Chapter 1
Introduction to Carbon

Carbon is a chemical element with symbol C, atomic number of 6, and electron configuration of [He]$2s^2 2p^2$. Its name origins from Latin *carbo* and French *charbon* meaning charcoal [1]. Carbon is the fourth most abundant chemical element in the universe by mass. It is also the second abundant element by mass in human body.

Carbon has been known since prehistoric time. Woods, mainly consisted of carbon, have been widely used for warming and cooking from prehistoric time. Diamond, another allotrope of carbon, has been treasured as gemstones because of remarkable optical characteristics and widely applied in industry because of superior hardness and good thermal conductivity. In the first chapter of this book, we briefly review the family of carbon.

The well-known allotropes of carbon are diamond, graphite, amorphous carbon, and fullerenes. Figure 1.1 shows crystallographic structures of these allotropes.

Diamond consists of pure sp^3 hybridized carbon atoms (Fig. 1.1a). It is renowned for its extreme hardness (hardest natural materials with Mohs hardness of 10 since antiquity) originating from the strong covalent bonding between carbon atoms and for its relatively high optical dispersion of visible spectrum coving 1–5.5 eV [2] and thermal conductivity (900–2,320 W/m/K [3]). Diamond is mainly applied in industrial cutting and polishing tools besides as the most popular gemstone in our life. There are many books which reviewed the properties and applications of diamond [4–8].

Graphite has a layered and planar structure (Fig. 1.1b). In each layer, the carbon atoms are arranged in a hexagonal lattice with a lattice parameter of 0.142 nm while the distance between planes is 0.335 nm, making it the softest natural materials with Mohs hardness of 1. Each graphite layer is consists of pure sp^2 hybridized carbon atoms and van der Waals force holds the layers together. Graphite is mainly applied in industry for lubrication. Physical properties, preparation, and applications of graphite are summarized in some books [8–11].

Amorphous carbon, such as soot and black carbon, does not have any crystalline structure (Fig. 1.1c). Amorphous carbon can be used as inks, paints, and industrial

Z. Ren et al., *Aligned Carbon Nanotubes*, NanoScience and Technology,
DOI: 10.1007/978-3-642-30490-3_1, © Springer-Verlag Berlin Heidelberg 2013

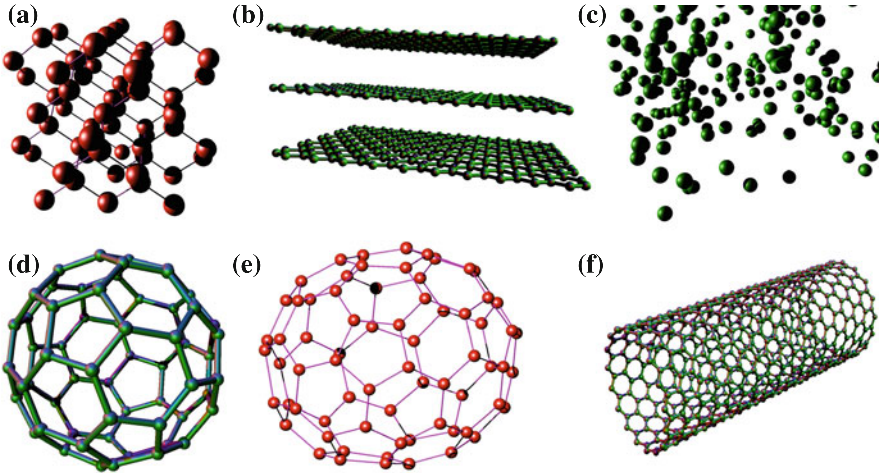

Fig. 1.1 Allotropes of carbon. **a** Diamond. The carbon atoms are bonded together in a tetrahedral lattice arrangement. The carbon atoms are sp^3 hybridized. **b** Graphite. The carbon atoms are bonded together in sheets of a hexagonal lattice. Van der Waals force bonds the sheets together. The atoms are sp^2 hybridized. **c** Amorphous carbon. The carbon atoms are randomly arranged. **d** Spherical fullerene, C_{60}. The carbon atoms of fullerenes are bonded together in pentagons and hexagons. **e** Ellipsoidal fullerene, C_{70}. The carbon atoms are bonded together in an ellipsoidal formation. **f** Tubular fullerene, SWCNT. The carbon atoms are in a tubular formation

rubber fillers. The detailed physical properties and applications of amorphous carbon are summarized in some books [12–14].

The fourth allotrope of carbon is fullerene that is at nanoscale. The physics, chemistry, properties, and applications of fullerenes are described in many books [8, 15–25]. In this chapter, we briefly introduce the family members of fullerenes and describe their crystallographic structures.

Figure 1.1d–f illustrates the structures of fullerene members. The family includes the spherical fullerene (buckyball), ellipsoidal fullerenes, elongated cylindrical carbon nanotubes, and planar graphene. With the development of nanotechnology and nanoengineering, fullerene plays an important role in the nanoapplications.

