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Revolution of Graphene for different applications: State-of-the-art

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ABSTRACT

Recent years have witnessed a revolution in Graphene and its applications. Presently, it is a hot subject in science and engineering circles, and gathering more and more interest. This one-atom-thick crystal of carbon has distinctive physicochemical properties, tremendous mechanical performance and outstanding electrical and thermal conductivities. These characteristics are making Graphene as an alternative to replace many traditional materials for many applications. There are different methods to fabricate and characterize 2D Graphene, some of these methods are currently scalable and others still on the lab scale. This state-of-the-art, aimed to achieve three goals: (1) provide a background that is easy to follow, (2) to make a short survey on Graphene history, properties, and different preparation methods, and (3) Current and future applications of Graphene and Graphene-based materials. This survey can help motivate and guide scientific community and the public that are interested in Graphene and its applications.

1. Background

The "Graphene" expression consists of a prefix of "graph" from graphite and suffix "ene" from the C—C double bonds [1] (Fig. 1). As Graphene is the essential, building blocks in graphite, by stacking Graphene in different ways, various and important properties are discovered. By the rapid steps forward of Graphene, several types of Graphene-like materials had been existing, from a monolayer to multilayer Graphene, Graphene quantum dots (GQDs), Graphene nanoribbons (GNRs), nanomesh, nanosheets, and Graphene oxide (GO) [2].

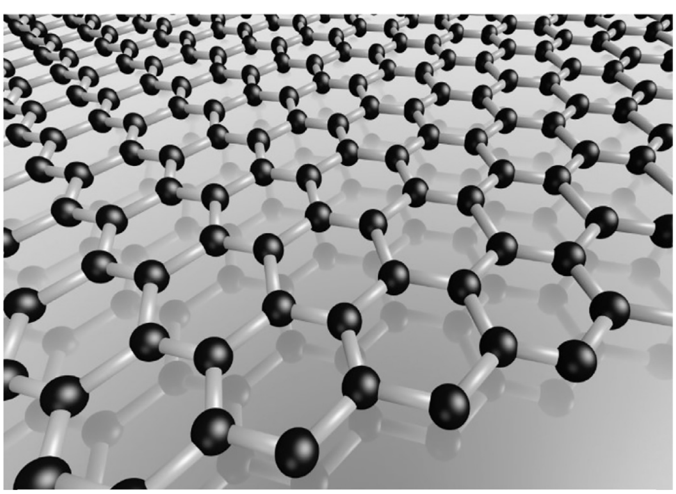

Fig. 1. Schematic presentation of Graphene layer structure [1].

Graphene has revolutionized the scientific frontier in nanoscience and condensed matter physics because of its extraordinary electrical, physical, and chemical properties. Projected as a possible substitution for silicon in electronics and applications in many other advanced technologies, Graphene has sparked huge interest in many research teams worldwide and has resulted in a rapid increase in literature on the topic.

After surveying the literature in the area of Graphene, and its applications, it is found that most of the Graphene produced are fabricated through exfoliation (Fig. 2(a)). This is because liquid exfoliation is considered as a cheap method as compared to the other methods (Fig. 2(b)).

Based on the data collected from Scopus, web science and the Engineering Village web-based information services, the intensive work on Graphene area was reflected on the number of articles and patents dealing with Graphene and Graphene-based materials. This number of publications is continuously increasing specifically in the last few years as shown in (Fig. 2(c)). The number is sharply increased from about 24 articles in 2004 to more than 11,326 in 2016. The total number of patents worldwide approaches 8416 by February 2013 [3]. The main research contents of the published work are concerned with the topics

