Chapter

Introductory Chapter: Introduction to Advanced Carbon Materials and Innovative Engineering Applications

Sadia Sharif, Sana Arbab, Amna Saeed, Khurram Shahzad, Muhammad Aamir Iqbal, Abdullah Khan Durrani, Asghari Maqsood and Mujtaba Ikram

1. Introduction

Carbon belongs to the group IV of periodic table with atomic number 6. Graphite, diamond and fullerene are the allotropic forms of carbon. Carbon-based materials are versatile in term of applications due to its nature to chemically combine with other carbon-based materials and to make a strong covalent bond with a range of different elements. Therefore, they have outstanding properties like high strength, high density, and high hardness. The amazing characteristics of carbon materials make them most suitable candidate in various applications of advance technology. Graphene, carbon fibers, carbon foams, structural graphite (special graphite), carbon nanotubes (CNT), diamond-like carbon (dlc) and nano-crystalline diamond (ncd) are all included in advance carbon materials category. Advance carbon material are backbone of next generation scientific revolution especially in field of nanotechnology and materials sciences, respectively. Advanced carbon materials which are graphene, fullerenes, CNTs are considered most researched nanostructures in last couple of decades. Due to outstanding physical properties of advanced carbon monoliths, it has been used in photovolatic, environment, energy, thermal, and electronic applications. 21st century is being considered as "Scientific era of graphene", which is most amazing form of carbon due to highest electrical conductivity, thermal conductivity, strength and permeabile properties. Graphene is a material which conducts electricity and heat to maximum, which makes it an ideal candidate for energy and thermal applications, respectively. The following chapter will have a detailed insight in various forms of advanced carbon materials especially graphene, structural graphite, carbon nanotubes, diamond-like carbon (DLC), carbon foam and fullerene, respectively. The chapter grants detailed insight into physical properties and applications of advanced carbons materials.

2. Types of advanced carbon materials and related application

2.1 Graphene

Graphene is first ever 2-D allotropic form of carbon with hybridized Sp2 bonding which gave rise to new advancements in research and technology. The mysterious

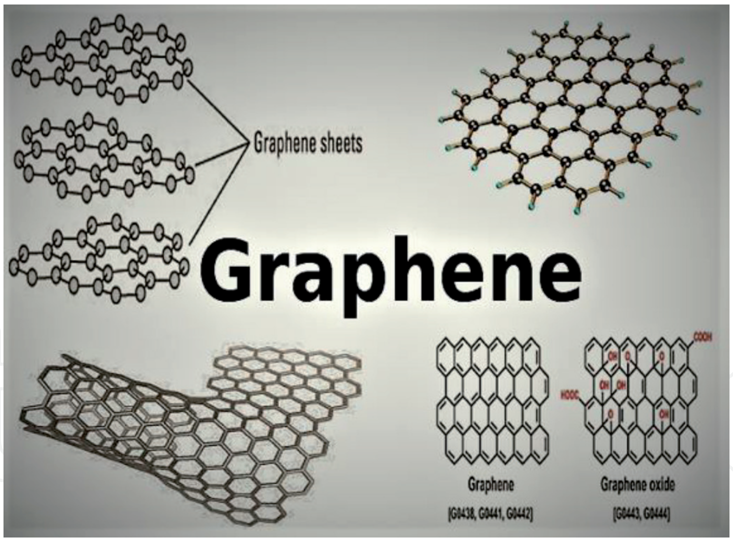

Figure 1.
Descriptive illustration of various structures of graphene.

electronics, structural, electrochemical, and physicochemical features of single layer of this material are significantly the big concern for the material scientists [1–4]. Mono atomic carbon layer extending across the two provided large surface areas due to an incredibly porous material [5], representing its potent absorbing ability. Hereby, scientists may conclude that it is a great adsorption applicant.

