International Journal of Information, Engineering & Technology

Volume 11, Issue 4, PP 90-99, ISSN: 2360-9194, March, 2021
Double Blind Peer Reviewed International Research Journal
garcjournalssubmit@gmail.com
Journal Series: Global Academic Research Consortium (garc)

Principles and Challenges of Miniaturization of Nano Electronics Device

Ali Ahmed Umar[1], Muhammad H. Abdulfattah[2], Falmata B. Wakil[3], Usman Ali[4] & Ndriza Yahi Musa[5]
[1,3,4] Department of Computer Engineering Technology Ramat Polytechnic Maiduguri
P.O.Box 1070 Borno State.
[2]Computer and ICT Centre, University of Maiduguri. mhabdulfattah@unimaid.edu.ng
[5]Department of Electrical and Electronics Engineering,
Umar Ibn Ibrahim Elkanemi College of Education, Science and Technology
Yahi.musa@yahoo.com

Correspondence Author Email: emfance@gmail.com

Abstract: *Present and future views of Nano electronic devices are discussed in "Nano" electronics spaces. It is possible that the evolutionary advances in all front of metal oxide interface semiconductor (MIS) will keep its stride despite a variety of challenges. The revolutionary Nano electronics, such as nanoionics, molecular electronics, single electronic, and resonant tunneling electronics would propose unique growth and development when engineering break-through for control of advancement comes real.*

Keywords: *Electronic Device, Miniaturization. & Nano*

1.0 Introduction

Over the years, electronic computers have become more powerful as the size of transistor, has shrunk [1]. However, the reduction in size may soon reach its threshold due to the limitations of fabrication techniques and laws of quantum mechanics especially in today's conventional field effect transistors (FET's). Many studies have shown that as the size of the transistor continue to shrink from 100nm and below, the devices will become more difficult operate and costly to fabricate. In addition, they may not function effectively in ultra-densely integrated electronic circuits [2]–[11]. In order to continue the miniaturization of circuit elements down to the nanometer scale, possibly even to the molecular scale, researchers have come up with several alternatives to the transistor for ultra-dense circuitry [3].

These new nanometer-scale electronic (nano electronic) devices perform as both switches and amplifiers, just like transistors. However, unlike FET's, which operate based on the movement of electrons, the new devices take advantage of quantum mechanical phenomena that emerge on the nanometer scale, including the discreteness of electrons and the transport of ions rather than electrons in nano scale systems. This paper looks into alternative nano devices, their mode of operation, shortcoming, and similarities to the conventional FET. However, this overview builds upon several earlier, more technical and specialized reviews [12]–[20], as well as the work of numerous research groups.

1.1 Microelectronic Transistors

Transistors in digital circuits are either used as a two state device, or switch. The state of a transistor can be used to set the voltage to be either high or low, which is a binary one or zero, in the computer. Arithmetic and logical functions can be implemented in a circuit using transistors as switches. It can also be used in a computer for amplification. A small input electrical signal can control an output signal many times larger. Amplification allows signals to be transmitted through switches inside the computer without loss of strength [6]. The main types of transistors in use today are the FET, in which a voltage is imposed on the device to control a second output voltage or current, and the bipolar junction transistor (BJT), in which a current is used to control another current.

1.2 Structure and Operation of a MOSFET

The metal-oxide semiconductor FET (MOSFET) is the most common type of transistor in modern microelectronic digital circuits [19], [20]. MOSFET circuits use very little power and are economical to fabricate. As shown in Fig. 1, the field effect transistor has three terminals which are called the source, the drain, and the gate. The channel through which current may flow from source and drain is altered more drastically in making the transition to nanoelectronic devices.

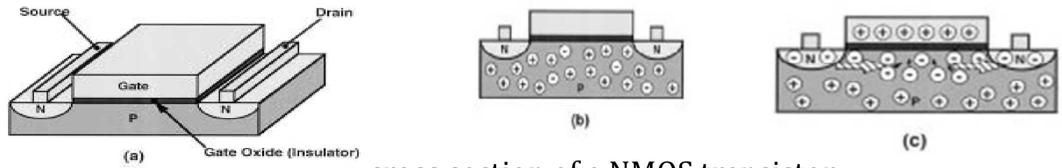

Fig. 1. Schematic cross section of a NMOS transistor.

