AN OVERVIEW OF NANOELECTRONICS AND NANODEVICES

OYUBU AKPOVI OYUBU*[1], OKPEKI UFUOMA KAZEEM[1]

[1]*Department of Electrical/Electronic Engineering, Delta State University, Abraka, Oleh, Campus, Nigeria*

Abstract: Nanoelectronics is a nascent area of making electronic devices at the atomic scale to utilize small-scale 'quantum' characteristics of nature. As the name suggests, Nanoelectronics refers to employing nanotechnology in building electronic devices/components; especially transistors. Thus, transistor devices which are so small such that inter-atomic cooperation and quantum mechanical characteristics cannot be ignored are known as Nanoelectronics. This article presents Nanoelectronics and Nanodevices, which are the critical enablers that will not only enable mankind to exploit the ultimate technological capabilities of electronic, mechanical, magnetic, and biological systems but also have the potential to play a part in transforming of the systems thus giving rise to new trends that will revolutionize our life style.

Keywords: nanophotonics, nanoionics, avionics, aensors, GMR, ferrocene

1. INTRODUCTION

The microminiaturization of electronic circuits and systems and the concomitant application to computers and communications which was anticipated by Gordon Moore in 1960 where he observed that the sum of transistors in a chip roughly doubled every 18 months, which has remained true for the past four decades represents major innovations of the twentieth century. This has resulted in the introduction of applications which were once not possible with discrete devices. The prediction is, by the year 2015 the feature sizes of devices will become less than 0.1 µrn. It is envisaged that close variants of conventional microelectronic transistors shall be miniaturized into the nanometer scale. Another consequence of Moore's Law is that as transistors get smaller, they contain fewer and fewer electrons [1, 2].

Realms of development have now reached ‘More than Moore’. A memory chip of nanoelectronic components measured on the nanoscale regime for devices has the gigascale intricacy [3]. Not only have advances in nanotechnology brought about breakthrough in the field of electronics, informatics and biomedical technologies, they are presently widely applied in other facets of life [4]. Nanomaterials have excellent motorized and physical characteristics as a result of their ultra-fine grain and boundary volume fraction [5].

Nanoelectronics, a branch of nanotechnology, is concerned with the integration of electronic devices, electronic chips and circuits at the nanometer scale [3]. Nanoelectronics has revolutionized electronics by reducing the size of transistors used in integrated circuits (ICs). A memory chip with an expected density of 1 terabyte of memory per square inch is being developed [3]. This will in effect increase the density of memory chips. As a result of the advances in nanolelectronics, display screens on electronic systems are enhanced, while power consumption, as well as, weight and thickness of the screens are drastically reduced. In effect, nanoelectronics which is sometimes considered a disruptive technology, in that its components and systems are significantly different from those of traditional CMOS technology has crossed the traditional scaling limits in standard CMOS technology [3].

* Corresponding author, email: ufuomakazeem@gmail.com

Nanoelectronics is mainly based on quantum devices and focuses on addressing their possibility for immense operation as a result of enhancement in density (factors of 5 to 100), speed (factors of 10 to 100), and reduced power (factors of more than 50) [6, 7, 8]. Nanoelectronics will ultimately replace the bulk-effect semiconductor transistors because as electronics approach the nanometer regime, the bulk characteristics of solid are replaced by the quantum mechanical properties of relatively few atoms. This in effect confers on nanoelectronics its strength when compared with corresponding bulk-effect semiconductor transistors.

This article aims not only to demystify nanoelectronics and nanodevices, but also help to succinctly portray nanoelectronics and nanodevices as the critical enablers that will not only help humanity to harness the eventual technological potentialities of electronic, mechanical, magnetic, and biological systems but also have the prospects to play a part in remoulding of the systems thereby bringing about new trends that will reshape our way of living.