Thanks to the intersection among conduction and valence band at six positions in momentum at the Dirac points, graphene is often considered a zero-gap semiconductor [6]. Zero band gap depicts "zigzag" with the presence of an "armchair". Descriptive illustration of various structure of graphene is represented in **Figure 1**. Moreover, high charge room temperature durability, as demonstrated by previous research, is 15000 $cm^2.V^{-1}.s^{-1}$ [7]. In some earlier studies, the identical charge flexibility for hole and electron was also stated [8–11]. The splitting stability of charge carriers at a room temperature of audible graphene phonons is noted to be 4.5×10^3 times more than copper [12]. At room temperature, graphene plates give lowest resistivity 10^{-6} Ω cm, which is lower compared to silver [13]. Graphene in twisted bilayer form exhibited superconductivity [8, 14]. Owing to its adsorption power which is nearly 2.3% of the red light, and approximately 2.6% of the green light, the mono-atomic dense bilayer surface can be observed with the naked eye [14]. Graphene has an exceptional clarity for monolayer atomic structure in vacuum [15]. Thermal behavior, one of the key characteristics of graphene, an efficient and desirable tested route for many researchers because of its high ability in thermal applications. In previous experiments, a comparative study of graphite and graphene found that the thermal conductivity varies in both materials at room temperature which are 2000 $W.m^{-1}.K^{-1}$ and 5300 $W.m^{-1}.K^{-1}$, respectively [16]. However, recent progress has demonstrated that the former thermal conductivity value is sustainable, in fact it ranges from 1500 to 2500 $W \cdot m^{-1} \cdot K^{-1}$ for individual layer of graphene [17–25].

Graphene has two dimensions. The LA and TA showed linear dispersion relation whereas the quadratic scattering relation was observed because of off-plane mode. That is why the linear dispersion mode has high thermal conductivity relative to the off-plane mode [26]. The negative GPs found by the phonon graphene bands and at low temperatures are significant, while the clear link between the negative GPs and thermal expansion coefficient [27]. The graphene structure is layered and the spacing is around 0.335 nm between each sheet. Toughness of graphene is 130 GPa and it has 1TPa Young's Modulus, which is why it is significantly a stronger material than others [28]. Scientists have found that Graphene monolayer have a large-angle-bent, which gives a slight strain, so 2D carbon monoliths displayed important mechanical and physical features. Moreover, the charge mobility in the monolayer of graphene does not alter after high disruption [29].

2.1.1 Applied applications of graphene based materials

Graphene is versatile material owing to excellent physical properties. It has been used in many applications in industry and environment. Following are the applications of components from graphene.

- Energy storage and solar cell [30, 31]
- Sensors, photo detectors, Transistors and memories [32–40]
- Flexible, stretchable and foldable electronics [41–45]
- Biotechnology and medicines [46–51]

2.2 Structural graphite

The word "Graphite" is taken from a Greek-word "graphein" having meanings of "to write". This is a grayish-black naturally-occurring carbon-material with a radiant black-shine. It is a unique material which shows properties of both crystalline & non-crystalline and of a metal & non-metal. On this basis, graphite can be classified as natural and synthetic-graphite.

2.3 Natural-graphite

Naturally-occurring graphite is further grouped into three classes:

- Crystalline-graphite or structural-graphite
- Amorphous-graphite
- Flake-graphite

2.3.1 Crystalline or structural-graphite

Graphite has a layer-structure with hexagonal-arrangement of C-atoms containing covalent-bonding "honeycomb-structure". The layers are stacked together by secondary-bonding type that is, Van-der-Waals interactions which measure the weak shear-strength of graphite. Therefore, by applying a small shear-stress, deformation in structure happens and thus graphite comes out to be anisotropic where properties depend on the direction of applied-force. In structural-graphite, every C-atom is covalently associated to three neighboring C-atoms and that is how each atom leaves a spare free-electron. These free-electrons form a delocalized-cloud of electrons which is weakly bonded to layers which is an ultimate-reason of graphite's good electrical-conductivity along each layer [52]. Structure of graphite is respresented in **Figure 2**.

