

Magnetic Properties Govern the Processes of DNA Replication and the Shortening of the Telomere

Adnan Y. Rojeab

Abstract—This hypothesis shows that the induction and the remanent of magnetic properties govern the mechanism processes of DNA replication and the shortening of the telomere.

The solenoid-like formation of each parental DNA strand, which exists at the initial stage of the replication process, enables an electric charge transformation through the strand to produce a magnetic field. The magnetic field, in turn, induces the surrounding medium to form a new (replicated) strand by a remanent magnetisation. Through the remanent [residual] magnetisation process, the replicated strand possesses a similar information pattern to that of the parental strand. In the same process, the remanent amount of magnetisation forms the medium in which it has less of both repetitive and pattern magnetisation than that of the parental strand, therefore the replicated strand shows a shortening in the length of its telomeres.

Keywords—DNA replication, magnetic properties, residual magnetisation, shortening of the telomere.

I. INTRODUCTION

BIOLOGICAL and chemical processes are playing an important role on the function of the DNA. Also, it is shown by variety of literatures that the electrical and magnetism are playing an important role on the function of the cell and that of DNA process.

Therefore, a general explanation to the function of electrical and magnetism is important in this matter.

A magnetic field can be produced by a current-carrying conductor. The magnetic field produced surrounds the conductor and, then, the outside medium is influenced by the effect of this magnetic field. A magnetic field intensity, H , [Ampere / meter] acts as a magnetising force to induce magnetisation in the medium of surrounding magnetic materials, where the magnetic materials will possess a magnetic flux density, B .

The relationship between the applied magnetic field intensity, H , and the induced magnetic flux density, B , in the medium is giving by:

$$B = \mu H$$

where μ represents the permeability of the medium, as the medium been induced by the flux density B when H is applied.

The variation of B with H is nonlinear, and can be represented by the magnetisation curve of, Fig. 1.

Adnan Y. Rojeab is with the School of Electronic Engineering and Computer Science Queen Mary University of London, U.K. (Tel: 0(44)208 648 6267, Mob: 0(44) 7758469962, e-mail: rojeab@btinternet.com, adnan.rojeab@ecps.qmul.ac.uk).

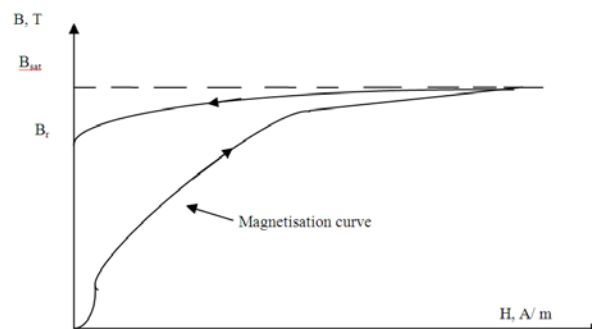


Fig. 1 B- H variation, and the residual flux density, B_r

When a non-magnetized magnetic material (as a medium) is exposed to a source of varied magnetic field, H , a different amount of magnetic induction, B , is applied to the material. As an increase in the magnetising force, [magnetic field] is applied, the medium will possess an increase in its induced magnetisation toward its saturation value, B_{sat} . When the magnetising force, H , is reduced to zero (or absent), the induced magnetisation of the medium is reduced as well, but it will not return to zero, as it lags behind the magnetising force of the field [1].

Therefore, the induced magnetisation of the medium is the amount of magnetisation which is residual (or remanent) in the medium, in the absence of the source.

This is represented by the remanent magnetic flux density, B_r , which is usually less than that of the saturation flux density, B_{sat} .

Induced magnetisation in the medium has two main properties:

1. Showing a similar repetition analogue to the patterns of the applied magnetising force (magnetic field), where the particles of the medium are magnetically aligned by the effect of the magnetising field.
2. The value of magnetic strength, in the induced medium, will be less than that of its maximum value, since the medium loses some of its induced magnetism by the absence of the magnetising force.

Magnetic phenomena may be used to explain important aspects of cell's functions, such as that of the cause of DNA replication and the shortening of the telomere.

II. STRUCTURE, REPLICATION AND ELECTRICAL PROPERTIES OF THE DNA

The most important property of DNA for a bio-molecular engineer is its ability to self- assemble, which makes it

possible to produce nano-structures [2]. Also, it is the best nano-wire known in existence, and it self-assembles, self-replicates and can adopt various states and configurations [3].

DNA is made up of double helix strands, which are two coiling structures spliced onto each other in an anti-parallel manner.

However, a telomere is a specialised structure composed of DNA-protein present at the end of a chromosome in a non-genetic way. Telomeres serve as protective caps to prevent a chromosomes end to end fusion, and allow complete replication.

The structure of the telomere is a repetitive DNA sequence TTAGGG, of base pairs, and in human consist of chemical clusters. The length of a telomere has frequently been used as a means to predict the life span of cells. But itself can be poor indicator of aging or cell viability [4].

Every time a chromosome is replicated, a bit of its telomere is lost. When the length of the telomere reaches a certain shortness (critically small), the chromosome reaches a critical length and this situation leads to no more replication of the chromosome in the nucleus of cells. This leads, in turn, to the cell becoming old and no longer producing new cells. The cell is then said to be die by a process called apoptosis.

The reason behind the cessation of division is that some of the essential genes are lost from the daughter chromosome if the division is continued while the telomere is at critical length, and the result is to form a different structure and function of DNA from that of the parental one.

Many research works have been carried out concerning with the DNA replication. King [5] has shown that the precise nature of the origins of DNA replication in higher eukaryotic organisms is unclear. Also, Health Encyclopaedia [6] has explained that the separation of the two strands of a DNA, in the replication process, is followed by the automatic formation of complementary strands on each of the separated strands.

It can be thought that the mechanism of these functions should not only be based on the biological and chemical aspects, but also the effect of electrical and magnetic phenomenon which has not been much addressed in scientific literature yet, have to be considered since the magnetic and electric effects have a great inheriting importance. Therefore, this hypothesis is concerned to explain the cause of the fundamental process of DNA replication.

As it is known that DNA replication involves the separation of the two strands over a short distance followed by the automatic formation of complementary strands on each of the separated strands; the parental double helix strands of DNA, which are coiled and spliced together, are unfolded and held apart. DNA does not split along its whole length at one time. Many short loops of separated DNA form simultaneously and the replication occurs in these loops [6]. Splitting the two strands apart starts at replication regions are rich in adenine-thymine base pairs. The reason for the separation of the strands is to expose the bases so that new nucleotides partners can bond to each of the parental strands.

When the unfolding process is formed, each parental strand is shaped a solenoid-like. It will then, go on to replication.

Each of the two strands in the original DNA acts as a template against which two new strands are built [7].

The surrounding environment to the parental strands is various types of amino acids, which are mainly a protein. The amino acid prepares the environment for the process of replication.

It is known that DNA has negative charges distributed along its length [8]. This interesting structure has led many scientists to carry out detailed research on many of its electrical aspects; almost 600 – nm ropes of DNA were studied by Fink [9] and were found to be good conductors. This was confirmed by other workers [10], who have found that DNA can acts as a molecular wire, with the phosphate bonds in the backbone acting as tunnel junctions allowing electrons to move along.

Even though the electrical conductivity of DNA is imperfect, it is of vital importance to the cell since the cell uses electrons through the charge transfer process to repair damaged bonds [11].

Further beneficial of DNA is to exhibit a property which is similar to the function of some electronic devices. Researches [12] have shown that a 10.4- nm - long, double stranded poly (G) – poly (C) DNA molecules that is connected to two metal nano-electrodes, possess electrical characteristics similar to that of semiconductors. The current measured was reported to be negligible up to threshold voltage which was followed by a sharp rise in the current. This result shows similarity to the behaviour of an electronic diode.

The other example of the electrical domain of DNA was noticed by a team of researchers [13], while exploring the potential of DNA as an electric wire, they have found that guanine is the base with the lowest oxidation potential which loses an electron during oxidative stress and becomes positively charged. This positive charge does not stay at the base where it was formed, but keeps moving along G-rich sequences.

Electric charges transfer on the DNA system is investigated by other researchers. Barton et al [14] in their examination of much longer charge-transport distance on DNA, they concluded that guanines are oxidized as a result of DNA-mediate charge transport over a significant distance (e.g. 200 Angstrom).

Also, the researchers found that, although long-range charge transfer is dependent on distance, it appears to be modulated by intervening sequence-dependent dynamics.

Barton et al stated that, single electrons can shoot far enough along DNA to influence genes activity. The electrical signals might help to switch genes that are far apart on and off. Also, the researchers stated that, it is a way of transmitting chemical information over a long distance that's dependent on a DNA sequence.

Regarding the current that can be included in DNA, Fink and Shonengerger [10], were the first to measure current through DNA. They have reported direct measurements of electrical current as a function of the potential applied across a few DNA molecules associated into single ropes of at least 600 nm long, which has indicated efficient conduction through the ropes.