(a) The transistor shown in the schematic cross section is the basic building block of microcomputers. (b) When there is no voltage applied to the gate electrode, no current can flow through the semiconductor. (c) However, when voltage is applied to the gate electrode, the electrons (negative circles) segregate from the holes (positive circles) to form a "channel" which permits current (large white hatched arrows) to flow between the source and the drain[1].

The MOSFET, in conjunction with other circuit elements, is capable of voltage gain and signal-power gain. The MOSFET is also used extensively in digital circuit applications where, because of its relatively small size, thousands of devices can be fabricated in a single integrated circuit. The MOSFET is, without doubt the core of integrated circuit design at the present lime.

The name "metal-oxide-semiconductor field effect transistor" is derived from its constituent materials. The more general terminology is metal-insulator-semiconductor (MIS), where the insulator is not necessarily silicon dioxide and the semiconductor is not necessarily silicon. MOSFET's are built upon a crystalline substrate of the doped semiconductor silicon[4]. Pure silicon is a very poor conductor, so doping impurities, such as boron or arsenic, are introduced into the silicon to create an excess of mobile positive or negative charges. Negatively doped (N-doped) silicon contains free electrons that are able to move through the bulk semiconductor. Positively doped (P-doped) silicon contains holes, which act as positive charges that move freely through the bulk material.

A metal electrode separated from the semiconductor below by an insulating oxide barrier serves as the gate of the MOSFET, whose voltage and associated electric field controls the flow of current from the source to the drain [28]. Hence the name "FET" field effect transistor. When the voltage on the gate is low, the region between source and drain contains few mobile negative charges, and very little current can flow. This is shown in Fig. 1(b). However, as illustrated in Fig. 1(c), increasing this voltage sufficiently attracts electrons to the region under the gate, opening the channel and allowing masses of electrons to flow from the source to the drain.

This corresponds to a dramatic rise in current. This distinct change in conductivity makes the MOSFET a two-state device. Since small changes of gate voltage result in large changes in conductivity, the MOSFET can also be used as an amplifier. Nanoelectronic devices to be used in computers must function as two-state device and amplifier. In the past, the commonest way to make smaller electronic circuits is simply to shrink the dimensions of the components by a constant factor, a process called "scaling." The MOSFET is still popular because of the very little changes in its operation and it maintains a reasonable cost-to-performance ratio as it is scaled down to much smaller sizes.

2.0 Challenges to Further Miniaturization of FET's

Many researchers envision the conventional microelectronic transistors becoming miniaturized into the nanometer-scale despite the posed obstacles [18]–[19], [20]. Individual working transistors with 40 nm gate lengths have already been demonstrated in silicon [15]. Transistors with gate lengths as small as 25 nm have been made using gallium arsenide [16]. It is unclear, though, whether such transistors can be made sufficiently uniform and reliable to build a densely integrated computer containing a billion or more of them. Additionally, a dense network of such transistors could be slowed down by the flow of current through extremely narrow wires from one device to the next.

However, to provide points of reference for contrasting nanoelectronic devices with scaled-down FET's, a few of the obstacles to FET scaling are enumerated below, in increasing order of their intractability.

- High electric fields, due to a bias voltage being applied over very short distances, can cause "avalanche breakdown" by knocking large numbers of electrons out of the semiconductor at high energies, thus causing current surges and progressive damage to devices [5], [6]. This may remain a problem in nanoelectronic devices made from bulk semiconductors.
- Heat dissipation of transistors (and other switching devices), due to their necessarily limited thermodynamic efficiency, limits their density in circuits, since

overheating can cause them to malfunction. This is likely to be a problem for any type of densely packed nanodevices [17].

- Vanishing bulk properties and non uniformity of doped semiconductors on small scales. This can only be overcome either by not doping at [14] or by making the doping atoms form a regular array. Molecular nanoelectronic is one path to the latter option.
- Shrinkage of depletion regions until they are too thin to prevent quantum mechanical tunneling of electrons from source to drain when the device supposedly is turned off [3]. The function of nanoelectronic devices is not similarly impaired, because it depends on such tunneling of electrons through barriers.
- Shrinkage and unevenness of the thin oxide layer beneath the gate that prevents electrons from leaking out of the gate to the drain. This leakage through thin spots in the oxide also involves electron tunneling.

