



CODEN [USA]: IAJPBB

ISSN: 2349-7750

**INDO AMERICAN JOURNAL OF  
PHARMACEUTICAL SCIENCES**<http://doi.org/10.5281/zenodo.1484422>Available online at: <http://www.iajps.com>**Review Article****A REVIEW ON FULLERENE EARTH****Athira.A.S, S.M.Sandhya, A.S William Arputha Sundar**  
Sree Krishna College of Pharmacy & Research Centre, Parassala**Abstract:**

*A fullerene is an allotrope of carbon in the form of a hollow sphere or in many other shapes. Spherical fullerenes are also referred to as Buckminster fullerenes or buckyballs. Cylindrical fullerenes are also called as buckey tubes. Fullerenes composed of less than 300 carbon atoms, or endohedral fullerenes, are commonly known as "buckyballs" and include the most common fullerene, buckminsterfullerene, C<sub>60</sub>. Giant fullerenes, or fullerenes with more than 300 carbon atoms, include single-shelled or multi-shelled carbon structures, onions, and nanotubes. The first buckminster-fullerene C<sub>60</sub> was actually discovered in 1985. It seems to be that the history of fullerenes research is very short. However it now has become clear that fullerenes exist much longer than mankind. They have been found in interstellar dust and meteor rocks and seem to be present everywhere in the universe. So one might be astonished that their discovery took that long. But since then fullerene research skyrocketed in a way that may only be compared with the field of high temperature superconductivity.*

**Corresponding author:****Athira.A.S,**  
Sree Krishna College of Pharmacy & Research Centre,  
Parassala  
E-Mail:[sudhagopanathi@gmail.com](mailto:sudhagopanathi@gmail.com)

Please cite this article in press Athira.A.S et al., **A Review on Fullerene Earth.**, *Indo Am. J. P. Sci*, 2018; 05(11).

**INTRODUCTION:**

Carbon, the basis of life, is one of the most common elements and one of the most studied. It comprises the whole discipline of organic chemistry. A study of pure carbon would not seem all that exciting to most chemists. However, for British chemist Harry Kroto and the colleagues he enlisted in his research, a study into carbon molecules led to the discovery of a previously unknown, all-carbon molecule known today as a fullerene.

Harry Kroto, an organic chemist in the University of Sussex in the United Kingdom, became fascinated with various "peculiar" aspects of carbon chemistry. He also was interested in astrochemistry, the makeup of space and celestial bodies in the universe. Kroto wanted to investigate the origins of the long linear carbon chain molecules he and Canadian scientists had discovered in interstellar space. He hypothesized that these unusual, long, flexible molecules had been created in the atmospheres of carbon-rich red giant stars, and he wanted to test this theory. But carbon, one of the most common elements, was already one of the most studied.

At first, it was difficult for Kroto to find support for his research. At a conference in 1984, Kroto met his friend Robert Curl, an American chemist who was working with colleague Richard Smalley at Rice University in Houston, Texas, to study atom clusters using a special instrument called an AP2 ("apptwo"), the machine helps scientists study clusters of any element. The three scientists, aided by graduate students Sean O'Brien, James Heath and Yuan Liu, conducted the study. The students ran the AP2 with Kroto directing the experiments. Within days, two significant results emerged from the experiments: First, the team found the long carbon chains in Kroto's hypothesis. Second, the scientists observed a previously unknown molecule of pure carbon.

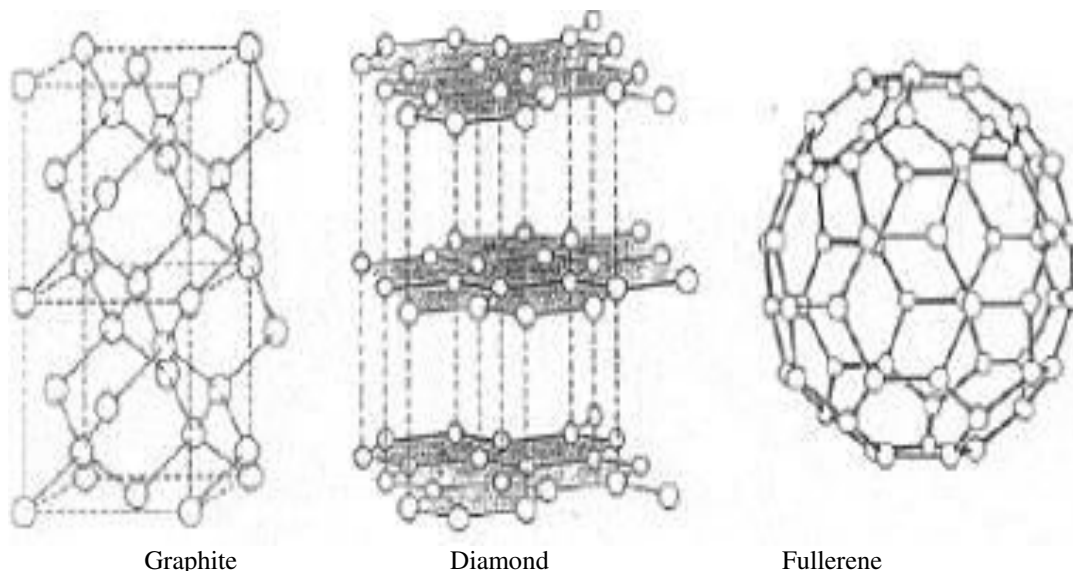
Using a mass spectrometer (a device used to determine the mass and molecular composition of molecules), the students noticed something remarkable: an odd indication of a molecule containing sixty carbon molecules. The molecule,

C<sub>60</sub>, formed very readily and exhibited extraordinary stability. All known carbon-containing molecules, even benzene, a very stable ring of carbon atoms, have edges that terminate with other elements. But C<sub>60</sub> was inert it did not need hydrogen, or any other element, to tie up its bonds.

