A Review of Carbon Nanotubes Electrical Properties for Future Nanotechnology Applications

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Abstract: *Interest in the field of carbon nanotubes is due to unique physical properties and to significant prospects for applied applications. In this review, the quantum nanostructures with outstanding electrical properties are studied on electron emission performance optimization of carbon nanotubes with the factors affecting aligning as mechanical elasticity in bending related to electronic structure. The phenomenon of field emission producing current when an electric field is applied to a conductor is also discussed. The carbon nanotubes applications in nanotechnology are clarified in this work and it can be metallic or semiconductor depending on diameter and chirality with high emission and conductivity properties to create electronic devices.*

Keywords: Carbon nanotubes, Electrical properties, electronic device

استعراض الخصائص الكهربائية للأنابيب النانوية الكربونية في تطبيقات تكنولوجيا النانو المستقبلية

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المستخلص

ان الاهتمام بمجال الأنابيب النانوية الكربونية (CNT) للتكنولوجيا النانوية يرجع إلى الخصائص الفيزيائية الاستثنائية والمنظور الهندسي للتطبيقات المستخدمة. في هذا الاستعراض، تتم دراسة البنى النانوية الكمومية ذات الخواص الكهربائية المتميزة التي تعمل على تحسين أداء انبعاثات الإلكترون للأنابيب النانوية الكربونية مع العوامل التي تؤثر على التوافق بين المرونة الميكانيكية في الانحناء المتعلق بالهيكل الإلكتروني وظاهرة انبعاث المجال التي تسبب التيار عندما يتم تطبيق المجال الكهربائي على الموصل حيث تمت مناقشتها أيضًا. وتم توضيح أن الأنابيب النانوية الكربونية الواسعة الاستخدام في التكنولوجيا النانوية يمكن أن تكون ذو انبعاثات عالية مع خصائص الموصلية لإنشاء الاجهزة إلكترونية وقد تم التركيز عليها.

الكلمات المفتاحية: الأنابيب النانوية الكربونية، الخصائص الكهربائية، الأجهزة الألكترونية.

1. Introduction

Comparatively new and unusual forms of carbon existence are fullerenes and nanotubes. Fullerenes were discovered in 1985 as an impurity in soot-shaped products. In a vacuum or in an inert gas atmosphere, the nuclei of the shells can interact with each other, forming a closed spherical surface of fullerene [1].

After 6 years the discovery of fullerenes a carbon nanotube is discovered by Sumio Yijima, as an employee of the Japanese corporation NEC in 1991[2], the existence of related extended structures, which are cylindrical particles formed from one or several layers, was established. Such particles, called carbon nanotubes, are formed in an electric arc with graphite electrodes in the presence of a buffer gas and under favorable conditions. The idealized structure of a typical single-walled nanotube is shown in Fig.1 [3]

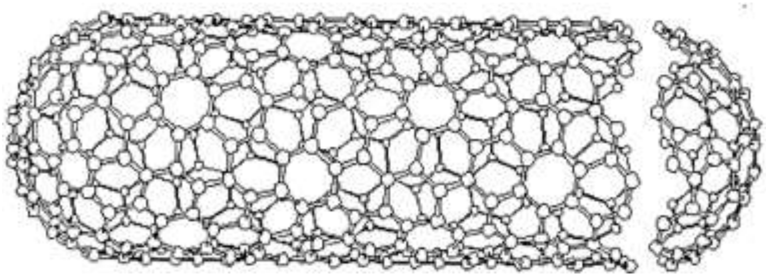

Fig.1. Idealized nanotube model [3].

The diameter of a typical single-walled nanotube ranges from 0.5nm to several nanometers, somewhat greater than the diameter of the fullerene C60 molecule [1].

The cylindrical surface of the nanotube is lined at the vertices of which are carbon atoms. At the ends of the nanotubes, as the layers increase, forming loops and other complex structures with extended shapes. Multilayer nanotubes differ from single-layer by a wider variety of shapes and configurations. There can be structures like a scroll [4].

The nanotube is a surface structure, and its entire mass lies in the surface of the layers. Therefore, nanotubes have an abnormally high specific surface, which determines the characteristics of their sorption and electrochemical characteristics. The distance between the layers in a multi-layered carbon nanotube (3.4nm) is sufficient for a certain amount of substance to be placed inside the tube. If the tubes are folded relative to different directions, then CNTs can be obtained with a fundamentally different structure and physical properties. The mutual orientation of the hexagonal grid and the nanotube axis is determined by the main characteristic of the nanotube, which is called chirality [3].

The study of carbon nanotubes is of considerable fundamental and applied interest. Fundamental interest is due to the unusual structure of nanotubes and the wide variation in their physicochemical properties. The mechanisms growth of carbon nanotubes in various experimental conditions, the nature of their properties, the applied use of carbon nanotubes depends on the cost of their production. Nevertheless, such properties of nanotubes as subminiature sizes, semiconductor and metallic properties, good electrical conductivity, high emission characteristics, capillarity, and high chemical stability, make it possible to hope for the effective use of nanotubes in measuring equipment, electronics, and Nano-electronics [4].

The carbon atoms of each layer are located against the centers of the hexagons located in the adjacent layers. Each layer is shifted relative to the other in the horizontal direction. It is possible to describe the most easily spaced carbon nanotube (CNT) with the help of the vector, which connects the two atoms on the graph sheet. The cylinder is obtained by rolling this leaf in such a way that the beginning and end of such vectors will move together. This vector can be expressed through the vital vectors of the elementary cell of the sheet $C = na_1+ ma_2$, where n and m are integers and a1 and a2 are the lattice vectors of grapheme, with it being assumed that $n \geq m$. Each pair of numbers (n,m) represents the potential structure of the nanotube. The symmetric tubes “zigzag” and “armchair” are presented by vectors (n,0) and (n,n) correspondingly. The nanotubes can be both current conductors and dielectrics can be used in many areas of electronics science and technology [5].

This work focuses on properties for carbon nanotubes that are an attractive object of basic science and broad prospects for applied development use in electronic and communication devices.

2. Physical properties of carbon nanotubes

2.1. Mechanical properties of nanotubes

Nanotubes have an abnormally high tensile, bending, and torsional strength [6]. The mechanical stress S in a tube is defined as the ratio of the load W to the cross section of tube A where stress $S = W/A$.The relative deformation ε is defined as the ratio of the elongation ΔL of the tube to its length L before loading: $\varepsilon = \Delta L / L$. According to Hooke's law, the stress S is proportional to the relative deformation: $S = E\varepsilon$. The proportionality coefficient $E = LW / A\Delta L$ is called Young's modulus and is a property of a particular material that characterizes its elasticity. The greater the value of Young's modulus, the more material is malleable. The Young's modulus of carbon nanotubes ranges from 1.28 to 1.8TPa, while the Young's modulus of steel is almost 10 times smaller (0.21TPa). This implies that the carbon nanotube is very tough and difficult to bend. However, this is not so because the nanotubes are very thin. Deviation of an empty cylindrical rod of length L, inner radius ri and outer radius r0 under the action of the force F applied to its end, the normal axis is given by the expression: $D = FL^3/3EI$ [7], where $I = \pi\,(r_0^4 - r_i^4)/4$ is the moment of inertia of the rod section. Since the wall thickness of a single-layer nanotube is -0.34nm, the value of $r_0^4 - r_i^4$ is very small [8], which compensates for the large value of Young's modulus. (Fig.2.a and b) shows the Carbon nanotubes at elastic in bending and without.

a) **b)**

Fig.2: The optimized bent tube a) at bending angle b) without bending angle [8].

