Nano World Journal

https://doi.org/10.17756/nwj.2018-056

Review Article

Open Access

Advances in Polymer/Graphene Nanocomposite for Biosensor Application

Ayesha Kausar

School of Natural Sciences, National University of Sciences and Technology (NUST), H-12, Islamabad, Pakistan

Correspondence to:
Dr. Ayesha Kausar, PhD
School of Natural Sciences
National University of Sciences and Technology (NUST), H-12, Islamabad, Pakistan
E-mail: asheesgreat@yahoo.com

Received: February 21, 2018
Accepted: May 07, 2018
Published: May 09, 2018

Citation: Kausar A. 2018. Advances in Polymer/Graphene Nanocomposite for Biosensor Application. *NanoWorld J* 4(2): 23-28.

Published by United Scientific Group

Abstract

In this article, polymer/graphene nanocomposite has been focused with reference to their application in biosensor. In this regard, various type of biosensors-based on polymer/graphene nanocomposite has been explored. Major categories of biosensors studied include electrochemical biosensor, flexible biosensor, field effect biosensor, and glucose biosensor. Owing to excellent electrical, mechanical, thermal, and biomedical features, polymer/graphene nanocomposite has been found to improve the performance of different type of biosensors.

Keywords

Polymer/Graphene, Nanocomposite, Glucose biosensor

Introduction

Theory of crystals pointed out that diverse contribution of thermal fluctuation in crystal lattice of low dimensionality may lead to variation of atoms relative to interatomic distance at any finite temperature [1]. The argument was greatly supported by experimental observation. Thus, with decrease in melting temperature of film decreases the film stability. The films becomes unstable (decompose or segregate into islands) at thickness of typically dozens of atomic layers. Thus, atomic monolayers have so far been recognized only as an integral part of larger 3D structures generally grown epitaxially on the monocrystals with matching crystals lattices [2, 3]. Until 2004, the common wisdom was flaunted by experimental discovery of graphene and other free standing 2D atomic crystals. At that time, 2D materials were presumed not to exist without a 3D base. These crystals were achieved on top of non-crystalline substrates as suspended membranes and non-crystalline substrates. Significantly, the 2D crystals were found not only to be continuous but to comprise high crystal quality. The later was clearer in the case of graphene in which the charged carriers may cover thousands of interatomic without scattering [4]. The name given to flat monolayers of carbon atom is graphene. The carbon atoms are tightly packed into two-dimensional honey comb lattice which is the basic building block of graphitic material of all the other dimensionalities as shown in figure 1. By wrapping it can be changed to 0D fullerenes, rolled into 1D nanotube, or 3D graphite. For 60 years, theoretical graphene or 2D graphite has been studied and is extensively employed for describing the features of several carbon-based graphene. It also provided outstanding condensed matter analogue of (2+1) dimensional quantum electrodynamics which propelled graphene into thriving theoretical toy model. On the other hand, however known as an integral part of 3D materials, graphene was not assumed to exist in free state. It was described as academic constituent and was supposed to be unstable with respect to the formation of unstable structures such as fullerene, nanotube, and soot [5, 6]. In biosensors, polymer/graphene nanocomposites have range of important applications.

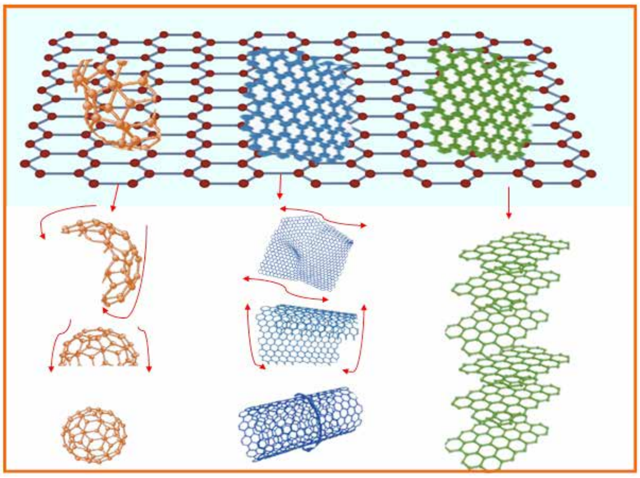

Figure 1: Graphene (2D building material for carbon material) wrapped up into 0D buckyball, rolled into 1D nanotubes, and stacked into 3D graphite.