The scientists were stumped at first by the stable, 60-carbon molecule that did not react with other molecules, which suggested it had no dangling bonds. Then they decided to find out the structure. The team considered two candidates for the structure of C<sub>60</sub>: a flatlander model where carbon was stacked in hexagonal sheets, with the dangling bonds tied up in some fashion; or a spherical form where the hexagonal graphite sheet curled around and closed. A spherical structure would have no dangling bonds.

At some point Buckminster Fuller, an American architect known for designing spherical structures called geodesic domes was mentioned. Kroto recalled Fuller's architecture from a visit to the 1967 World Exposition in Montreal. At first, some scientists were skeptical of the team's discovery. With carbon being so well studied, few imagined that new all-carbon structures would be possible. However, by the late 1980's, further proof of the existence of fullerenes made acceptance widespread. In 1996, Curl, Kroto and Smalley received the Nobel Prize in Chemistry for their discovery of fullerenes. Research on fullerenes has resulted in the synthesis of more than a thousand new compounds. The discovery of fullerenes also led to research in carbon nanotubes, the cylindrical cousins of buckyballs.

Research on fullerenes has resulted in the synthesis of more than a thousand new compounds. The discovery of fullerenes also led to research in carbon nanotubes, the cylindrical cousins of bucky balls. six crystalline forms of the element carbon were known, namely two kinds of graphite, two kinds of diamond, chaoit and carbon. The latter two were discovered in 1968 and 1972. Fullerenes are the third allotropic form of carbon material after graphite and diamond.



When fullerene was first discovered, there was much excitement about practical applications. It was speculated that buckyballs would make great lubricants, rolling like little ball bearing between other molecules. Or perhaps drugs could be trapped inside the cages, and then released slowly by a triggering mechanism that could break open the cages inside the body.

$C_{60}$  is a molecule that consists of 60 carbon atoms, arranged as 12 pentagons and 20 hexagons. The shape is the same as that of soccer ball: the black piece of leather are the pentagons, the hexagons are white. There are 60 different points where three of the leather patches meet. Imagine a carbon atom sitting at each of these points, and you have a model of the  $C_{60}$  molecule. That model, however, is vastly out of the scale and if the  $C_{60}$  molecules were the size of a soccer ball in turn would be roughly the size of the earth. The most striking property of the  $C_{60}$  molecule is its high symmetry. There are 120 symmetry operations, like rotations around an axis or reflections in a plane, which map the molecule onto itself. This makes  $C_{60}$  the molecule with the largest number of symmetry operations, the most symmetric molecule. Based on a theorem of the mathematician Leonhard Euler, one can show that a spherical surface entirely built up from pentagons and hexagons must have exactly 12 pentagons. Depending on the number of hexagons, molecules of different sizes are obtained. They are called fullerenes. Fuller are based on hexagons and pentagons. Fullerenes are a class of closed-cage carbon molecule,  $C_n$ , characteristically containing 12 pentagons and a variable number of hexagons.

$$\text{Hexagons} = (\text{carbon atoms}) - 20/2$$

Fullerenes composed of less than 300 carbon atoms, or endohedral fullerenes, are commonly known as “buckyballs” and include the most common fullerene, buckminsterfullerene,  $C_{60}$ . Giant fullerenes, or fullerenes with more than 300 carbon atoms, include single-shelled or multi-shelled carbon structures, onions, and nanotubes.

#### Chemistry of fullerene

The  $C_{60}$  surface contains 20 hexagons and 12 pentagons. All the rings are fused, all the double bonds are conjugate. Initially hypothesized as a ‘super aromatic’ molecule, carbon was rather found to possess a polyenic structure, with all the double bonds inside the six-membered rings. X-Ray crystal structure determinations on  $C_{60}$  and on some of its derivatives have proved the existence of two different types of bonds: ‘short bonds’ or 6,6 junctions, shared by two adjacent hexagons (1.38 Å long) and ‘long bonds’, or 5,6 junctions, fusing a pentagon and a hexagon (1.45 Å long). The geometric demand of the spherical cage is such that all the double bonds in  $C_{60}$  deviate from planarity.

This pyramidalization of the  $sp^2$  hybridized carbon atoms confers an excess of strain to  $C_{60}$  which is responsible for the enhanced reactivity of the fullerene. A release of strain is in fact associated with the change of hybridization from  $sp^2$  to  $sp^3$  that accompanies most chemical reactions. The chemical reactivity of  $C_{60}$  is typical of an electron deficient olefin.  $C_{60}$ , in fact, reacts readily with nucleophiles and is a reactive 2p component in cyclo additions.

The vast majority of reactants will attack the 6,6 ring junctions of  $C_{60}$ , which possess more electron density. Insertions into 5,6 bonds have been reported only as rearrangements following a 6,6 junction attack. The main objective of fullerene chemistry is the production of well-defined, stable and characterizable adducts. Adducts can be obtained by careful hydrogenation ( $Nu=E=H$ ), or by addition of a nucleophile followed by quenching with acid or an electrophile.