Carbon nanotubes are very elastic in bending. They do not break and can straighten without damage, because they have few structural defects (dislocations, grain boundaries). In addition, the carbon rings of the walls in the form of regular hexagons change their structure during bending. The tensile strength characterizes the stress required to break. The tensile strength of a single-layer carbon nanotube is 45GPa, while for steel it is 2GPa. Multilayer nanotubes also have better mechanical properties than steel, but they are smaller than single-walled nanotubes. For example, a multilayer nanotube with a diameter of 200nm has a tensile strength of 7GPa and Young's modulus of 0.6TPa [9].

Table 1 shows the main mechanical characteristics of single-walled carbon nanotubes in comparison with known materials [10].

Table 1: Mechanical characteristics

Material	Elastic moduli GPa	Resistance to break gPa	Density (g /cm^3)
Single layer carbon nanotube	1210	65.0	1.4
Graphite kernel	152	2.1	1.6
Titanium	103	0.9	4.5
Aluminum	69	0.5	2.7
Steel	207	0.8	7.8

The difference lies in the chirality vector, which in turn exhibits different mechanical properties of the carbon nanotubes have very good mechanical properties, because the carbon nanotubes are extremely elastic, can be bent over large angles due to its hollow capillary characteristics, their Young's modulus and tensile strength is hundreds of times stronger than that of steel wires, graphite kernel, titanium, and the aluminium but their weight is extremely light, and they have both metal properties and semiconductor properties. The Young's modulus is 1210 GPa for a single-walled carbon nanotube, which is about more than 5 times that of steel. The density is only 1/6 of that of steel and makes the tensile strength is very high. The composite material can exhibit good strength, elasticity, and break resistance. The composite material is made of other engineering materials and carbon nanotubes, which greatly improves the performance of the composite material.

Carbon nanotubes have the hardness but have good flexibility and can be stretched. The strength factor is determining the ratio of length to diameter, which gives an ideal high-strength fiber of carbon nanotubes referred to as super fibers.

2.2. Electronic field emission.

In terms of electrical properties, the single-walled CNTs can exhibit semiconductor or metal properties and this depends on the way they are convolved. The phenomenon of field emission occurs when an external electric field is applied to a conductor. As a result of this effect, conduction electrons, originally located in a rectangular potential well [11], have the possibility of going beyond the conductor due to quantum tunneling.

Traditionally it is believed that the source of field emission is the top of the nanotube, in the vicinity of which the field strength is maximum. However, recent studies have shown that the lateral surface of nanotubes serves as a good source of field emission. At certain orientations of the nanotube with respect to the direction of the electric field, the contribution of emission from the side surface to the total current of field emission can be decisive, since the area of the side surface significantly exceeds the surface area of the top, the electron work function for single-walled nanotubes is ~ 4-5eV, for multilayer ~ 0.2-7eV [12].

Fig.3 shows the current-voltage characteristics of emitters obtained with different orientations of nanotubes relative to the substrate [13]. The threshold value of the electric field strength was determined by a minimum emission current as the value of the emission current density of 1mA/cm - 2 required for the operation of flat-panel displays is achieved at electric field strengths (E) of 4.2, 6 and 6.8V/cm for the three orientations as: parallel to the substrate plane, at an angle of 45°, and perpendicular to the substrate plane, respectively.

It turned out that due to their specific structure, nanotubes have emission properties, in particular field emission. The threshold tensions for them turned out to be an order of magnitude smaller than the typical metal dioxide cathodes used now.

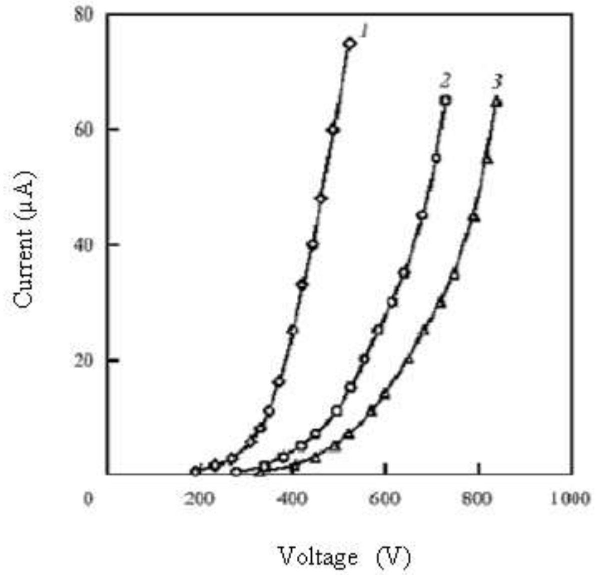

Fig.3: The current-voltage characteristics of emitters with different orientations [13].

Field emission is described by the Fowler-Norgeim formula[14] :

$$J = E^2 \exp\left(\frac{-C_2}{E}\right) \quad (1)$$

$$C_1 = \frac{e^3}{8\pi ht(y)^2\varphi}, C_2 = \frac{8\pi\sqrt{2m}}{3he}\ \varphi^{3/2}\theta(y), y = e(eE)^{1/2}/\varphi \quad (2)$$

Where J: the emission current density on the electric field strength E. The parameters C1 and C2 are expressed through the magnitude of the basic constants are charge (e) , mass m of the electron, the Plank constant (h), electron work function (φ) of the conductor where θ is the tilting angle of the nanotube and the temperature effect t. At tensions of the order of 10 6 -10 7 V/m, the current density begins to increase.

2.3. The conductivity of carbon nanotubes.

Large mechanical stresses arise, which leads to a distortion of the electronic structure. There are not very many atoms in a nanotube (with chirality = 1 hundred atoms), it is not energy zones that are formed, but separate states. The overlap of free states is described by the formula: m-n =3q (the difference of the numbers of chirality, a multiple of three).

Measuring the conductivity of individual nanotubes is a rather difficult task. It is necessary to use an atomic force microscope, and it turns out that the resistance of metallic nanotubes is ~1–10kΩ. This resistance corresponds to the ballistic mechanism of charge transfer, in which the electron overcomes a piece of tube of approximately 1μm without scattering, as it occurs in a vacuum. The conductivity of nanotubes depends not only on chirality but also on structural defects and the presence of attached radicals (OH, CO, etc.)[15]. In addition, the conductivity of the nanotube is extremely sensitive to the degree of bending. For example, the conductivity of a straight-line portion of a single-walled nanotube, which does not experience an external load, at room temperature is ~100μS, which corresponds to a resistance of 10kΩ. As a result of the bending of a nanotube at an angle of 105°, its conductivity decreases by a factor of 100, reaching a value of ~1μS. The study of the temperature (T) dependence of the conductivity of the bent portion of the nanotube made it possible to establish that the electron tunnels through the bend site (Fig.4)[16]. Therefore, bending the tube, you can create a tunnel junction in it and devices based on it. These dependencies are usually modeled by a power function, because of the absence of dependences reliable data on the temperature of transport coefficients:

$$R(T) = R_0 \left(\frac{T}{T_0}\right)^{\propto} \quad (3)$$

Where: R_0 is the resistance at $T = T_0$, and α is the fitting parameter. A similar approach is used for representing the temperature dependence of the thermal conductivity coefficient.