Graphene

Graphene is an outstanding material. It has large theoretical surface area (2630 m^2/g), high Young's modulus (~1.0 TPa), thermal conductivity (~5000 $Wm^{-1} K^{-1}$), optical transmittance (~97.7%), and excellent electrical conductivity (10^2 S/m) at high pressure. Graphene merits attention for applications such as transparent conducting films among other perspective applications [7]. Over 40 years, graphene has been studied experimentally and for measurement of transport properties in micromechanically exfoliated layers of graphene (grown on SiC). Large surface area graphene have been grown on copper substrate. Variety of studies involving the employment of chemically modified graphene have been found in literature [8, 9]. A dynamic yet flexible graphene provides essentially infinite perspectives for its functionalization and modification of the carbon backbone. Comparison of relevant electronic and thermal properties of graphene with other related carbon material (Si, Cu, and single walled CNT) is shown in table 1.

Table 1: Comparison of physical properties of graphene with other materials.

Physical Properties	Graphene	Carbon nanotube	Si	Cu
Melting point (K)	3800	3800	1687	1357
Thermal conductivity (10^3 W/mK)	3-5	1.75-5.8	0.15	0.385
Current density (A/cm²)	> 10^8	> 10^9	-	10^7
Electron mobility (cm²/(V.s))	> 10,000	> 10,000	1400	-
Mean free path (nm)	1 × 10^3	> 10^3	20-30	40

The graphene honeycomb lattice is comprised of two equivalent sub lattices of carbon atoms bonded together with σ bonds. Each carbon atom in lattice has π orbital that links to a demoralized electron network. Freely suspended graphene has intrinsic ripples as addressed by Monte Carlo stimulation and transmission electron microscopy (TEM) studies [10]. The microscopic suggestions were estimated to have lateral dimension of about 8 to 10 nm height displacement of about 0.7 to 1 nm. Thus, due to outstanding thermal, mechanical, and electrical properties of graphene filler, they have been employed in several of applications in the form of polymer nanocomposite due to interaction of nanofiller with the polymer. Various current reviews have been appeared about graphing and relevant constituent [11-17]. The appraisals on the chemistry of graphene or exfoliated platelets have been originated from graphene oxide (GO). A brief summary of graphene production techniques are shown in table 2.

Table 2: Various techniques used for fabrication of graphene.

Technique used	Graphene synthesis
Chemical vapor deposition (CVD)	Production of single layer graphene
Liquid exfoliation method	Large scale production of graphene from graphite powder
Mechanical technique	Formation of atomic layer of graphene on SiO_2 (~300 nm)
Epitaxial growth	Graphene synthesis at high temperature (~1300 °C) on SiC substrate

Biosensor

The molecular sensors link biological mechanism for recognition using physical transduction route. They offer a novel class of portable and inexpensive instruments that allow sophisticated physical measurement to be undertaken rapidly at decentralized location [18]. Moreover, adoption of biosensor for practical applications rather than the measurement of blood glucose is recently restricted by insensitivity, expense, and inflexibility of available transduction routes. Thus, the progress of biosensing route is through population conductance of molecular ion channels by recognition events. The approach mimics biological sensory functions and can be employed with various types of receptors comprising nucleotides and antibodies [19]. Schematic of ion channel biosensor is shown in figure 2. The route is very flexible and even flexible form is sensitive to picomolar protein concentration. It is essentially an element of impedance whose dimensions can readily be decreased to become an integral constituent of microelectronic circuit. It is utilized in extensive range of applications and in complex media comprising blood. These sensors might comprise cell typing, detection of viruses, large proteins, antibodies, DNA, electrolyte, pesticides, drugs, and other low molecular weight constituents [20].