2. BASICS OF NANOELECTRONICS

The fundamentals of Nanoelectronics are:

2.1. Nanofabrication

Nanofabrication refers to fabrication methodologies employed for nanoelectronic materials. With the advancements in these technologies scientists have been able to construct ultra-dense parallel arrays of nanowires, as an alternative to synthesizing nanowires individually [9, 10].

2.2. Nanomaterials electronics

Apart from the small size and accommodating more transistors in a single chip, the unchanging and harmonious structure of nanotubes favours an exceptional electron mobility (faster electron movement in the material), a higher dielectric constant (faster frequency), and a harmonious electron/hole characteristics [11].

2.3. Molecular electronics

If the miniaturization of devices continues at its exponential pace, the size of all devices will go near the size of molecules in the nearest future. However, for this to occur, the physics governing electronic devices and the manufacturing processes employed in making them will have to change, in that present day electronics are primarily based on classical mechanics; however, at molecular level, electrons become quantum mechanical in nature. In addition, the budget required for the building of factories (fabs) where electronic devices are made is rising at a rate that is far higher than the sale/consumption of electronics; as a result, cheaper manufacturing processes must be contrived [12, 13].

Thus, an important aspect of research is molecular electronics, whereby molecules which are quantum electronics are made into useful circuits. This field, though a very new technology that is still in infancy, gives assurances for the synthesis/production of atomic sized electronic system in the nearest future.

One of the promising applications of molecular electronics is nonvolatile memories which will not only be greater than the bit area density of present day's DRAMs but one billion times more efficient than known CMOS circuitry. Other applications are molecular electronic switching devices [14].

2.4. Molecular logic

Studying the transport of Electron in molecular-scale systems have has become possible as of today. This results from the use of advanced microfabrication and self-assembly techniques. Investigations can now be conducted on electronic conduction via coupled molecules which are end-bound onto surfaces. These have been illustrated with a scanning tunneling microscope with micromachined silicon nanopores, and proximal probes. From works on the proximal probes, it has been demonstrated that 0.1 microamp of current can be transported across a single molecule. However, in all of the past embodiments, the electronic characteristics show primal diodic behaviour that are not suitable for possible circuit use [15, 16].

2.5. Nanoionics

A subfield of nanoelectronics that studies the conveyance of ions instead of electrons in nanoscale systems. It also studies the use of phenomena, characteristics, effects and workings of processes which are related to fast ion transport (FIT) in all-solid-state nanoscale systems.

2.6. Nanophotonics

Also known as nano-optics; it simply studies of the characteristics of light on the nanometer level, and how nanometer-dimension objects interact with light. This aims at inventing devices that benefit from such characteristics.

3. NANO CIRCUITS AND DEVICES

3.1. A field-effect transistor devised from a single-wall carbon nanotube

Many researchers word-wide have made electrical switches such as the field-effect transistor from single-walled carbon nanotubes. In the case illustrated in Figure 1, a single-walled carbon nanotube 1.6 nm in diameter was manipulated into place using an atomic force microscope.

The moment it was manipulated on the metal interface, the tube which is a semiconducting material acted like the n-channel field-effect transistor, switching on and off depending on the voltage applied. Nanotubes will become very useful as elements for electronics in the near future [17].

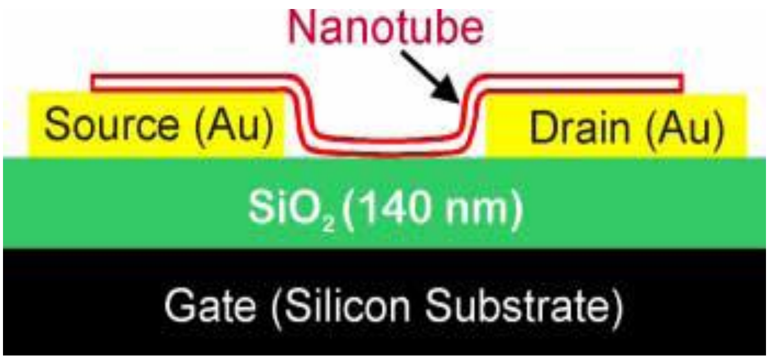

Fig. 1. Field-effect transistor based on a single 1.6 nm diameter carbon Nanotube [17].

3.2. Nanowires

These are Semiconductor one-dimensional structures with novel electrical and optical characteristics that could be employed as building blocks in nanoscale devices like field-effect transistors, sensors and light-emitting diodes.

Mixed devices aggregate the flexible nature of organic materials such as polymers with suited electronic and optical characteristics of semiconductor materials. However, at the moment these structures do not have mechanical strength, thus limiting theirs use in practical operations [8, 18].

3.3. Commercial IBM giant magnetoresistance read head

Whenever some certain kinds of materials are uncovered in a magnetic field, their electrical resistance becomes altered. This phenomenon, which is known as the magnetoresistive effect, is applied in perceiving the presence of magnetic fields such as those in the magnetic bits of data stored on a computer hard drive among others.

Following the discovery of the giant magnetoresistive effect in 1988 and the work in the IBM Almaden Research Center in 1991 where it was ascertained that a spin valve could perceive very small magnetic fields, the door to the use of GMR in the read heads for magnetic disk was thrown opened.

The spin valve GMR head depicted in Figure 2, has a copper spacer layer of about 2 nm thick, and a cobalt GMR pinned layer of about 2.5 nm thick. The dimensions of these layers have to be regulated with atomic precision [19, 20].

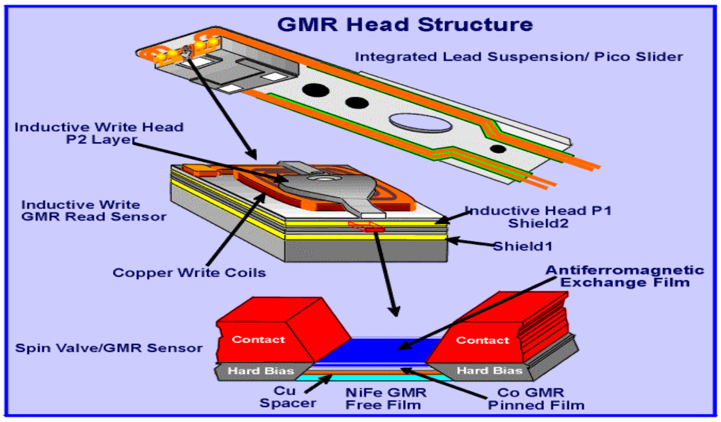

Fig. 2. Commercial IBM giant magnetoresistance read head [19].

4. FUTURE TRENDS IN NANOELECTRONICS

The evolution and improvement in nanoelectronics regarding Carbon nanotubes, molecular electronics, Spintronics, and Single Electron transistor have resulted in the production of novel tools in the field of electronics and sensors. Newly contrived materials present novel and uncommon quality giving to the development and cost-effective formation new of state-of-the-art components that have immense sensitivity, operate faster, use less energy, and can be compacted at much greater densities.

Future trends in Nanoelectronics include but not limited to the followings:

4.1. Solar cells

Nano porous oxide films like $Ti0_2$ are at present being employed to boost photovoltaic cell technology. Nanoparticles are the best at absorbing solar energy can also employed in very thin layers on common metals to absorb incident solar energy. Current solar cells are built from nanoparticles of semiconductors, nano films and nanotubes by ingraining in a charge exchange medium. Films formed by sintering of nano-metric particles of $Ti0_2$ having a diameter of 10-20 nm coalesce high surface area, clarity, excellent stability and excellent electrical conductivity and are perfect for photovoltaic operations. Nano porous oxide films are extremely auspicious materials for photovoltaic operations. Nanotechnology unshackles the hope to build low-cost and more beneficial solar cells. Trials on the use of nanowires and other nanostructured materials with the aspiration to creating low-cost and more active solar cells than are currently obtained with common planar silicon cells is in progress. It is believed that making more active solar cell would greatly contribute to the world-wide energy solution [12].

4.2. Avionics and space exploration

After more than three decades of exploring space, the National Aeronautics and Space Administration (NASA) has finished an initial investigation of the solar system. The missions that will follow will comprise launching spacecraft to regions that were difficult to reach, like the sun or Pluto. Also, spacecraft would be required to do more challenging jobs like landing on celestial bodies, getting samples of their materials, and bringing such samples to Earth. To succeed in such a challenging mission at an inexpensive budget, NASA has formulated the Deep Space Systems Technology Programme, the X2000, wherein either biennially or triennially beginning from the year 2000, the programme will expand and turn in advanced spacecraft systems and body structures to be used in missions bound for different regions of our solar system and beyond. For size reduction of spacecraft to be possible, the avionics of spacecraft is being miniaturized with successive delivery of X2000 by combining nanotechnology with microtechnology. ‘System on a Chip’ (SOAC) shall archetype single-chip and multi-chip module solution that will result in creating avionics system on a chip. This chip shall amalgamate the avionics system which are being made for the X2000 avionics products. That is, the chip will include power management, sensor technology, and telecommunications modules, together with CPU and storage technology. To achieve this, nanotechnology must be employed to reduce and amalgamate the various subsystems. As devices become smaller, lighter, and use less energy, NASA can effectively build and launch space probes on expeditions that are impossible at the moment [21, 22].

4.3. Quantum computing

The thrill in the area of quantum computing was generated in 1994 by Peter Shor who displayed how a quantum algorithm will rapidly accelerate classical computation. Although, quantum computers as a concept is simple, its realization is not. Two issues inspire quantum computing:

- Quantum mechanical views must be engaged in solving difficult (NP-complete) computing issues.
- From a computer miniaturization point of view, the dimension limit of a bit of information is important. Lately, this concern has captivated heightened consideration, as a result of the present advancement of nanotechnology and the design issues of semiconductor and metal materials that are going near the quantum dimension limit. Consequently, the concept of quantum computing, whereby atoms are the elements that carry information has captivated the interest of a number of scientists.

Given that the physical laws governing the characteristics of a system at the atomic level are essentially quantum mechanical, nanotechnology has come up as the best instrument to accomplish quantum computers. Large-scale quantum computers will have the ability to handle some problems quicker than classical computers employing the leading presently available algorithms, like integer factorisation employing Shor's algorithm or the simulation of quantum many- body systems [23].

4.4. Single molecule memory device

Modern memory devices in their normal operation, store every bit of data by charging up a minute capacitor. The repeated miniaturization of electronic circuits, in this case, means storing less charge in a miniature capacitor. Eventually, as memory device sizes get near the nanometer scale, a single organic molecule like Ferrocene, whose oxidation state can be changed by moving an electron into or out of the molecule can be employed to replace the capacitor. Figure 3 shows the alteration in state between the Ferrocene molecule from "0" to "1" state with the application of an external electrical field. As this single molecule memory device is still being developed, it cannot be fully understood as it has some uncertain points like "How long will it stay in the changed state" and "How can we determine the condition of each molecule" [24].

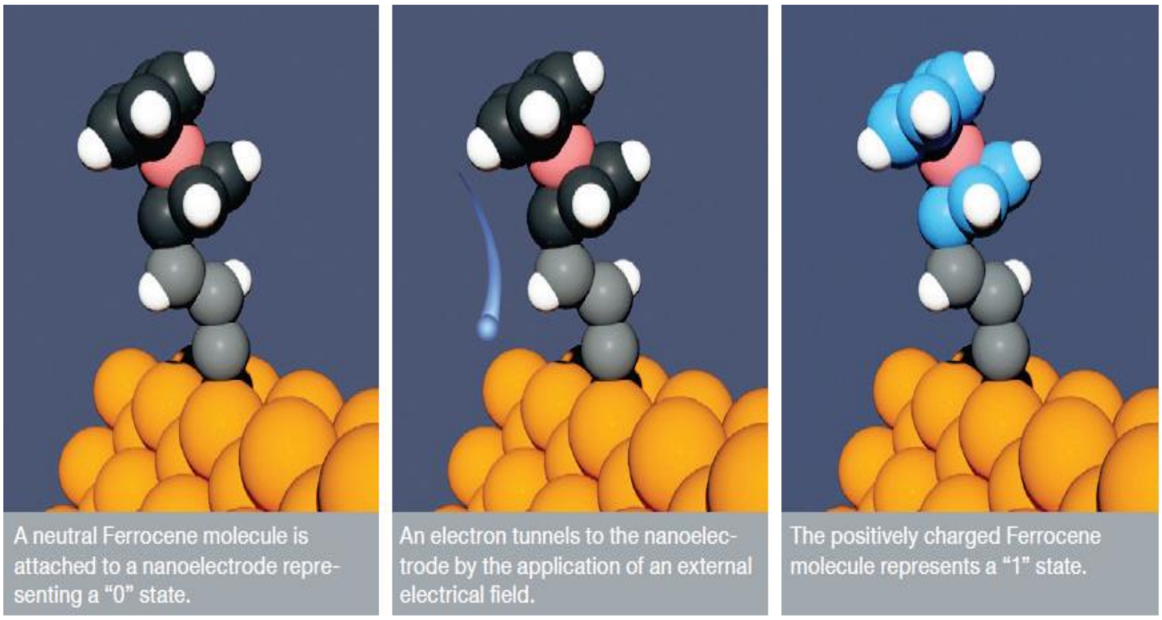

Fig. 3. Illustration of the alteration in state between the Ferrocene molecule from "0" to "1" state with the application of an external electrical field [25].

4.5. Single electron transistor

Contrasted with ordinary transistors where the switching operation needs thousands of electrons, a single electron transistor shown in Figure 4 requires just one electron to shift from the insulating to the conducting state. Transistors such as this have the possibility of offering very large device density and energy efficiency with exceptionally high working speed. For single electron transistor to be implemented, very small metallic islands with sub-100 nm size must be made. These islands which are known as quantum dots, can be made using processes made possible by the growth in nanotechnology [26].

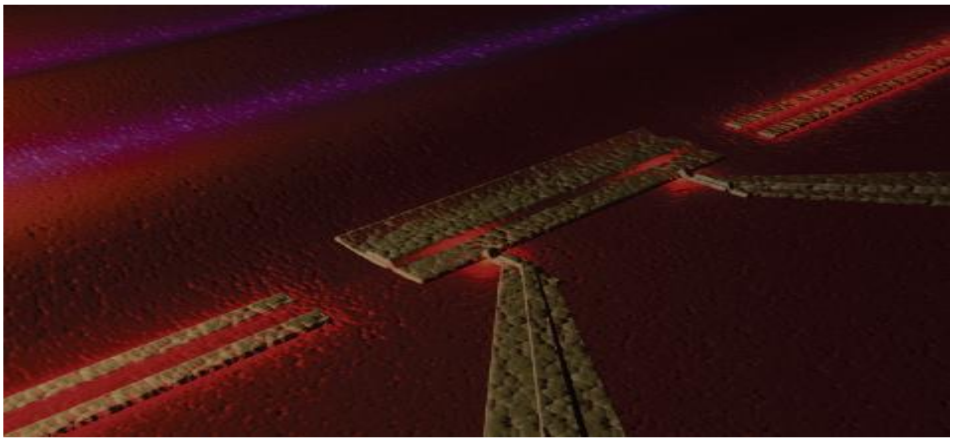

Fig. 4. A single electron transistor in a surface acoustic wave echo chamber [25].

4.6. Communication networks

Advances in nanoelectronics are expected to take central stage in addressing ongoing and future challenges in the area of communication. Equipment and systems for ultra-high-speed short- and long-range communication channels, compact and energy-saving computing machines, high- density memory and logic, high speed interlinks, and independent and powerful energy scavenging equipment for accessing surrounding intelligence and essential information will crucially rely on the gains of next-version emerging nanoelectronics and devices.