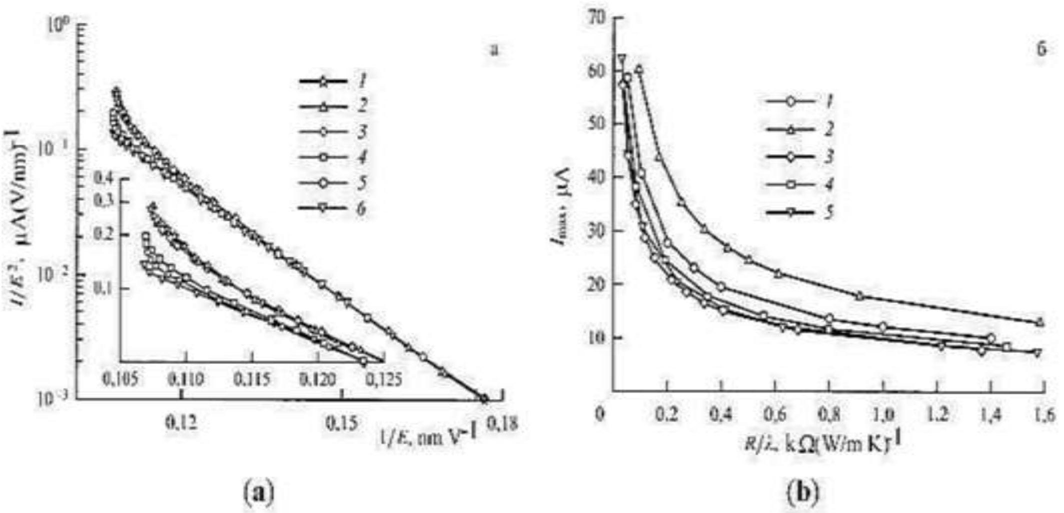

Fig.4. Results of the solution of the electrical conduction, (a) I–V characteristics of Fowler-Nordheim a carbon nanotube 5 nm in radius and 1.6mm in length and b) Dependences of the emission current I_max on the ratio R/λ, where the λ thermal conductivity[16].

Fig.4.a calculated for various model temperature dependences of transport coefficients: 1: experiment; 2: α=4; 3: α=−1; 4: α=0; 5: α=0; the thermal conductivity λ=constant; 6: α =1. The inset presents an enlarged part of the current-voltage characteristics. The Fig.4.b calculated for various model temperature dependences of transport coefficients: 1: α =0, λ=constant; 2: α=4; 3: α=−1; 4: α=0; and 5: α=1.

If a nanotube has semiconductor properties, it is concentrated in barriers located approximately every 100nm along the length of the nanotube. Then its resistance is tens of MegaOhms, and it is not distributed evenly along the length, like a normal conductor, but according to the experimental data obtained [17], the resistance of a multilayer nanotube with good accuracy is described by the relation;

$$R = \frac{\rho L}{\pi d^2} \quad (4)$$

Where: ρ ≈700 Ω / cm is the resistivity of the nanotube; L is the length of the nanotube and d is the diameter of the nanotube. This resistance behavior indicates the nonballistic nature of charge transfer[18]. Therefore, a multilayer nanotube is a two-dimensional conductor of length L and thicknessd.

3. Carbon nanotubes application in nanotechnology.

3.1. Nanomechanisms and Nanomachines

After cutting off several layers from one of the ends of a multi-layered CNT, the inner nanotubes can slide back and forth with very little friction. That is what is required for the mechanical parts of nanoscale mechanisms [19].

The experiments also demonstrated that the van der Waals forces, which attract all neutral atoms to each other, force the internal nanotubes to retract back into the shell (Fig.5). It is theoretically shown that after the inner tubes ("core") is stretched and released, they will be pulled inward and having passed through the shell from the outer tubes, will come out from the other side[20]. Low friction between the tubes by the force of attraction is no more than 10 -10 N. The gear train is a carbon nanotube with a diameter of 1 to 10 nanometers. Benzene molecules (like teeth) attach to a carbon nanotube, forming a gear that operates at gigahertz frequencies Fig.6.

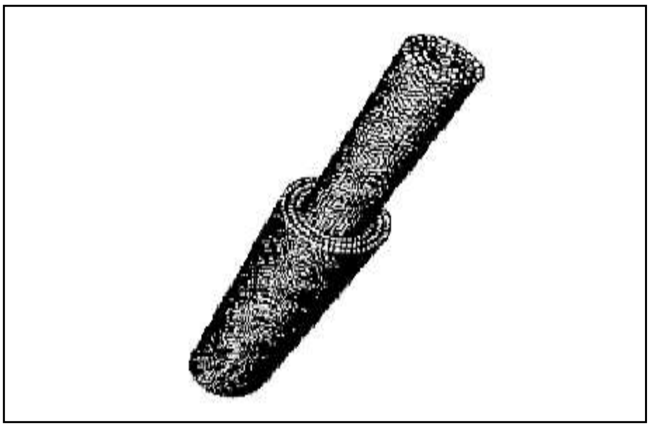

Fig.5. Shell retract back by force the internal nanotubes which attract all neutral atoms to each other [20].

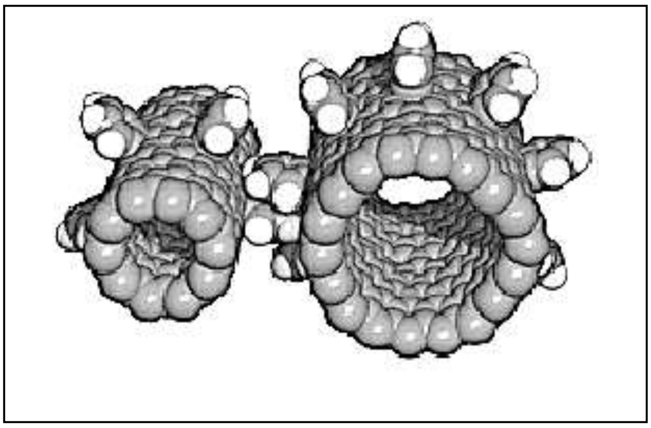

Fig.6 Benzene molecules (like teeth) attach to a carbon nanotube [20].

Theoretical studies of the structure and operating conditions of nanomachines show that gears based on carbon nanotubes are very strong and can function even when slipping in conditions where the conventional gear does not work. Based on the results of computer simulations, scientists have concluded that nano-transmission or other nanomachines in the future can be used to control the power of laser radiation or control external electric fields[21].

3.2. Carbon nanotubes in electronics

3.2.1. Electronic devices on nanotubes

Interconnects today, electrical connections inside chips are provided with the finest copper contacts. Chip manufacturing has come to the limit of further reducing the electrical conductors connecting the various components of a single silicon chip. Currently, electron-beam lithography allows you to create lines 50nm wide and several nm thick. Due to the reduction in the size of transistors and the increase in their number, problems arise with a high density of electric current which must pass through increasingly thin conductors. Therefore, single-layer nanotubes 0.6–1.8nm in diameter (1.4nm typical) grown on a silicon substrate can serve as interconnecting conductors in microchips [22].