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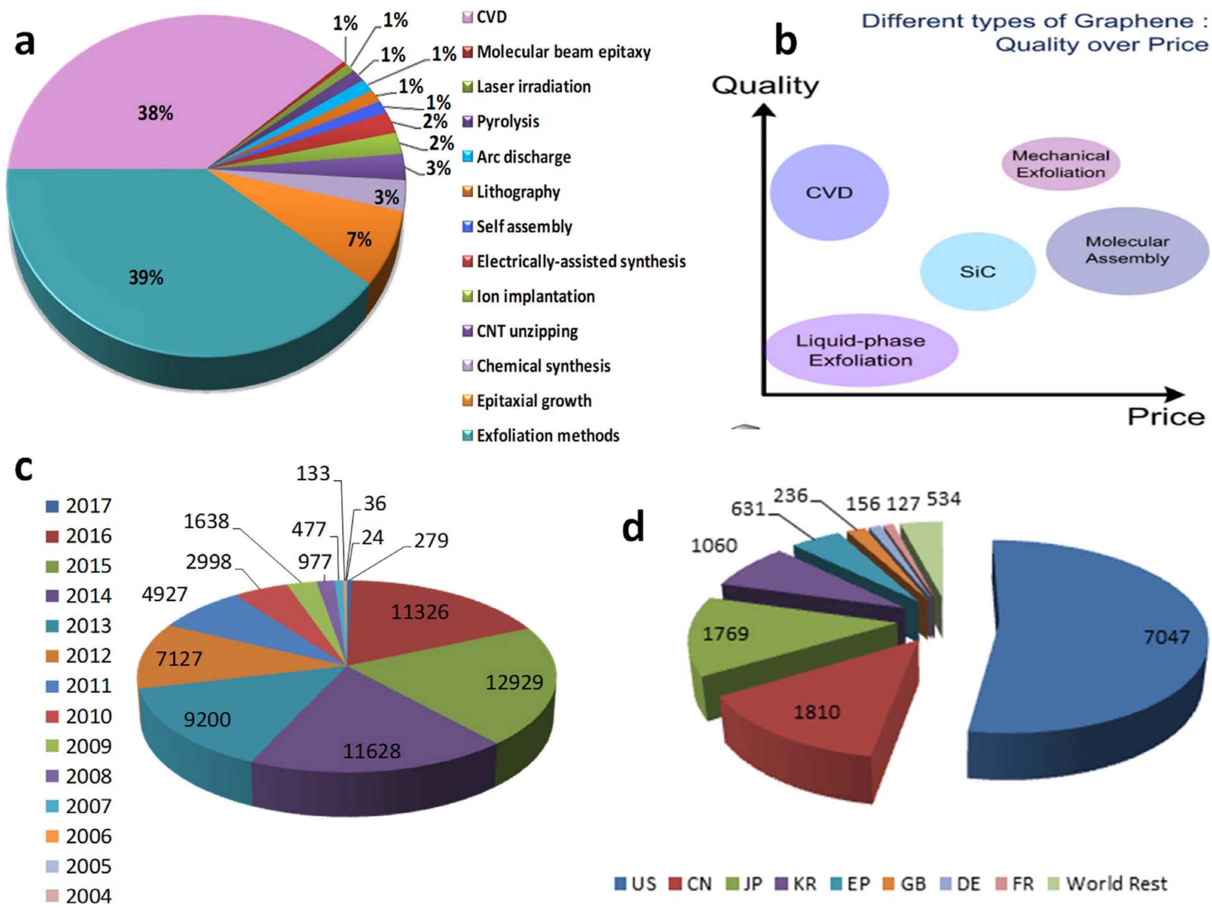

Fig. 2. **(a)** Segmentation of the methods of preparation of Graphene, **(b)** plot of the quality versus price of Graphene produced from the different synthetic routes, **(c)** number of annual articles in Graphene based materials published in the period from 2004–2017, and **(d)** number of annual patent on Graphene based compounds per country [4].

of synthesis, Graphene properties and applications. Referring to the IFI CLAIMS [4] Global Database and (Fig. 2(d)), most of the research work has been done in 30 countries with 96% of the work was done only in 8 countries in the period from 1996–2012 with a great contribution comes from United States (US), China (CN) and Japan (JP).

2. Graphene history

Carbon is an essential material for life and all organic chemistry sources. Carbon-based systems present a large number of different structures with different physical properties, which results from dimensionality of these structures due to carbon bond flexibility. Graphene is considered the starting point to recognize the electronic properties in other allotropes of carbon [5].

Theoretically, 2D graphite has been studied 6 decades ago [6,7] and extensively used for relating properties of various carbon-based materials. Four decades later, it was accomplished that Graphene also offers a fabulous condensed matter analogue of 3D quantum electrodynamics [8,9], which pushed Graphene into a flourishing theoretical toy model as shown in Fig. 3. Conversely, while known as vital part of 3D materials, Graphene was supposed not to be found in the free state and depicted as an "academic" material [10]. In addition, it is presumed to be unstable regarding the construction of the warped structures such as fullerenes and nanotubes. In 2004, the vintage model became a certainty, when free standing Graphene was unpredictably found, particularly when experiments verified that its charge carriers were, in fact, massless Dirac fermions [11,12]. Nobel Prize in Physics 2010 was awarded to Geim and Novoselov for innovative experiments concerning the 2D Graphene material.

Graphene is the flat single layer of carbon atoms strongly compacted into 2D honeycomb lattice and is the mother block for all graphitic materials (Fig. 4) [12]. It can be wrapped up into 0D fullerenes, rolled into 1D nanotubes or stacked into 3D graphite [6,14]. The Graphene crystals could be grown on the top of substrates [15], prepared in liquid suspension [16] or obtained as suspended membranes [17]. Therefore, the Graphene “gold rush” has begun.

3. Properties of Graphene

There has been a revolution in terms of discovering the complete range of Graphene properties, since the discovery of Graphene and description of its outstanding electronic features. Table 1 shows some of its exceptional properties that have been established to date [18,19]. Graphene is described as "the thinnest, most flexible and strongest material known" [20]. Graphene has C—C bond length ~1.42 Å, with a tough bond in a specific layer but weak bonding between layers, and specific surface area of a monolayer ~2630 $m^2\ g^{-1}$ [21]. Moreover, it has marvellous optical properties (~97.7% transmittance), high carrier mobility (~200,000 $cm^2\ Vs^{-1}$) and high Young's modulus (1.0 TPa) [22]. Graphene-based materials can be used as semi-conductors owing to their amazing conducting properties. Enoki et al [22], examined the exclusive magnetic properties of Graphene, such as spin glass states, magnetic switching, and edge-state spin gas probing, for the applications in electronic and magnetic devices. Chen, S. et al [23], stated short experimental studies on the isotope effects on the thermal properties of Graphene and discovered that the ratios of ^{12}C and ^{13}C play a vital role in the thermal conductivity of Graphene. All these extraordinary properties of Graphene have led to its inherent use for real applications.

Main advantages of Graphene are [24]: