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REVIEW ARTICLE

Shifting towards Nanoelectronics: A device level overview

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Abstract

Nowadays technology scales towards its least possible feature size of components. The reduction of size, power dissipation, noise immunity, logic swing, gain and feature size are some of the key player in nanoelectronics world. The trends shows that, as physical properties approaches to its technological limitation, then new domain of electronics will give the technological breakthrough. From this view point, this review presents the development of nanoelectronics and its allied fields. In addition to that, this review also presents an overview of paradigm shift of nanoelectronics and its counterparts in various domains.

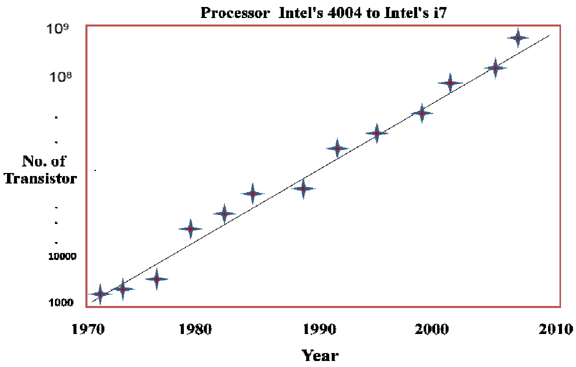
Keywords: CMOS, nanoelectronics, quantum effect, SETs, RTDs, QDs, molecular electronics.

Introduction

The modern semiconductor industry is characterized by its miniaturization of products. There are plenty of trends which developed today's semiconductor industry. The remarkable technological progress has been obtained from radical idea of reductions in the size of transistors, thereby increasing the number of transistors possible per chip. With more transistors per chip, designers are able to create more sophisticated integrated circuits. With this achievement the *Gordon Moore Law* is satisfactory achieved (Kim, 2009). This transformation is shown in figure 1.

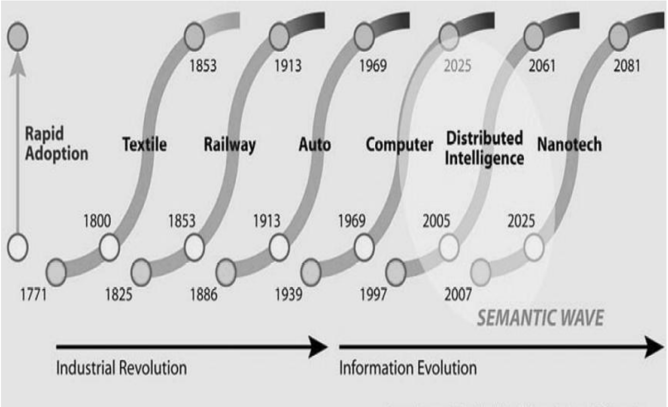
In last 60 years, electronics industry is going through many development phases. In primary days of logic families, the switching element is only the vacuum tubes, electromagnetic relays; due to limitations of earlier switching element, the fast and small dimension transistor was developed. The transistor gives rapid development to time to market. But the limitation of transistor gives the new technological perspective to the electronic industries, this new dimension of the electronics popularly known as metal oxide semiconductor technology (MOS). The MOS technology added another dimension of compactness and reliability. MOS transistors were electronically superior than their bipolar counterparts, hence the MOS technology also called as the *corner stone of Moore's law.* The consideration of ideal logic family is the zero dissipation power, has zero propagation delay, very small rise and fall times and has noise immunity equal to 50% of the logic swing. The properties of CMOS begin to approach these ideal characteristics. First, CMOS dissipates low power. Typically, the static power dissipation is 10 NW per gate which is due to the flow of leakage currents (Fairchild Semiconductor, 1983).

Fig. 1. Moore's law for transistor which stated that doubling of transistor every 18 months.



In short, the CMOS devices have been used for low power consumption, wide power–supply range, and high noise immunity for solution of semiconductor field. Apart from that, electronics evolution was successful because high gain, signal to noise ratio and scalability of CMOS technology. The CMOS technology is scaling from micrometer to nanometer. The rapid shrinkage of the feature size has forced the CMOS industry to facing many serious problems such as increased leakage currents, difficulty on increase of ON current, large parameter variations, low reliability and yield, increase in manufacturing cost, fundamental material limits etc (Kim, 2009). For the improvement of new trends in semiconductor field, the research in new material and method is further going towards its horizon. This new trends is shifting towards the searching of new devices using Nanoelectronics methodology. It is now ideally say that the Nanoelectronics replace ultimately conventional CMOS devices.