In addition to miniature sizes, carbon nanotubes are more thermally resistant up to -2800°C in a vacuum and up to 750C° in the air than metal wires in microcircuits that melt at 600-1000°C. The thermal conductivity of nanotubes is up to 6000W/m·K, which exceeds the thermal conductivity of diamond (3320W/m·K).

The record of electron mobility in carbon nanotubes at room temperature is 100,000 cm 2/V·s. This mobility value is 23% higher than the mobility value in InSb (77000 cm 2/V·s); 70 times higher than silicon (1500 cm 2/V·s). Carbon nanotubes with such high mobility can be used to make faster transistors.

At present, prototypes of field-effect transistors based on a single nanotube have been created (Fig.7): upon application of a blocking voltage of several volts, the conductivity of single-layer nanotubes changes by 5 orders of magnitude. The bandgap of semiconductor nanotubes depends on the diameter of the nanotube and varies in the range of 0.7-1.1 eV[23] .

When creating an LED-based on nanotubes, a three-pole configuration of a field-effect transistor was implemented using a SiO2 substrate as the base (Fig.8) [24]. The photon is emitted during the recombination of current carriers with opposite charges: electrons and holes. The electrons and holes are injected into the nanotube in the area of contact with the metallic conductor of the emitter and collector by creating a Schottky barrier, therefore, the contact potential difference of the corresponding sign.

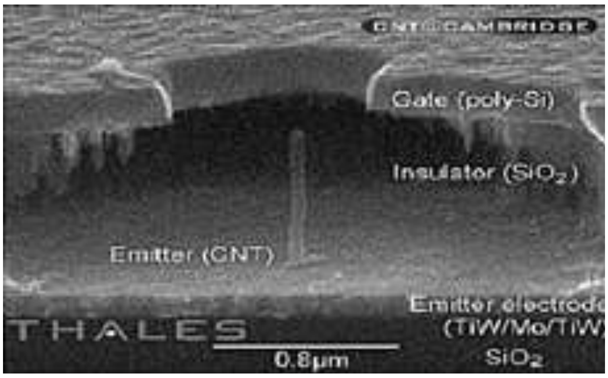

Fig.7 High electron mobility in CNT to make faster transistors

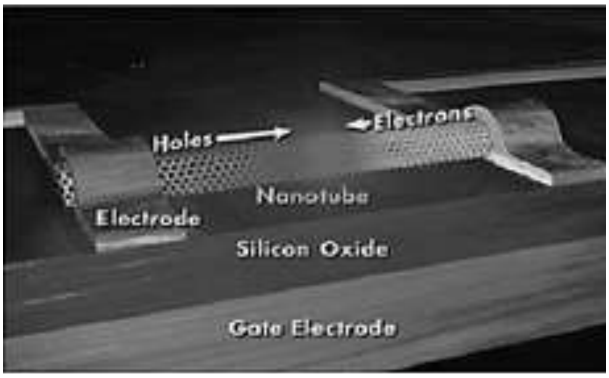

Fig.8 Three-pole of field-effect transistor based on nanotubes.

The nanotube has finite dimensions; therefore, the levels at which electrons can be located in it are discrete, and the possibility of conduction is determined by electron tunneling. The position of these states can be controlled by the field allocated on the substrate, and thus determine the conductivity. The splitting of the levels depends on the size of the nanotube. If the nanotube is about 1 micron in size, then 1-10 μV, the temperature is 1-10 K. If the size of the nanotube is about 1-10 nm, then 1-10 mV, and it is possible to work at room temperature [25].

3.2.2. Displays and lighting devices on nanotubes

Nanotubes are capable of significant electron emission, 1-2 orders of magnitude smaller than traditional emitters (10^5-10^6V/ m). Nanotube displays combine the advantages of LCD displays and CRT screens [26].

A phosphor is applied to the anode, which glows when electrons are bombarded. If we place the grid close enough (modern technologies allow us to do this at 1..10 nm), we can form an image by controlling the voltage on the grid. In this way, we can have the glow of the phosphor without limiting the viewing angle, as in CRT screens, and controlling the emitter, as in LCD displays. They have a fairly low field, causing emission, which allows for tens of volts to cause emission. The Light is determined by phosphors are red, blue, and green. Red - Y2O3 : Eu Green - ZnS: Cu Blue - ZnS: Ag, Cl. But in Lighting fixtures, the idea is the same, but there is some struggle to cover as large a surface as possible with phosphor, which will entail a greater distance and more voltage [27].

One of the manufactured samples had the following characteristics: 50 mm in length and 42 mm in diameter; 5.4kV supply voltage, wire diameter 1mm, made of iron, aluminum and chromium, the output of the nanotubes was about 5 eV, which is comparable to typical emitters, and the gain relative to the Fowler-Norgeim formula is about 23000. The current density on the anode - 0.06A/cm, which gives a brightness of 10,000 cd/m^2 (comparable to modern fluorescent lamps). Such a lamp can be used to illuminate the TV [28].

Flat displays are considered one of the promising areas for the use of carbon nanotubes (CNTs). Their work is based on the ability of CNT to emit electrons when exposed to an electric field (due to the quantum-mechanical effect of tunneling through a potential barrier). In this case, the CNTs actually perform the function of a cathode ray tube of conventional monitors [29].

A group of researchers from Northeastern University (Northeastern University, Boston, USA) under the guidance of Professor Yun Jun (Yung Jung) proposed an original approach to the design of displays from CNT. They manufactured large arrays of vertical (perpendicular to the substrate) CNTs in a dimethylsiloxane polymer matrix by chemical gas-phase deposition. In this case, the CNTs are grouped into regularly arranged “columns” with a diameter of 0.5mm and a height of 0.1mm each. Such a composite "polymer / CNT" is easily separated from the substrate after polymerization. All CNTs retain their excellent emission characteristics, and the gain (the ratio of the electric field strength at the edge of the “column” to the external field strength) reaches 10,000. This property will allow in the near future to produce flexible displays that can literally be rolled up into a tube.

In order to obtain an image using field emission, a phosphor is fixed on the anode[30]. For example, when used as a phosphor zinc sulfide with the addition of copper and aluminum, there is a green glow, and with the addition of silver-blue. The red color is obtained using europium-doped yttrium oxide (Fig.9). Color panels and carbon nanotube displays made in this way can have high mechanical strength, high brightness up to 8000 cd /m^2 , viewing angle up to 160°, high speed and the ability to work continuously for thousands of hours [31].

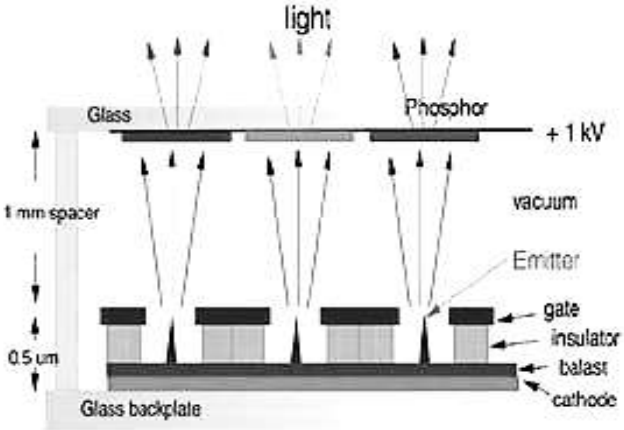

Fig.9. Diagram of the display based on CNT [31].

