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Perspective

Graphene—A hello and goodbye

Ayesha Kausar

National Center for Physics, Quaid-i-Azam University, Islamabad 45320, Pakistan; dr.ayeshakausar@yahoo.com

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Abstract: After years of research, it can be stated that graphene was an initial game changer and jack of all trades in the world of nanotechnology, owing to innumerable structural/physical characteristics and mammoth range of hi-tech applications. Undoubtedly, since the discovery of graphene, it almost ruled all possible nanotechnological fields, from electronics/energy—to—defense/transportation/civil—to—biomedical. Nevertheless, this statement remained no longer valid after the discovery of more erudite nanostructures, like fullerene, quantum dots, and similar nanoparticles. Reasons for today's technology turns towards tiny symmetrical nanoparticles seem to be the limitations/hinderance for integrating graphene into energy/semiconducting/photonic devices, and subsequent commercialization over past two decades. In this novel perspective report, therefore, we first time critically analyzed the nanotechnological shifts from graphene, yet despite its early promises, towards proficient zero dimensional entities.

Keywords: graphene; limitations; nanotechnology shifts; quantum dots; fullerene

1. Introduction

Graphene, a two dimensional carbon nanoform, has been immensely studied for its inimitable nanostructure, properties, and wide ranging applied attributes [1]. In era of modern nanotechnologies, graphene, modified graphene, and graphene derivative nanomaterials have fascinated huge scientific curiosity owing to distinct surface, structural, electrical, optical, mechanical, thermal, and other properties [2]. Therefore, graphene has been researched as a striking candidate for energy production/harvesting systems, energy storage devices, sensing/wearable electronic sensing (e-sensing) equipment, portable electronics, space, transport vehicles, textiles, biological, and countless related high-tech areas [3].

Despite the technical progress attained by graphene over last two decades, its importance in nanotechnological arenas seems frequently diminishing with the discovery of further smaller and symmetrical nanoparticles [4]. Consequently, fullerene and quantum dots like nanoparticles have been continuously focused by the field researchers and offered efficient platform for industrial level applications, ranging from smart maneuvers or devices and advanced architectures to medical systems (**Figure 1**).

This innovative perspective article judgmentally examined the property/applied advantages as well as limitations responsible for hindering the further advances and commercialization of graphene. Even in the chiefly claimed to date energy/electronics applications, graphene seems to be frequently replaced by the use of other nanocarbons or hybrid nanostructures. Herein, according to literature reports hitherto, we notice the successful substitution of graphene by using advanced nanoparticles, like fullerene, quantum dots, and many more.

Figure 1. Graphene—nanotechnological revolutions and technology turns.

2. What's graphene

Before we move to the main context of this article, it is important to see the essentials of graphene. Word 'graphene' is derived from graphite with suffix 'ene' allocated due to the presence of double bonding in its structure [5]. The name graphene also indicates its structural similarity to graphite, i.e., it is considered as a single layer of graphite. It is a two dimensional single layer of carbon atoms (sp^2 hybridized) hexagonally arranged into honeycomb lattices. The hybrid nanostructure of graphene allows the formation of three sigma as well as π bonding of each of its carbon atom to the neighboring atoms. In simple words, graphene is a carbon nanoallotrope or a carbonaceous nanoparticle. Looking at the history of graphene, which is not merely its recognition/documentation in 2004 (Geim and Novoselov), but seems connected to 1947 when it was first theoretically reported (Wallace) and prepared in 1962 (Hanns-Pete) [6]. Later, in 1986, after thorough structural studies it was named as graphene (1986). Although, Nobel prize for this discovery was credited to Andre Geim and Konstantin Novoselov in 2010, after realizing its technical worth.

3. Ruling the world of nanotechnology

Since discovery, graphene acquired mammoth curiosity of materials/nanoscientists and researchers, therefore opening countless new ways in the nanotechnological world, as discussed in this section. Looking at the two ruling decades of graphene in the nanotechnological world, it seems ruling or sweeping almost every possible technological materials science arena, both experimentally and theoretically [7]. In this concern, we note a range of research articles, reviews, books/book chapters, and industrial patents in the literature from last two decades. Accordingly, notable practical applications of graphene can be named for energy production (photovoltaics, fuel cells), energy storage (capacitors, supercapacitors, micro supercapacitors, lithium or other ion batteries), electronics (optoelectronics, sensors, transistor, diodes), catalysis, aerospace/automotive, defense, civil and engineering structures, environment (radiations, water, air remediation), textiles (smart/e-textiles), and biomedical (drug delivery, tissue engineering, biosensors, bioimaging, antimicrobials, pharmaceutics), to name a few [8]. All these limitless applications of graphene appeared after its commercialization in 2014 (UK manufacturers). Here, it is important to mention that such marvels of graphene (a transparent nanostructure) are actually linked to its intrinsic structural, microstructural, and physical characteristics, including anomalous surface area, electron conductivity ($\approx$ 200,000 $cm^2V^{-1}s^{-1}$), thermal conductivity (up to 5000 W/mK), Young's modulus ($\approx$ I TPa), optical, magnetic, quantum hall effect (quantized version of Hall effect, i.e., potential difference/voltage in an electrical conductor), permittivity (electric polarizability of dielectric material), and countless other valuable properties. All these spectacular features of graphene, responsible for its nanotechnological breakthroughs, in turn seems depending upon its successful fabrication via opting an appropriate processing strategy (top down/bottom up) out of a number of proficient reported methods, such as mechanical/chemical exfoliation, electrochemical, hydrothermal (method with high temperature/vapor pressure conditions), physical/chemical vapor deposition, laser/plasma methods, and so on. Further advancements of graphene can be seen in the form of innumerable modified graphene nanostructures (graphene oxide, reduced graphene oxide, surface functional graphene), and nanoderivatives (graphene nanoplatelets, graphene nanoribbons, graphene nanodots, nanoporous graphene), as well as nanocomposites and hybrid with inorganic (metal, metal oxides, inorganic compounds) or organic (polymer, carbon, nanocarbon) materials/nanomaterials.