The thermodynamic obstacle to FET scaling, heat dissipation, suggests that it would be desirable to find replacements for FET's that might permit the construction of circuits that require fewer switching devices in order to perform the same functions. Furthermore, one of the other obstacles to scaling results from the simultaneous decrease in the effectiveness of doping and the increase in quantum mechanical effects. Once electronic devices reach the nanometer and the molecular scale, the properties of solids are replaced by that of the quantum mechanics. Quantum mechanical effects, such as energy quantization and tunneling, become much more significant.

3.0 Solid-State Quantum-Effect of Nanoelectronic Devices

Quite a number of solid-state replacements for the bulk-effect semiconductor transistor have been suggested to overcome the difficulties associated with it. All of these devices function by taking advantage of effects that occur on the nanometer-scale due to quantum mechanics [11], [12]. The primary feature that all of these devices have in common is a small "island" composed of semiconductor or metal in which electrons may be confined. This island assumes a role analogous to that of the channel in a FET. The extent of confinement of the electrons in the island defines the basic categories of the solid-state nanoelectronic devices.

- Quantum Dots (QD's or "artificial atoms") [16] Island confines electrons with zero classical degrees of freedom.
- Resonant Tunneling Devices (RTD's) [20] Island confines electrons with one or two classical degrees of freedom.
- Single-Electron Transistors (SET's) [15], [13]. Island confines electrons with three classical degrees of freedom.

The distinct properties of the solid state nanoelectronic devices are determined by the composition, shape, and size of the island. Controlling these factors allows the designer to effectively control the passage of electrons on to and off the island. For instance, the mean free path of mobile electrons can be much greater in semiconductors than in metals. Thus a mobile electron might travel coherently all the way across a semiconductor island, without severe collisions. This means that conductivity of a device can be strongly enhanced or suppressed by quantum mechanical interference between separate paths an electron might take through the device.

Presently, most solid-state nanoelectronic devices incorporate semiconductors made from combinations of elements from groups III and V of the periodic table—e.g., gallium arsenide (GaAs) and aluminum arsenide (AlAs) [19], [17]. The mobility's of electrons are higher in these III–V semiconductors, and it is also easier to fabricate defect-free junctions between different III–V semiconductors than it is for junctions between two group IV semiconductors, such as Si and Ge.

3.1 Structure and principle of operation

The dimension of the island in a solid-state nanoelectronic device ranges from approximately 5–100 nm. The island may consist of a small region different from the surrounding material. Otherwise, edges of the island may be defined by electric fields from small electrodes patterned in the shape of the desired island boundary. Mostly, the island is embedded between two narrow walls of some other material, or an insulating oxide of the island material, or an insulating defect zone in the substrate.

In any case, the island is surrounded by potential energy barriers, which hinders the movement of electrons in and out of the island region. This is illustrated in Fig. 2, in which the energy barrier is formed from walls of a different material. Within the island, mobile electrons tend to form a puddle, usually much smaller than the dimensions of the island. The puddle is surrounded by the depletion region, because electrons in the puddle are repelled from surface charges that are on the boundaries of the island. Thus, the features that form the island may have to be fabricated many times the size of the useful region for electron confinement [8]. This particular factor works against the miniaturization of such quantum-effect and single-electron solid-state devices.

Two essential quanta mechanical effects are exhibited by electrons confined in the islands between closely spaced potential energy barriers [16], [2]. First, quantum mechanics restricts each electron's energy to finite number of one-electron energy levels ("quantized" energies). The smaller the island, the more widely spaced energy are the levels for the electrons in the potential well between the barriers. In Fig. 2, the symbol is used to indicate the energy spacing between two energy levels. Second, if the potential barriers are thin enough (approximately 5–10 nm or less), electrons occupying energy levels lower than the height of the barrier have a finite probability of "tunneling" through the barrier to get on or off the island.

