International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 03 Mar. 2024, pp: 491-495 www.ijaem.net ISSN: 2395-5252

Nanobioelectronics – the Futuristic Technology

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Date of Submission: 15-03-2024 Date of Acceptance: 28-03-2024

ABSTRACT

Electronics has been the lifeline of modern technological advancement. Consistent increase in the component density of integrated circuits virtue miniaturization of transistor has been instrumental in development of high speed electronic systems with enormous memory space. The trend of denser integrated circuits has been as per roadmap predicted by Gordon Moore. But it is being predicted that silicon will no longer be able to handle the downscaling due to physical limitations. So need of the hour is to study some other materials which can be used to replace silicon so that the Moore's Law might be sustained. Molecules, especially biomolecules offer an attractive option to be used as electronic material and DNA is a strong contender for the job. Utilisation of these nanometer scale biomolecules as electron devices form the basis of nanobioelectronics.

Key Words: biomolecules, dna, nanobioelectronics**.**

I. INTRODUCTION

The technical and economic growth of the twentieth century was marked by evolution of electronic devices and gadgets. The day-to-day lifestyle has been significantly affected by the advancement in communication systems, information systems and consumer electronics. The lifeline of progress has been the invention of transistor and it's dynamic up gradation. Discovery of fabricating Integrated Circuits (IC's) revolutionized the concept of electronic circuits. With advent of time the size of components decreased which led to increase in component density. The increase in density was as per Moore's Law [1]. The transistor has seen a consistent decrease in size over last six decades. This trend of decreasing device size and denser integrated circuits is being limited by the current lithography techniques. Non-uniformity of doping, quantum mechanical tunneling of electrons from source to drain and leakage of electrons through gate oxide limit scaling down of devices. Heat dissipation and capacitive coupling between circuit components becomes significant with decreasing size of the components. Along with the intrinsic technical limitations, downscaling of devices to nanometer sizes leads to a change in the physical mechanisms controlling the charge propagation.

Some researchers predict that silicon based devices are going to face a bottleneck in near future. To deal with this constraint, search is on to look around for alternative materials, which might facilitate even more dense packing of transistors in a given space. While transistor –based electronic circuit design will continue to be the fundamental aspect of technology, the search for new materials with new and novel properties will lead to new circuit architectures that can fundamentally change the way electronic circuit designing and the technologies evolved hence.

II. MOLECULAR ELECTRONICS

Last decade has seen significant efforts aimed at developing new materials for electronic device application and new methods for electronic device fabrication. Contrary to the present technique of making devices out of bulk material, completely new approach of fabrication is being envisioned where one starts with a nanometer-scale material and assembles them into macro scale circuit architecture. This approach is known as bottom-up technology.

The bottom-up approach is inspired from nature. It is well known that matter organic or inorganic is composed from the 108 naturally occurring elements. Hydrogen, oxygen, nitrogen and carbon are responsible for almost 95% of total weight of living organisms. Along with these essential elements, some trace elements like zinc, iron, vanadium, manganese, selenium, copper etc (as listed on any supplement bottle) are required by human body for appropriate biological functioning.A human body is a machine comprising of various groups of molecules that grow from a single cell by bottom–up technology.The various molecular groups are responsible for respiration, digestion, temperature regulation, immunity and other jobs that a body requires. The molecules contributing in formation of living beings should be able to assemble easily and should also be ready to recognize and bind with other molecules. The ability of one molecule to attract and combine with another molecule is called molecular recognition.

The molecules of our body display different kinds of senses: eyes respond to light and sees things, pressure is felt by skin and ears, tongue recognizes taste, temperature variation is detected by skin etc. The interaction of sensory organs of body and external stimulus (maybe molecules, energy or physical objects) with brain via nerves results in local area network of body. The driving force between all kinds of interactions is flow of electrons. It is the flow of electronic charge through nervous system that informs the brain about an injury on hand. Metals are rich in free electrons which facilitate convenient flow of electrons, but even in non-metallic structure like our nerves or our noses there is exchange of electrons. So it can be said that electrostatics and coulombic forces play an important role in the molecular systems.