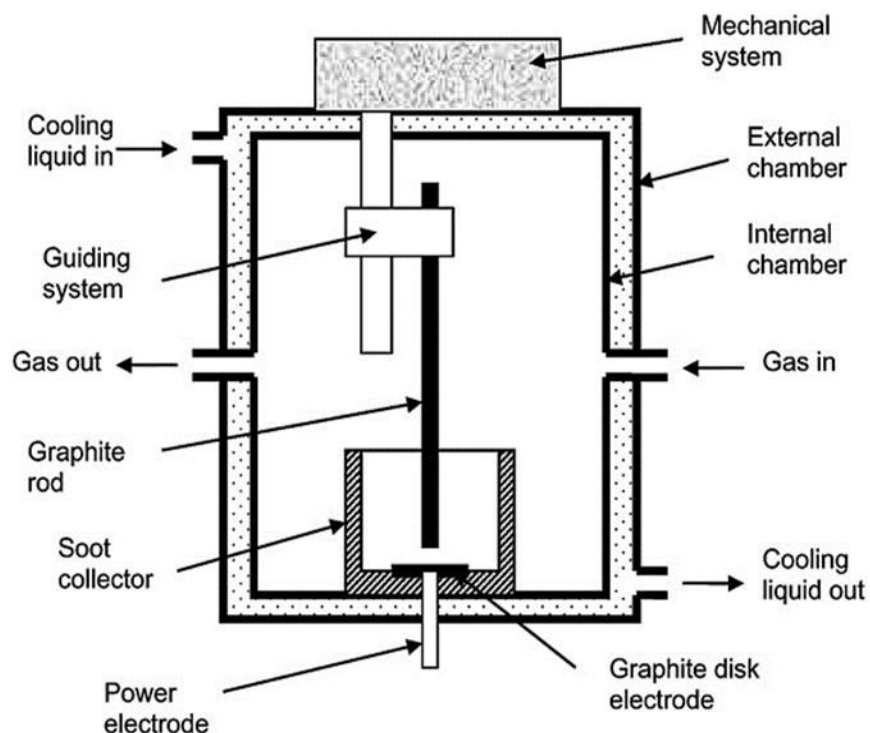
### Production

The arc discharge method developed by Kratschmer's group in 1990 remains until now the major tool for synthesizing fullerenes. Several works have been done for the macroscopic production of the fullerenes by using other different techniques, laser ablation, electron beam evaporation, heat resistive method, diffusion flame and ion beam sputtering.

It is generally accepted that the fullerenes and carbon nanotubes are formatted in special conditions: at a very high temperature (a laser beam or an electric arc discharge evaporation of graphite) and in an inert gas atmosphere at a reduced pressure. On the other hand, fullerenes, fullerene derivatives and fullerene-like structures have been detected in the soot produced for technical applications and also in the diesel motor soot. The electric arc is still one of the best methods to produce fullerenes, which is why we decided to

carry out an installation in order to produce carbon nanostructures with large values of the fullerene yield (fullerene mass proportion in the soot) and productivity.

The fullerenes were prepared by evaporation of carbon electrodes in an electric arc discharge process in helium atmosphere. The main part of the deposition system consists in a stainless steel, double walled, cylindrical chamber. Between the two chamber walls is flowing the cooling agent, the temperature being automatically controlled. The two electrodes were horizontally mounted near the bottom of a reaction chamber. For the anode electrode we have used pure graphite electrodes of a diameter of 6 mm and the length of 140 mm. The second electrode consists in a pure graphite disk, mounted at the bottom of the reaction chamber. The reaction chamber acts also like a soot collector. The anode is mounted in a guiding system, controlled by a mechanical system in order to assure a constant distance between the two electrodes during arc discharge. DC power supply unit was used and operated at the voltage of 10–20 V and the current of 0–250 A. In order to avoid the heating of the connection connectors, the electrical contact was made directly between the two electrodes and the discharge chamber walls.



To obtain the carbon soot, the chamber is evacuated of the air until a pressure of 10–3–10–4 Torr. The arc discharge is start up for 2–3 minutes, in order to heat the electrodes at the working temperature. After that, the chamber 3 Arc discharge installation for fullerene production 275 was filled in with a noble gas (argon or helium) at the pressure between 50 and 200 Torr. The arc intensity is controlled by the distance between the electrodes. During the process, the temperature of the chamber walls is maintained at  $30 \pm 2^\circ\text{C}$ . The carbon soot was investigated using X-ray diffractometry with a "DRON 2.0" apparatus. Fullerene C<sub>60</sub> was extracted from de soot with toluene and by vacuum evaporation.

### Types of Fullerene

#### Buckyball clusters

Smallest member is C<sub>20</sub> (unsaturated version of dodecahedrane) and the most common is C<sub>60</sub>.

#### Nanotubes

These are cylindrical fullerenes. These tubes of carbon are usually only a few nanometres wide, but they can range from less than a micrometer to several millimeters in length. They often have closed ends, but can be open-ended as well. There are also cases in which the tube reduces in diameter before closing off. Their unique molecular structure results in extraordinary macroscopic properties, including high tensile strength, high electrical conductivity, high ductility, high heat conductivity, and relative chemical inactivity (as it is cylindrical and "planar" that is, it has no "exposed" atoms that can be easily displaced).

#### Megatubes

Larger in diameter than nanotubes and prepared with walls of different thickness, potentially used for the transport of a variety of molecules of different sizes.

#### Polymers

Chain, two-dimensional polymers are formed under high-temperature conditions, single-strand polymers are formed using the Atom Transfer Radical Addition Polymerization (ATRAP) route.

#### Nano onions

Spherical particle based on multiple carbon layers surrounding a buckyball core ;proposed for lubricants.

#### Linked ball-and-chain dimers

Two buckyballs linked by a carbon chain.