However, for an electron with certain energy to tunnel through a barrier, there must be an empty state with same energy waiting on the other side. These two effects, energy quantization and tunneling, strongly influence the flow of electrons through a nanoelectronic device. When a bias voltage is applied across the island, it induces mobile electrons in the conduction band of the source region to move through the potential well in the island region to the region of lower potential in the drain region. The only way for electrons to pass through the device is to tunnel on to and off of the island through the two high potential barriers that define the island and separate it from the source and the drain. But tunneling can occur and charge can the flow toward the drain only if there is an unoccupied quantum energy level in the well at an energy that matches one of the occupied energy levels in the source band.

In an extended systems, such as the bulk metals or semiconductors in the source and drain, the allowed energy levels for electrons are so closely spaced that they form bands over a range energies, in contrast to the discrete energy levels in a single atom or in a nanometer-scale potential well. As shown schematically in Fig. 2, the electrons occupying the source conduction

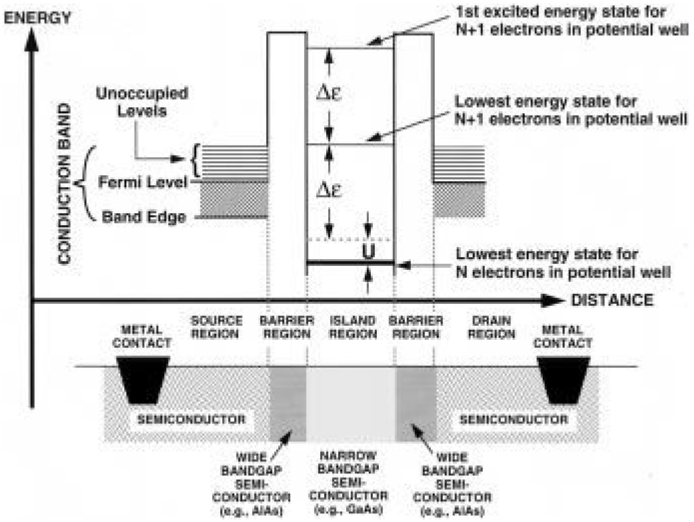

Fig. 2. Quantum well for a resonant tunneling diode (RTD).

The barrier regions around the island in the RTD shown at the bottom of the figure create the potential energy “well” graphed in the top part of the figure. Energies of the electrons trapped in the well on the island are “quantized”—they can only have the energy states or “levels” shown. Mobile electrons in the source region (and the drain region) occupy the energy levels between the band edge and the Fermi level, with unoccupied energy levels above that in energy [7]. Similarly in Fig. 2, a similar energy band contains the conduction electrons on the drain, and usually there are many available unoccupied one-electron quantum states at energies above this band. Therefore, when an electron is able to tunnel from the source to the island under a bias, it is usually free to complete its passage through the device by tunneling once again from the well onto the drain.

3.2 Resonant Tunneling Devices (RTD)

A resonant-tunneling device [16], [18] normally has a long and narrow island with shortest dimension of 5–10 nm [3]. The island is made from semiconductor consisting of many mobile electrons. Thus, when a resonant-tunneling device is subject to a voltage bias between the source and the drain, it produces a current versus voltage plot like that sketched in Fig. 3(b), in which the distance between current peaks is dominated by and there is little effect of the charging energy observable. Fig.3 also contrasts the current versus voltage behavior of a resonant tunneling diode with the behaviors of a QD and an SET.

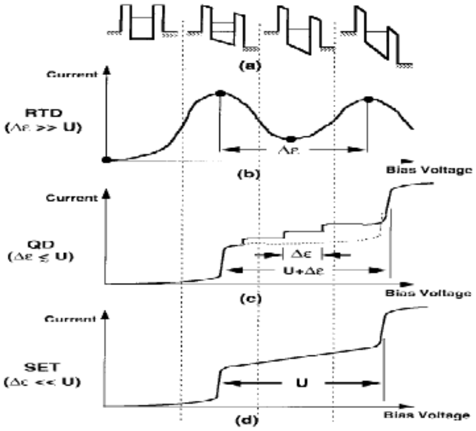

Fig.3. Current Vs bias potential plotted for three categories of solid state nanoelectronics devices

