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Carbon Nanotubes and Its Applications: A Review

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***Abstract*— Carbon nanotubes also known as CNTs are allotropes of carbon with a tubular nanostructure, having diameters ranging from less than 1 nanometre (nm) up to 50 nm. CNTs have extraordinary electrical, mechanical, optical, thermal and chemical properties. These properties make them potentially useful in the fields of nanotechnology, bio-medical sciences, pharmacology, instrumentation and various other industrial applications. Nanotubes are characterised as single walled or multi walled. Various techniques such as arc discharge, laser ablation, and chemical vapour deposition (CVD) have been developed for the economic synthesis of CNTs in sizeable quantities. They are still a subject of research and possess immense potential. Overall, recent studies regarding nanotubes reveal a very promising sight of what lies ahead in the fields of nanotechnology and medicine.**
***Keywords*— Carbon nanotubes, Single and multiple walled nanotubes, Nano-electronics, Buckminsterfullerene, Orientation.**

I. INTRODUCTION

During the last few years there has been the discovery, development, and large scale manufacturing and production of innovative materials that lie within the nanometer scale. Such nanomaterial's consist of organic or inorganic matter and in most cases have never been studied in the context of nano-sciences and pharmaceuticals. Carbon nanotubes (CNTs) are one of them. In 1991, Sumio Iijima of NEC 'discovered' carbon nanotubes, which are effectively long, thin cylinders of graphite, which is the material in a pencil and found in some lubricants. They can be thought of as a sheet of graphite (a hexagonal lattice of carbon) rolled into a cylinder. The structure of graphite is made up of layers of carbon atoms, known as graphene, arranged in a hexagonal lattice, resembling a chicken wire (see Fig. 1). These graphene layers are individually very strong, but are held together by weak van der Waals forces because of which they are capable of sliding over each other that provides graphite its lubricating properties.

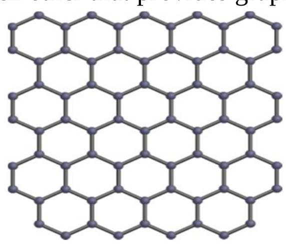
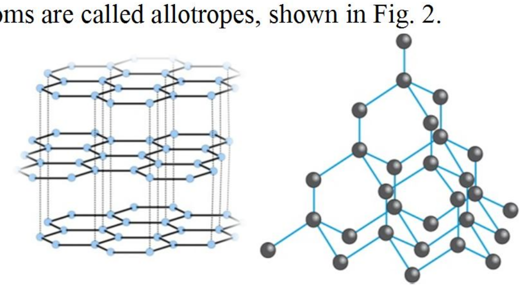


Fig. 1 Graphene

II. BACKGROUND LEADING UP TO CARBON NANOTUBES

Till the mid-1980s, pure solid carbon was thought to be in two physical forms, diamond and graphite. These two forms have different physical properties and structures, however, their atoms are held against each other by covalently bonded networks. These two different physical forms of carbon atoms are called allotropes, shown in Fig. 2.



(a) (b)
Fig. 2 Graphite, (b) Diamond

In 1985, an interesting discovery was made by a group of researchers led by Richard Smalley and Robert Curl of Rice University in Houston and Harry Kroto of the University of Sussex in England. They performed an experiment by vaporizing a sample of graphite with a short and acute pulse of laser light and used a stream of helium gas to deliver the vaporized carbon into a mass spectrometer. The mass spectrum displayed peaks corresponding to clusters of carbon atoms, with a particularly strong peak corresponding to molecules composed of 60 carbon atoms, C_{60}.

The fact that C_{60} clusters were so easily formed led the group to propose that a new form or allotrope of carbon had been discovered. It was exactly like a soccer ball, spherical in shape and with 32 faces out of which 12 were pentagons and 20 were hexagons.

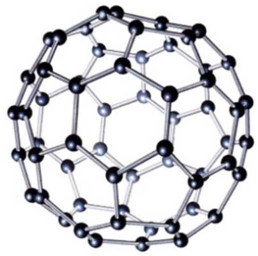


Fig. 3 Buckminsterfullerene

These molecules were named after an architect, Buckminster Fuller, who designed the first geodesic domes. The soccer ball shaped C_{60} molecule was named "buckminsterfullerene". After this discovery, other related molecules (C_{36}, C_{70}, C_{76} and C_{84}) composed of only carbon atoms were also discovered, and they and the buckminsterfullerene were recognized as the new allotropes of carbon. This new class of carbon molecules is called the fullerenes.

Fullerenes consist of hexagons and pentagons that combine to form a spherical shape. Fullerenes have also been proposed as possible HIV inhibitors as well as potential constituents in interstellar space. The unique geometric properties of this new allotrope of carbon did not end with soccer shaped molecules, it was also discovered that carbon atoms can form long cylindrical tubes. These tubes are known as carbon nanotubes or CNTs for short.

III. WHAT IS SO SPECIAL ABOUT CARBON NANOTUBES?

Carbon nanotubes (CNTs) are tubular cylinders of carbon atoms that exhibit extraordinary electrical, mechanical, optical, thermal and chemical properties. The individual tubes possess unique structures that have 200 times the strength and 5 times the elasticity of steel. They can conduct heat as efficiently as most diamond (only diamond grown by deposition from a vapour is better), conduct electricity as efficiently as copper, yet also be semiconducting (like the materials that make up the chips in our computers). They are capable of producing streams of electrons efficiently (field emission), which can be utilized to create light in televisions or computers displays, even in domestic lighting. Application of mechanical stress or the presence of certain substances can alter their electrical properties. As a carbon based product, CNTs have almost none of environmental or physical degradation issues common to metals— corrosion, thermal expansion and contraction, and sensitivity to radiation— which result in greater system failures in performance-sensitive applications in aerospace and defence, automotive, aviation, energy and consumer products.

IV. NANOTUBE GEOMETRY

Nanotubes can exist having single walls or multiple walls (cylinders inside other cylinders of carbon). Carbon nanotubes have a range of electric, thermal, and structural properties that can change based on the physical design of the nanotube.

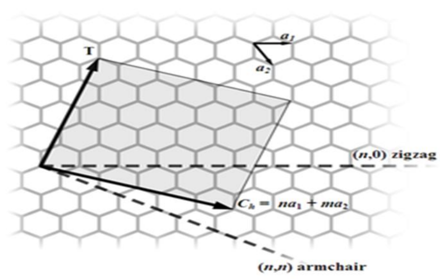


Fig. 4 The (n,m) nanotube naming scheme can be thought of as a vector (C_h) in an infinite graphene sheet that describes how to

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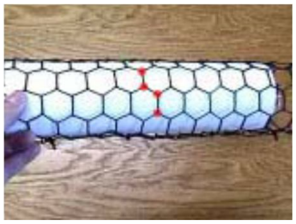
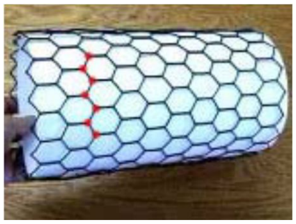
"roll up" the graphene sheet to make the nanotube. T denotes the tube axis, and a_1 and a_2 are the unit vectors of graphene in real space.

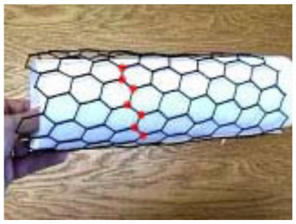
Single-walled carbon nanotubes can be formed in three different designs: Armchair, Chiral, and Zigzag. The design depends on the way the graphene is wrapped into a cylinder. A single-walled nanotube structure is depicted by a pair of indices (n,m) known as chiral vector. The integers n and m denote the number of unit vectors along two directions in the honeycomb crystal lattice of 560rapheme. If m = 0, the nanotubes are called zigzag nanotubes, and if n = m, they are called armchair nanotubes. Else, they are called chiral.



(a)



(b)



(c)

Fig. 5 (a) Armchair arrangement of carbon atoms, (b) Zigzag arrangement of carbon atoms, (c) Chiral arrangement of carbon atoms

V. CLASSIFICATION OF CARBON NANOTUBES

Carbon nanotubes are classified in following two types:

A. Single-Walled Carbon Nanotubes (SWNTs)

As previously mentioned, they are tubes of graphite and are usually capped at the ends (see Fig. 6), although the caps can be eliminated. CNTs typically have diameters ranging from less than a nanometer (nm) up to 50 nm. Average diameters tend to be around the 1.2 nm mark, which depends on the process used to synthesize them.

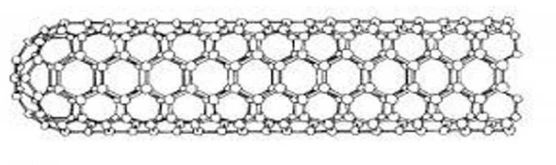


Fig. 6 SWNT capped at one end

As previously mentioned, they can be conducting, like metal (such nanotubes are often referred to as metallic nanotubes), or semiconducting, which means that the flow of current through them can be stepped up or down by varying an electrical field. The latter property has given rise to dreams of using nanotubes to make extremely dense electronic circuitry and the last years has seen major advances in creating basic electronic structures from nanotubes in the lab, from transistors up to simple logic elements.

B. Multi-Walled Carbon Nanotubes (MWNTs)

There are two structural models of multi-walled nanotubes— Russian Doll model and Parchment model. In the Russian Doll model, a carbon nanotube contains another nanotube inside it (the inner nanotube has a smaller diameter than the outer nanotube). In the Parchment model, a single graphene sheet is rolled around itself multiple times, resembling a rolled up scroll of paper. Multi-walled carbon nanotubes have similar properties to single-walled nanotubes, yet the outer walls on multi-walled nanotubes can protect the inner carbon nanotubes from chemical interactions with outside materials. Multi-walled nanotubes also have a higher tensile strength than single-walled nanotubes.

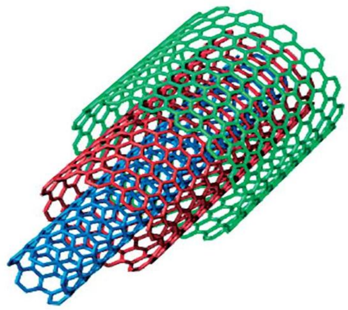


Fig. 7 MWNT

VI. PROPERTIES

A. Strength

Carbon nanotubes are the strongest and one of the most rigid materials yet discovered in terms of tensile strength and elastic modulus respectively. This strength is due to the covalent sp^2 bonds existing between the individual carbon atoms. In the year 2000, a multi-walled carbon nanotube was studied to have a tensile strength of 63 GPa (9,100,000 psi). Further studies, such as one conducted in 2008, revealed that individual CNT shells have strengths of up to ~100 GPa (15,000,000 psi), which is in agreement with quantum/atomistic models. Since carbon nanotubes possess a low density for a solid of 1.3 to 1.4 g/cm^3, its specific strength of up to 48,000 $kN{\cdot}m{\cdot}kg^{-1}$ is the best of known materials, in contrast to high-carbon steel's 154 $kN{\cdot}m{\cdot}kg^{-1}$.

B. Hardness

Standard single-walled carbon nanotubes can stand a pressure up to 25 GPa without getting deformed. They then undergo a transformation to super hard phase nanotubes. Maximum pressures measured using current experimental techniques are around 55 GPa. However, these new super hard phase nanotubes collapse at an even higher, albeit unknown, pressure.

The bulk modulus of super hard phase nanotubes is 462 to 546 GPa, even higher than that of diamond (420 GPa for single diamond crystal).

C. Kinetic Properties

Multi-walled nanotubes are multiple concentric nanotubes nested within one another. They show a striking telescoping property wherein an inner nanotube core may slide, almost without friction, within its outer nanotube shell, thereby creating an atomically perfect linear or rotational bearing. This is one of the first true examples of molecular nanotechnology, the precise positioning of atoms to create useful machines. This property has already been utilized to create the world's smallest rotational motor. Future applications such as a gigahertz mechanical oscillator are also proposed.