#### Buckminster fullerene

Buckminsterfullerene is the smallest fullerene molecule containing pentagons share an edge. It is the most common in terms of natural occurrence, as it

can often be found in soot. The structure of C<sub>60</sub> is truncated icosahedrons, which resembles an association football of the type made of twenty hexagons and 12 pentagons, with a carbon atom at the vertices of each polygon and a bond along each polygon edge. The vander waals diameter of C<sub>60</sub> molecule is about 1.1nm. The nucleus to nucleus diameter of a C<sub>60</sub> molecule is about 0.71nm. The C<sub>60</sub> molecule has two bond lengths.

#### Boron buckyball

A type of buckball which uses boron atoms, instead of the usual carbon atom. The B<sub>80</sub> structure, each atom form in 5or6 bond is predicted to be more stable than the C<sub>60</sub> buckyball . The number of 6 numbered ring in this molecule is 20 and number of 5 membered rings is 12. There is an additional atom in the center of each 6 member ring bonded to each atom surrounding it.

#### Fullerite

These are the solid-state manifestation of fullerenes and related compounds and materials. "Ultradhard fullerite" is a coined term frequently used to describe material produced by high-pressure high-temperature (HPHT) processing of fullerite. Such treatment converts fullerite into a nanocrystalline form of diamond which has been reported to exhibit remarkable mechanical properties

#### Electrochemical properties

From the early days of the functionalization chemistry, the electrochemistry of fullerene derivatives has been systemically studied. In fact, a striking feature of C<sub>60</sub>, as shown by cyclic voltammetry, is that, in solution, this fullerene can accept reversibly up to six electrons. The UCSB group found that both fulleroids and methanofullerenes essentially retain the electronic properties of C<sub>60</sub>. The same behavior has been observed for most C<sub>60</sub> derivatives. This is expected on considering that saturation of double bond in C<sub>60</sub> causes a partial loss of conjugation.

A more incisive control of the electronic properties of the fullerenes might still be a relevant issue. The conjugated p-syst em of C<sub>60</sub> seems ideally suited for non-linear optical (NLO) applications. In principle attachment of donors and acceptors in conjugation with the fullerene p system should result in an interesting push-pull assembly.

#### Optical properties

The ground state absorption properties of C<sub>60</sub>, characterized by strong bands in the UV region and weaker absorptions in the visible region up to 650nm, are retained in most derivative .In addition, di

hydro fullerenes extend their absorptions throughout the entire visible region, with a weak maximum at 700nm. Dihydro fullerenes are excited to a short-lived singlet which convert rapidly into a long-lived triplet, with quantum yields slightly lower than C<sub>60</sub>. Whereas C<sub>60</sub> exhibit a triplet-triplet absorption at 750nm a same peak is shifted to 700nm in C<sub>60</sub> derivatives. This triplet-triplet transition is characterized by a higher absorption coefficient than the ground state, and may be responsible for its non-linear behavior.

### Chemical properties

The carbon atoms within a Fullerene molecule are sp<sup>2</sup> and sp<sup>3</sup> hybridized, of which the sp<sup>2</sup> carbons are responsible for the considerably angle strain presented within the molecule. C<sub>60</sub> and C<sub>70</sub> exhibit the capacity to be reversibly reduced with upto six electrons. This high electron affinity results from the presence of triply-degenerate low-lying LUMOs (lowest unoccupied molecular orbital). Oxidation of the molecule has also been observed; nevertheless, oxidation is irreversible. C<sub>60</sub> has a localized pi-electron system, which prevents the molecule from displaying superaromaticity properties.

### Applications

#### Tumor research

While past cancer research has involved radiation therapy, photodynamic therapy is important to study because breakthroughs in treatments for tumor cells will give more options to cells in cancer research involves the developments of new photosensitizers with increased ability to be absorbed by cancer cells and still trigger cell death. It is also important that a new photosensitizer does not stay in the body for a long time to prevent unwanted cell damage.

Fullerene can be made to be absorbed by HeLa cells. The C<sub>60</sub> derivatives can be delivered to the cells by using the functional groups L-arginine and L-phenylalanine, folic acid, among others. The purpose for functionalizing the fullerene is to increase the solubility of the molecule by the cancer cells. Cancer cells take up these molecules at an increased rate because of an upregulation of transporters in the cancer cells, in this case amino acid transporters will bring in the L- arginine and L- phenylalanine functional groups of the fullerenes.

Once absorbed by the cells, the C<sub>60</sub> derivatives would react to light radiation by turning molecular oxygen into reactive oxygen which triggers apoptosis in the HeLa cells and other cancer cells that can absorb the fullerene molecule. This research shows that a reactive substance can target cancer cells and then be triggered by light radiation, minimizing damage to

surrounding tissues while undergoing treatment. When absorbed by cancer cells and exposed to light radiation, the reaction that creates reactive oxygen damages the DNA, proteins, and lipids that make up the cancer cell. This cellular damage forces the cancerous cell to go through apoptosis, which can lead to the reduction in size of a tumor. Once the light radiation treatment is finished the fullerene will reabsorb the free radicals to prevent damage of other tissues. Since this treatment focuses on cancer cells, it is a good option for patients whose cancer cells are within reach of light radiation. As this research continues into the future, it will be able to penetrate deeper into the body and be absorbed by cancer cells more effectively.