The existence of C_{60}, nanospheres formed by 60 carbon atoms, was proposed in 1970 [26] and first discovered in arc-discharged carbon-soot in laboratory in 1985 [27]. Later C_{60} was found in various natural environments, like in rocks [28] on the earth, and in space [29]. C_{60} is the simplest buckyball with each carbon atom covalently bonded to three adjacent carbon atoms (Fig. 1.1d). The diameter of C_{60} sphere is around 1 nm. The hardness of buckyballs is greater than that of diamond, promising applications as polymer fillers to increase mechanical strength. Functionalized buckyballs have been developed for targeted drug delivery and antioxidants. The interested readers can refer to some books [30] and reviews [31].

Besides spherical C_{60}, ellipsoidal fullerenes are also observed in nature and synthesized in laboratories, such as C_{70} (Fig. 1.1e), C_{72}, C_{76}, and C_{84}. Icosahedral

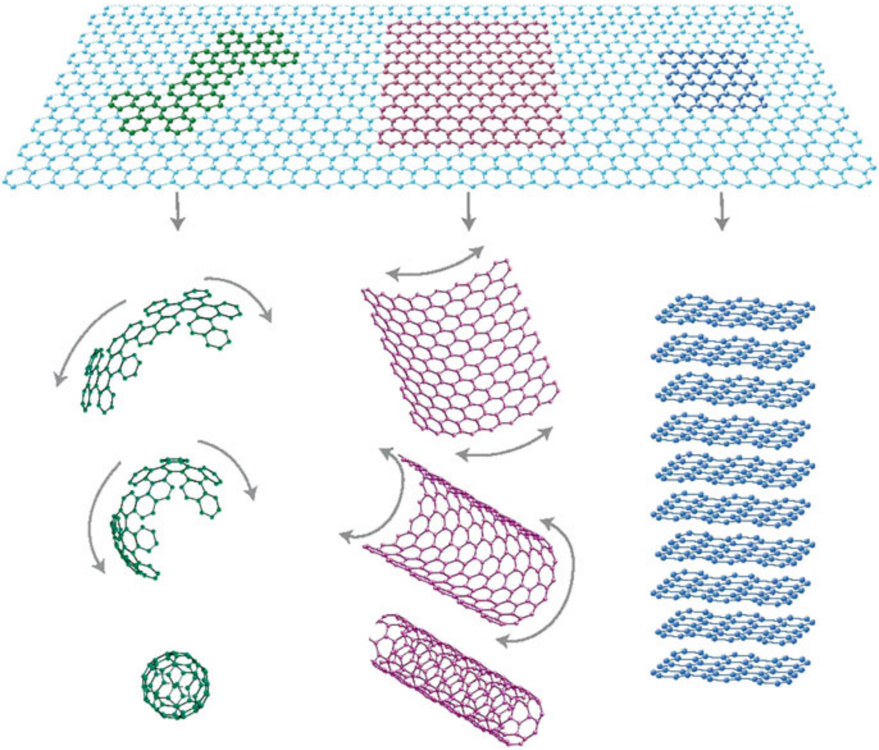

Fig. 1.2 Mother of all graphitic forms. Graphene is a 2D building material for carbon materials of other dimensionalities [36]. It can be wrapped up into 0D buckyballs (*left*), rolled into 1D nanotubes (*middle*) or stacked into 3D graphite (*right*)

fullerene, such as C_{540}, is also observed. The details of spherical-like fullerenes are summarized in some books and papers [32].

Carbon nanotubes (CNTs, also called buckytubes in earlier days) are elongated cylindrical fullerenes with diameters of nanometers and lengths of microns even millimeters. The carbon atoms in a CNT are bonded trigonally in a curved sheet (graphitic layer) that forms a hollow cylinder. Such unique nanostructures result in many extraordinary properties [33, 34], such as high tensile strength, high electrical and thermal conductivities, high ductility, high thermal and chemical stability, making them suitable for various applications.

CNTs are typically categorized as single-walled (SWCNTs), double-walled (DWCNTs), and multi-walled (MWCNTs) with respect to the number of graphitic layers. The nature of the atomic bonding in a CNT is described by applied quantum chemistry or, specifically, orbital hybridization. The chemical bonds in CNTs are sp^2 bonds, similar to those in graphite. More detailed atomic structures of individual CNTs are well described in many books [33, 34].

Graphene is a one-atom-thick planar sheet of carbon atoms with sp^2 hybridization (Fig. 1.2). The term *graphene* was coined as a combination of *graphite* and the suffix *-ene* to describe single-layer carbon foils in 1962 [35]. Graphene is most easily visualized as an atomic layer made of carbon atoms and their bonds. The sp^2 carbon atoms form a honeycomb crystal lattice [36].

Graphene is the basic structural element of some carbon allotropes and can be considered as mother of all graphitic forms. The graphene can be wrapped up into 0D buckyballs, rolled into 1D nanotubes, or stacked into 3D graphite (Fig. 1.2). For example, the crystalline form of graphite consists of many graphene sheets stacked together.

Graphene has potential applications in single molecule gas detection due to its 2D structure, in transistors because of its high electronic quality, in integrated circuits, in transparent conducting electrodes, as well as in solar cells, ultracapacitors, and biodevices because of its super physical properties in electric, electronic, optical, thermal, mechanical properties. The interested readers are referred to recent review papers [36].

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Aligned Carbon Nanotubes
Physics, Concepts, Fabrication and Devices
Ren, Z.; Lan, Y.; Wang, Y.
2013, XVI, 300 p., Hardcover
ISBN: 978-3-642-30489-7