The reactive elements of ion channel switch include gold electrode to which a membrane containing gramicidin ion channels was combined to antibodies. The molecular structure of the tied membranes results in an ionic reservoir being formed among the gold electrode and membrane. The ionic reservoir can be electrically processed by connection through gold electrode. In the presence of an applied potential, when the channels are conductive, ions flow occurs between the external solution and reservoir [21, 22]. When the mobile channels diffusing with in outer half of membrane become cross-linked to antibodies immobilized at the surface of membrane, the ionic current is switched off. This inhibits the diner formation with channels immobilized with the membrane inner half. The measurement of number of dimers has been carried out from the electrical conduction of membrane. The switch has high gain, single channels flourishing the flux of up to million ions per second. Thus, verification on the quantitative model of biosensors has also been carried out. The analyses recognition comprising multiple detection sites performed by employing the structure is displayed in figure 3.

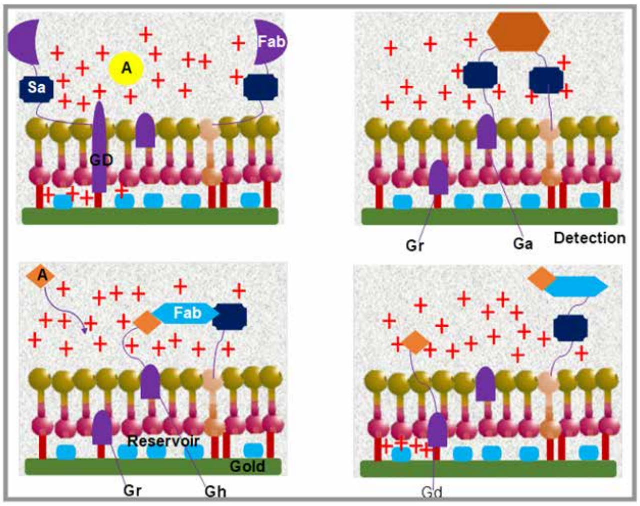

Figure 2: Schematic ion-channel switch (ICS) biosensor.

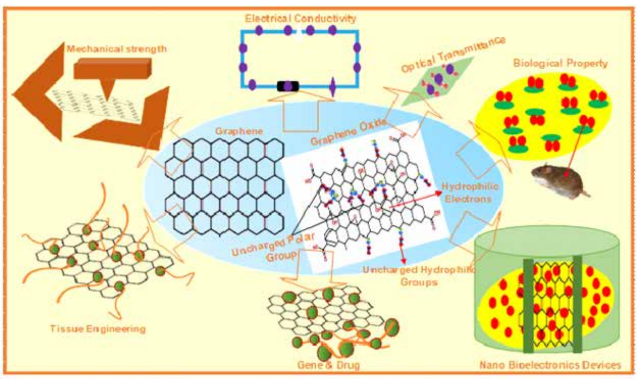

Figure 3: Representation of graphene-based electrochemical sensor in DNA, protein, and cancer cell detection.

The structure is collected employing a combination of sulphur gold chemistry and physisorption [23]. The membrane comprises of lipids and channels which remains immobilized on gold surface, while some of these diffuse literally with in the membrane plane. The antibodies of mobile channel cause scanning of an area of the order of 1 mm^2 less than 5 min. Thus, with the channels of low density and immobilized antibodies of high density, each channel may access up to 103 more capture antibodies in comparison to that of gating mechanisms triggered by direct analyte binding to channels. The sensitivity and speed of biosensor response may be adjusted in direct proportion to the number of binding sites accessible to each channel of mobile. This permits for quantitative recognition of analyte from sub-picomolar concentration of less than 10 min [24].