They have also found that the resistivity values derived from these measurements were comparable to those of conducting polymers, and have indicated that DNA transports electrical current as efficiently as a good semiconductor.

Similarly, the researchers have measured current versus voltage (I-V) characteristics of the DNA ropes to obtain upper values for their resistivity. The voltage applied to the manipulation- tip was continuously swept and the current was monitored with an electrometer.

These currents must be attributed to the current through the molecules as they are in vacuum. The researchers, also, indicated that, although their experiments established that DNA molecules are conductors, the mechanism allowing the transport of charges remain unclear.

Electric conductance of DNA molecules was studied [15] theoretically by adopted the tight binding small polaron model to calculate the molecular conductance both in quasi-coherent and the incoherent regime. In the experiment of the poly(dA) – poly(dT) and the poly(dG) – poly(dC) DNA molecules, a unique current – voltage (I-V) curve; [$I \propto \sinh(bV)$], was observed, where coefficient b is the temperature dependences.

Besides the temperature dependence of b, the length dependences of the electric current in the two regimes were derived.

A model of electric charge travelling on DNA molecules is demonstrated by Yi and Orland [16]. Their research was carried out to elucidate the effects of interference on electronic properties of single stranded DNA or RNA molecules.

They showed that in double stranded DNA, base which pairs wind about the helical axis can be modelled as electrons travelling on a twisted ladder-like structure. They also stated that, when a magnetic flux is present, the current amplitude can be modulated.

Authors [17] work on direct measurement of electrical transport through single DNA molecules has stated that: seemingly contradicting results raised a debate over the ability of DNA to transport charge and the nature of the conduction mechanisms through it.

They confirm that, they develop an experimental approach for measuring current through DNA molecules, chemically connected on both ends to a metal substrate and to a gold nanoparticle, by using a conductive atomic force microscope. Many samples could be made because of the experimental approach adopted here, which enabled them to obtain reproducible results with various samples, conditions, and measurement methods.

They presented multileveled evidence for charge transport through 26 – bp – long ds DNA of a complex sequence, characterized by s-shaped current voltage curves that show currents greater than 220 nA at 2 V.

They stated that significant observation implies that a coherent or band transport mechanisms takes over for bias potentials leading to high currents of greater than 1 nA.

More evidence for electrical transport, and that of current – voltage characteristics, also for a semiconductor applicable of DNA strands were studied.

In their research [18], gold-DNA-gold nanoparticle (GNP) complexes were studied by scanning tunnelling microscopy (STM). I-V characteristics were collected from distinct positions of gold nanoparticle clusters and qualitatively explained by a tip-surface configuration model. Double-stranded DNA (ds DNA) of poly(dT)-poly(dA) was found to be slightly n-type semiconductor by theoretical simulation of the S-shaped I-V curves employing the Landauer formalism.

Research by Takagi et al [19] showed that, DNA electronic devices were prepared on silicon-based three-terminal electrodes. Both ends of DNA molecules (400bp long, mixed sequences) were bridged via chemical bonds between the source-drain nanogap (120nm) electrodes. S-Shaped I-V curves were obtained and the electric current can be modulated by the gate voltage. The DNA molecules act as semiconducting p-type nanowires in the three-terminal device.

While the mapping of the DNA process has opened up a great diversity of opinion, researchers world-wide intended to continue on a wider scale concerning its properties and functions and therefore an intense exploration of the biological and electrical properties and functions of DNA is taking place. The electrical potential of DNA and its nano-scale have given researchers a great hope to investigate and exploit the properties of DNA in an attempt to build nano-electric technology; A-T and C-G base pairs combination aim to replace the semiconductor devices.

III. MAGNETIC DEVICES

Practical magnetic applications can be expressed by using magnetic devices, such as solenoid, which can act to produce an induced magnetisation in the surrounding medium.

A. The Solenoid

It is known that a solenoid carrying a current is acting in similarity to that of a bar magnet. The effect of the magnetic field of the solenoid forms a pattern of a separated magnetic line of flux. Each magnetic line is surrounding the solenoid from its inside to outside, where this pattern of the field is affecting the outside medium to induce magnetisation in the medium. The formation of the magnetic lines is representing the direction of the north and the south magnetic poles of the solenoid. These phenomena are acting in a similar way to that of a bar magnet [20].