3.2.3. CNT lithography

Carbon nanotubes can be used as probes for atomic force microscopy (AFM) (Fig.10)[32]. Such probes for AFM can be used to create nano-patterns for nanolithography or for surface etching in the production of semiconductor chips. Thus, the CNT probe is used as a nano-forceps to remove atoms from the surface.

In etching mode, the nano-probe slightly touches the surface and selectively removes atoms from the surface. In the identification mode, the CNT probe presses against the surface to make nanholes[33]. Branched grids in biological dendritic neural trees provide signal switching and processes at branch points.

In Fig.11 a model of a 4-level neural tree made of 14 carbon nanotubes connected by a Y-junction is considered. At each branch level, the Y-junction is shown in one color[34].

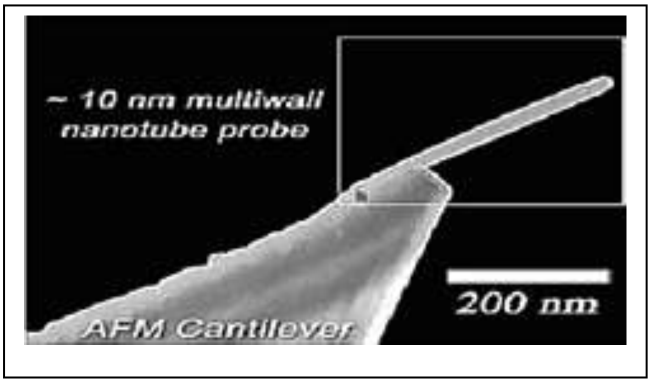

Fig.: 10. (AFM) probes of the carbon nanotubes.

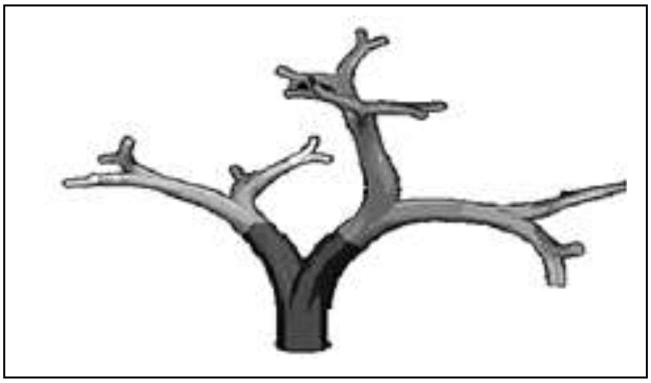

Fig.11. Model of neural tree based Y-tube connections.

3.3. Cold carbon nanotube cathodes

Auto electronic cathodes in nanotubes have obvious advantages - negligible height variation (10nm), uniform current collection over the surface[35], high emission current density (up to 1A/cm^2), the ability to vary the cathode geometry, a record low work function (1eV). Power consumption with performance comparable to those of a 100watt incandescent lamp is only 25 watts. Metal nanotubes activate the phosphor at 1-3V/µm, while molybdenum filaments at 50-100V/µm.

Fig.12. Schematic depicts the experimental setup for detecting nanotube field emission source, and collector plate are housed in a vacuum chamber at 1026torr. The prepared surfaces were brought into contact with a 50% transmitting copper grid and then withdrawn by 10–100mm from the grid by using a precision micrometer. By the bias towards the grid were caused accelerated the electrons field emitted from the sample surface. current I detected by using an electrometer as half of the total emitted electrons passed through the grid and were collected onto a plate. the voltage bias could be ramped in 70mV , the temperature at T=5300K under control and the emission characteristics are for a cold-cathode configuration[36].

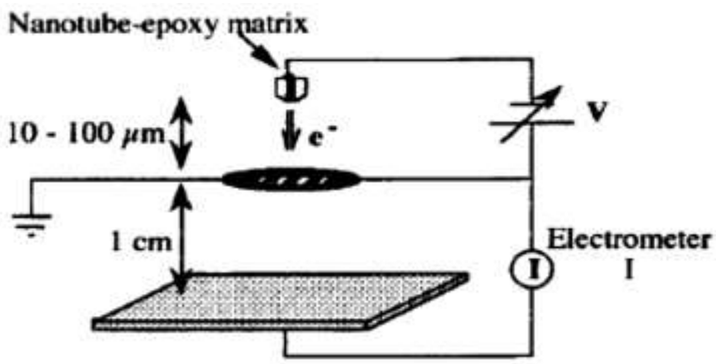

Fig.12. Schematic of the carbon nanotube field emission with emission current transmitted detected by electrometer through the acceleration grid [36].

3.4. Fuel cells based on carbon nanotubes

Carbon nanotubes can be used in the manufacture of batteries. Lithium, which is the carrier of charge in some batteries, can be placed inside the nanotubes. It is estimated that you can place one lithium atom for every six carbon atoms. Another possible use of nanotubes is hydrogen storage in them, which can be used in the design of fuel cells as sources of electrical energy.

The method of filling carbon nanotubes with hydrogen consists in using an electrochemical cell (Fig.13)[37]. Multi-walled nanotubes in the form of a sheet of paper make up the negative electrode in the H_2O electrolyte solution. The other electrode consists of Ni $(HO)_2$. Oxidation of hydrogen molecules takes place at the anode to produce protons and electrons, where the electrolyte water decomposes with the formation of hydrogen ions (H^+) moving to the negative electrode of the nanotubes. The presence of hydrogen bound in nanotubes is determined by the decrease in the intensity of Raman scattering. To operate such a fuel cell, a carbon nanotube must absorb 6.5% of hydrogen by weight. At present, only 4% hydrogen by weight has been put in the nanotube.

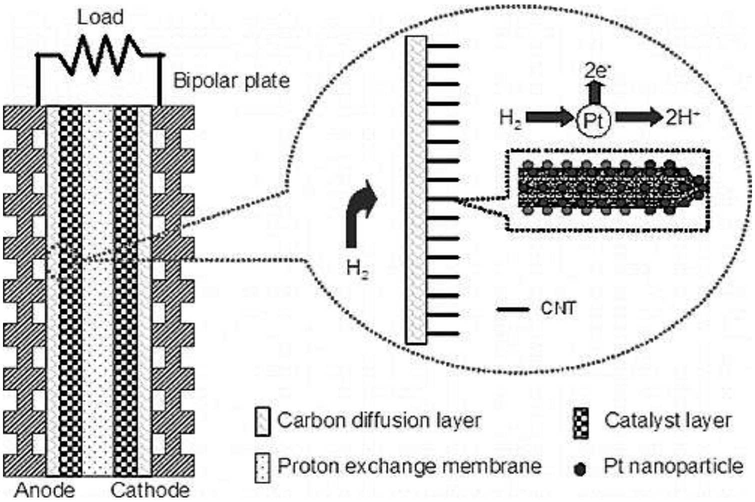

Fig.13: The multi-walled carbon nanotubes used as platinum support for proton exchange membrane fuel cells have been investigated as increased utilization of platinum a way to reduce the cost of fuel cells [37].

3.5. Carbon nanotube biosensors

Biosensors allow you to quickly and with high selectivity to carry out an automated analysis of complex objects, determining glucose, cholesterol, urea, amino acids, and other substances, the content of which can vary from 0.05µg /l to 1mg /l.