3.3 Quantum Dots (QD's)

QD's are formed with islands that are short in all three dimensions, confining the electrons with zero classical degrees of freedom—electronic states are quantized in all three dimensions. The dot-like island may be made from either metal or semiconductor. It consists of small deposited or lithographically defined regions [4]; small, self-organized droplets [5]; or nanocrystallites deposited in a film [11], [12]. Thus, making an island short in all three dimensions leads to widely spaced quantum energy levels for an electron on the island. The charging energy is also large, because a pair of electrons cannot get far from each other. As a result, both the interaction among the electrons on a QD and the energy levels for each individual electron influence the flow of current through the dot.

A schematic plot of current versus voltage for a typical QD is shown in Fig. 3(b). A sequence of steps in current associated with each of the two energy levels is observed as the bias voltage is varied. The current jumps to a finite value when electrons first travel through the island one at a time, and further large jumps herald the ability of electrons to go through two, then three at a time. Smaller and more frequent jumps occur when an electron can travel across the dot not just in the island's lowest vacant quantum state but also in one or more excited states. The more paths are available, the greater the flow of current. Categories of QD's include individual dots, also known as "artificial atoms" [13], as well as coupled dots ("quantum-dot molecules") [17], and a kind of composite device called a "QD cell," where about four or five QDs form a single two-state device.

3.4 Single-Electron Transistors (SET)

A single-electron transistor (SET) [15], [10] is a three-terminal device, with gate, source, and drain, unlike QD's and RTD's, which have two terminal devices without gates. A SET switches the source-to-drain current on and off in response to small changes in the charge on the gate amounting to a single electron. SET's operate based on an island, usually made of metal, containing a million or more mobile electrons. Unlike QD or RTD, a SET's island has no very short dimension and no very long one, either. An island with "short" dimensions will have well separated quantized energy levels for electrons, but in a semiconductor this may occur at lengths of 100 nm while for metals the lengths must be at least ten times smaller. Hence, making "small" metal particles requires heroic efforts.

Metal islands are emphasized over, which is another defining characteristic of SET's. This limit is called "Coulomb blockade," since the Coulomb interactions among electrons block electrons from tunneling onto the island at low bias voltage. As depicted schematically in Fig. 3(d), the current versus potential curve for a biased SET exhibits only thresholds associated with , not with , which is negligibly small for such a device. Increasing the gate voltage of a SET to a critical value suddenly allows current to flow from source to drain, but a further increase turns off the current just as suddenly.

Additional increases in gate voltage repeat this on/off cycle [19]. Despite these similarities to RTD, SET's operate according to a completely different physical principle. Electrons could, in principle, tunnel onto the island one at a time from the source, and then off onto the drain. This would produce a measurable flow of current. However, extra electrons generally cannot tunnel onto the island due to the electrostatic repulsion of the electrons already there, so no current flows. This Coulomb blockade is a classical effect, depending on the island being sufficiently isolated that an electron cannot quantum mechanically spread over both the island and the source or drain.

3.5 Molecular Electronics

Molecular electronics uses primarily covalent bonded molecular structures, electrically isolated from a bulk substrate [17]. Devices of this description, wires and switches composed of individual molecules and nanometer-scale supramolecular structures, sometimes they are said to form the basis for an "intramolecular electronics" [16]. This is to differenciate them from organic microscale transistors and other organic devices that use bulk materials and bulk-effect electron transport just like semiconductor devices.

Increasingly, this is driving investigators to design, model, fabricate, and test individual molecules and nanometer-scale supramolecular structures that act as electrical switches and even exhibit some similar properties as small solid-state transistors [15]. Molecular electronics does remain a more speculative research area than solid-state nanoelectronics, but it has achieved steady advances for making molecular electronic circuits viable, inexpensive, and truly integrated on the nanometer scale.

3.6 Molecular Electronic Switching Devices

After many years of work, at least four broad classes of molecular electronic switching devices can be distinguished in the research literature:

- electric-field controlled molecular electronic switching devices, including molecular quantum-effect devices [12];
- electromechanical molecular electronic devices, employing electrically or mechanically applied forces to change the conformation [15] or to move a switching molecule or group of atoms to turn a current on and off;
- photoactive/photochromic molecular switching devices [14], which use light to change the shape, orientation, or electron configuration of a molecule in order to switch a current;
- electrochemical molecular devices, which use electrochemical reactions to change the shape, orientation, or electron configuration of a molecule and hence to switch a current.

