

## Editorial

# Self-Assembled Fullerene Nanostructures at Liquid Interface

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Fullerene is one of the most exciting nanocarbon materials. It has been widely investigated due to its interesting physical, chemical and optoelectronic properties, and has been used in diverse fields including device fabrications and drug delivery [1-3]. Prior to its discovery, diamond and graphite consisting of extended networks of  $sp^3$ - and  $sp^2$ -hybridized carbon atoms, respectively represented the only known allotropes of carbon for a long time. The discovery of functional molecule fullerene  $C_{60}$  in 1985 by Kroto et al. [4] changed the scenario and marked the beginning of new era of synthetic carbon allotropes. The advancement of synthetic carbons then continued rapidly enabling a success of producing carbon nanotubes in 1991 [5] followed by the rediscovery of graphene in 2004 [6]. Numerous possible carbon modifications are now being under investigation. It is anticipated that this challenge will reveal newer carbon nanostructures with fancy structure and properties in future.

Recent development in nanoscience and nanotechnology research has enabled to design functional nanomaterials whose properties can be controlled in microscopic and macroscopic length scales via self-assembly of building blocks in molecular level precision. Therefore, nanostructured assemblies have become one of the most attractive nanomaterials in tailoring of properties, arising from the confinement effects of the building blocks. Various building units have been assembled into functional nanostructures. Structural dimension is one of the useful classifications of nanostructures or nanomaterials. Interestingly the entire range of dimensionalities can be found in the nanocarbon family. Zero-dimensional (0D) fullerenes, one-dimensional (1D) nanotubes, two-dimensional (2D) graphene sheet, and three-dimensional (3D) nanocrystalline diamond and fullerite represent 0 to 3D carbon nanostructures. These are  $\pi$ -electron systems carbon nanostructures and depending on their dimensionality display excellent electrical, mechanical, and thermal properties and cover wider range of technological applications including anode materials for rechargeable lithium ion rechargeable batteries, optoelectronic devices, biomedicine, sensing, and catalysis [7-13].

Fullerene is an extensively studied nanomaterial in carbon family. Fullerene  $C_{60}$  is the smallest, stable and most prominent

molecular carbon allotropes consisting of a spherical network of sixty structurally equivalent  $sp^2$ -hybridized carbon atoms in a cage lattice (diameter  $\sim 0.8$  nm) in the shape of a soccer ball. It has truncated icosahedron symmetry,  $I_h$ , and composed of 12 pentagons and 20 hexagons with alternative single and double bonds. Furthermore, the curvature induced by the cage structure increases the energy associated with the double bonds enhancing the reactivity of the molecule. Fullerenes are therefore stable but not totally unreactive. The  $sp^2$ -hybridized carbon atoms, which are at their energy minimum in planar graphite, must be bent to form the closed sphere, which produces angle strain. The characteristic reaction of fullerenes is electrophilic addition at 6,6-double bonds, which reduces angle strain by changing  $sp^2$ -hybridized carbons into  $sp^3$ -hybridized ones. One of the most intriguing features of fullerene  $C_{60}$  is its electron accepting behavior, i.e., it is an electron deficient molecule due to the presence of energetically unfavorable double bond in pentagonal rings. This property has been utilized to design bulk heterojunction in combination of suitable electron donor molecules [14,15]. Until now, this molecule has become the most popular electron acceptor material in organic solar cells due to its superior electron conductivity and efficient charge separation at electron donor/acceptor interface [16]. Particularly, in organic photovoltaics, major attention is focused to develop newer type of donor materials. Nevertheless, fullerene remains as the main acceptor material as it matches well with a wide variety of donor materials [17].

Growing interest in fullerenes has allowed exploring the many possibilities in various applications. In many designs for fullerene-based functional materials, assemblies of 0D fullerene into structures with well-defined dimension are required. Fullerene  $C_{60}$  is a 0D small isotropic spherical object and can be employed as an ideal building block for generating higher dimensional functional nanostructures [18,19]. Experiments have shown that fullerene  $C_{60}$  can be assembled into various shapes and sizes thereby advancing its optoelectronic properties compared to the bulk or pristine fullerene [20]. Among the various synthetic methods explored for the production of shape-controlled fullerene crystalline assemblies, liquid-liquid interfacial precipitation (LLIP) method has become one of the versatile methods of producing dimension-controlled nano- to micron size fullerene crystals [21]. In this method crystal formation is driven by the supersaturation related to the low  $C_{60}$  solubility in alcohols (alcohols are regarded as poor solvent or antisolvent for  $C_{60}$  as the solubility of  $C_{60}$  in alcohols is very low). Tuning solvent and antisolvent combinations, their volume ratios, temperature, and concentration,  $C_{60}$  crystalline assemblies of controlled shape and size have been produced [18]. Recent success on producing a newer type of fullerene crystals, which consist of meso- and macroporous bimodal pore architecture has opened new avenue towards the development of newer type of multifunctional fullerene [22].

Nanoporous fullerene could offer huge scientific and technological

importance owing to the presence of controllable voids of sizes in atomic, molecular, and nanometer length scales. Nanoporous fullerene with unique surface, structural, and bulk properties can underline their important uses in various fields such as energy storage, sensing, ion exchange, separation, catalysis, biological molecular isolation, and purifications. Proper doping of semiconducting nanomaterials in porous fullerenes is expected to enhance the optoelectronic properties, which is expected to enhance the performance of devices. Furthermore, micron size fullerene crystals with pore architecture could be a better scaffold for cell culture whereas the nano size porous fullerenes can be used in drug delivery. These wider applications offer exciting opportunities for researchers, engineers or biologists to develop new strategies and techniques for the synthesis and applications of nanoporous fullerene inserting multifunctionalities. Nevertheless, the remaining challenges of molecular modeling and design of nanoporous fullerenes with superior surface area and pore volume, the fundamental understanding of structure-property relations, and tailor-design of fullerene nanostructures for specific properties and applications are essential to be addressed.

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