Fig. 2. Nanoelectronics are the next semantic wave (Adapted from Ionescu, 2011).



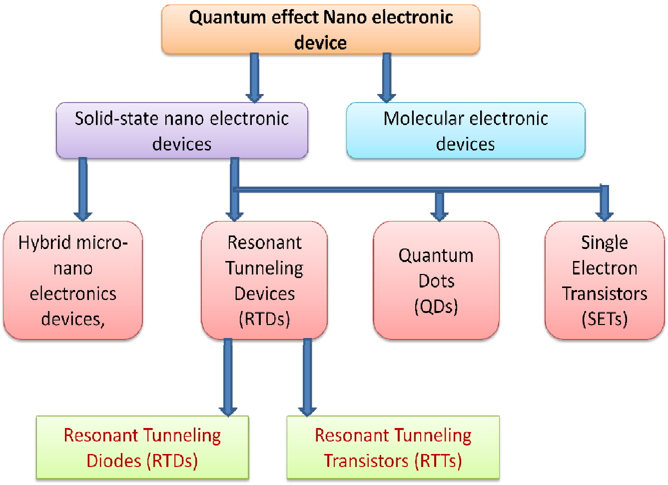
The nanoelectronics devices possess high density system integration; but reliability is the major issue of Nanoelectronics device fabrication. To continue the remarkably successful scaling of conventional complementary metal oxide semiconductor (CMOS) technology and possibly produce new paradigms for logic and memory, many researchers have been investigating devices based on nanostructures, and in particular carbon nano tubes (CNTs) and semiconductor nano wires (McEwen *et al.,* 2002; Lieber, 2003; Lu and Lieber, 2007; Kim, 2009).

As predicted by Norman Poire and Merrill Lynch based on Joseph Schumpte, the nanoelectronics is the next semantic wave of miniaturization of semiconductor industry (Ionescu, 2011). As seen in figure 2, now we are in the era of information revolution. The information revolution is due to rapid development and research in the field of miniaturization of semiconductor field. The miniaturization is rapidly going towards the nano scale. As predicted in Ionescu (2011), the next revolution in information era is only the Nanoelectronics. In order to continue the miniaturization of integrated circuits towards nano scale or microelectronic device designs will be replaced with new designs that take advantage of the quantum mechanical effects that dominate on the much smaller, nanometre scale. Further, the quantum effect nano electronic device is subdivided into two broad areas, as follows (Ellenbogen, 2012):

1. Solid-state nano electronic devices
2. Molecular electronic devices

Further the solid state nano electronics devices are classified as the hybrid micro nano electronics devices, Quantum Dots (QDs), Resonant Tunnelling Devices (RTDs) and Single-Electron Transistors (SETs). The RTDs are further classified as the Resonant Tunnelling Diodes (RTDs), Resonant Tunnelling Transistors (RTTs). The taxonomy of nano electronics devices is shown in figure 3.

Fig. 3. Taxonomy of quantum effect nanoelectronics devices.



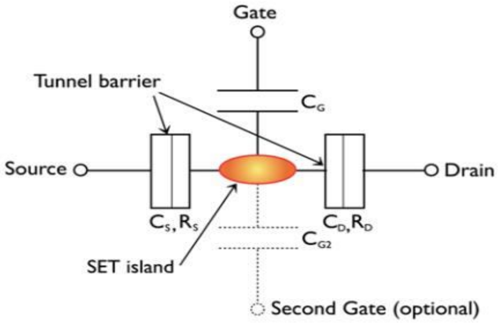
Apart from Nanoelectronics the field of Nano is much broader, it is consist of,

- *Nano architectonics:* It deals with the creating large systems composed of nanometer-sized components.
- *Nano mechanics:* It is mainly concerned with building devices with features that are nanometers in size, working on sensing things that are smaller than an atom.
- *Nano photonics:* This science is deals with the studying the quantum behavior of light on length scales of a few hundred nanometers.
- *Nano-Bio-Info-Cogno:* It is mainly supporting for interaction between information and communication technologies and life science.

Solid-state nano electronic devices

Single electron devices (SETs): The law of quantum mechanics in the atomic level prevents from further miniaturization of size in the switching devices. In order to keep this technological revolution of semiconductor devices, then there is need of new alternative solution for the semiconductor field. The search is partially completed with development of single electronic devices. SETs having small size and low-power dissipation at excellent speed, hence they are very attractive devices for future large-scale integration.