#### Solar cells

The high electron affinity and superior ability to transport charge make fullerenes the best acceptor component currently available. First, they have an energetically deep-lying LUMO, which endows the molecule with a very high electron affinity relative to the numerous potential organic donors. The LUMO of C<sub>60</sub> also allows the molecule to be reversibly reduced with up to six electrons, thus illustrating its ability to stabilize negative charge. Importantly, a number of conjugated polymer – fullerene blends are known to exhibit ultrafast photo induced charge transfer, with a back transfer that is orders of magnitude slower. The state of the art in the field of organic photovoltaic is currently the Bulk Heterojunction (BHJ) solar cells based on Fullerene derivative phenyl- C<sub>61</sub> butyric acid methyl ester (PCBM), with reproducible efficiencies approaching 5%.

Conventional silicon solar cells exceed 20% efficiency. First, the cost of production of organic light-converting devices compared to the corresponding inorganic analogues is lower by more than two orders of magnitude. And second, an important merit of organic solar cells is their flexibility. They can be rolled up, cut, and spread over any surface. Particularly, such plastic can be used for covering both the inner and outer walls of buildings; cells of any color and texture can be manufactured. For example, a cell phone can be painted with this material, thus walking in a sunny day will be enough to charge the device battery. American military departments actively support projects associated with organic cells because these materials demonstrate high capabilities to be used in new armaments and attendant systems.

Finally, great expectations are also associated with the use of organic cells in the advertising and

packaging business. These involve autonomous luminous banners, large liquid – crystal line displays and packaging for food.

### Hydrogen gas storage

Due to its unique molecular structure, fullerene is the only form of carbon, which potentially can be chemically hydrogenated and de-hydrogenated reversibly. When fullerenes are hydrogenated, the C=C double bonds become C-C single bonds and C-H bonds. The bond strength of single C-C bonds is 83 kcal/mole, and theoretical calculations show that the bond strength of the hydrogenated C-H bond is 68 kcal/mole. This means that for fullerenes hydrides, the H-C bonds will break before the C-C bonds, and the fullerene structure should be preserved.

The considerably lower heat of formation for  $C_{60}H_{36}$  indicates that  $C_{60}H_{36}$  as a molecule is thermally more stable than  $C_{60}$ . Therefore, hydrogenation of  $C_{60}$  is thermodynamically favored and can be accomplished under the right chemical conditions. The color of the hydrogenated fullerene changes from black to brown, then to red, orange, and light yellow with increasing hydrogen content. A fullerene with up to 6.1% hydrogen content has been developed experimentally. A potential application of fullerene hydrides is in hydrogen gas storage device for electric vehicles that would employ a fuel cell.

Currently available hydrogen storage technologies like compressed gas or storage as a metal hydrides are potentially hazardous and/or have low hydrogen storage densities. Table shows a comparison of the amount of media required for storage when using fullerenes versus a metal hydride. The metal hydride storage media used in this comparison is Titanium Zirconium Vanadium.

Comparison of Hydrogen storage capacities for internal combustion engines

Comparison of Hydrogen storage capacities for internal combustion engines		
	Fullerenes	Metal Hydride
Hydrogen Required to operate 250 Miles	12 Ibs	12 Ibs
Amount of storage media required	197 Ibs	1200 Ibs

### Fullerene strengthening/ hardening of metals

Fullerenes offer unique opportunities to harden metals and alloys without seriously compromising their ambient temperature ductility. This is due to the

unique characteristics of fullerenes, namely their small size and high reactivity, which enable the dispersion strengthening of metallic matrices with carbide particles that result from in-situ interactions between fullerenes and metals. In a comparison of the hardness of a popular aerospace inter metallic compound Ti-24.5Al-17Nb, with and without fullerene additives, a 30% hardness enhancement was measured for the material with fullerene additives.

### Fullerene as precursor to diamond

Fullerenes have proven to be an excellent precursor to diamond. This can be attributed in part to the curved structure of fullerenes, which possess a partial  $sp^3$  (diamond) bonding configuration, as opposed to graphite, which is planar. Argonne National Laboratories and MER Corporation have investigated fullerenes as the source of carbon to CVD deposit diamond with excellent results. MER has demonstrated excellent diamond coating using fullerenes as the only source of carbon to deposit diamond at five times the growth rate of methane carbon sources, resulting in a projected 70% cost savings. With low cost fullerenes it can be expected that conversion to diamond will be a very important commercial application.

### Optical application of fullerene

Optical limiting refers to a decrease in transmittance of a material with increased incident light intensity. The phenomenon of optical limiting has a significant potential for applications in eye and sensor protection from intense sources of light. Based on the optical limiting properties of fullerenes, one can make an optical limiter, which allows all light below an activation threshold to pass and maintains the transmitted light at a constant level below the damage threshold for the eye or the sensor.

### Fullerenes based sensors

Fullerene – based interdigitated capacitors (IDCs) recently have been developed to explore sensor applications. This novel solid-state sensor design is based on the electron accepting properties of fullerene films and the changes that occur when planar molecules interact with the film surface. Fullerene chemistry provides a high degree of selectivity and the IDC design provides high sensitivity. The solid-state chemical sensor's small size, simplicity, reproducibility and low cost make them attractive candidates for fullerene applications development.