4. Today's technology turns

At this point, it is important to survey key points accountable for modern day nanotechnological shifts, from graphene—to—sophisticated carbon nanoentities (like quantum dots, fullerenes, etc.). Despite the myriad of applied attributes of graphene, a number of challenges seem to be hindering its reliable long term industrial or commercial level scale utilizations, including intricate control of size/shape, raised cost, zero band gap, feeble fluorescence, toxicity, low dispersion/solubility, processing/structure relying conductivity, scalability confines, and all that, in turn restricting the future technical implication of graphene [9]. For that reason, owing to the stated inadequacies of graphene, recent nanotechnological trends seem shifting towards the development and utilization of more structurally symmetrical and precise nanostructures, for example, zero dimensional carbon nanoparticles like fullerene molecules, quantum dots (carbon nanodots, graphene quantum dots), and allied nanocarbons.

Moving technologies from graphene towards fullerene, quantum dots, and related sophisticated nanostructures looks worthwhile in terms of advantageous structural, property, and practical promises. For instance, fullerene molecules are symmetrical nanoparticles (polygons of five to seven membered rings consisting of sp^2 hybridized carbon atoms) having smaller sizes and larger surface area than graphene [10]. Numerous fullerene molecules have been prepared and studied in the literature up to now, like C_{20}, C_{28}, C_{30}, C_{60}, C_{70}, C_{120}, and many more, pointing towards the expanded advanced uses. In addition, fullerene (synthesized by nano-cutting, deposition, plasma/laser, arc discharge, organic routes) own numberless electronic, optical, electrical/heat conductivity, heat/mechanical constancy or stability, and surface/chemical reactivity properties. Furthermore, we notice valuable applications of fullerene for solar cells, fuel cells, capacitors, batteries, sensors, engineering, and biological sectors. Today's advances also show applications of fullerene in environmental friendly electric vehicles and sophisticated equipment for hydrogen storing/gas capturing and other technical applications.

Similarly, when we look at carbon nanodots, like graphene quantum dots, have sizes of just few nm, i.e., < 10 nm. According to surveys, we observed several beneficial properties of tiny graphene quantum dots (compared with graphene), such as non zero band vary small crystalline lattice of 0.24 nm, band gap, photoluminescence (radiation emissions due to absorption of photons), optoelectronic, electron/thermal conductivity, photoelectric, and so forth. Consequently, these tiny nanoparticles gained immense curiosity of the nanotechnological researchers/scientists, therefore, leading to miracles in the fields of microelectronics, photovoltaics (solar cells), sensors/actuators, light emitting diodes, capacitors/batteries, transportation, corrosion/chemical/radiation defense, and biomedical areas (tissue scaffolds, drug transfusion/delivery). As per our analysis, zero dimensional nanoparticles have been further surface modified and composited to develop high performance fullerene or quantum dots based nanomaterials, so further enhancing the technical worth of these nano-entities. **Figure 2** presents a comparative snapshot of structure, essential properties, and applied aspects of graphene with zero dimensional quantum dots/fullerene and technology trends.