The fact that current can flow through molecules endorses the idea of using them in electronic circuits leading us into the realm of Molecular Electronics. Molecular Electronics is based on use of organic and organo-metallic molecules as electronic components. Self-assembly and self-recognition are extremely attractive aspect of these molecules which can be utilized in for bottom-up approach in nanoelectronics. Though most organic molecules are soft-insulators, these can conduct current under particular conditions. Molecular devices exhibit non-dissipative passage of electrical current that would lead to cooler integrated circuits and electronic gadgets. There are various candidates for molecular devices such as- organic polymers [2],[3], large bio-molecules [4],[5], nanotubes & fullerines [6],[7]. Bio-molecular compounds such as proteins and nucleic acids are being explored to be the building blocks of nanometer scale functional devices[8]. Also the properties of self assembly by these groups exhibit on specific electrodes render them to be suitable for organic-inorganic hybrid structures.

DNA, the blueprint of life has been the focus of research for the past half century. Biotechnologists have been unraveling the mysteries of hereditary and genetic information sparking the creation of a whole new industry based on this huge database of knowledge [9]. The recent discovery of electrical conductivity properties by DNA has brought it into the spotlight of research. Rare quality of DNA to store information might be utilised in artificial storage devices. DNA is being prophesised to be as much an integral ingredient of electronic circuits as it is of living beings.

III. DNA AS ELECTRONIC MATERIAL

A. DNA

DNA comprises of four nitrogenous bases: Adenine (A), Thymine (T), Guanine (G) and Cytosine (C), These bases are attached to a backbone formed of repeating chains of sugar and phosphate units. The bases are attached to the sugar groups in the backbone. The arrangement of bases in a sequence on the backbone is called single strand DNA. Two complementary single strands can pair with each other through hydrogen bonding as per fixed combination A with T and G with C forming a double stranded DNA helix [10] as shown in Fig.1. This property of combining with complementary strands is called self recognition.

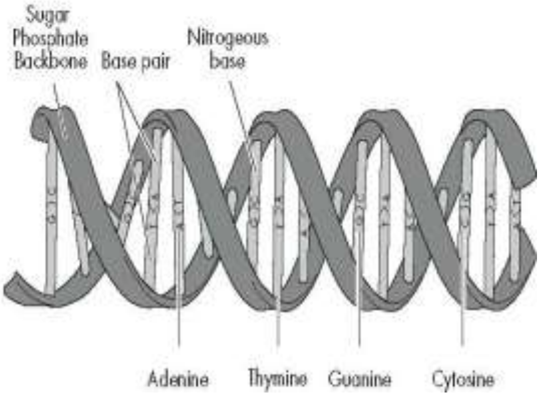

Fig.1. DNA Helix

Sugar molecule of backbone is connected to a base and the assembly is called a grain. Phosphate bridges forming a strand connect the grains to each other. The bases of the strand are connected to complementary bases of another strand through hydrogen bonds. In the phosphate bond the two transverse oxygen atoms connected to phosphorous give rise to two σ and one π bond. The tunneling and the capacitive effects exhibited at the bonds of DNA sequence [11] can be exploited to realize devices, which are characterized by these electrical parameters. As the DNA bases are rich in π-bonds, in the typical structure of DNA the π-bonds of the bases overlap each other thus forming a conduit for electron transfer. Also the energy level is for the A-T pair is higher than that of the G-C pairs. The enrgy difference can be exploited to create energy barrier by appropiate sequencing of the base pairs. The charge conduction through DNA strands is still under investigation. The

B. Charge Transport through DNA

Charge transport through DNA has been topic of great interest among researchers. During the course of research various experiments have been carried out to study the charge transport characteristics of DNA. The first direct electrical measurements on small bundles of DNA were made in 1999[12], DNA sequences with various lengths and random base arrangements were observed. DNA was reported to act as conductor, semiconductor and insulator in different observations, which seem to be contradictory results. Porath et al observed poly (dG)- poly (dC) sequence and suggested that this type of sequence acts like a large –gap semiconductor.[13,14] On further probing it was observed that various parameters like base sequence, base length, orientation and temperature played a major role in defining conduction properties of DNA.