Fig. 4. Schematic of a basic single electron transistor (Adopted from Kim, 2009).



The basic structure of SET consists of three terminals such as drain, gate, source, and the second gate is an optional. However, SET has a tiny conductive island coupled to a gate electrode with gate capacitance Cg. Source and drain electrodes are connected to the island through a tunnel barrier. The tunnel barrier, which controls the motion of every single electron, consists of two conductors separated by thin layer and it is modelled as tunnelling resistances R_D and junction capacitances C_D. This is illustrated in figure 4 (Kim, 2009; Wasshuber, 2001; Inokawa *et al.,* 2003). Further, the single electron devices are classified as:

- *Coulomb blockade based device*: It is a SET device having three terminals which is based on the Coulomb blockade principle where the number of electrons on an island or dot is an integer number controlled by a gate. The dot may have up to thousands of electrons depending on the size and material (Compano, 2000).
- *Nano-flash memory based devices*: It is also three terminal devices, but it is without a tunnel barrier between source and drain. When fabricated at nanoscale dimensions, the increase of charge by one electron causes an abrupt shift in the turn off voltage (Compano, 2000).
- *Yano-type based devices*: It is two terminal devices. In this device the information is stored in deep traps in poly-Si. The devices are created on a 3 nm thick Si film using 0.25 μm technology where one or more dots are formed naturally in the vicinity of a FET in which trapped charge modulates the threshold voltage of the FET (Compano, 2000).

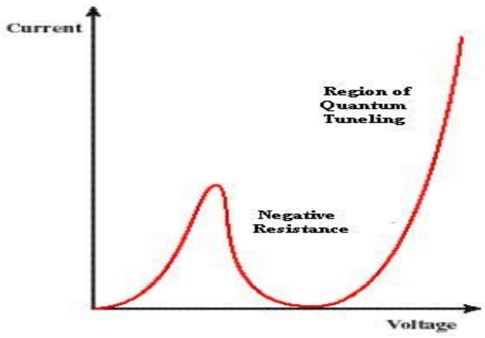
Problem regarding with SETs

- Difficulty regarding with the background charge fluctuations.
- Cost issue and technology issue is the major hurdle for practical use of SETs.
- Problem of electrostatic interactions between devices and tolerance of devices.

Resonant Tunnelling Devices (RTDs)

The RTDs employ quantum effects in their simplest form. The RTDs usually are fabricated from layers of two different III/V semiconductor alloys called as a binary semiconductor, such as the pair GaAs and AlAs. The simplest type of resonant tunnelling device is the Resonant Tunnelling Diode (RTD) and Resonant Tunnelling Transistor (RTTs). Resonant tunnelling devices are being explored with demonstrated successes in multi-valued logic and various logic circuits and memory circuits (Ellenbogen, 2012). The resonant-tunnelling diode is made by placing two insulating barriers in a semiconductor, and then it can create an island where electrons can exist. When electrons are restricted between two closely spaced barriers, quantum mechanics confined their energies to one of a finite number of discrete quantized levels.

Fig. 5. Typical I-V characteristics of RTD devices.



This energy quantization is the basis for the operation of the resonant-tunnelling diode. The electron can tunnel when the energy is equal to resultant resonant energy of barriers, then devices are considered as the ON state (Pomrenke, 2000). Whenever we can add small gate terminal to island then it form a RTT i.e. Resonant Tunnelling Transistor. It is voltage controlled devices having three terminals. The voltage across gate terminal controlled the current through the devices. The small amount of voltage can produce the large amount of current which is called as the amplification of RTTs. The RTT and RTD possess the very important characteristic i.e. the RTT and RTD having several switching states. It is due to the quantum well on the island may exhibit several possible energy levels (Pomrenke, 2000). The typical I-V characteristic of RTDs is shown in figure 5.

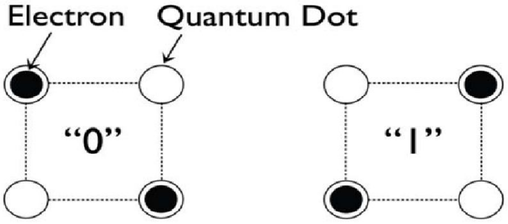
The current-voltage characteristic of this device is similar to that of the Esaki tunnel diode, in that it exhibits a peak and a valley in the curve. The difference is that RTDs have a much lower device capacitance, which allows them to oscillate faster, and their current-voltage characteristics (i.e., the positions of the peak and the valley) can be shaped with the appropriate band gap (Pomrenke, 2000).