Studies of IDC configurations with fullerene film have able to sense water in isopropanol with a resolution of 40 ppm. These results demonstrate the

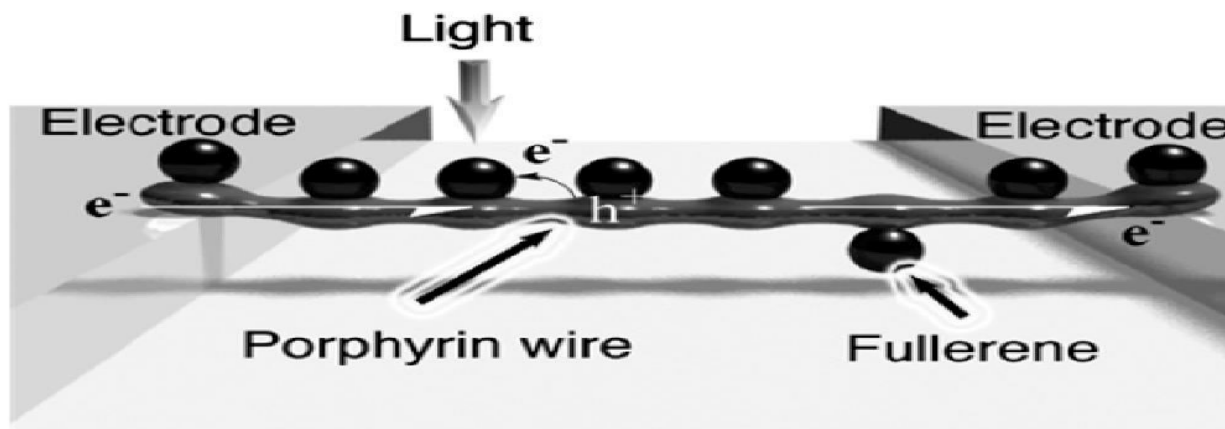
feasibility of using fullerene as selective dielectric film for IC chemical sensors.

#### Fullerene as molecular wires

Recent experiments have documented electron transport through single molecules. Under certain experimental conditions molecular conduction through a single molecule rather than through an ensemble of molecule is guarantee. This phenomenon is possible due the high electron affinity of fullerenes. If a molecular computer is ever to be built, then it

will need molecular wires in order to connect to its various components. Figure shows a computer created scenario of a possible use of fullerenes in the manufacture of molecular conductors.

When source of UV light is applied to the system in figure, the fullerene molecules get excited and electrons move from the porphyrin wire towards the fullerenes. These electrons leave holes in the porphyrin through which electrical current can flow from one electrode to the other.



#### Fullerene in medicine

Interest of scientists in water-soluble fullerene compounds is directly related to their biological activity. Dendrimer 4p containing 18 carboxyl group is the more promising today. The synthesis and the use of this compound in medicine were patented in the U.S. (C-sixty corporation); at present, this drug undergoes clinical trials as a promising medication for treatment of AIDS. Fullerene derivatives can be used in the photodynamic cancer therapy as antibacterial agents and medications of neuroprotective action.

Because of their ability to enclose atoms, Fullerenes promise to be of great use as drug carriers. Additionally, noble gases have been encapsulated in Fullerenes, which have no desire to bond with the surrounding carbon atoms but can be used in

applications such as magnetic resonance imaging (MRI). Researchers at Rice University have designed  $C_{60}$  and other fullerenes molecules with an atom of gadolinium inside and with chemical appendages that make them water-soluble. In typical MRI contrast agents, the metal gadolinium is linked to a non-fullerene molecule, which is normally excreted quickly from the body. Fullerenes encapsulated with gadolinium might allow the contrast agent to remain in the body longer, allowing doctors to perform slower studies.

#### Endohedral fullerenes

Endohedral Fullerenes are created when an atom is inserted inside a Fullerene molecule. Fig. illustrates an example of a fullerene containing a non-carbon atom inside.



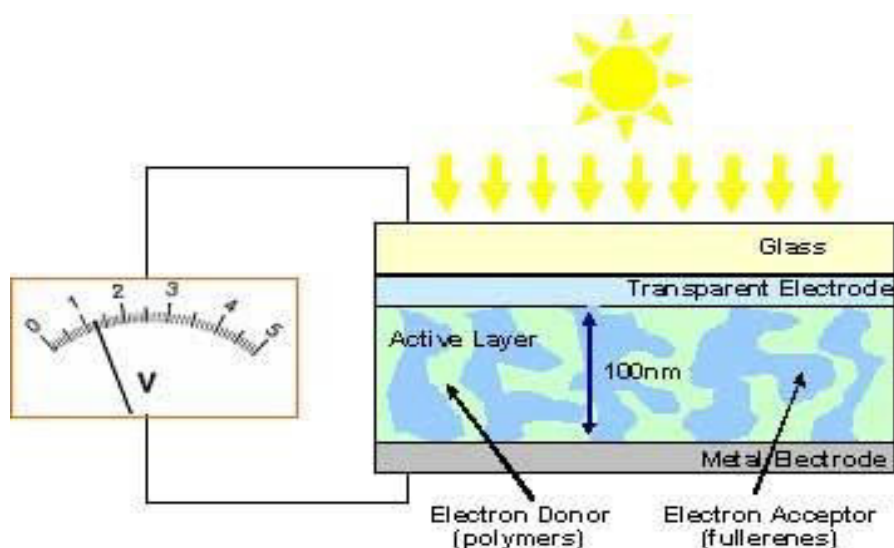


In one of the methods employed for this purpose, ions are accelerated and implanted to the  $C_{60}$  cage. The first collision should absorb and redistribute a good part of the kinetic energy to ensure that the ions have just enough energy to open the cage and enter, without having sufficient kinetic energy left to escape.