Therefore, while the surrounding medium is magnetically induced by the magnetic field intensity, H, of the solenoid, the medium will possess a pattern formation which is similar to that of the applied magnetic field.

The induced and remanent magnetic phenomena are of a practical property and are widely applied in many technological aspects, such as that of the magnetic recording process which is used in various devices.

B. Magnetic Recording Procedure

Magnetic recording is a method used to store, (called “write”), information on a magnetic medium, by a magnetic field signal. The information occurs on the medium in the form of spatially separated regions of varying magnetisation.

In the procedure of the magnetic recorder device, a magnetic tape is used as the storage medium.

In a magnetic recording device, the recording transducer or "head" converts an electrical signal to a magnetic signal (field). This field is applied to form a pattern of magnetisation in the tiny magnetic particles of the tape (medium). The magnetic field of the recording head has the effect of altering the magnetic direction of the tiny particles on the tape so that these particles align their magnetic domains with the applied magnetic field. The pattern of the residual magnetisation on the tape thus stores the representation of the signal of the applied field [21].

So the magnetic particles of a tape are induced by the effect of the magnetic signal of the recording head as they pass by a gap in the head.

As the tape passes against the position of the acting magnetic field of the recording head, different regions of the tape are magnetically induced in a magnetic spatial pattern corresponding to the acting field.

When a region of the tape is away from the acting magnetic field, a remanent magnetisation is retained in that region. This region, through its remanent magnetisation, possesses a similar pattern of magnetic information as that of the acting field of the head, but it will have less strength of magnetisation.

This means that the region keeps the similar manner of the particular information in the head at that time when it has passed against the acting field

The fixing process of the retained magnetic pattern in the medium depends on the magnetic coercivity of the medium. The medium of a higher coercivity is the more able to fix its magnetisation when the applied magnetic field is removed.

The recorded magnetic tape can be used as a source to store its magnetic information on a second (i.e. a new) magnetic tape. The second magnetic tape will also possess a remanent magnetisation, by the magnetic induction of the first tape (as a source). The amount of the magnetisation, (the information) of the second tape, therefore, will be less than that of the first one.

This process can be continued when the second magnetic tape is used as a source to record its information on a third magnetic tape, and so on. As the process is continued, a situation will occur when a certain generation of magnetic tape will possess a very small amount of information, (magnetisation), which is practically recorded as null information.

Similar results can be shown on the process of photo-copier machine action. A brief of the items and function of the machine is that: developer of the machine is usually of magnetic ferrite. This developer acts as a magnetic / electrical carrier which allows the toner to be carried from the magnetic developer roller onto the electrically charged sensitive drum.

A thin wire(s) housed in a lightweight metal slide framework that electrical attracts the image / toner formed on to the drum onto the copy paper.

It can be shown that a first copy from an original [source] document is approximately similar to the original. If this copy

is, now, used as a source for new copies, then a second generation copy [which is a copy from a first generation copy], is going to be less clear comparing with original document. Again, if the second generation copy is used to produce a third generation copy, and the third one is used to produce a fourth generation copy, and so on. Then each generation of a copy will be far to be clear in comparison with that of the original document. So, then, the nth copy generation will be like a poor paper, approximately has no any information.

This is again is the action of magnetic residual phenomenon during the copy process.

The fundamental idea applied in the magnetic recorder is similar to that used in every-day equipment such as sound recording (in an audio cassette), TV pictures (in a video cassette), data in the form of coded numbers and letters (in the memory of a computer disk).

IV. DISCUSSION

The initial process of the replication of a DNA strand is, as is mentioned above, initiated when the parental double helix strands of the DNA are unfolded and held apart, from their splice together. The result of this process forms each strand into a solenoid-like shape.

Also, as is shown in the literatures, the DNA molecule is an electrically conducting and an electrically charged material, through which electrical charges may be carried. It may be shown that these travel charges, along the solenoid-like strand of the DNA, form a sort of a Nano-electric current. This current, in turn, produces a magnetic field which possesses a signal of a similar pattern to that of the electric current.

A magnetic field of the whole structure of the DNA molecule encounters difficulty to be detected, although some measurements have shown no net magnetic field. This result does not mean that the component constructions of DNA have no magnetic field.

It is believe that each single strand of the DNA may be a source of a magnetic field, which is produced by the current-like charges travelling along the system of the strand.

In an attempt to show the existence of a magnetic field on each single strand of a DNA molecule rather than on the whole structure of the DNA, it is believed that it is important to emphasis on the situation of the parental DNA strand at the initial procedure before the completion of the replication process.