D. Electric Properties

When the structure of atoms in a carbon nanotube minimizes the collisions between conduction electrons and atoms, a carbon nanotube is highly conductive. The strong bonds between carbon atoms also allow carbon nanotubes to withstand higher electric currents than copper. Electron transport occurs only along the axis of the tube. Single walled nanotubes can direct electrical signals at speeds up to 10 GHz when used as interconnects on semi-conducting devices.

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E. Thermal Properties

Due to the strength of the atomic bonds in carbon nanotubes, they can withstand high temperatures. Because of this property, carbon nanotubes have shown to be excellent thermal conductors. When compared to copper wires, which are commonly used as thermal conductors, the carbon nanotubes can transmit over 15 times the amount of watts per meter per Kelvin. The thermal conductivity of carbon nanotubes is dependent on the temperature of the tubes and the outside environment.

VII. SYNTHESIS

A. Arc Discharge

Arc discharge was the first recognized technique for producing MWNTs and SWNTs. The arc discharge technique generally involves the use of two high-purity graphite electrodes as the anode and the cathode. The electrodes are vaporized by passing a DC current (~100 A) through the two high-purity graphite separated (~ 1–2 mm) in 400 mbar of Helium atmosphere. Experimental set up of arc discharge apparatus is shown in Fig. 8. After conducting this process for a period of time, a carbon rod is deposited at the cathode. This method can mostly produce MWNTs but can also produce SWNT with the addition of metal catalyst such as Fe, Ni, Co, Mo or Y, on either the anode or the cathode. The quantity and quality such as lengths, diameters, purity and etc. of the nanotubes obtained depend on varied parameters such as the inert gas pressure, metal concentration, type of gas, plasma arc, temperature, the current and system geometry. The yield for this method is up to 30% by weight and it produces both single- and multi-walled nanotubes with lengths of up to 50 micrometers with few structural defects.

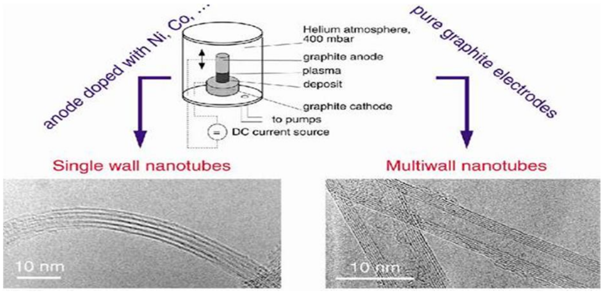

Fig. 8 Arc discharge method

B. Laser Ablation

In the laser ablation technique, a high power laser is used to vaporize carbon from a graphite specimen at high temperature. Both MWNTs and SWNTs can be produced with this technique. In order to generate SWNTs, metal particles as catalysts must be added to the graphite targets similar to the arc discharge technique. Several factors such as the amount and type of catalysts, laser power and wavelength, type of inert gas, temperature, pressure, and the fluid dynamics near the carbon specimen determine the quantity and quality of produced carbon nanotubes. Schematic diagram of the laser ablation apparatus is shown in figure 9. The laser is focused onto a carbon targets containing 1.2 % of cobalt/nickel with 98.8 % of graphite composite that is placed in a 1200°C quartz tube furnace in an atmosphere of argon (~500 Torr). In this technique, argon gas carries the vapours from the high temperature chamber into a cooled collector positioned downstream. The nanotubes then self-assemble from carbon vapours and condense and get deposited on the walls of the flow tube. Carbon nanotubes synthesized by this method are purer (up to 90 % purity) than those produced in the arc discharge process and have a very narrow distribution of diameters.

