COMMENT

Not just graphene

Read the news, flick through a journal, or browse the internet: it’s impossible to ignore a certain hexagonal monolayer. But there’s more to carbon than just graphene.

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When one thinks of carbon, graphite is probably the first thing that comes to mind; and there are good reasons for this. I have been drawing and writing with pencils, leaving traces of multilayer graphene on white paper, from a very early age. As I became older, I noticed that graphite was used everywhere; from motor brushes to battery electrodes. However, when I attend scientific meetings I see that graphene, not graphite, is king. Rooms are packed in graphene symposia; plenary and keynote talks on graphene attract large audiences at professional society meetings and materials science conferences. This is where the excitement is nowadays. The Nobel Prize for graphene in 2010 has led to a burst of interest in the thinnest of all carbon materials. Lectures on graphene currently collect huge crowds. Six of the ten most downloaded papers currently listed on the website of the premier journal in the field, Carbon, deal with graphene. Is this good, bad, or just typical when “a new kid on the block” appears?

Scientists often behave like children: when they get a new toy, they forget about the old ones, letting them collect dust under the bed. This first happened in carbon science after the invention of diamond synthesis methods followed by the discovery of fullerene, then nanotubes and, most recently, single-layer graphene. Is the latest favorite, graphene, (which is currently being tested in every application where graphite, nanotubes, and other graphitic carbons have been used) the best carbon material of all? It may appear so. However, it is important not to forget that other carbons exist, including graphite (from single crystals, to exfoliated and spherical), carbon fibers, glassy carbon, porous (activated, templated, and carbide derived) carbons, carbon black, soot, and, of course, diamond. Some of the more conventional and well-known materials, such as activated carbon (charcoal) or graphite, have been used for many centuries or even millennia. There also exist amorphous varieties, often with mixed sp²/sp³ bonding; diamond-like carbon, a -CH, and hard carbon films. Carbon nanomaterials that have been attracting a great deal of attention in the past 20+ years include fullerenes (also polymerized, endohedral, and exohedral fullerenes), carbon onions (multi-shell fullerenes) nanotubes, whiskers, nanofibers, cones, nanohorns, nanodiamonds, and others. Many of them are, in fact, entire families of materials. For example, nanotubes can be single-, double-, triple-, or multi-walled. The zigzag, armchair, or chiral wrapping of single-walled tubes determines their electrical properties (metal or semiconductor) and the diameter determines the band gap of semiconducting nanotubes. Multi-walled nanotubes can be seamless graphitic cylinders, scrolls, or have a polygonal cross-section. Fullerene-filled nanotubes form hybrid structures known as carbon peapods. A paper on carbon nanotubes published by Iijima in 1991 stimulated the development of the entire nanotechnology field. Dramatic progress in synthesis and purification of nanotubes has been achieved and many applications are emerging. This fact, along with substantial funding for nanotube research over the past decade, explains the steady growth of papers on nanotubes. The number of nanotube papers published annually increased by almost an order of magnitude between 2000 and 2010, while the number of papers on fullerenes (which have not yet found significant applications) did not even double during the same period of time. As the interests of researchers and funding shifted towards graphene, it is not surprising that the number of papers on graphene increased by a factor of twenty over the past five years (according to Scopus), and keeps growing.

Carbons can be hard (diamond) or soft (graphite and fullerene crystals), chemically passive (basal planes of graphite) or active (graphene edges), transparent or opaque, semiconducting, metallic, or dielectric. Moreover, the band gap of semiconducting nanotubes or graphene ribbons can be tuned. Thus, virtually any combination of mechanical, electrical, or chemical properties can be achieved by controlling carbon structure and surface chemistry. This is why we need many different carbon materials, because no single material is appropriate for all applications. For example, based on the literature, nanodiamonds are the most biocompatible of all carbon nanoparticles and are well suited for in vivo applications, while spherical carbon onions and carbon blacks can be easier to mix with other materials (as a conductive additive) than high aspect ratio nanotubes or graphene.

Carbon is exciting as a material because it has the potential to adopt such a variety of allotropes and forms. We can expect new carbon structures to be discovered in the future: a number of hypothetical structures have been theoretically predicted, but not yet synthesized. Already reported, but poorly studied, structures (carbynes, n-diamond, etc.) provide scope for new discoveries and novel applications, if they can be better understood and produced in quantities that will allow thorough structural analysis and property characterization. Every new carbon structure discovered and every new modification of known allotropes adds to the variety of materials that scientists and engineers have in their toolbox. With the number of carbon applications steadily growing, we may find ourselves in the carbon age within less than a decade, especially if carbon electronics become a reality.

Carbon is the most versatile material and there are already thousands of carbon materials to choose from. Graphene and its modifications are a part of this large family, and while the ability of scientists to tailor nanostructures from single or multiple graphene layers is a triumph of nanotechnology, let’s not forget that other carbons possess many valuable properties and should not be ignored.