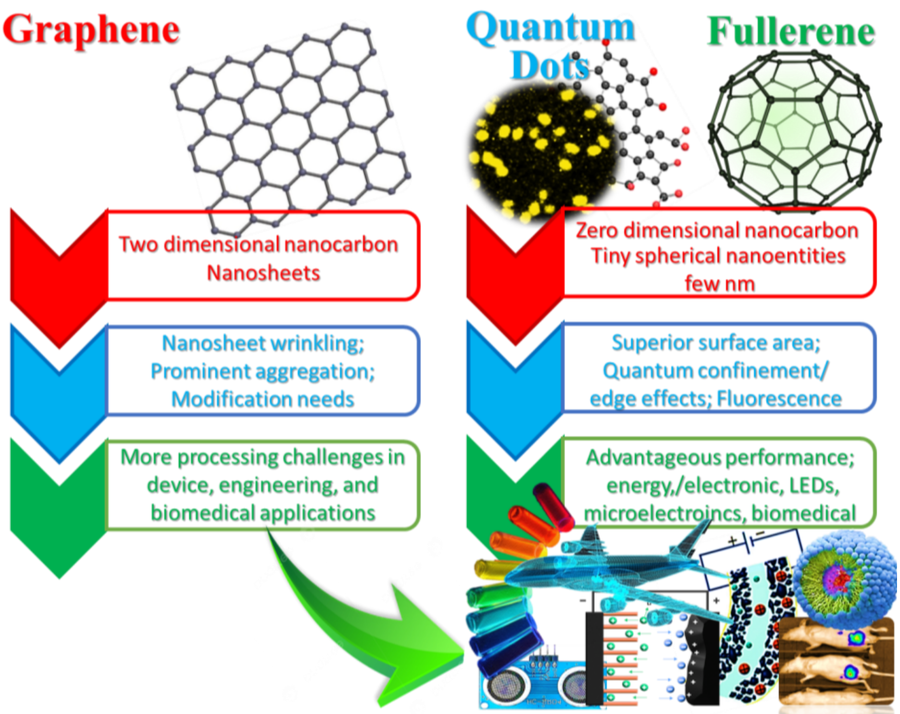

Figure 2. Comparison of structure/features/aspects of graphene with zero dimensional quantum dots/fullerene.'

It is important to mention that using environmental friendly and non-toxic zero dimensional nanomaterials like quantum dots or fullerene can reduce the environmental burden, therefore, leading to present-day ecological sustainability solutions [11]. Since, using minute nanoparticle contents may influence our ecosystem due to hazardous consequences, so, researches must be steered to greenhouse emissions and energy expenses involved in using quantum dots or fullerene nanoparticles. Suitably, zero dimensional nanoparticle and related nanomaterials must be assessed for life-cycle to know their sustainability and influence on ecosystem.

Recent industrial scale metrics and market data as well as strategic growth analysis till 2031 also seem supporting rise of quantum dots/fullerenes, in place of graphene based systems [12]. The quantum dots market is continuously experiencing noteworthy progressions and has predicted growth rate of > 30%–50% annually through 2030. Consequently, zero dimensional nanoparticles have growing demand for electronics, energy, and biological sectors. Specifically, quantum dots linked designs and technologies seem replacing graphene in next-generation light emitting diodes, electronic, and microelectronic devices [13]. In addition, graphene quantum dots offer high surface area, surface functionalities, and conducting network formation suitable for today's energy-related applications [14]. Explicitly, for supercapacitor electrodes, graphene quantum dots depicted advantageous pseudocapacitance, charge discharge, and cyclic stability, to replace traditional graphene designs. It is important to mention that quantum dots derived nanomaterial must be considered for their challenges related to high costs, scalability, standardization of processing, and applied conditions for their industrial uses.

Although current industrial era relies on graphene based designs for a range of technological applications, as stated above, nevertheless, we can categorize quantum dots more as erudite future nanomaterials, relative to traditional graphene systems [15]. Here, we can state obvious reasons for bright technical future of quantum dots, instead of graphene, such as sizes down to few nm leading to enormously high larger surface area, surface functionalization, and unique quantum confinement/edge effects rendering, so rendering them promising nanoentities for innumerable methodological applications replacing the traditional two dimensional designs.

5. Summation

After looking at the basics of graphene, its scientific revolutions, and today's high-tech demands of using more fastidious nanocarbon nanoparticles, we conclusively analyzed a visible nanotechnology shifting tend, from two dimensional graphene—to—zero dimensional nanodots, fullerene, and similar nanoparticles. We can say that, owing to countless advantageous characters, technical demand of quantum dots or fullerene based nanomaterials are continuously and massively increasing in industrial and commercial market places. Noticeably, such technology shifting attitude (from graphene and advances towards sophisticated symmetrical nanodots, etc.) are due to noteworthy applications (smart electronics/energy devices—to—biomedical) that are put forth to elevate the credibility of industries thru.

In other words, future nanotechnological shifts towards fullerene and quantum dots demand well defined potential research directions for technical and industrial applications. Looking ahead, integration of quantum dots/fullerene in emerging technologies such as renewable electronics and energy solutions may revolutionize future industrial era. Although, worldwide research initiatives have been launched for using zero dimensional nanoparticles on trade level, yet concentrated and predefined R&D attempts may promise future breakthroughs to redefine next end industrial sectors.

Despite the bright technical future of zero dimensional nanoparticles (in spite of graphene) there are several possible limitations which may hinder their desirable industrial application, for instance: (i) Intricate surface chemistry and phenomenon; (ii) unclear relationship between surface chemistry and physicochemical properties; (iii) undefined origin and low emission intensities/weak fluorescence; (iv) ambiguous fluorescence mechanism; (v) high cost precursors and fabrication routes; (vi) unoptimized synthesis conditions; (vii) lack of precise surface/chemical modification; (viii) probable toxic effects, to list a few.

Conflict of interest: The author declares no conflict of interest.

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