Fig. 15 shown the biosensor on an individual single-layer carbon nanotube allows you to control the pH up to 0.1 (Fig.14)[38]. Immobilization of Glucose Oxidase (GOx) significantly reduced the conductivity of single-layer CNT. CNT coated with GOx, in contrast to the initial ones, turned out to be very sensitive to pH in the range of 4-5.5. At pH=5.5, their conductivity increases significantly, and the changes in conductivity are reversible. It also turned out that GOx-coated semiconductor CNTs are sensitive to BD-glucose — when added to a solution, their conductivity increases.

The part of the construction task for a structural model of a carbon nanotube with metallic and semiconductor properties with given chirality indices (n, m). The cylindrical carbon nanotubes are so thin that 50,000 of these nanotubes, stacked in a row, hardly reach the thickness of a human hair. Due to its unique properties, nanotubes can be an effective means of delivering a wide variety of therapeutic agents to patient cells. However, the insufficient amount of data on what happens to nanotubes after they have become detached from their “load” has been the main obstacle in their use up to now [39].

Researchers from Stanford University (Stanford University) (USA) traced what happens to the nanotubes after their introduction into the body of the mouse. The results of the study were published in the journal PNAS (Proceedings of the National Academy of Sciences). The study eliminates the possibility that the nanotubes can be toxic to the body while remaining in the tissues for a long time[40] .

By modulating the structure of nanotubes, one can change the duration of their persistence in the bloodstream, according to researchers. The best results were obtained when nanotubes were coated with polyethylene glycol (PEG) as shown in Fig.15[41]. The branched form of the polymer was used, which proved to be more effective than the unbranched. PEG coated nanotubes are biologically inert and do not react with molecules of the extracellular matrix and the cytoplasm of cells. They also have a high solubility in water, which contributes to their long-term (up to 10 hours) circulation in the bloodstream[42].

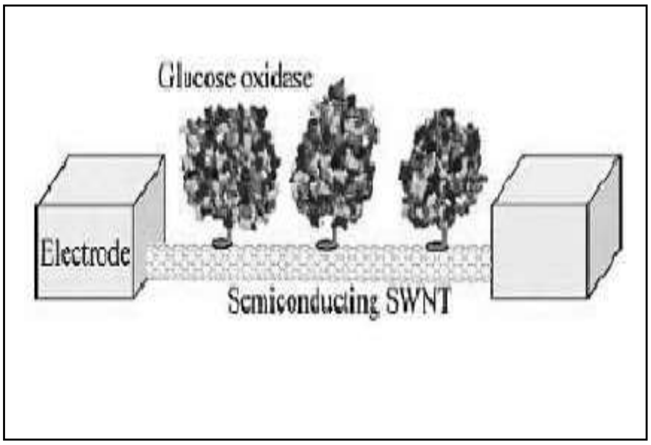

Fig. 14: The biosensor on an individual single-layer carbon nanotube [38].

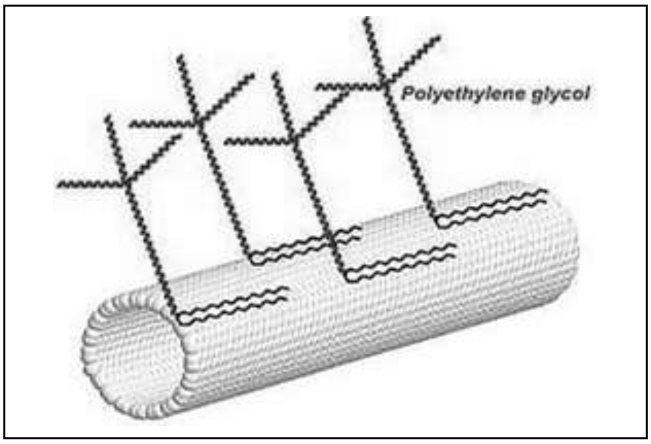

Fig.15: Carbon nanotube coated with polyethylene glycol[41].

3.6. Carbon nanotube antenna oscillator

An antenna has been created in Boston College that can detect optical radiation in the same way that ordinary antennas catch radio waves. An antenna is a surface covered with a kind of nanoscale of short carbon nanotubes. Under the action of light waves, electrons in nanotubes begin to oscillate, generating a super high-frequency electric current. The developers believe that such devices can form the basis of optical television, and also serve to convert sunlight into electricity[43].
Antenna-oscillator - the creation of a new generation of antennas for the transfer of huge amounts of information. Further research is aimed at creating oscillators for telecommunications as an oscillator antenna with a size of about 1 micron was obtained in the laboratory of the University of Boston. This device has 50 million atoms and can oscillate with a frequency of 1.49GHz. This will allow transferring large amounts of information with it [44].

In everyday life, we regularly come across the usual antennas used to receive or transmit television and radio signals. It is known that the same idea of receiving electromagnetic waves can also be used for optical radiation, but in this case, the geometric dimensions of the antenna will have to be reduced to nano-scales. Nano-antennas are characterized by so-called plasmon modes, which can be tuned to resonance with optical transitions in molecules located in the immediate vicinity of the antennas. It is the tuning for these modes that ensures the connection of photons emitted by the antenna and neighbouring molecules.

Television and radio antennas are easily tuned, which makes it possible to receive or emit electromagnetic waves from a specific spectral range. For a wide practical application of nano-antennas, the same capabilities are needed. Unfortunately, compared to conventional antennas, nano-antennas working with optical waves are difficult to configure.

It seems that a group of scientists from Harvard University (USA) has found a worthy solution to this problem. Scientists have shown that the resonant frequency of a nano-antenna constructed according to a specific scheme and containing graphene can be tuned within the middle IR region of the electromagnetic spectrum by applying external voltage. The nano-antenna designed for our CNT based nano IR detectors as depicted in Fig.16. It consists of two symmetric thin metal wires which are separated by a nanometric gap[45].

As experiments conducted by scientists have shown, the gate voltage applied to graphene allows changing the concentration of free charge carriers in the material (electrons and conduction holes), thus affecting the conductivity and optical constants of the material. Therefore, a small fragment of graphene, located in the nano space of an optical antenna, acts as a tunable element of the circuit, allowing you to control the resonant frequency of the entire system. The main feature of the material is that it allows you to tune the antenna in a wide spectral range.

As part of the experiment, an array of nanoantennas containing graphene was built by scientists on a silicon substrate equipped with a thin layer of silicon oxide as insulation as in Fig.17[46].

The scientists themselves believe that the nanoantennas proposed by them may in the future find application in a wide variety of fields, from the construction of various sensors to the development of new optoelectronic devices. At the moment, the research team is looking for a new structure that would allow them to expand the range of settings for nanodevices. At the same time, studies of the behavior of meta-surfaces, which are arrays of hundreds of similar nanoantennas, are being conducted.

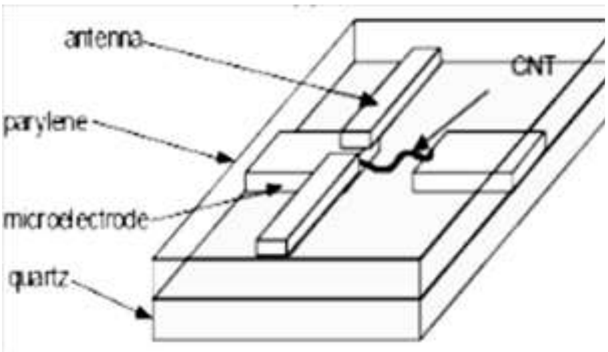

Fig.16: Schematic structure based a nanoscale antenna of CNT [45].

