NANOELECTRONICS: AN EFFORT TO SUSTAIN MOORE'S LAW

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ABSTRACT

The quest for increase in the number of devices on a chip has lead to the reduction of sizes of electronic devices. Increase in component density has revolutionised the electronic processing systems. In this paper effort has been made to review evolution of electronics towards nanometric regime. Various nanomaterials being studied for use in nanoelectronics are also discussed. A brief discussion of the electronic devices like single electron devices and resonant tunnelling devices is also done.

Keywords: Mos, Moore's Law, Nanotechnology, Nanoelectronics, Carbon Nanotubes, Quantum Dots, Single Electron Transistor, Resonant Tunnelling Devices.

I. INTRODUCTION

Last few decades, world has witnessed a revolution in the field of electronics. This revolution has opened up the doors for a whole new variety of electronic applications. Transistor brought a change in the semiconductor industry. After the discovery of transistor, the focus was shifted to the reduction in size of the transistor; this would increase the number of transistors on a chip. With the increase in the number of transistors on a chip, computational circuits were designed. Gordon Moore, co-founder of Intel Corporation, in 1965, predicted that the number of transistors on an IC would double every two years [1]. This is termed as the "Moore's Law". Given that the number of transistors would double every two years, the cost of fabrication increases. As the number of transistor on a chip increase, the heat dissipation also increases. Also, the transistor having its limitations, gave birth to a new technology called the MOS; Metal Oxide Semiconductor. The MOS transistors were a superior class of transistors than their bipolar counterparts; this was because of its better reliability and compactness. MOS technology became the corner stone of Moore's Law. Presently, the CMOS (Complementary Metal Oxide Semiconductor) is instrumented for sustaining the Moore's Law. CMOS devices provide the benefits like low power consumption and high noise immunity [2].

Modern semiconductor industry is categorized by miniaturization of devices. The CMOS devices are scaling from Microelectronics to Nanoelectronics. But this size reduction caused increased leakage current, low reliability, increased manufacturing cost etc. This led to the proposal that to sustain electronic development, the research should begin at an atomic level [3]. Also, the scaling down of transistors could not continue forever. The continued improvement in the communication and computational systems has been supported by miniaturization of devices on the chip. Scaling down of MOSFETs helps in sustaining the Moore's law. The scaling down process reduces the power consumption. However, this scaling down can only be done up to a certain level. Scaling down of MOSFET below 50 nm leads to performance degradation [4,5].

Fig 1: Graph showing the Moore's Law

II. NANOTECHNOLOGY AND NANOELECTRONICS

"*Nanotechnology*" term defined by Tokyo Science University Professor Norio Taniguchi in a 1974 paper, as follows: "'Nano-technology' mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or one molecule". Nanotechnology refers to dealing with materials on a nanometric scale. These materials are studied on an atomic molecular level. Nanoelectronics refer to using nanotechnology in electronic components [2]. By mixing the fields of chemistry, biology, physics and engineering, nanomaterials can be fabricated. It is also proposed that nanoelectronics will integrate devices at a smaller level. Richard Feynman gave a lecture on nanotechnology saying that, "There's plenty of Room at the Bottom". He suggested that materials can be manipulated at an atomic level [4].

Scaling down of transistors could not continue forever. Nanoelectronics may be able to continue this scaling down process. The idea of nanoelectronics was popularized in the 1980's, when work on resonant tunnelling and band gap engineering in low-dimensional semiconductor quantum wells and super lattices grew. This led to the creation of new opportunities for finding out the limits on the downscaling of conventional transistors. It is well known that when the size of a system becomes comparable to the electron wavelength, quantum effects become dominant [6]. This occurs when transistors are downscaled and their characteristic dimensions reach the nanometre range, leading to new phenomena and possible novel devices based on quantum tunnelling mechanisms. For nanoelectronics to become a reality, it is essential that the new devices and circuits must be fabricated with nanometric precision [9,10].