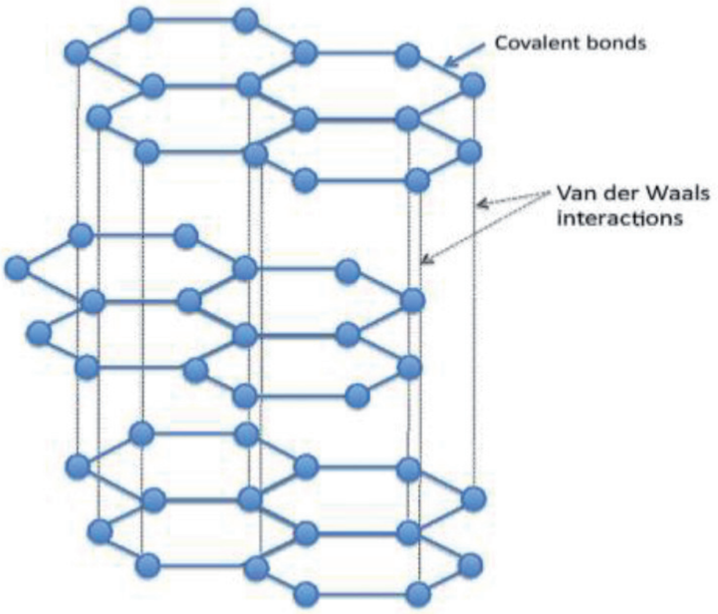

Figure 2.
Structure of graphite [52].

2.3.2 Artificial or synthetic-graphite

Artificial-graphite is obtained by graphitization of nongraphitic carbon and via chemical-vapor-deposition CVD from hydro-carbons using higher temperatures. This graphite is not highly crystalline as natural-graphite or structural-graphite. Example includes synthetic-graphite obtained via heating calcined-petroleum at about 2800°C.

2.3.3 Applied applications and physical properties of graphite

On account of structural, chemical and mechanical properties of graphite, some important applications are listed in the table below:

Properties	Areas of application
Chemical-inertness & high-T stability	Used as refractory-materials such as in making of refractory-bricks Mag-Carbon 'Mg-C'.
Directional electrical-conductivity	In chemical-industry, graphite is used as an electrode [53] in specific electrolytic-solutions and in various anti electrical-instrumental coverings as charges-passivator.
High-coefficients of thermal-conductivity & low-absorption of neutron	These properties enable graphite to use as moderator-rods and reflector-components in nuclear-reactors [54].

2.4 Carbon foam (C-foam)

The C-materials are best known for their wide-range porous-structure with variety of size and number of pores [55, 56]. Among fibrous, tubular, granular and other platelet & spherical morphologies of C-materials, C-foam has a particular-pore organization, where there is an interconnection of various macropores (cells) to form an open-cell-structure. Actually, this unique cell-structure defines the novel characteristics and features of these substances such as low density, high thermal-stability, water resistive surfaces, efficient thermal and electrical-conductivities, etc.

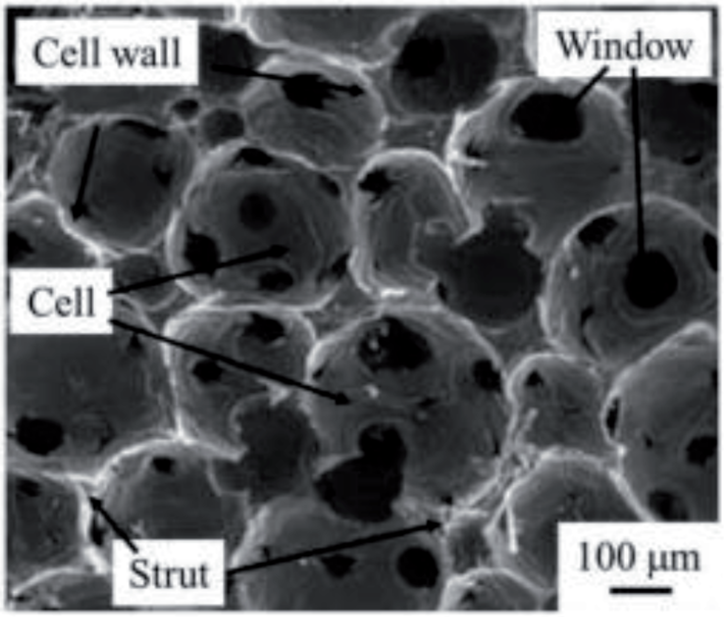

Figure 3.
SEM-shot of C-foam [57].

Thermal and electrical conductivities can be altered for bulky-C-products by making controlled-changes in the internal. Cell-structure to define C-foam can be understood thoroughly from the SEM-image in **Figure 3**. Two distinct pores can be observed in the image: a macropore called "cell" which is surrounded by "C-wall" and other is a hole in C-wall called "window". Window connects the neighboring cells together to form a Cell-structure. With these terminologies, the concept of C-foam is described as: Components with enlarged pores where cells (macropores or sometimes mesopores) are interconnected through windows and thus provide space to introduce other types of substances inside the pores to increase substrate compatibility [58].