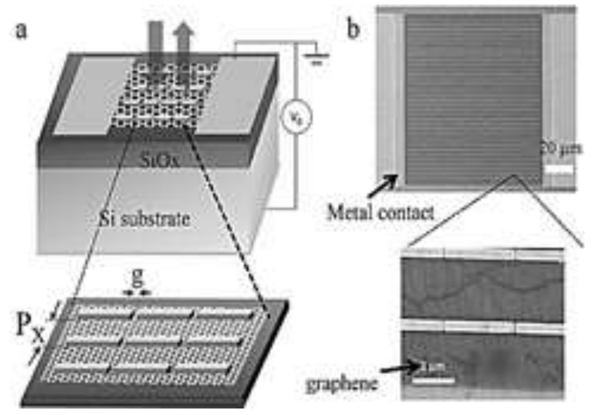

Fig.17: Array of nano-antennas a) An Si substrate b) A graphene and metal contains.

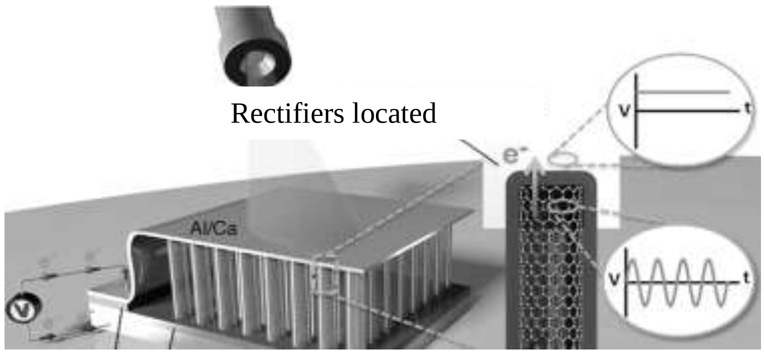

Fig.18: The scheme rectenna (rectifying antenna) as multi-layered carbon nanotubes and rectifier diodes [47].

Scientists at technology have developed a technology capable of capturing light and converting it into electrical energy. The rectenna (rectifying antenna) created not on its basis consists of multi-layered carbon nanotubes and rectifier diodes. When solar, or light from any other source gets to the antenna from the nanotubes, an alternating current arises in it, and the rectifiers located on it switching to ultrahigh frequencies convert the alternating current to direct current. To do this, researchers had to create an array of billions of carbon nanotubes located on a silicon substrate formed using plasma - chemical processes [47]. Each nanotube is an alumina insulator. The anode is an optically transparent layer of calcium and aluminium, which covers the entire array, as shown in Fig.18.

4. Conclusion

The unusual properties dimension measurements of biomolecules are illustrated of the nanotubes, and more studied applications in nanoelectronic fields are provided to proposed and analyzed. The use of nanotechnology in solving environmental problems of the future nano practical industry and materials science. Nanotubes come in very different shapes: single-layer and multi-layered, straight and spiral. In addition, they demonstrate a whole range of unexpected electrical, magnetic and optical properties such as displays combine the advantages of LCD displays and CRT screens based on modern fluorescent lamps. Prospects for the use of nanotechnology in the medicine biosensor, which with the same volume can be ten times stronger than biological ones, they are not afraid of high temperatures, vacuum and many chemical reagents as new bactericidal, antiviral agents and creation of nanorobots doctors. Then analyzed the direction of development of electrochemical sensors manufactured by these methods. They are creating smart materials that can change their structure depending on the environment depending value of Young's modulus for elastic in mechanical bending as a creation of a new generation of antennas for the transfer of huge amounts information and the development possibility of nanoparticles.

References

[1] S. Duan et al., “Formation of C60 fullerene-bonded-CNTs using radio frequency plasma,” RSC Adv., vol. 7, no. 34, pp. 21124–21127, 2017.

[2] D. Heltina, P. P. D. K. Wulan, and Slamet, “Photocatalytic activity of titania nanotube (tint)-carbon nanotube (CNT) composite for degradation of phenol,” in AIP Conference Proceedings, vol. 1840, no. 1, pp. 1-6, 2017.

[3] I. V Zaporotskova, N. P. Boroznina, Y. N. Parkhomenko, and L. V Kozhitov, “Carbon nanotubes: Sensor properties. A review,” Mod. Electron. Mater., vol. 2, no. 4, pp. 95–105, 2016.

[4] Hussein, F. H. et al. “Pharmaceutical Application of Carbon Nanotubes Synthesized by Flame Fragments Deposition Method, ” Journal of Environmental Analytical Chemistry, vol. 4, no. 4, 2018.

[5] R. Zhang, Y. Zhang, and F. Wei, “Horizontally aligned carbon nanotube arrays: growth mechanism, controlled synthesis, characterization, properties and applications,” Chem. Soc. Rev., vol. 46, no. 12, pp. 3661–3715, 2017.

[6] R. Ghaffari and R. A. Sauer, “Modal analysis of graphene-based structures for large deformations, contact and material nonlinearities,” J. Sound Vib., vol. 423, pp. 161–179, 2018.

[7] T. Bensattalah, K. Bouakkaz, M. Zidour, and T. H. Daouadji, “Critical buckling loads of carbon nanotube embedded in Kerr’s medium,” Adv. NANO Res., vol. 6, no. 4, pp. 339–356, 2018.

[8] A. Todoroki, K. Kumagai, and R. Matsuzaki, “Self-deployable space structure using partially flexible CFRP with SMA wires,” J. Intell. Mater. Syst. Struct., vol. 20, no. 12, pp. 1415–1424, 2009.

[9] E. Randjbaran, D. L. A. H. A. Majid, M. T. B. H. Sultan, N. Mazlan, and others, “Literature Review Paper on Mechanical Properties of Types of Carbon Nanotubes,” J. New Dev. Chem., vol. 1, no. 4, p. 27, 2018.

[10] X. Chen, R. Bao, J. Yi, D. Fang, J. Tao, and Y. Liu, “Enhancing Interfacial Bonding and Tensile Strength in CNT-Cu Composites by a Synergetic Method of Spraying Pyrolysis and Flake Powder Metallurgy,” Materials (Basel)., vol. 12, no. 4, p. 670, 2019.

[11] Z. Xiao et al., "Field electron emission characteristics and physical mechanism of individual single-layer graphene," ACS Nano, vol. 4, no. 11, pp. 6332–6336, 2010.

[12] J. W. Gadzuk and E. W. Plummer, "Field emission energy distribution (FEED)," Rev. Mod. Phys., vol. 45, no. 3, p. 487, 1973.

[13] M. Krüger, C. Lemell, G. Wachter, J. Burgdörfer, and P. Hommelhoff, "Attosecond physics phenomena at nanometric tips," J. Phys. B At. Mol. Opt. Phys., vol. 51, no. 17, 2018.

[14] Y. Feng and J. P. Verboncoeur, "A model for effective field enhancement for Fowler--Nordheim field emission," Phys. Plasmas, vol. 12, no. 10, 2005.

[15] S. Jessl et al., "Carbon nanotube conductive additives for improved electrical and mechanical properties of flexible battery electrodes," Mater. Sci. Eng. A, vol. 735, pp. 269–274, 2018.