Some of the expected next generation technologies in future communication networks are presented in the next sections.

4.6.1. Nanophotonic Communication

The colossal access time required by the microprocessor to communicate with the off-chip main memory is one of the major impediments preventing high speed computing. Nano-photonics has the capability to provide a technology solution that will not only boost the functionality of communication and future computers but will also cause an essential transformation in the area of computer architecture. Proven ultra-high throughput, low access latencies, and low energy consumption of nanophotonic equipment remain independent of capacity and distance.

In contrast with preceding versions of optical technologies, nanoscale photonics offer the prospect of originating exceptionally integrated platforms having sizes and fabrication techniques harmonious with nanoelectronic logic and memory devices, and it is anticipated to greatly influence future computing and communication systems. Nanophotonic interlinks can potentially remodel forthcoming computing and communication by bringing parity, enormous interconnection bandwidths, and wavelength routing potential without electrical impedance or crosstalk limitations [27].

4.6.2. Nanosensors for Embedded Ubiquitous Intelligence

Future communication infrastructure with ingrained intelligent and independent devices are going to be fitted with many powerful sensors to ensure flawless connectivity with ambient and intelligent networks. In the recent past, researchers have been actively developing nanoscale sensors, instigating a new era of ubiquitous nanosensors. Nanosensors were realized on the basis of the amazing progress in the synthesis of nanomaterials with rationally predictable size, shape, and surface properties resulting in extraordinary sensitivity [28].

5. CONCLUSIONS

Nanoelectronics and Nanodevices will undoubtedly reform technological processes in the 21st century and beyond as operations which used to be impossible will become not only possible but very easy to carry out. The sizes of devices will not only become smaller, whilst having power efficiency several million times greater than present devices, Nanoelectronics and Nanodevices will also consume less power.

Communication will be more effective as many of the impediments preventing ultra-fast computing will be eliminated. Future communication infrastructure with ingrained intelligent and autonomous devices are going to be fitted with many powerful sensors to ensure seamless connectivity to ambient intelligent networks.

Virtually every area of our lives will be positively imparted. Advances in Nanoelectronics have birthed solar cells with more efficiency that will enhance photovoltaic cell technology which shall ultimately lead to producing clean and abundant energy especially in sub-Saharan Africa where energy crisis is rife.