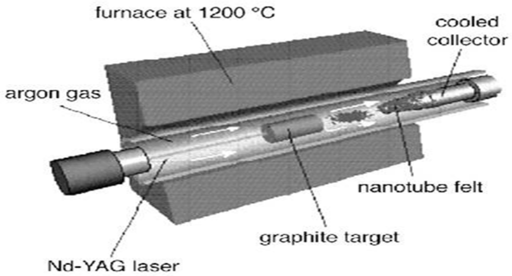

Fig. 9 Laser ablation method

C. Chemical Vapour Deposition (CVD)

Chemical vapour deposition (CVD) technique was initially reported to produce MWNTs. Some years later, CO-based CVD produced SWNTs successfully. CVD technique is achieved by taking a carbon source in the gas phase and using an energy source, such as a resistively heated coil or plasma, to carry energy to a gaseous carbon molecule. This process uses hydrocarbons as the carbon sources including methane, carbon monoxide and acetylene. The hydrocarbons flow through the quartz tube being in an oven at a high temperature (~ 720 C). Schematic diagram of the chemical vapour deposition apparatus is shown in figure 10. At high temperature, the hydrocarbons consisting of hydrogen-carbon bonds are broken down to produce pure carbon molecules. Then, the carbon diffuses toward the substrate, which is heated and coated with a catalyst (usually a first row transition metal such as Fe, Ni, or Co) where it binds. Carbon nanotubes are formed if the proper parameters are maintained. The advantages of the CVD process were low power input, relatively high purity, lower temperature range, and most importantly, possibility to scale up the process. Both MWNTs and SWNTs can be produced by this method, depending on the temperature, in which production of SWNTs will occur at a higher temperature than MWNTs.

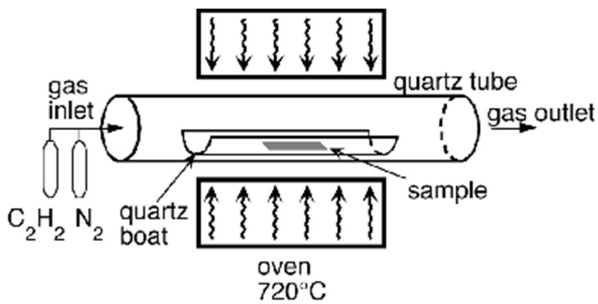

Fig. 10 Chemical vapour deposition

VIII. POTENTIAL APPLICATIONS

Carbon nanotubes have numerous potential applications ranging from waterproof and tear resistant cloth fabrics, to concrete and steel like applications (a space elevator has even been proposed) based on the property of strength, electrical circuits based on the property of electrical conductivity, sensors based on the property of thermal conductivity, vacuum proof food packaging, and even as a vessel for delivering drugs.

A. Nano-Electronics

One of the most significant potential applications of single-walled nanotubes is believed to be in the domain of nano-electronics. This is due to the high conductivity of SWNTs. In fact, single-walled nanotube ropes are the most conductive carbon fibres known. Alternative configurations of a carbon nanotube can result in the resultant material being semi-conductive like silicon. Conductivity in nanotubes is a result of the degree of chirality – i.e. the degree of twist and size of the diameter of the actual nanotube - which results in a nanotube that is extremely conductive (making it suitable as an interconnect on an integrated circuit) or non-conductive (making it suitable as the basis for semi-conductors).

B. Cancer Treatment

The nanotubes might be the future of cancer treatment one day. In a recent study, researchers injected carbon nanotubes into kidney tumours in mice, and then aimed a near-infrared laser at the tumours. The tubes responded to the laser pulse by vibrating, and creating enough heat to kill surrounding malignant cells. This research on mice revealed that the tumours shrank and completely disappeared in 80% of the mice. The procedure didn't appear to harm the animals' internal organs, besides leaving only a slight burn on the skin. But it hasn't been fully proven that nanotubes are safe and non-toxic, and therefore more research must be done before such procedures are ready to be tested on humans.

C. Chemical Sensor

The presence of certain gases such as NO_2 and NH_3 change the conductance of semiconducting carbon nanotubes to large extent in comparison to conventional sensors, therefore carbon nanotubes provide the advantages of increased sensitivity, faster response and smaller size.

D. NanoThermometer

A carbon nanotube can be partly filled with gallium metal. Changing the temperature makes the gallium metal to expand or contract to fill or empty the carbon nanotube. The gallium level in the carbon nanotube varies proportionally with temperature.

E. Scanning Probe Tips

Due to their flexibility, carbon nanotubes can be used in scanning probe instruments. The flexibility of the nanotubes prevents damage to the sample surface and also the probe tip if it happens to crash into the surface. Moreover, a better image resolution is achieved in contrast to that observed using standard nanoprobes.