[16] J. L. Shaw, J. B. Boos, B. D. Kong, J. T. Robinson, and G. G. Jernigan, "Field emission energy distribution and three-terminal current-voltage characteristics from planar graphene edges," J. Appl. Phys., vol. 125, no. 5, p. 54502, 2019.

[17] S. Li, Y. Liu, S. Zhou, C. Zhou, and M. Chan, "Contact resistance reduction of carbon nanotube via through O 2 plasma post-synthesis treatment," J. Mater. Chem. C, vol. 6, no. 18, pp. 5039–5045, 2018.

[18] N. Yu et al., "Characterization of the resistance and force of a carbon nanotube/metal side contact by nanomanipulation," Scanning, vol. 2017, 2017.

[19] E. Dujardin, T. W. Ebbesen, H. Hiura, and K. Tanigaki, "Capillarity and wetting of carbon nanotubes," Science, vol. 265, no. 5180, pp. 1850–1852, 1994.

[20] P. Keinänen et al., "Optimized dispersion quality of aqueous carbon nanotube colloids as a function of sonochemical yield and surfactant/{CNT} ratio," Heliyon, vol. 4, no. 9, 2018.

[21] Y. Wang, G. Colas, and T. Filleter, "Improvements in the mechanical properties of carbon nanotube fibers through graphene oxide interlocking," Carbon N. Y., vol. 98, pp. 291–299, 2016.

[22] L. Xiang, H. Zhang, Y. Hu, and L.-M. Peng, "Carbon nanotube-based flexible electronics," J. Mater. Chem. C, vol. 6, no. 29, pp. 7714–7727, 2018.

[23] Y. Chu, P. Gautreau, T. Ragab, and C. Basaran, "Strained phonon{\textendash}phonon scattering in carbon nanotubes," Comput. Mater. Sci., vol. 112, pp. 87–91, 2016.

[24] P. Prakash, K. M. Sundaram, and M. A. Bennet, "A review on carbon nanotube field effect transistors ({CNTFETs}) for ultra-low power applications," Renew. Sustain. Energy Rev., vol. 89, pp. 194–203, 2018.

[25] F. Obite, G. Ijeomah, and J. S. Bassi, "Carbon nanotube field effect transistors: toward future nanoscale electronics," Int. J. Comput. Appl., vol. 41, no. 2, pp. 149–164, 2018.

[26] K. Xia, H. Zhan, and Y. Gu, "Graphene and Carbon Nanotube Hybrid Structure: A Review," Procedia {IUTAM}, vol. 21, pp. 94–101, 2017.

[27] J. M. Kim, W. B. Choi, N. S. Lee, and J. E. Jung, "Field emission from carbon nanotubes for displays," Diam. Relat. Mater., vol. 9, no. 3, pp. 1184-1189 2000.

[28] Y. Zhou and R. Azumi, "Carbon nanotube based transparent conductive films: progress, challenges, and perspectives," Science and Technology of Advanced Materials, vol. 17, no. 1, 2016.

[29] A. N. Abood, I. A. Mahmood, E. E. Kader, "Effect of Carbon Nanotube on Damping Characteristic of Epoxy Polysulfide Blend Composite," Engineering and Technology Journal ,vol. 34, no. 1, pp. 73-84, 2016.

[30] H. A. Hussian, K. S. Hassan, and M. K. Ismeal, "Corrosion Behavior of Nanocomposite Al-9 wt% Si Alloy Reinforced with Carbon Nanotubes," Al-Khwarizmi Engineering Journal,vol. 13, no. 1, pp. 66-73, 2017.

[31] J. E. Jung et al., “Fabrication of triode-type field emission displays with high-density carbon-nanotube emitter arrays,” Phys. B Condens. Matter, vol. 323, no. 1–4, pp. 71–77, 2002.

[32] J. Tang et al., “Rapid and reproducible fabrication of carbon nanotube AFM probes by dielectrophoresis,” Nano Lett., vol. 5, no. 1, pp. 11–14, 2005.

[33] Q. Huang et al., “Ultraviolet/ozone and oxygen plasma treatments for improving the contact of carbon nanotube thin film transistors,” Sci. Bull., vol. 63, no. 12, pp. 802–806, 2018.

[34] D. Liao, W. Chen, J. Zhang, and Y. Yue, “Tuning thermal conductance of CNT interface junction via stretching and atomic bonding,” J. Phys. D. Appl. Phys., vol. 50, no. 47, p. 475302, 2017.

[35] J. H. Kim, J. S. Kang, and K. C. Park, “Fabrication of Stable Carbon Nanotube Cold Cathode Electron Emitters with Post-Growth Electrical Aging,” Micromachines, vol. 9, no. 12, p. 648, 2018.

[36] X. Yuan et al., “A truncated-cone carbon nanotube cold-cathode electron gun,” Carbon N. Y., vol. 120, pp. 374–379, 2017.

[37]] A. A. Yazdi, L. D’Angelo, N. Omer, G. Windiasti, X. Lu, and J. Xu, “Carbon nanotube modification of microbial fuel cell electrodes,” Biosens. Bioelectron., vol. 85, pp. 536–552, 2016.

[38] O. Rahman, F. Obite, and G. Ijeomah, “Development of carbon nanotube-based biosensors,” Int. J. Nano Biomater., vol. 6, no. 2, p. 83, 2016.

[39] M. Sireesha, V. J. Babu, A. S. K. Kiran, and S. Ramakrishna, “A review on carbon nanotubes in biosensor devices and their applications in medicine,” Nanocomposites, vol. 4, no. 2, pp. 36–57, 2018.

[40] L. Su, “Carbon Nanotube-Based Biosensors,” in Carbon Nanotubes and Their Applications, Pan Stanford, pp. 368–427.

[41] M. Bottini, N. Rosato, and N. Bottini, “PEG-Modified Carbon Nanotubes in Biomedicine: Current Status and Challenges Ahead,” Biomacromolecules, vol. 12, no. 10, pp. 3381–3393, 2011.

[42] S. Gupta, C. N. Murthy, and C. R. Prabha, “Recent advances in carbon nanotube based electrochemical biosensors,” Int. J. Biol. Macromol., vol. 108, pp. 687–703, 2018.

[43] J. Xie et al., “Theoretical study of extended interaction frequency-locking oscillator based on carbon nanotube cold cathodes,” IET Microwaves, Antennas Propag., vol. 12, no. 11, pp. 1771–1774, 2018.

[44] Y. Yang, L. Ding, H. Chen, J. Han, Z. Zhang, and L.-M. Peng, “Carbon nanotube network film-based ring oscillators with sub 10-ns propagation time and their applications in radio-frequency signal transmission,” Nano Res., vol. 11, no. 1, pp. 300–310, 2017.

[45] V. Mahore and Namrata Sahayam, “A REVIEW ARTICLE ON DIELECTRIC RESONATOR NANO ANTENNA,” Int. J. Eng. Sci. Res. Technol., 2018.

[46] J. Xie et al., “Simulation of extended interaction oscillator based on carbon nanotube cold cathode,” in 2017 10th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies ({UCMMT}), 2017.

[47] I. Puchades, J. E. Rossi, C. D. Cress, E. Naglich, and B. J. Landi, “Carbon nanotube thin-film antennas.,” ACS Appl. Mater. Interfaces, vol. 8, no. 32, pp. 20986–20992, 2016.