2.4.1 Applied application and physical properties of C-foam

Properties	Applications
Low & High-electrical-conductivity (0.01-10^6 Ω)	Low conductivity-foams are perfect-electrical-conductors having a wide-bandgap to use in radar-absorption and electromagnetic-shielding applications. Similarly, RVC-foams (foams obtained through reticulated-vitreous-carbon) with high conductivity, 97% high-pore volume and honeycomb-structure are used as optically-transparent electrodes [59].
High-thermal conductivity	With good thermal conductivity and low thermal-expansion coefficients, C-foams can be used in thermal-energy storage-devices [60].
Coupling of low-weight, high-strength & resistance to fire	These properties enable C-foam to use in air-crafts and ship materials.
High-specific-area due to open-cell structure	Activation agents are used in C-wall to increase the volume of pores which ultimately provide a larger-specific-area for the adsorption/desorption of water [61–63], radioactive-Cs [61–65], carbon-dioxide and oxygen.

2.5 Carbon nanotubes (CNTs)

As the name suggests, these are tubes of carbon with diameters of nanometer-range which are also known as "bucky-tubes". The tubular C-structure was first studied in 1991 by Iijima [66, 67]. These were named as "multi-walled CNTs

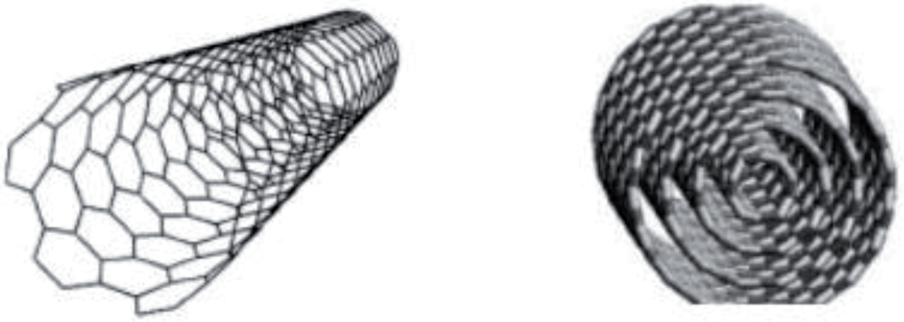

Figure 4.
(a) SW-NT [4] & (b) MW-NTs [71].

(MW-CNT)". Single-partition (SW) CNT was synthesized by Bethune [68]. Both the types can synthesize using three methods: arc-ablation, thermal decomposition and catalytic-growth. To understand the structure of SW-CNT, structure of crystalline-graphite should be known. As graphite contains stacked-layers of hexagonally-arranged C-atoms with sp^2-configuration. The stacking of these layers is due to inter-molecular forces and separately single layer is known as "graphene sheet". Each nanotube comprises of millions of C-atoms and in SW-NT only ten atoms are arranged at circumference and thickness of tube is ~1 atom [69, 70]. The structures of single wall and multi wall nanotubes are shown in **Figure 4**.

2.5.1 Applied applications and physical properties of CNT's

CNTs show a great combination of superlative-mechanical, electrical and thermal properties which is mainly due to sp^2 C-C bonding ability. These properties have opened their ways to the various areas of industrial-applications, some of them are listed below.

Properties	Areas of application
High-stiffness & High-tensile strength	CNTs are the strongest-material among other C-materials ever discovered by humans' history. These are the materials with Young's Modulus >1TPa which is 5× more than of steel and tensile-strength of ~63GPa which is 50× more than that of steel [72]. Due to these properties, CNTs have replaced steel in many applications such as sports-goods: bicycle-components, ice hockey-sticks, baseball-bats, skis etc.
Strong chemical and environmental-reliability & efficient thermal-conductivity	If these properties of CNTs are coupled with the light-weight property of C-based materials, then these materials have potential applications in the field of aerospace [73].
Electrical-conductivity	CNTs have high-electrical conductivity which is comparable to that of copper and are being used in electronics [74].

2.6 Fullerene

The fullerene discovery in 1985 has revotulized the scientific field. It has been used widely in physical, biological and chemical applications, respectively. Amazing physical properties are attribute of C60, which is actually a member of fullerene family.

2.7 Diamond-like carbon (DLC)

Diamond-like carbon (DLC) is undefined carbon [75, 76]. In DLC, considering the hybridization of sp3, no periodicity exists because of the heterogeneity of the bond angle C-C-C. The DLC has low density than that of diamond. Preferably DLC is composed of only sp3 carbon atoms. The processed content, though, sometimes contains sp3 and s2 carbon atoms. The existence of sp2 carbon atoms does not make the substance electrically isolated. In terms of hardness and thermal conduction, DLC is not as strong as diamond, but is much cheaper. The DLC is widely used for painting purposes for better wear resistance and thermal conductivity, owing to its low coefficient of friction. The DLC is normally produced by plasma enhanced chemical vapor deposition (PECVD. The accumulation conditions vary from DLC to diamond. The DLC is hydrogenated frequently during its development to inactive the collar bonds. Such passivation is beneficial to minimize the electric capacitance in the DLC [77].

3. Conclusion

Advanced carbon materials are backbone for scientific revolution of 21st century especially in nanotechnology. Carbon nanotubes (CNTs) and graphene are most researchered nanomaterials for the last decade due to outstanding physical properties. Graphene, being the first ever 2-D material, bring huge opportunities and potential for novel materials research due to good electrical conductivity, thermal conductivity, tensile strength and good dielectric properties, respectively. Due to unique characteristics of graphene monoliths, it has been employed in various fields such as electrical, thermal. Mechanical, and optical applications. In conclusion, advanced carbon materials will be the driving force for next generation scientific revolution.

Author details

Sadia Sharif[1], Sana Arbab[2], Amna Saeed[2], Khurram Shahzad[2],
Muhammad Aamir Iqbal[3], Abdullah Khan Durrani[2], Asghari Maqsood[4]
and Mujtaba Ikram[2]*

1 Department of Physics, Government College University, Lahore, Punjab, Pakistan

2 Institute of Chemical Engineering and Technology (ICET), University of the Punjab (PU), Lahore, Punjab, Pakistan

3 School of Materials Science and Engineering, Zhejiang University, China

4 Nanoscale Laboratory, Department of Physics, Air University, Islamabad, Pakistan

*Address all correspondence to: mujtaba.icet@pu.edu.pk

References

[1] Boehm, H. P.; Setton, R.; Pure and Applied Chemistry. 66(2012)1893-1906

[2] Simpson, C. D.; Brand, J. Diedrich; Berresheim, Alexander J.; Przybilla, Laurence; Räder, Hans Joachim; Müllen, Klaus 8(2002)1424-1429

[3] Geim, A. Science.324(2009) 1530-1534

[4] Ghoneim, Mohamed T.; Smith, Casey E.; Hussain, Muhammad M. (6 May 2013). AppliedPhysicsLetters.102(2013)

[5] Fraundorf, P.; Wackenhut, M. (2002). Astrophysical Journal Letters.578 (2) 153-156

[6] Jussila, Henri; Yang, He; Granqvist, Niko; Sun, Zhipei Optica.3 (2016) 151-158

[7] Carlsson, J. M. Nature Materials. 6(2007) 801-802

[8] Novoselov, K. S.; Geim, A. K.; Morozov, S. V.; Jiang, D.; Katsnelson, M. I. Grigorieva, I. V.;Dubonos, S. V.; Firsov, A. Nature.438(2005)197-200

[9] Morozov, S.V.; Novoselov, K.; Katsnelson, M.; Schedin, F.; Elias, D.; Jaszczak, J.; Geim, A. Physical Review Letters.100(2008)16602

[10] Chen, J. H.; Jang, Chaun; Xiao, Shudong; Ishigami, Masa; Fuhrer, Michael S. Nature Nanotechnology. 3(2008).206-9

[11] Akturk, A.; Goldsman, N. (2008). Journal of Applied Physics.103 (5) 053702 15. F. V.; Wu, W. M.; Pierpoint, M. P.; Yung, K. C. 67(2014)785

[12] Neto, A Castro; Peres, N. M. R.; Novoselov, K. S.; Geim, A. K.; Geim, A. Rev Mod Phys. 81(2010)109-162 90

[13] Zhu, Shou-En; Yuan, Shengjun; Janssen, G. C. A. M. EPL.108 (2014) 17007

[14] Nair, R. R.; Blake, P.; Grigorenko, A. N.; Novoselov, K. S.; Booth, T. J.; Stauber, T.; Peres, N. M. R.; Geim, A. K. Science.320 (2008)1308-1308

[15] Kuzmenko, A. B.; Van Heumen, E.; Carbone, F.; Van Der Marel, D..Physical Review Letters. 100(2008) 117401

[16] Balandin, A. A.; Ghosh, Suchismita; Bao, Wenzhong; Calizo, Irene; Teweldebrhan, Desalegne; Miao, Feng; Lau, Chun Ning. Nano Letters ASAP.8 (2008) 902-907

[17] Yousefzadi Nobakht, Ali; Shin, Seungha (14 December 2016) Journal of Applied Physics. 120(2016) 225111

[18] Cai, Weiwei; Moore, Arden L.; Zhu, Yanwu; Li, Xuesong; Chen, Shanshan; Shi, Li; Ruoff,Rodney S. Nano Letters. 10(2010)1645-1651

[19] Faugeras, Clement; Faugeras, Blaise; Orlita, Milan; Potemski, M.; Nair, Rahul R. ; Geim, A. K.ACS Nano. 4(2010)1889-1892

[20] Xu, Xiangfan; Pereira, Luiz F. C.et al; Nature Communications. 5 (2014)3689

[21] Lee, Jae-Ung; Yoon, Duhee; Kim, Hakseong; Lee, Sang Wook; Cheong, Hyeonsik Physical Review B. 83(2011)081419. 91

[22] Seol, J. H.; Jo, I.; Moore, A. L.; Lindsay, L.; Aitken, Z. H.; Pettes, M. T.; Li, X.; Yao, Z.; Huang, R.; Broido, D.; Mingo, N.; Ruoff, R. S.; Shi, L. 328(2010)213-216

[23] Klemens, P. G. " International Journal of Thermophysics. 22 ((2001) 265-275

[24] Jang, Wanyoung; Chen, Zhen; Bao, Wenzhong; Lau, Chun Ning; Dames, Chris NanoLetters. 10(2010)3909-3913

[25] Pettes, Michael Thompson; Jo, Insun; Yao, Zhen; Shi, Li Nano Letters. 11 (2011) 1195-1200

[26] Lifshitz, I.M. "Journal of Experimental and Theoretical Physics 22(1952)475

[27] Lee, C.; Wei, X.; Kysar, J. W.; Hone, J.Science. 321(2008)385-388

[28] Briggs, Benjamin D.; Nagabhirava, Bhaskar; Rao, Gayathri; Deer, Robert; Gao, Haiyuan; Xu, Yang; Yu, Bin Applied Physics Letters. 97 (2010) 223102

[29] Zandiatashbar, A.; Lee, G.-H.; An, S. J.; Lee, S.; Mathew, N.; Terrones, M. Hayashi, T.; Picu, R. C.; Hone, J.; Koratkar, N. Nature Communications. 5(2014) 3186

[30] Yin, Zongyou, Jixin Zhu, Qiyuan He, Xiehong Cao, Chaoliang Tan, Hongyu Chen, Qingyu Yan, and Hua Zhang. "Graphene-based materials for solar cell applications." Advanced energy materials 4, no. 1 (2014): 1300574.

[31] Li, Xianglong, and Linjie Zhi. "Graphene hybridization for energy storage applications." Chemical Society Reviews 47, no. 9 (2018): 3189-3216.

[32] Hill, Ernie W., Aravind Vijayaragahvan, and Kostya Novoselov. "Graphene sensors." IEEE Sensors Journal 11, no. 12 (2011): 3161-3170.

[33] Justino, Celine IL, Ana R. Gomes, Ana C. Freitas, Armando C. Duarte, and Teresa AP Rocha-Santos. "Graphene based sensors and biosensors." TrAC Trends in Analytical Chemistry 91 (2017): 53-66.

[34] Wang, Tao, Da Huang, Zhi Yang, Shusheng Xu, Guili He, Xiaolin Li, Nantao Hu, Guilin Yin, Dannong He, and Liying Zhang. "A review on graphene-based gas/vapor sensors with unique properties and potential applications." Nano-Micro Letters 8, no. 2 (2016): 95-119.

[35] Gan, Tian, and Shengshui Hu. "Electrochemical sensors based on graphene materials." Microchimica Acta 175, no. 1-2 (2011): 1.

[36] Schwierz, Frank. "Graphene transistors." Nature nanotechnology 5, no. 7 (2010): 487.

[37] Wang, Han, Thiti Taychatanapat, Allen Hsu, Kenji Watanabe, Takashi Taniguchi, Pablo Jarillo-Herrero, and Tomas Palacios. "BN/graphene/BN transistors for RF applications." IEEE Electron Device Letters 32, no. 9 (2011): 1209-1211.

[38] Schwierz, Frank. "Graphene transistors: status, prospects, and problems." Proceedings of the IEEE 101, no. 7 (2013): 1567-1584.

[39] Wu, Chaoxing, Fushan Li, Yongai Zhang, and Tailiang Guo. "Recoverable electrical transition in a single graphene sheet for application in nonvolatile memories." Applied Physics Letters 100, no. 4 (2012): 042105.

[40] Nashed, R., C. Pan, K. Brenner, and A. Naeemi. "Field emission from graphene sheets and its application in floating gate memories." Semiconductor Science and Technology 33, no. 12 (2018): 125003.

[41] You, Rui, Yu-Qing Liu, Yi-Long Hao, Dong-Dong Han, Yong-Lai Zhang, and Zheng You. "Laser fabrication of graphene-based flexible electronics." Advanced Materials 32, no. 15 (2020): 1901981.

[42] Kim, Sang Jin, Kyoungjun Choi, Bora Lee, Yuna Kim, and Byung Hee Hong. "Materials for flexible, stretchable

electronics: graphene and 2D materials." Annual Review of Materials Research 45 (2015): 63-84.

[43] Sharma, Bhupendra K., and Jong-Hyun Ahn. "Graphene based field effect transistors: Efforts made towards flexible electronics." Solid-State Electronics 89 (2013): 177-188.

[44] Koppens, F. H. L., T. Mueller, Ph Avouris, A. C. Ferrari, M. S. Vitiello, and M. Polini. "Photodetectors based on graphene, other two-dimensional materials and hybrid systems." *Nature nanotechnology* 9, no. 10 (2014): 780-793.

[45] Furchi, Marco, Alexander Urich, Andreas Pospischil, Govinda Lilley, Karl Unterrainer, Hermann Detz, Pavel Klang et al. "Microcavity-integrated graphene photodetector." *Nano letters* 12, no. 6 (2012): 2773-2777.

[46] Zhou, Xianfeng, and Feng Liang. "Application of graphene/graphene oxide in biomedicine and biotechnology." Current medicinal chemistry 21, no. 7 (2014): 855-869.

[47] Hakimi, Mohammad, and Paransa Alimard. "Graphene: synthesis and applications in biotechnology-a review." (2012).

[48] Yang, Mei, Jun Yao, and Yixiang Duan. "Graphene and its derivatives for cell biotechnology." Analyst 138, no. 1 (2013): 72-86.

[49] Feng, Liangzhu, and Zhuang Liu. "Graphene in biomedicine: opportunities and challenges." Nanomedicine 6, no. 2 (2011): 317-324.

[50] Priyadarsini, Subhashree, Swaraj Mohanty, Sumit Mukherjee, Srirupa Basu, and Monalisa Mishra. "Graphene and graphene oxide as nanomaterials for medicine and biology application." Journal of Nanostructure in Chemistry 8, no. 2 (2018): 123-137.

[51] Ding, Xili, Haifeng Liu, and Yubo Fan. "Graphene-based materials in regenerative medicine." Advanced healthcare materials 4, no. 10 (2015): 1451-1468.

[52] Tanzi, M. C., Farè, S., & Candiani, G. (2019). *Organization, Structure, and Properties of Materials.* Foundations of Biomaterials Engineering, *3-103.* doi:10.1016/b978-0-08-101034-1.00001-3.

[53] "Graphite Statistics and Information". USGS. Retrieved 2009-09-09.

[54] Arregui-Mena, J. D.; Bodel, W.; et al. (2016). "Spatial variability in the mechanical properties of Gilsocarbon". Carbon. 110: 497-517. doi:10.1016/j.carbon.2016.09.051.