III. NANOMATERIALS

According to Moore's law the number of transistors on an IC would double up every two years. This has its own limitations; like greater complexity and heat dissipation. Apart from these limitations there are several other limitations that are imposed by silicon itself; 1) Silicon has low mobility 2) Silicon lattice absorbs some vibrations from transfer carriers, which converts to access heat. 3) Shallow source/ Drain material – As transistors get smaller, doped wells are getting small that even ion implantation becomes difficult to control.4) Silicon gets contaminated at high temperature. Therefore, silicon cannot be used at nanolevel [7]. The various nanomaterials that have been discovered are: 1) Carbon nanotubes 2) Quantum Dots 3) Single Electron Devices 4) Resonant Tunnelling Devices.

3.1 Carbon Nanotubes

Carbon nanotubes, abbreviated as CNTs are seamless cylinders of carbon. [3]These cylinders are formed by rolling of the graphene sheet into a tube. For clarity, imagine a chicken wire rolled into a tube. CNTs have transformed the electronic industry entirely; from large scale bulky systems to miniaturized systems. CNTs due to their wide range of properties, find use in many areas ranging from large scale automobile industry to nanometric scale electronics. Carbon nanotubes have extraordinary properties like small size and mass, high tensile strength and high thermal and electrical conductivities. These properties enable the use of CNTs in a number of applications. CNTs is categorize into two broad types; Single walled nanotubes (SWNTs) and Multi-walled nanotubes (MWNTs). The electronic structure of nanotubes can be determined by the 'Chirality Vector'. CNTs due to their chirality , can be metallic or semiconducting. CNTs are used in making transistors called CNT FETs. Nanotubes's structure shows electrical properties due to unique and symmetric electronic structure of graphene. Nanotubes with smaller diameters show stronger electrical properties as compared to the nanotubes with larger diameters. CNTs are one dimensional conductors because of its nanoscale cross section, electrons propagate only along the tube's axis. Metallic nanotubes can carry an electric current density of 4 x 10^9 A/cm^2, which is more than 1000 times metals like copper. The strength of atomic bonds in carbon nanotubes allows them to withstand high temperatures. Hence, carbon nanotubes are very good thermal conductors. When compare to copper, commonly used as a thermal conductor, CNTs can transmit over 15 times more the amount of power (per meter per kelvin) than copper [3].

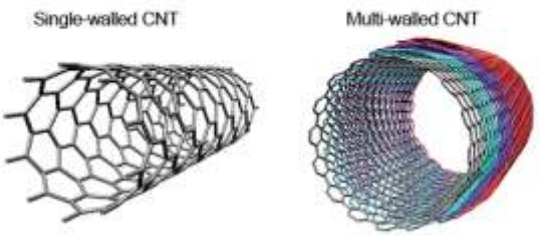


Fig 2: Carbon Nanotubes – Single Walled and Multi-Walled

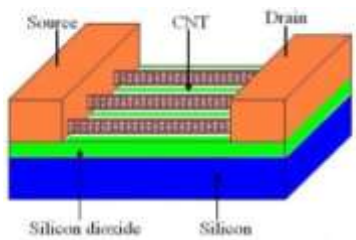
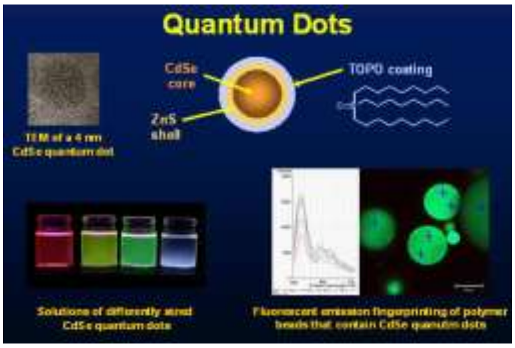


Fig 3: CNT based FET

The limitation of CNT is that it is produced in bulk. Single walled CNT and multiwalled CNT cannot be differentiated. Also, chirality and width of CNT is not under control during fabrication [5].