This procedure is as the following:

The parental strands, which are coiled together, are unfolded and held apart. The result of this procedure is going to occur the vital effect of the magnetic field's strength of each single strand, which means that each single strand can clearly show the effect of its magnetic strength.

By viewing the anti-parallel spliced direction of helical double strands in the structure of the DNA molecule, it can be understood that the single effect of the magnetic field strength of the two strands will cancel each other out.

Therefore, this situation can lead to preventing the spliced double helix stranded, in the structure of the DNA molecule,

to form any strength of magnetisation. This would leave the whole structure of the DNA molecule at zero net magnetisation. Clearly, the result of this process would not allow the whole spliced structure of the DNA molecule to share in any replication function.

Accordingly, a surrounding medium could be magnetically induced by the action of the magnetic field of each parental strand individually, (after the double stranded are unfolded).

In addition it has been shown [6] that the double helix stranded in replication of DNA does not split along its whole length at one time, but in steps.

This means that the magnetic field intensity of each single parental strand increases gradually against the surrounding medium. This process could lead, also, to a gradual increase in the magnetic induction in the medium towards its saturation magnetic flux density, B_{sat} . It is a procedure which is analogous to that of the induced magnetisation effect, as is mentioned earlier.

These procedures, in turn, may allow the medium to possess a remanent magnetisation. This means that the medium is formed its magnetic pattern structure analogous to that of the signal magnetic effect of the parental strand. Therefore, there is an acting information which is supplied by the magnetisation of each parental strand to induce the medium.

This is a magnetic information process in the medium. It is similar, in its phenomenon, to that occurs in the photo-copier machine action and in the magnetic recording process. In the magnetic recording process the tape recording medium is magnetically induced to form a similar pattern to that of the main acting magnetic source signal.

Now, each separated single parental strand is, therefore, acting by it induces magnetic field strength on the amino acid surrounding medium, in the nucleus.

Therefore, this medium is induced to form molecular structure analogous to that of the individual parental strand.

Accordingly, the main result shows that, through the replication process, each separated parental strand is acting by its magnetisation, and, then, it will induce the pattern of its magnetic information in the surrounding medium.

The magnetically induced medium, which possesses the remanent magnetisation, [by the strand's magnetic field], may show two important characteristics:

1. The retention, through the remanent magnetisation, of an analogue pattern construction is representing the magnetic formation as that of the parental strand. Where this is the result of the magnetic induction in the medium.
2. There will be a reduction in the strength of the magnetisation occurs in the surrounding medium compare to that of the full repetition of the magnetic pattern of the parental strand. This reduction is due to the fact that the induced surrounding medium is formed by the remanent magnetisation, B_r , which is less in magnetisation strength than that of the parental strand (as a magnetic source). As that shown in Fig. 1, where, B_{sat} represents the magnetisation strength [magnetic flux density] of the source, which is as that of parental strand.

Therefore, it can be shown that:

- A. The constructive formation of the surrounding medium molecules will be arranged similar to that of the single parental strand. This means that an induced (new) DNA strand is formed, which is a replicated strand by magnetic induction process.
- B. The reduction of full repetition of the magnetic pattern, in the surrounding medium, may lead to replicate a less number of DNA bases. The lack in the number of DNA bases may be in such an order to form the telomere parts, as they are positioned at the terminals of a daughter strand, where the magnetic action is less comparing to other parts of the strand.

This result may show that the length of the replicated telomere is reduced in the comparison with the telomere of the parental strand.

The replication process, as is known, will lead to nucleus division, and the daughter chromosome will possess less length, (i.e. shortening), in its telomeres compared with the parental chromosome. The division sequence ends, after a certain number of generations of nuclear divisions, in forming a critical shortening in length of the telomere. The result may indicate that the nucleus, and then the cell itself, will not be able to divide again.

It can be realised that the fundamental DNA replication process may be shown as analogous to that of the magnetic recording process. The magnetic recording process indicates a series of reductions in the amount of magnetic information in the process of recorded tapes. Some reduction in magnetic information will occur in each later recorded tape generation, when it is magnetised by the act of the magnetic induction of the upper generation tape.

It is believed that an important issue may be developed from the method of the DNA replication, as long as it is indicated that the replication process is performed by the magnetic induction action of the separated single strand only, which is as the follows:

The original formation of the two spliced strands forming a molecule of DNA is of importance matter, because the implication of this formation is to prevent the DNA as a whole molecule, [i.e. as one entity], from acting in replication. Where instead, each separated single strand is individually involved in the replication process, which the right life process.