Polymer/Graphene in Biosensor

The discovery of the capability of carbon to form two-dimensional (2D) modification in the form of graphene led to extensive growth in material features and its perspective application in electronics. It is recognized that graphene comprises excellent set of electrical features including high charge mobility at low concentration and maximum perspective ratio of surface area to volume and low noise level [25]. Because of this combination, the adsorption of an extremely low amount of impurity on graphene surface can remarkably alter the total conductivity. Graphene is an outstanding material for creation of numerous sensors. It is displayed that graphene is capable of detecting absorption of even single molecule [26, 27]. The attached molecules of gas, depending on their charge and graphene conductivity, act as donor or acceptors that cause modification in concentration of mobile charge carrier. Consequently, the resistance of graphene film is reduced or enhanced depending on the absorbed type of molecule. It should be noted that considerable disadvantage of graphene-based gas sensors is the lack of selectivity [28]. In general, an alteration in conductivity does not recognize that which of the particular molecule is adsorbed on graphene surface. However, some molecules contribute to conductivity with opposite signs, so that the total change in the resistance is nearly zero [29]. The problem is the selection of graphene based sensors. It can be solved by employment of antigen-antibody reaction. The constituent of such pair can only be interfaces with each other and not with any other type of protein. It is well recognized that certain stages of many diseases involve emergence of antigen markers that are specific of one disorder or group of numerous disorders. The antigens may cause binding to specific antibodies preliminary immobilized on graphene sensor surface [30]. Thus, the antigen-antibodies reaction may lead by similarity with gas sensors to alteration in resistivity of graphing film. By using antigen-antibodies pair, it is perspective to solve the sensitivity problem in biosensors and broad possibilities for application of graphene-based sensors in medicine and biology. This approach may direct to creation of miniature biosensor capable of the detection of diagnostically remarkable markers in biological fluids in the regime of rapid analysis for diseases which are presently only detected by laborious and time consuming procedure of enzyme immunoassays [31, 32].

Types of Polymer/Graphene-based Biosensor

Since graphene and its relevant derivatives have fascinated the interest of numerous scientific fields mainly energy technology, nanoelectronics, sensors, bioscience, and biotechnologies because of their electric-electronic and physiochemical features. Generally, these exceptional features comprise excellent electrical conductivity, high surface area, strong electrical conductivity, good thermal conductivity, high charge mobility, good optical transparency, and ease of biological as well as chemical functionalization [33, 34]. Because of outstanding physiochemical features, graphene-based nanomaterial presents great opportunities into wide variety of biomedical applications. Accordingly, they comprise various types of biosensors mainly graphene-based DNA biosensors, graphene-based glucose biosensors, graphene-based Hb biosensors, graphene-based cholesterol biosensor, and graphene-based electrochemical biosensors, etc. [35].

Electrochemical biosensor

The electrochemical detection is highly sensitive to electrically active molecules which is the feature of electrical detection. It also presents detection selectivity due to the oxidation and reduction of different molecules at different potential. Graphene nanofiller is excellent conductor of electrical charge. The heterogeneous transfer of electrons occurs at the defects in basal planes or at the edge of graphene [36, 37]. Thus, the excellent surface area of graphene facilitates greater amount of defects and thus electroactive sites. Graphene has been used in numerous schemes for glucose sensing. This is reflected by the fact that electrochemistry is crucial for the glucose sensing for diabetic patients. Graphing has also used for electrochemical immunosensing. In immunosensing the direct electrochemical detection of antibody antigen detection is generally not possible and so electrochemically active labels must commonly be employed [38]. First graphene can be utilized as electrode surface for sensitive detection of label. This case was utilized for graphene enhanced detection of α-fetoprotein, which is biomarker for cancer. The modification of graphene sheets was carried out by antibodies, then the α-fetoprotein was added and consequently secondary antibodies loaded with microspheres bearing horseradish peroxidase enzyme were sensitive labels [39, 40]. The second approach utilizes graphene as label bearing nanocarriers. More generally a gold nanoparticles was modified with probe antibody to phosphorylated protein p53. Thus, the conjugation of secondary antibodies was carried out with graphene oxide for the generation of large amount of electrically active molecules and thus large signals were produced [41]. The sensing depends on conjugation of graphene oxide with antibody to offer assessable binding sites.