4.0 Conclusions

In considering prospects for continuing the exponential rate of miniaturization of electronics well into the next century, one must always be cognizant of the obstacles. These include the fundamental limitations of thermodynamics and quantum mechanics, as well as the practical limitations arising from the cost and difficulty of fabrication. However, as explained in this overview, progress is being made in harnessing the principles of quantum mechanics to design and to build solid-state and molecular devices that can function well on smaller and smaller scales, even after aggressive miniaturization of solid-state FET's has ceased to be feasible and cost-effective. MIS will keep its strides despite a variety of challenges. Any revolutionary nanoelectronics devices need to wait for certain engineering break through before being considered as serious contender.

References

[1] Goldhaber-Gordon, D., et al., Overview of nanoelectronic devices. Proceedings of the IEEE, 1997. 85(4): p. 521-540.

[2] Nishi, Y. and J. Jameson. Challenge of nanoelectronic materials and devices toward new nonvolatile memories. in 2008 9th International Conference on Solid-State and Integrated-Circuit Technology. 2008.

[3] Radhakrishnan, M.K. Search of a needle in Haystack : Analysis and reliability of nanoelectronic devices. in 2010 International Conference on Enabling Science and Nanotechnology (ESciNano). 2010.

[4] Yoshio, N. Nanoelectronic materials and devices as new opportunity. in 2006 IEEE Nanotechnology Materials and Devices Conference. 2006.

[5] W F. Brinkman and M. R. Pinto, "The future of solid-state electronics," proc.IEEE, vol.2, no.4 pp. 57–75, Aug. 1997.

[6] , "The future of the transistor," Sci. Amer., pp. 70–78, June 1993.

[7] C. L. Seitz and J. Matisoo, "Engineering limits on computer performance," Physics Today, pp. 38–45, May 1984.

[8] J. D. Meindl, "Low power microelectronics: Retrospect and prospect," Proc. IEEE, vol. 83, no. 4, pp. 619–635, 1995.

[9] R. T. Bate et al., "An overview of nanoelectronics," Texas Instruments Tech. J., pp. 13–20, July/Aug. 1989.

[10] D. Hamilton and D. Takahashi, "Silicon slowdown: Scientists are battling to surmount barriers in microchip advances," Wall Street J., p. A1, Dec. 10, 1996.

[11] W. Broad, "Incredible shrinking transistor nears its ultimate limit: The laws of physics," New York Times, p. C1, Feb. 4, 1997.

[12] R. T. Bate, "The quantum-effect device: Tomorrow's transistor?," Sci. Amer., pp. 96–100,
Mar. 1988.

[13] "Nanoelectronics," Nanotechnol., vol. 1, pp. 1–7, 1990.

[14] R. R. Birge, Ed., Molecular and Biomolecular Electronics, in Advances in Chemistry Series. Washington, D.C.: Amer. Chem. Soc., 1994, vol. 240.

[15] M. A. Kastner, "The single-electron transistor," Rev. Modern Physics, Vol.64, pp. 849–858,
1992.

[16] F. Buot, "Mesoscopic physics and nanoelectronics: Nanoscience and nanotechnology," Physics Rep., pp. 73–174, 1993.

[17] Y. G. Krieger, "Molecular electronics: Current state and future trends," J. Structural Chem., vol. 34, pp. 896–904, 1993.

[18] C. S. Lent, "Quantum computation and its perspective," R&D Assoc. Future Electron Devices, 1995.

[19] T. D. Schneider, “Sequence logos, machine/channel capacity, Maxwell’s demon, and molecular computers: A review of the theory of molecular machines,” Nanotechnol., vol. 5, pp. 1–18 1994.

[20] A. C. Seabaugh, J. H. Luscombe, and J. N. Randall, “Quantum functional devices: Present status and future prospects,” Future Electron Devices (FED) J., vol. 3, suppl. 1, pp. 9–20, 1993.