3.2 Quantum Dots

Quantum dot is stated as zero dimensional confined systems. Quantum dots are the semiconductors that have their dimensions in nanometric scale. These "quantum dots" obey the principle of quantum confinement. Quantum dots are the nano-particles having size from 10nm to 1000 nm. The term "Quantum Dots " is made from the combination of two words - quantum and dot; because of their small size they are known as "Quantum" and 'Dots' is due to their zero dimension. When the size of the semiconductor falls below the bohr radius then the material is called as Quantum Dot. The phenomena of quantum dot followed the older method of absorption and emission [6].



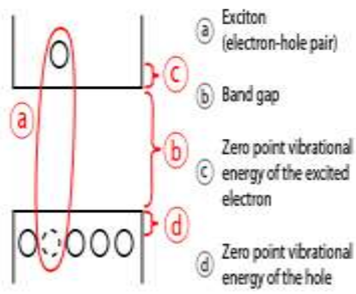


Fig 4: Quantum Dots **Fig 5: Mechanism of Quantum Dots**

Quantum dot were discovered by Russian researcher Alexi Ekinov & Louis E. Brus. The mechanism of quantum dot states that with the absorption of energy, may it be in the form of heat or light, given to a semiconductor material; the electron will jump from the conduction band to valence band. This leaves behind a "hole" in the valence band. The hole and the electron together called as an "exciton". The quantum dots are designed by the researchers by considering the properties of semiconductor material. When these excited electrons fall from their higher energy levels to the ground level, they emit energy in the form of light or heat. Quantum dot encodes the information by looking upon the position of the electron [8].

3.3 Single Electron Transistor (Set)

Due to the miniaturization of size in switching devices, the law of quantum mechanics cannot stay forever. Therefore, in order to solve this problem for semiconductor field, the single electron devices were developed. These artificially structured single electron transistors were studied to operate at low temperatures. But the molecular or atomic sized single electron transistor could function at room temperature.

3.4 History of SET

In 1968, in the tunnel junction containing metal particles, the effects of charge quantization were first observed. After that, an idea to overcome Coulomb Blockade with a gate electrode was proposed. Kulik and Shekhter developed the theory of coulomb blockade oscillations. This theory includes charge quantization, but not energy quantization. After that, in 1987 Fulton and Dolan made the first SET. They connected a metal particle to two metal leads by tunnel junctions. This arrangement was then kept on top of an insulator with the gate electrode underneath. Therefore, due to the reduction in capacitance of SET, very precise charge quantization was produced. In 1989, Scott Thomas fabricated the first semiconductor SET in narrow silicon field effect transistor.

3.5 Structure and Working

Due to small size, SETs have low power dissipation. Even at high speed the SET have low power dissipation. SET consist of two tunnel junctions sharing one common electrode with low self capacitance; that is known as island [6]. The electrical potential of island can be tuned by a third electrode (the gate) capacitively coupled to the island. In blocking state, the energy is not accessible with tunnelling range of electron.

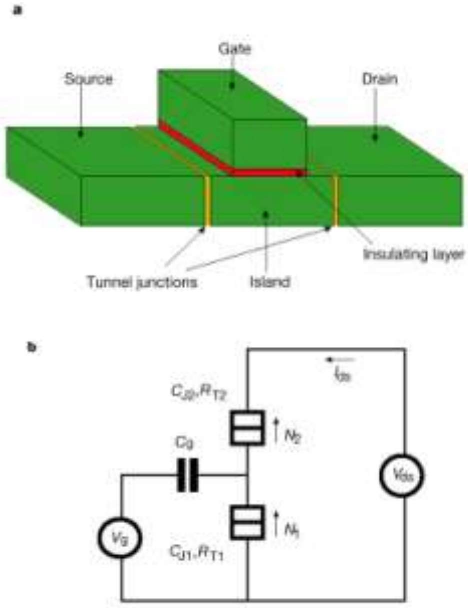


Fig 6 : Simplified structure of SET

When a positive voltage is applied to the gate electrode, the energy levels of island electrode are lowered. The electron can tunnel onto the island. From there it can tunnel onto the drain electrode Fermi level. All the energy levels of island electrode are spaced by the separation of Δ E. Basically, ΔE is the energy needed for each subsequential electron to island and to act as a self capacitance 'C'. As the value of capacitance decreases, the value of Δ E increases. In other words, the capacitance and ΔE are inversely proportional to each other in a SET. Single electron devices are categorized as: 1) Coulomb Blockade device. It is a SET device with three terminals based on coulomb blockade principle. 2) Nano flash memory based devices. It also has three terminals but it is without tunnel barrier between source and drain. 3) Yano type based devices. It is a two terminal device; information is stored in deep traps in poly-Si [7].