Electrode in glucose biosensor

One of the most clinically critical diseases in the world is diabetes and it is significant to make a quantitative determination of the glucose level in blood for diagnosis of this disorder. This metabolic disorder results in insulin deficiency and hyperglycemia and it is reflected by blood glucose concentration lower or higher in comparison to that of normal range of 80-120 mg dL^{-1}. The disease causing severe conditions comprising death and disability [42]. Accordingly, the treatment and diagnosis of this disease needs close monitoring of blood glucose level. Graphene supplies highly sensitive and cost efficient material for the production of glucose biosensors. The graphene-based glucose biosensors with polyethylenimine/graphene-functionalized ionic liquids nanocomposite modified electrode have been synthesized [43]. It comprises extensive linear glucose response, efficient reproductivity, and strong stability. The exploration on the efficiency of chitosan in dispersing graphene and constructed glucose biosensors with desired sensitivity was also studied [44]. Thus, it was shown that chitosan helped to form well-integrated graphene suspension and immobilized the biomolecules. Graphene-based biosensors displayed high sensitivity (37.93 μA $mM^{-1}cm^{-2}$) and long term stability of measuring glucose. Graphene/metal nanoparticle-based biosensors have also been developed to detect glucose. Qui et al. [45] synthesized Pt/PANI/GN-based sensor comprised a detection limit of 50 mM for H_2O_2. After immobilization of GO, Pt/PANI/GN modified electrode indicated a detection limit of 0.18 μM for glucose.

Graphene paper as flexible biosensor

Flexible biosensor comprising dramatic shape alteration are instrumental for the progress of portable point of care medical products, minimally invade implantable devices, and complex diagnostic platform. Biosensors based on electrochemical read out offers a major class of analytical tools in clinical applications [46]. A capable building block of intriguing actual technological and scientific interest is graphene. It has two-dimensional single atom thick sheet of sp^2 hybridized carbon atom arranged in a honeycomb lattice with outstanding mechanical, electrical, and thermal features. Individual water soluble graphene sheets are heavily oxygenated comprising hydroxyl and epoxy functional groups on their basal planes (in addition to carboxyl and carboxyl groups located at the sheet edges). It is collected by flow directed vacuum filtration process into interlocking tile arrangement yielding free standing and highly flexible GO paper [47]. Thus, the presence of oxygen moieties provides GO sheets with the hydrophilic character and imparts versatile high volume processing possibilities from stable aqueous suspension into GO paper and other microscopic assemblies. They also heavily disrupt the conjugated sp^2 network of basal plane of single graphene sheet and drastically degrade their electronic features [48].