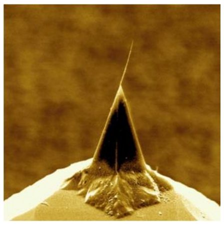

Fig. 11 CNT on a cantilever tip

F. Field Effect Transistors

It is known that a carbon nanotube can be metallic or semiconducting tube depending on the cylinder’s diameter. The semiconducting nanotubes can be used to construct molecular field-effect transistors (FETs) while metallic nanotubes can be used to construct single-electron transistors. The carbon nanotube FETs consist of a semiconducting carbon nanotube about 1 nm in diameter bridging two closely separated metal electrodes on top of a silicon surface layered with SiO_2. Application of an electric field to the gate electrode controls the movement of charge carriers onto it which turns on and off the flow of the current across the nanotube.

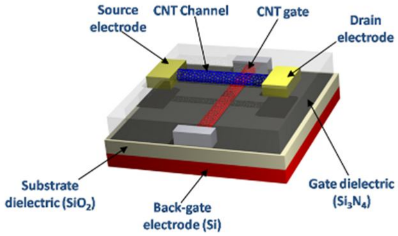

Fig. 12 Carbon nanotube based field effect transistors

G. Field emission display

When a nanotube is put into an electric field, it can emit electrons like a small cannon. If these electrons are bombarded on a phosphor screen then an image can be formed. Carbon nanotube screens are advantageous over liquid crystal displays (LCD) owing to their low power consumption, wider viewing angle, fast rate response, intense brightness, and a wider operating temperature range.

Fig. 13 CNT field emission lamps arrayed in a 5-by-7 matrix

IX. CURRENT HURDLES

There are several obstacles, technical and non-technical to the success of CNTs. A couple of the major impediments are discussed as follows.

A. Electronic Heterogeneity

One problem with nanotube production for electronics is that batches of nanotubes are heterogeneous mixtures of metallic and semiconducting tube types. Electrical devices typically require these types to be separated, but so far it has been difficult to tune production in this regard. There also remain issues with doping, or tuning conductivity, and electrical behaviour at contact points.

B. Orientation

A problem with nanotubes where recent progress has been made is controlling their orientation. Nanotubes are commonly grown in a chaotic organization, which are difficult to use in microprocessors.

X. ENVIRONMENTAL CONCERNS

The environmental risks of nanotubes are still unclear. Carbon, which is naturally occurring, is fairly benign, and is largely unregulated, but nanotubes interact with the environment differently. Several studies have been performed to test the effects of CNTs on living systems.

Fruit fly larvae fed a diet containing nanotubes appeared to develop normally.

One study showed that CNTs delay embryo development in zebra fish, but the fish otherwise appeared normal.

Mice lungs became inflamed when exposed to nanotubes. Though the inflammation subsided within a few months, this has stark parallels to the affect of asbestos on human lungs.

Some human tumour cells seem to proliferate more rapidly in the presence of nanotubes.

In some situations, coatings applied to the nanotubes, rather than the nanotubes themselves, may become environmental hazards. The solar cells produced using CNTs are coated with a cadmium-telluride mix, which could be too toxic for widespread use. Perhaps most sobering to consider is that some forms of nanotubes biodegrade slowly, tubes released into the environment may make their way into our food supply, and from there, throughout our bodies. It is believed by some researchers that nanotube use in electronics is probably not very risky because of the small volumes involved, but this argument hinges on computing being limited to small numbers of devices.

More investigations and regulations are being conducted. One possibility is treating nanotubes as a new chemical, rather than as an isoform of Carbon. Another approach is to adjust regulations on toxic exposures to take into account the number of particles in an exposure or their surface area, as opposed to the mass. However, there is a silver lining. CNTs also hold promise for cleaning up polluted environments. Nanotubes are very effective at absorbing chemicals from their surroundings and have possible applications in water filtration and in air filters, such as smokestacks.

XI. CONCLUSIONS

Nanotechnology is an ever growing field and CNTs possess properties which may completely revolutionize its study and applications, and of various other fields as well. Researchers are looking for ways for the economic and sizeable synthesis of CNTs. Also, the effect of CNTs on living beings and the environment may be a matter of concern. Overall, the immense potential possessed by this substance shows a very promising sight of what lies ahead in the future of nanotechnology and medicine.