Problem regarding with RTDs

- If the thickness fluctuation occurs in the RTDSs fabrication then large sensitivity fluctuations also occur in the device.
- The operation can only be realized in III-V semiconductors, the other material is not compatible with the CMOS technology.
- The output power is quite low in the THz range.

Quantum dots: One nanostructure paradigm is QDs which exploits arrays of coupled quantum dots to implement Boolean logic functions (Lent and Tougaw, 1993; Lent *et al.,* 1993; Tougaw and Lent, 1994; Snider *et al.,* 2008). The advantage of QCA lies in the extremely high packing densities possible due to the small size of the dots, the simplified interconnection, and the extremely low power-delay product (Kim, 2009; Snider *et al.,* 2008).

Fig. 6. Four Dot QCA Cells (Adopted from Kim, 2009).



As presented by Kim *et al*. (2009), the schematic diagram of a four-dot QCA cell is shown in figure 6. This is the simplest non-clocked QCA cell. The cell consists of four quantum dots positioned at the comers of a square. The cell contains two extra mobile electrons, which are allowed to tunnel between neighbouring sites of the cell, but not out of the cell. If the tunnel barriers between cells are sufficiently high, the electrons will be well localized on individual dots. The Coulomb repulsion between the electrons makes them occupy antipodal sites in the square as shown. For an isolated cell, there are two energetically equivalent arrangements, polarizations, of the extra electrons that we can denote as binary 1 and binary 0. The two polarization states of the cell will not be energetically equivalent if other cells are nearby, because the Coulomb interaction with other cells breaks the degeneracy (Snider *et al.,* 2008; Kim, 2009).

Hybrid micro nano electronics devices: The hybrids of solid-state quantum-effect devices are made up from with micron-scale transistors and RTTs. The limitation of RTTs introduces new hybrids devices. The limitation includes fabrication difficulty, small size, material limitation, sensitivity etc. The hybrid devices possess exhibit multistate switching behaviour in the switching state. Hence hybrid device can represent more logic states than pure bulk effect devices. It also low power and high speed than conventional nanoelectronics devices. Highly integrated circuits with features size smaller than 10 nm provide benefits for technologies such as, quantum computing, networking, and signal processing. But current trend based on CMOS technique does not fulfill the practical need below a 10nm gate length. Hence the nano devices replaced the CMOS, but at this stage the nano devices also having practical problem. This problem can be overcome by hybrid manufacturing of micro and nano devices.

Molecular electronics devices: Due to the reduction in size of electronic devices an extremely important area of research is *molecular electronics*, for which molecules that are quantum electronic devices are designed and synthesized using the batch processes of chemistry and then assembled into useful circuits through the processes of self-organization and self-alignment (Williams, 2000). Molecular nano electronics is used to distinguish switching at the single molecule level compared to the molecular electronics at the bulk, large molecular number level as used in displays. Aviram and Ratner proposed in 1974 that suitable molecules could be used as functional electronic components, specifically for rectification. Ashwell (1990) demonstrated such rectification behaviour using molecules and a magnesium evaporated electrode. Among molecular switches, electric-field controlled molecular electronic switching devices are closest to conventional semiconductor devices and therefore the most likely candidates for applications (Compano *et al.,* 2000). For molecular electronics, one of the great challenges is to develop two-terminal and three-terminal devices than can be incorporated in circuits. Then, it must be demonstrated that such molecular switches can be used to make reliable logic (Ellenbogen and Love, 1998a, b; Ellenbogen, 2012). From the basic theory and practical application the molecular electronic can be further divided into following categories:

- Electric field control molecular switching devices.
- Electromechanical molecular switching devices.
- Photoactive molecular switching devices.
- Electrochemical molecular devices.

Conclusion

As the feature size of component reaches to its fundamental limits, then various type of research is carried out for fulfilling the next century technology demands. It will give birth to new type of devices that promises advantages of reduction of size, low power dissipation, high noise immunity, faster and better logic swing, high gain and least possible feature size. The future is near when the Gordon Moore law is satisfactory achieved by advancement of nanoelectronics. With the advanced research work in the field of nanoelectronics and its allied fields the coming future hold the hands of nanoscience for better pleased future of technology.

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