Field-effect transistor biosensor

Graphene is a single layer of graphite that has the ability to solve the problem with CNT-based Field-effect transistor (FET). They are ideal two dimensional crystals that displays an extremely high mobility of ~10^4 $cm^2V^{-1}s^{-1}$ and large carrier capability of ~10^{12} cm^{-2} even at room temperature without doping. As their electrical features are sensitively effected by surface conditions, gas molecule sensors by employing graphene field effect transistor (GFET) have been reported [49]. However, many electrical features of GFET have been investigated for the electrical detection of biological and chemical sensing using GFET. The mechanism of action for GFET sensors is their biological and chemical species absorbed on the graphene surface. It acts as electron acceptors or donor resulting in alteration in conductance. To realize GEFT biological sensors, it is significant to investigate the electrical features under low electrical field because of avoidance of biomolecules oxidization [50]. The general size of graphene obtained by this route was 10 μm. The formation of Ti/Au (5 nm/30 nm) was carried out by conventional e-beam lithography, metal deposition, and lift-off route. The degenerately doped silicon substrate was also employed for black gate. Numerous pH solutions were made by mixing of 10 mM phthalate buffer solution at pH of 4, a 10 mM phosphate buffer solution at pH of 6.8, and 10 mM borate buffer solution at pH of 9.3. The leakage current between the Au electrode and solution was found to be negligible. Initially, the investigation was carried out on the transport behavior of GEFT in electrolyte. In an electrolyte, the electrical double layer acts as the top-gate insulator with thickness generally defined by Debye-Huckel equation. The thickness was dependent upon the ionic strength and was as small as 1-5 nm in an electrolyte with the concentration of several millimolar. The GFET was immersed in the electrolyte and silicon rubber was placed on GFET to allow the graphene surface channels to be filled with numerous buffer solution and analyses for sensing and electrical measurements [51].

Summary

Graphene is an outstanding nanofiller with excellent electrical conductivity and durability under atmospheric conditions. Because of these properties, they have been used in almost all fields. Thus, the applications of graphene in biosensors have been summarized. The types of polymer/graphene have been used as glucose biosensor, electrical field transistor, electrochemical biosensor, and graphene paper. Accordingly, polymer/graphene nanocomposite has outstanding properties and has been employed on large scale in biosensors.