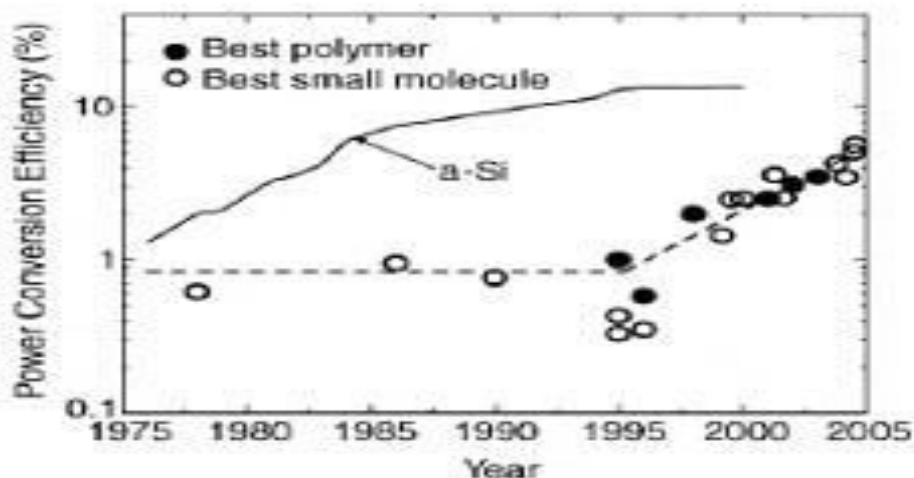
Metallofullerenes made this way include  $M@C_{60}$  with  $M=Li, Ca, Na, K, Rb$ . Larger yields can be achieved by co-evaporation of the carbon and the metal in an arc discharge chamber (typical for fullerene production). However, in this process mostly higher endohedral fullerenes, like  $M@C_{82}$ , are formed. These Metallofullerenes are very stable molecules and can be used in many applications. For example, it has been shown that the bulk modulus of  $K@C_{60}$  is higher than that of  $C_{60}$ , and while  $C_{60}$  rolling dynamics are the same as  $K@C_{60}$  intercalated between layers is higher than that of  $C_{60}$  intercalated between layers was. From this it can be concluded that for nano ball-bearing applications, Metallofullerenes are more effective than fullerene.

### Organic photovoltaics(opv)

Fullerene can be used as organic photovoltaics



Currently, the record efficiency for a bulk heterojunction polymer solar cell is a fullerene/polymer blend. The fullerene acts as the n-type semiconductor (electron acceptor). The n-type is used in conjunction with a p-type polymer (electron donor), typically a polythiophene. They are blended and cast as the active layer to create what is known as a bulk hetero junction.



Fullerenes are used as is, or they are derivitized to increase their solubility. The most commonly used derivative in photovoltaics is  $C_{60}$ , but  $C_{70}$  has been shown to have a 25% higher power conversion efficiency than  $C_{60}$ . In addition, alternative derivative such as  $C_{60}$  PCBB have been shown to increase conversion efficiency by over 40%

when compared to C<sub>60</sub> PCBM in like systems. In November of 2005 a record cell efficiency of 4.4% using a fullerene derivative and illustrating the importance of the characteristics of the active layer on performance was published. As the preferred n-type material, fullerenes can comprise up to 75% of the active layer by weight. Solar cell efficiency continues to increase steadily, placing the potential for commercialization in the not-too-distant future.

The performance of polymer transistors e.g. Organic Field Effect Transistors (OFETS) and photodetectors has also been increasing, in part due to a great deal of synergy between OFETS and OPVs. The leading OFETS use the n-type semiconducting properties of fullerenes based on C<sub>60</sub>, C<sub>70</sub> along with C<sub>84</sub>. Fullerene OFETS fabricated with C<sub>84</sub> show greater mobility than C<sub>60</sub> or C<sub>70</sub> and exhibit greater stability. While more work is needed, the world of polymer electronics is opening up for both fullerenes and single-walled carbon nanotubes.

#### Antioxidants and biopharmaceuticals

Fullerenes are powerful antioxidant, reacting readily and at a high rate with free radicals, which are often the cause of cell damage or death. Fullerenes hold great promise in health and personal care applications where prevention of oxidative cell damage or death is desirable, as well as in non-physiological applications where oxidation and radical processes are destructive (food spoilage, plastics deterioration, metal corrosion). Major pharmaceutical companies are exploring the use of fullerenes in controlling the neurological damage of such disease as Alzheimer's disease and Lou Gehrig's disease (ALS), which are a result of radical damage. Drugs for atherosclerosis, photodynamic therapy, and anti-viral agents are also in development.

Fullerenes are known to behave like a "radical sponge," as they can sponge-up and neutralize 20 or more free radicals per fullerene molecule. They have shown performance 100 times more effective than current leading antioxidant such as vitamin E. Fullerene is highly soluble in almond oil and thus it can be used for screening test for ocular tissue toxicity indicating no adverse effect.

#### Additives

##### Polymer Additives

Fullerenes and fullerene black are chemically reactive and can be added to polymer structures to create new copolymers with specific physical and mechanical properties. They can also be added to make composites. Much work has been done on the

use of fullerenes as polymer additives to modify physical properties and performance characteristics.

**Catalysts** : Marked ability to accept and to transfer hydrogen atoms; hydrogenation and hydrodealkylations. Highly effective in promoting the conversion of methane into higher hydrocarbons. Inhibit coking reactions.

**Water purification &**

**Bio-hazard protection** : Single oxygen catalysis of organics with fullerene C<sub>60</sub>

**Portable power** : Proton exchange membranes for fuel cells

**Vehicles** : Enhanced durability, lower heat build-up, and better fuel economy with use of fullerene black/rubber compounds.