IV. RESONANT TUNNELLING DEVICES (RTDs)

The devices which have resonant tunnelling structure are said to be resonant tunnelling devices. The RTDs employ quantum effects in their simplest form. In RTD, the electrons can tunnel through some resonant states at certain energy levels. The simplest resonant tunnelling devices are resonant tunnelling diodes and resonant tunnelling transistors. RTDs can be fabricated from layers of two different III-V semiconductor alloys called as binary semiconductors like GaAs and AlAs.

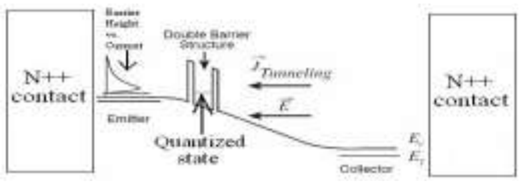


Fig 7: Structure of Resonant Tunnelling Diode

To achieve a maximum frequency up to 2.2 THz as opposed to 215 GHz in conventional CMOS (Complementary Metal-oxide Semiconductor Transistors), RTDs are used. RTDs have very high switching speed. Therefore, they can be used in a variety of applications in wide band secure communication systems, higher resolution radar and imaging systems for low visibility environment. The resonant tunnelling diodes have much lower capacitance when compare to the Esaki diode; this allows resonant tunnelling diodes to oscillate faster [6].

V. OPERATION OF RESONANT TUNNELLING DIODE

The resonant tunnelling diode is made by placing two insulating barriers in a semiconductor to create an island where electrons can exist. The quantum mechanics confined their energies to one finite number of discrete quantized levels, when the electrons are restricted between two closely spaced barriers. For the operation of the resonant tunnelling diode, energy quantization is the basis.

The tunnelling diode consists of a PN junction in which both p and n regions are degenerately doped. There are empty states in the valence band of the p type material and high concentration of electrons in the conduction band of the n type. Initially, the diode is in thermal equilibrium with no external bias voltage. Therefore, the Fermi level is constant [8]. When the forward bias voltage is applied, the Fermi level will start to decrease in p type and increase in n type. At the time when the depletion region is very narrow, the electrons can tunnel through easily and create a forward current as shown in the figure [8].

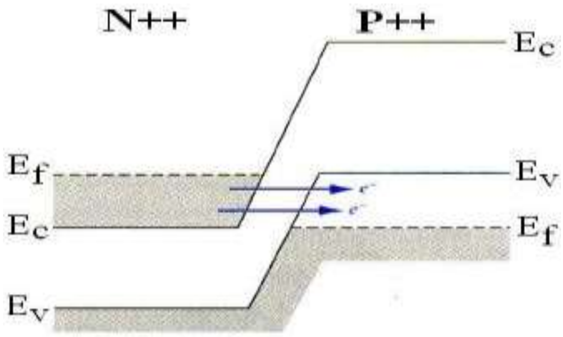


Fig 8: Band diagram showing maximum current across diode

As the bias voltage continues to increase the ideal diffusion current will cause the current to increase. After that when the reverse bias voltage is applied, the electrons in the p region are aligned with empty states in the n region causing a large reverse bias tunnelling current [9].

VI. CONCLUSION

This paper presents a comprehensive review of electronic components and their evolution from microelectronic and nanoelectronics regime. Nanoelectronics is the future of electronics. Nanoelectronics promises higher functionality with reduction in size. The various nanomaterials that have been discovered are faster, better and easy to handle. They display promising properties. Nanotechnology will give birth to new type of electronic components which are small in size, have lower power consumption and have increased functionality. Molecular Electronics is still in infancy, but has given hope for the future of electronic systems.

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