References

1. Kausar A. 2016. Investigation on nanocomposite membrane of multiwalled carbon nanotube reinforced polycarbonate blend for gas separation. *J Nanomater* 2016: 7089530. https://doi.org/10.1155/2016/7089530
2. Kausar A. 2016. Composite of triglycidyl *para*-amino phenol, polystyrene and [3-(2-aminoethylamino) propyl] trimethoxysilane-modified graphite. *Int J Compos Mater* 6(6): 167-171. https://doi.org/10.5923/j.cmaterials.20160606.01
3. Kausar A. 2016. Poly (acrylonitrile-co-butadiene-co-styrene)/fly ash/halloysite nanotube composites: a study on physical properties and performance in fuels. *Int J Plast Technol* 20(1): 57-66. https://doi.org/10.1007/s12588-016-9133-8
4. Kausar A. 2016. Performance of epoxy and nanodiamond exfoliated montmorillonite nanocomposite. *Int J Aerosp Sci* 4(1): 9-13. https://doi.org/10.5923/j.aerospace.20160401.02
5. Nawaz S, Siddiq M, Kausar A, Hussain ST, Abbas F. 2014. Facile synthesis and properties of multilayered polyaniline/polypyrrole/epoxy/polystyrene/functionalized carbon nanotube composites. *Polym Plast Technol Eng* 53(7): 661-670. https://doi.org/10.1080/03602559.2013.874032
6. Kausar A. 2014. Synthesis and properties of melt processed poly(thiourea-azosulfone)/carbon nanotubes nanocomposites. *Chinese J Polym Sci* 32(1): 64-72. https://doi.org/10.1007/s10118-014-1379-z
7. Kausar A, Ashraf R. 2014. Electrospun, non-woven, nanofibrous membranes prepared from nano-diamond and multi-walled carbon nanotube-filled poly(azo-pyridine) and epoxy composites reinforced with these membranes. *J Plast Film Sheet* 30: 369-387. https://doi.org/10.1177/8756087913518546
8. Anwar Z, Kausar A, Khan LA, Muhammad B. 2016. Modified graphene nanoplatelet and epoxy/block copolymer-based nanocomposite: physical characteristic and EMI shielding studies. *Nanocomposites* 2(3): 141-151. https://doi.org/10.1080/20550324.2016.1236535
9. Kausar A. 2016. Physical properties and shape memory behavior of thermoplastic polyurethane/poly(ethylene-alt-maleic anhydride) blends and graphene nanoplatelet composite. *Iran Polym J* 25(11): 945-955. https://doi.org/10.1007/s13726-016-0481-1
10. Kausar A. 2016. Thermal conductivity measurement of polyvinylpyrrolidone/polyethylene/graphene nanocomposite. *Nanoscience and Nanotechnology* 6(2): 34-37. https://doi.org/10.5923/j.nn.20160602.03
11. Ahmed N, Kausar A, Muhammad B. 2016. Shape memory properties of electrically conductive multi-walled carbon nanotube-filled polyurethane/modified polystyrene blends. *J Plast Film Sheet* 32(3): 272-292. https://doi.org/10.1177/8756087915595454
12. Ullah M, Kausar A, Siddiq M, Subhan M, Abid Zia M. 2015. Reinforcing effects of modified nanodiamonds on the physical properties of polymer-based nanocomposites: a review. *Polym Plast Technol Engineer* 54(8): 861-879. https://doi.org/10.1080/03602559.2014.979505
13. Kausar A. 2016. Estimation of thermo-mechanical and fire resistance profile of epoxy coated polyurethane/fullerene composite films. *Fuller Nanotub Carbon Nanostruct* 24(6): 391-399. https://doi.org/10.1080/1536383X.2016.1172067
14. Ashraf A, Tariq M, Naveed K, Kausar A, Iqbal Z, et al. 2014. Design of carbon/glass/epoxy-based radar absorbing composites: microwaves attenuation properties. *Polym Engineer Sci* 54(11): 2508-2514. https://doi.org/10.1002/pen.23801
15. Ashraf R, Kausar A, Siddiq M. 2014. Preparation and properties of layered carbon nanotube/polyazopyridine/nanodiamond composites. *J Plast Film Sheet* 30(4): 412-434. https://doi.org/10.1177/8756087914527982
16. Khan LA, Kausar A, Hussain ST, Iqbal Z, Day RJ, et al. 2014. Cure characterization of cycom 977-2A carbon/epoxy composites for quickstep processing. *Polym Engineer Sci* 54(4): 887-898. https://doi.org/10.1002/pen.23629
17. Hussain, ST, Abbas F, Kausar A, Khan, MR. 2013. New polyaniline/polypyrrole/polythiophene and functionalized multiwalled carbon nanotube-based nanocomposites: layer-by-layer *in situ* polymerization. *High Perform Polym* 25(1): 70-78. https://doi.org/10.1177/0954008312456048
18. Kausar A. 2016. Synthesis and properties of novel polystyrene/polyurea and functional graphene-based nanocomposite foams. *J Cell Plast* 53(3): 305-318. https://doi.org/10.1177/0021955X16652104
19. Kausar A. 2017. Pb (II) selective sensor of poly(vinyl chloride-vinyl acetate)/polyaniline/carbon black. *Int J Instrumentat* Sci 6(1): 8-11. https://doi.org/10.5923/j.instrument.20170601.02
20. Kausar A. 2016. Poly(vinylacetate)cyanomethyl diphenylcarbamodthioate/poly(vinyl acetate)/carbon black composite-based sensor. *Int J Instrumentat Sci* 5(2): 19-23. https://doi.org/10.5923/j.instrument.20160502.01
21. Kausar A. 2016. Design of polydimethylsiloxane/nylon 6/nanodiamond for sensor application. *Int J Instrumentat Sci* 5(1): 15-18. https://doi.org/10.5923/j.instrument.20160501.03
22. Javed N, Habib A, Amin Y, Loo J, Akram A, et al. 2016. Directly printable moisture sensor tag for intelligent packaging. *IEEE Sensor J* 16(16): 6147-6148. https://doi.org/10.1109/JSEN.2016.2582847
23. Florin E-L, Gaub HE. 1993. Painted supported lipid membranes. *Biophys J* 64(2): 375-383. https://doi.org/10.1016/S0006-3495(93)81378-X
24. Lang H, Duschl C, Vogel H. 1994. A new class of thiolipids for the attachment of lipid bilayers on gold surfaces. *Langmuir* 10(1): 197-210. https://doi.org/10.1021/la00013a029
25. Khan DM, Kausar A, Salman SM. 2016. Exploitation of nanobifiller in polymer/graphene oxide-carbon nanotube, polymer/graphene oxide-nanodiamond, and polymer/graphene oxide-montmorillonite