If DNA molecule was able to act in the replication as a one complete structure, then the replication process would be continued without any interval stages. This would keep the nucleus packed with a huge number of chromosomes, which will change the whole of life.

V. SUGGESTION

Concerning with the action of the electric and magnetic phenomena on the processes of the DNA replication, it is believed that by applying these phenomena may play an important role to cure the cancer.

REFERENCES

- [1] Morris, N. M. (1991). *Mastering Electrical Engineering*, The Macmillan Press LTD.
- [2] Winfree, E., Liu, F., Wenzler, L.A., and Seeman, N.C. (1998). Design and self-assembly of two dimensional DNA crystals. *Nature*, 394, 539-544.
- [3] Bachtold, A., Hadley, P., Nakanishi, T. and Dekker, C. (2001). Logic circuits with carbon nanotube transistors. *Science*, 294, 1317 – 1320.
- [4] Blackburn, E. H. (2000). Telomere states and cell fates, *Nature* 408, 53-56.
- [5] King, M. N. (2004), (the Internet). Medical Biochemistry search, IU School of Medicine.
- [6] Dr. Youngson, R. (2001). *The ROYAL SOCIETY of MEDICINE, HEALTH Encyclopedia*, Bloomsbury Publishing Plc. London.
- [7] Medical Editor: Smith, T. (2000). *Complete Family Health Guide*, The British Medical Association, Dorling Kindersley limited, London.
- [8] Green, N.P.O., Stout, G.W. and Taylor, D.J. (1990). *Biological Science 1&2*, Cambridge University Press.
- [9] Fink, H.W. (2000). Electrical DNA, Press Conference for the American Physical Society. March 20-24.
- [10] Fink, H.W. and Schonberger, C. (1999). Electrical conduction through DNA molecules. *Nature*, 398, 407-410.
- [11] Netherlands Organisation for Scientific Research. (Sep. 11, 2002). Report titled: DNA's oscillating double helix hinders electrical conduction.
- [12] Porath, D., Bezryadin, A., de Vries, S. and Dekker, C. (2000). Direct measurement of electrical transport through DNA molecules. *Nature*, 403, 635-
- [13] Bharadwaj, L.M., I. Kaur, I., Kumar, R. and Bajpai, R.P. 2000a. Design simulation of DNA based electronic components. *Proc. SPIE*, 4937, 319-325.
- [14] Nunez, M.E., Hall, D.B. and Barton, J.K. (Feb. 1999). Long-range oxidative damage to DNA: effect of distance and sequence. *Chemistry & Biology* 6 (2): 85-97.
- [15] Asai, Yoshihiro, (2003), Small polaron model for electric current through single DNA molecule. *J. Phys. Chem, B* 107, 4647.
- [16] Yi, J., and Orland, H. (Oct. 2004), Electric response of DNA hairpins to magnetic field. Cite Base (autonomous citation navigation and analysis).
- [17] Cohn, H., Nogues, C., Naaman, R. and Porath, D. (2005), Direct measurement of electrical transport through single DNA molecules of complex sequence. *Proceedings of the National Academy of Sciences of the United State of America* (2005), Volume: 102, Issue: 33, Publisher: National Academy of Sciences, PP: 11589 – 11593.
- [18] Jun Qian, Jun Qian, Sicheng, Liao Sicheng, Liao Stroschio, M.A. , Dutta, M. ,Song Xu, Song Xu , (2009), *Electrical Transport through Single DNA Molecules by Distinct Tip-Surface Configurations*, 2009 13th International Workshop on Computational Electronics, ISBN: 9781424439256, DOI: 10.1109/IWCE.2009.5091111
- [19] Takagi, S., Takada, T. Matsuo, N. , Yokoyama, S., Nakamura, M. and Yamana, K. , (2012), Gating electrical transport through DNA molecules that bridge between silicon nanogaps. *Nanoscale* (2012) Volume: 4, Pages: 1975-1977 ST - Gating electrical transport through. ISSN: 20403364, DOI: 10.1039/c2nr12106a
- [20] Williams, J. E., Metcalfé, H.C., Trinklein, F.E. and Lefler, R.W. 1968. *Modern Physics*, Holt, Rinehart and Winston, Inc.
- [21] Editors: Bisacre, M., Carlisle, R., Robertson, D. and Ruck, J. 1979. *The Marshall Cavendish Illustrated Encyclopedia of SCIENCE AND TECHNOLOGY*, Marshall Cavendish Books Ltd.