION[7]

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. Since in such small conductors the quantum kinetic energy gives a dominant contribution to the electron addition energy (Ek >> Ec,), 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.

Room Temperature Operation- The first big problem with all the known types of single-electron logic devices is the requirement Ec ~ 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.[12]

Linking SETs with the Outside Environment- The individual structures patterns which function as logic circuits must be arranged into larger 2D patterns.

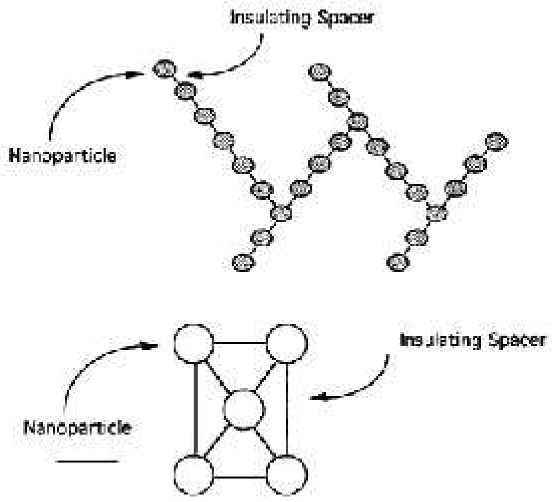

Fig. 5. Nanoparticle–insulator structures proposed in the wireless computing schemes of Korotkov (top) and Lent (bottom). The circles represent quantum dots, the lines are insulating spacers.[11]

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.

IX. CONCLUSION

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 Vth and the flat zero current persist for 2Vth.

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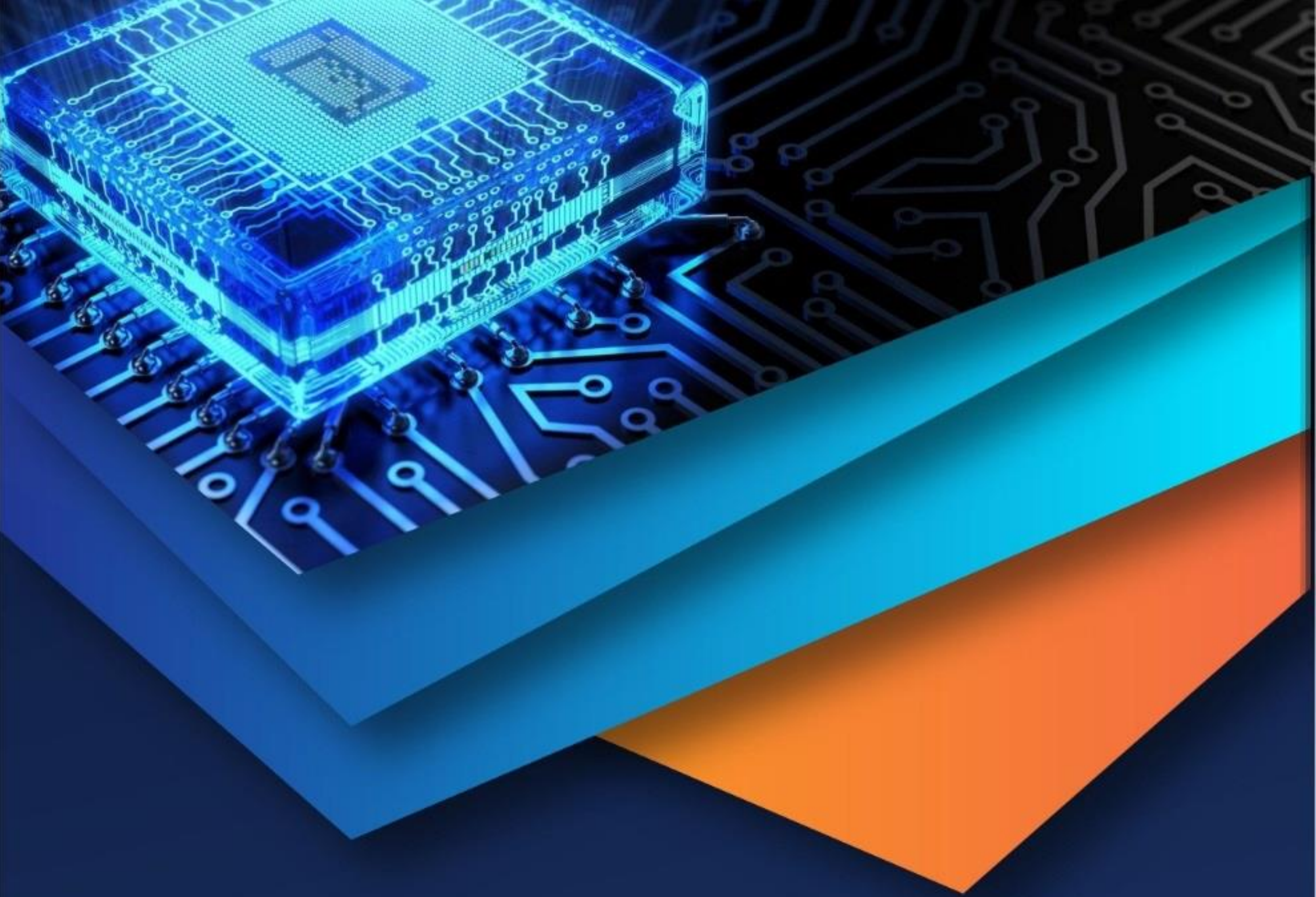

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