REFERENCES

[1] Robert, R.S., IEEE Spectrum archive, vol. 34, no. 6, 1997, p.52-59.
[2] Stokes, J., Understanding Moore's Law, Ars Technica, 2003.
[3] Dalvinder, S.G., Present and future nanoelectronics devices-an analytical study, Research and Development in Material Science, vol. 8, no 4, 2018, p. 925-930.
[4] Ganau, M., Paris, M., Syrmos, N., Ganau, L., Ligarotti, G.K.I., Moghaddamjou, A., Prisc, L., Ambu, R., Chibbaro, S., How nanotechnology and biomedical engineering are supporting the identification of predictive biomarkers in neuro-oncology, vol. 5, no. 23, 2018, p.1-11.
[5] Ingle, K.P., Deshmukh, A.G., Padole, D.A., Dudhare, M.S., Moharil, M.P., Khelurkar, V.C., Silver nanoparticles: A new era of nanobiotechnology, The Pharma Innovation Journal, vol. 6, no. 1, 2017, p. 1-4.
[6] Das, S., Gates, A.J., Abdu, H.A., Rose, G.S., Picconatto, C.A., Ellenbogen, J.C., Designs for ultra-tiny, special-purpose nanoelectronic circuits, IEEE Transactions on circuits and systems—I: Regular papers, vol. 54, no. 11, 2007.
[7] Becerril, H.A., Randal, M.S., Dean, R.L., Robert, C.D., John, N.H., Adam, T.W., DNA - Templated three-branched nanostructures for nanoelectronic devices, Journal of the American Chemical Society, vol. 127, no. 9, 2005, p. 28–29.
[8] Tian, B., Zheng, X., Kempa, T.J., Fang, Y., Yu, N., Yu, G., Huang, J., Lieber, C.M., Coaxial silicon nanowires as solar cells and nanoelectronic power sources, Nature, vol. 449, 2007, p. 885-889.
[9] Aviram, A., Molecules for memory, logic and amplification, Journal of the American Chemical Society, vol. 110, no. 17, 1988, p. 5687-5692.
[10] Aviram, A., Ratner, M., Molecular electronics: Science and technology, Annals of the New York Academy of Sciences, vol. 852, 1998.
[11] Cavalcinti, A., Shirinzadah, B., Zhang, M., Kretly, L.C., Nanorobot hardware, Architecture for Medical and defense Sensors, vol. 8, no. 5, 2008, p. 2932-2958.
[12] Petty, M.C., Bryce, M.R., Bloor, D., An introduction to molecular electronics, (eds.) London: Edward Arnold, 1995.
[13] James, M.T., William, A.R, Leroy, J.I.I., Timothy, P.B., Chong-Wu, Z.; Muller, C.J., Deshpande, M.R., Mark, A.R., Recent advances in molecular scale electronics, Annals of the New York Academy of Sciences, vol. 852, no. 1, 1998, p.197-204.
[14] Jean-Pieere, C., Multiple-gate SOl MOSFETs, Solid-State Electronics, vol. 48, no. 6, 2004, p. 897-905.
[15] Aviram, A., Ratner, M.A., Molecular rectifier, Chemical Physics Letters, vol. 29, no. 2, 1974, p. 277-283.
[16] Zhou, C., Deshpande, M.R., Reed, M.A., Jones, I.I.L., Tour, J.M., Nanoscale metal/self-assembled monolayer/metal heterostructures, Applied Physics Letters, vol. 71, no. 5, 1997, p. 611.
[17] Martel, R., Schmidt, T., Shea, H.R., Hartel, T., Avouris, P., Single and multi-wall carbon nanotube field effect transistors, Applied Physics Letters, vol. 73, no. 17, 1998, p. 2447.
[18] James, R., Ultra density nanowires lattice and circuits, Pierre & Heath, 2003.
[19] Grochowski, E., Emerging trends in data storage on magnetic hard disk drives, IBM Almaden Research Center, San Jose, CA, USA, Datatech: 11.16, 1998.
[20] Gurney, B., Grochowski, E., Spin-valve sensors take up where MR heads leave off, Data Storage, no. 59. 1998.
[21] Worner, D., X2000 systems and technologies for missions to outer planets, International Astronautical Federation Congress, Melbourne Australia, 1998.
[22] Deutsch, L.J., Salvo, C., Worner, D., An institutional approach to enabling smaller spacecraft. Technical report-Jet Propulsion Laboratory, California Institute of technology, Pasadana, CA United States, 2000.
[23] Lent, C., Tougaw, D., A device architecture for computing with quantum dots, Proceedings of the IEEE, vol. 85, 1997, p. 541.

[24] Hyunwook, S., Mark, A.R., Takhee, L., Single molecule electronic devices, Advanced Materials, vol. xx, 2011, p. 1-26.
[25] Rakesh, K., (PID: 4672248), Nano devices in electronics, Department of Electrical Engineering, Florida international University, USA, p. 1-8.
[26] Vladimir, V.M., Viatcheslav, A.K., Michael, A.S., Introduction to nanoelectronics, Cambridge University Press, 2007.
[27] Saif, M.I., Logeeswaran, V.J., Nanoscale materials and devices for future communication networks, IEEE Communication magazine, 2010.
[28] Saif, M.I., The all pervading nanosensors, International journal of Nanotech, Special Issue on Nanosensors, vol. 5, 2008, p. 4-5.