[55] Zhou P and Chen Q L 2016 J. Anal. Appl. Pyrolysis 122 370

[56] Inagaki M, Konno H and Tanaike O 2010 J. Power Sources 195 7880-7903.

[57] Inagaki M., Qiu J., Guo Q., Carbon foam: preparation and application, Carbon (2015), doi:10.1016/j.carbon.2015.02.021.

[58] Klett J, Hardy R, Romine E, Walls C, Burchell T, High-thermal conductivity, mesophase-pitch-derived carbon foams: effect of precursor on structure and properties. Carbon 2000; 38: 953-973.

[59] Norvell V E, Mamantov G. Optically transparent vitreous carbon electrode. Anal Chem 1977; 49: 1470-1472.

[60] Hoogendoorn C J and Bart G C J 1992 Sol. Energy 48 53-58.

[61] Xiaon N, Ling Z, Wang L, Zhou Y, Qiu J. Preparation of zeolite/carbon foam monolithic composites with a hierarchical structure. New Carbon Mater 2010; 25: 321-324.

[62] Narasimman R, Prabhakaran K. Preparation of carbon foams by thermo-foaming of activated carbon powder dispersions in an aqueous sucrose resin. Carbon 2012; 50: 5583-5593.

[63] Tanzi, M. C., Farè, S., & Candiani, G. (2019). *Organization, Structure, and Properties of Materials.* Foundations of Biomaterials Engineering, *3-103.* doi:10.1016/b978-0-08-101034-1.00001-3.

[64] "Graphite Statistics and Information". USGS. Retrieved 2009-09-09.

[65] Arregui-Mena, J. D.; Bodel, W.; et al. (2016). "Spatial variability in the mechanical properties of Gilsocarbon". Carbon. 110: 497-517. doi:10.1016/j.carbon.2016.09.051.

[66] H.W. Kroto, J.R. Heath, S.C. O'Brien, R.F. Curl, R.E. Smalley, C60: buckminsterfullerene, Nature 318 (1985) 162.

[67] S. Iijima, Helical microtubules of graphitic carbon, Nature (London) 354 (1991) 56.

[68] S. Iijima, T. Ichihashi, Single-shell carbon nanotubes of 1-nm diameter, Nature (London) 363 (1993) 603.

[69] Saether E, Frankland SJV, Pipes RB. Transverse mechanical properties of single walled carbon nanotube crystals. Part I: determination of elastic moduli. Compos Sci Technol, 63, 1543 (2003). http://dx.doi.org/10.1016/S0266-3538(03)00056-3.

[70] Dresselhaus MS, Lin YM, Rabin O, Jorio A, Souza AG, Pimenta MA, Saito R, Samsonidze G, Dresselhaus G. Nanowires and nanotubes. Mater Sci Engg: C, 23, 129 (2003).

[71] T. Lin, V. Bajpai, T. Ji, and L. Dai, "Chemistry of carbon nanotubes," Australian Journal of Chemistry, vol. 56, no. 7, pp. 635-651, 2003.

[72] R. Saito, G. Dresselhaus, and M. S. Dresselhaus, *Physical Properties of Carbon Nanotubes*, London and Imperial College Press, 1998.

[73] M. F. Yu, B. S. Files, S. Arepalli, and R. S. Ruoff, "Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties," Physical Review Letters, vol. 84, no. 24, pp. 5552-5555, 2000.

[74] J. A. Elliott, J. K. W. Sandler, A. H. Windle, R. J. Young, and M. S. P. Shaffer, "Collapse of Single-Walled Carbon Nanotubes is Diameter Dependent," Physical Review Letters, vol. 92, no. 9, pp. 1-4, 2004.

[75] Robertson, John. "Classification of diamond-like carbons." In *Tribology of Diamond-Like Carbon Films*, pp. 13-24. Springer, Boston, MA, 2008.

[76] Ohgoe, Yasuharu, Kenji K. Hirakuri, Hidetoshi Saitoh, Takahiro Nakahigashi, Naoto Ohtake, Atsushi Hirata, Kazuhiro Kanda, Masanori Hiratsuka, and Yasuhiro Fukui. "Classification of DLC films in terms of biological response." Surface and Coatings Technology 207 (2012): 350-354.

[77] Grill, A. "Diamond-like carbon coatings as biocompatible materials—an overview." Diamond and related materials 12, no. 2 (2003): 166-170.