Experiments have demonstrated that DNA exhibits rare super conducting properties similar to those of carbon nanotubes. [15,16] By depositing long DNA molecules across a 500nm gap between special electrodes, scientists were able to apply voltages to the quantum wires and measure their conductivity at various temperatures. While most molecular wires become insulating at low temperatures, the DNA exhibited an increased conductance. [17] Charge transport measurements were also carried out at room temperature, both in and out of solution. At room temperature, the conductance seemed unaffected by addition of a biological buffer solution to the dried sample [18-21]. This is good news for nanoengineers who might want to build solid-state nanoelectronic devices with DNA. The unique properties of DNA, self-assembly and molecular recognition has rendered the “molecule of life” a promising candidate in molecular nano-electronics. [22-27].

C. DNA Bases for Single Molecule Electronics

In this paper a novel idea of using DNA bases as material for electronic devices is introduced. The bases can be separated from the DNA strands and then the open end may be terminated using a hydrogen bond.The structures thus obtained are as shown in Fig.2.

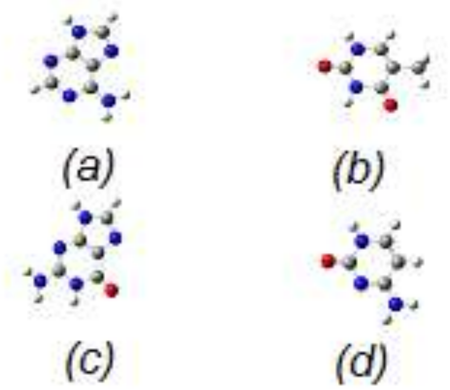

Fig.2 DNA Bases (a) Adenine (b) Thymine (c) Guanine (d) Thymine

The molecular structures of the four bases were optimized using HF-STO-3G basis set in Gaussian 03 program. The energy level values were obtained for the occupied and unoccupied molecular orbitals of the four DNA bases. The band gap energy of the molecules can be expressed as the energy difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital(LUMO). The HOMO-LUMO gaps (HLG) of the bases were calculated from the energy level profile of the molecules. The obtained values are listed in TABLE 1.

It is observed that the HLG of all the four bases is larger than the room temperature thermal energy (k_BT = 0.026eV at T= 300K).This means the DNA bases A,T, G and C are suitable for use at room temperature. Hence these bases can be used in single molecule electronic applications depending upon their current-voltage characteristics.

Table 1. HLG Values For DNA Bases A, T, G & C

DNA Base	HOMO	LUMO	HLG (eV)
Adenine	-6.61	6.15	12.76
Thymine	-7.07	6.61	13.68
Guanine	-6.17	6.44	12.62
Cytosine	-6.42	6.36	12.78

To plot the current-voltage characteristics we need to apply voltage across the molecule and measure the corresponding current flow. Though experimentally this is not possible as yet, but predictive results can be obtained by simulation softwares based on the quantum science. The individual base molecules can be inserted between two metallic electrodes forming a two terminal organo-metallic assembly as shown in Fig . A third terminal can also be coupled capacitively to the molecule forming a three terminal device.

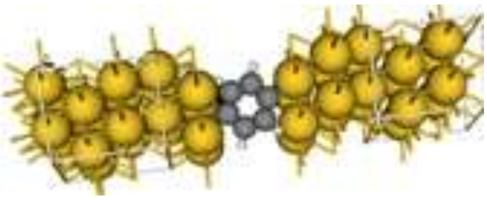

Fig.3. DNA base between two gold electrodes

The third gate terminal can be used to tune the energy levels of the molecule to control the conductivity properties of the base molecules.

IV. CONCLUSION

The continuous miniaturization of transistor is leading us into the realm of nanobioelectronics. As we are approaching the physical limitations of silicon, bio-molecules offer an attractive alternative, where DNA is predicted to be strong contender. Self-recognition and self-assembly property of DNA would shift the integrated circuit fabrication from a lithographic process plant to a test-tube. Exact replication would help in realizing exactly similar devices in a defect free fashion.DNA based devices would be all terrain devices as they have proved over millions of years that they can sustain variation in temperature and humidity conserving their identity. The ability of DNA to store information offers an excellent proposal for fabrication of storage devices. Hence in futuristic electronics, DNA will form an integral part of integrated circuits providing us with high speed cooler electronic gadgets supported by ultra-high density memories with minimal heat dissipation.

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