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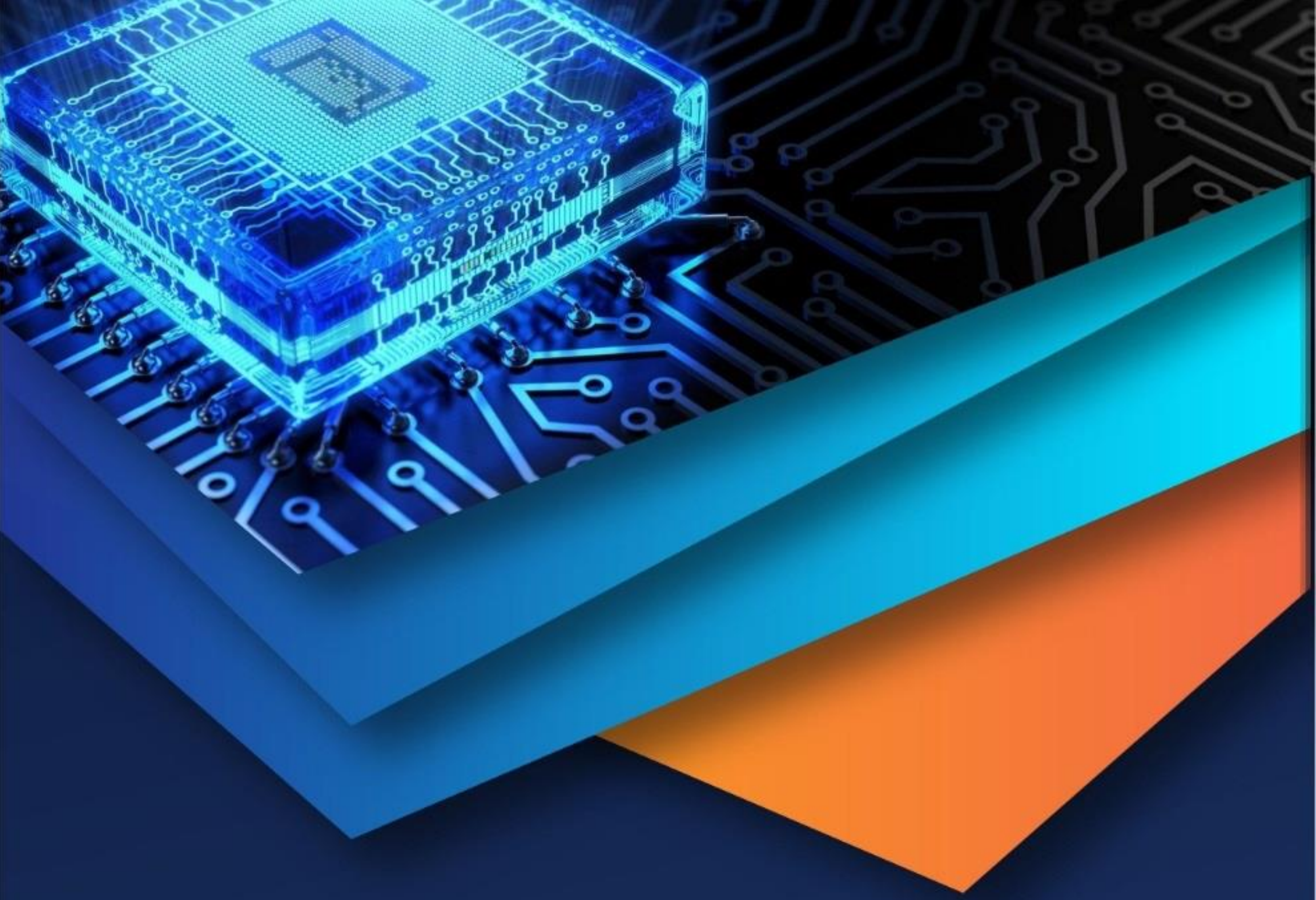

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