**Medical** : MRI agents

The body of research on fullerene black is small compared to fullerenes and less is known about the physical properties and the potential application. Certain features however show promise for the use of fullerene black as an improvement over carbon black in various applications. The distinguishing feature of fullerene black compared to typical carbon blacks is that the carbon layer planes of fullerene black are curved and fullerene-like in nature. This curvature is thought to explain the observed higher reactivity of fullerene black compared to conventional carbon black. This feature offers potential for use in various applications, such as catalysts, catalyst supports and rubber additives.

The most common fullerene is the classic "Buckminster Fullerene" with 60 carbon atoms. It is the most abundant form, followed by C<sub>70</sub>, C<sub>76/78</sub>, C<sub>84</sub> and finally the higher fullerenes of C<sub>90</sub> and above. For particularly demanding applications, sublimed fullerenes with 99.95% purity are available.

#### REFERENCES:

1. H. W. Kroto, J. R. Heath, S. C. O'Brien, R. F. Curl, R. E. Smalley, C<sub>60</sub>: Buckminsterfullerene, *Nature*, 318, 162–163 (1985).
2. W. Kratschmer, L. D. Lamb, K. Fostiropoulos, D. R. Huffman, Solid C<sub>60</sub> – a new form of carbon, *Nature*, 347, 354–358 (1990).
3. R. E. Haufler, J. Conceicao, L. P. F. Chibante, Y. Chai, N. E. Byrne, S. Flanagan, M. M. Haley, S. C. O'Brien, C. Pan, Z. Xiao, W. E. Billups, M. A. Ciufolini, R. H. Hauge, J. L. Margrave, L. J. Wilson, R. F. Curl, R. E. Smalley, Efficient production of C<sub>60</sub> (buckminsterfullerene), C<sub>60</sub>H<sub>36</sub>, and the solvated buckide ion, *J. Phys. Chem.*, 94, 8634–8636 (1990).

4. R. F. Bunshah, S. Jou, S. Prakash, H. J. Doerr, L. Isaacs, A. Wehrsig, C. Yeretizian, H. Cynn, F. Diederich, Fullerene formation in sputtering and electron beam evaporation processes, *J. Phys. Chem.*, 94, 6866–6869 (1992).
5. P. Hebggen, A. Goel, J. B. Howard, L. C. Rainey, J. B. Vander Sande, Synthesis of fullerenes and fullerene nanostructures in a low-pressure benzene/oxygen diffusion flame, *Proceedings of the Combustion Institute*, 28, 1397–1404 (2000).
6. S. Chuanchen, G. Haibin, F. Dufei, Extraction of C60 cluster ion beam, *Review of Scientific Instruments*, 65, 1405–1407 (1994).
7. J. J. Langer, S. Golczak, S. Zabinski, T. Gibinski, Fullerenes and carbon nanotubes formed in an electric arc at and above atmospheric pressure, *Fullerenes Nanotubes and Carbon Nanostructures*, 12, 593–602 (2004).
8. X-ray Powder Diffraction Data File, A.S.T.M. (American Society for Testing Materials), 1967.
9. F. A. Khalid, O. Beffort, U. E. Klotz, B. A. Keller, P. Gasser, S. Vaucher, Study of microstructure and interfaces in an aluminium-C60 composite material, *Acta Materialia*, 51, 4575–4582 (2003).
10. W. J. Anton, R. W. Stephen, I. S. David, *Biological Applications of Fullerenes*. New York City, NY: Elsevier Science, 1996.
11. M. S. Dresselhaus, G. Dresselhaus, P. C. Eklund, *Science of Fullerenes and Carbon Nanotubes*. Boston, MA: Academic Press, 1996.
12. R. S. Rouff, The bulk modulus of C60 molecules and crystals: a molecular mechanics approach, *Applied Physics Letters*, Vol 59, pp. 15553-1557, 1991.
13. B.C. Thompson, J.M. Fréchet. Polymer-Fullerene composite solar cells. DOI: 10.1002/anie.200702506
14. M. Shwartz. (2012). Stanford scientists build the first allcarbon solar cell. <http://news.stanford.edu/news/2012/october/carbon-solar-cell-103112.html?view=print>
15. B. M. Alice, M. Milton, Y. Sun, Infrared spectroscopy of all-carbon poly[60] fullerene dimer model, *Chemical Physics Letters*, Vol 288, pp. 854-860, 1998.
17. J.W. Withers, R. O. Laoufy, T.P. Lowe (1997). Fullerene commercial vision <http://legacy.library.ucsf.edu/tid/kve34a00/pdf;jsessionid=ED6BCF667CC63447AC275FDA4F421E65.tobacco03>
18. H. Imahori, Y. Sakata. Donor-Linked Fullerenes: Photoinduced Electron Transfer. DOI:12.1902/minn.203007901
19. D.M. Guldi, B.M. Illescas, C. M. Atienza, "Fullerene for organic electronics," *Chemical Society Reviews*, iss. 6, pp. 1587-1597, May. 2009.
20. H. Paul, R. Cristina, H. Tim, *Fullerenes*, *Cientifica.*, iss. 7, October. 2003.
21. D. Lothar, Y Shangfeng, The recent state of endohedral fullerene research, *The Electrochemical Society Interface*, Summer, 2006
22. Mroz, Pawel; Pawlak, Anna; Satti, Minahil; Lee, Haeryeon; Wharton, Tim; Gali, Hariprasad; Sarna, Tadeusz; Hamblin, Michael R. (2007). "Functionalized fullerenes mediate photodynamic killing of cancer cells: type I versus type II photochemical mechanism". *Free Radical Biology & Medicine*. 43 (5): 711–71.