composite: a review. *Polym Plast Technol Engineer* 55(7): 744-768. https://doi.org/10.1080/03602559.2015.1103266

26. Kausar A. 2016. Bucky papers of poly(methyl methacrylate-co-methacrylic acid)/polyamide 6 and graphene oxide-montmorillonite. *J Dispers Sci Technol* 37(1): 66-72. https://doi.org/10.1080/01932691.2015.1027908
27. Khan ZU, Kausar A, Ullah H, Badshah A, Khan WU. 2016. A review of graphene oxide, graphene buckypaper, and polymer/graphene composites: properties and fabrication techniques. *J Plast Film Sheet* 32(4): 336-379. https://doi.org/10.1177/8756087915614612
28. Anwar Z, Kausar A, Rafique I, Muhammad B. 2016. Advances in epoxy/graphene nanoplatelet composite with enhanced physical properties: a review *Polym-Plast Technol Engineer* 55(6): 643-662. https://doi.org/10.1080/03602559.2015.1098695
29. Kausar A, Rafique I, Anwar Z, Muhammad B. 2016. Perspectives of epoxy/graphene oxide composite: significant features and technical applications. *Polym Plast Technol Engineer* 55(7): 704-722. https://doi.org/10.1080/03602559.2015.1098700
30. Pimenta MA, Dresselhaus G, Dresselhaus MS, Cancado LG, Jorio A, et al. 2007. Studying disorder in graphite-based systems by Raman spectroscopy. *Phys Chem Chem Phys* 9(11): 1276-1290. https://doi.org/10.1039/B613962K
31. Ni ZH, Chen W, Fan XF, Kuo JL, Yu T, et al. 2008. Raman spectroscopy of epitaxial graphene on a SiC substrate. *Physical Review B* 77(11): 115416. https://doi.org/10.1103/PhysRevB.77.115416
32. Kausar A, Rahman AU. 2016. Effect of graphene nanoplatelet addition on properties of thermo-responsive shape memory polyurethane-based nanocomposite. *Fuller Nanotub Carb Nanostruct* 24(4): 235-242. https://doi.org/10.1080/1536383X.2016.1144592
33. Balandin AA, Ghosh S, Bao W. 2008. Superior thermal conductivity of single-layer graphene. *Nano Lett* 8(3): 902-907. https://doi.org/10.1021/nl0731872
34. Kausar A. 2014. Fabrication and properties of polyamide and graphene oxide coated carbon fiber reinforced epoxy composites. *Am J Polym Sci* 4(3): 88-93. https://doi.org/10.5923/j.ajps.20140403.03
35. Celik N, Balachandran W, Manivannan N. 2015. Graphene-based biosensors: methods, analysis and future perspectives. *IET Circuits, Devices & Systems* 9(6): 434-445. https://doi.org/10.1049/iet-cds.2015.0235
36. Kausar A. 2014. Formation and properties of poly(vinyl butyral-co-vinyl alcohol-co-vinyl acetate)/polystyrene composites reinforced with graphene oxide-nanodiamond. *Am J Polym Sci* 4(2): 54-62. https://doi.org/10.5923/j.ajps.20140402.05
37. Naz A, Kausar A, Siddiq M, Choudhary MA. 2016. Comparative review on structure, properties, fabrication techniques, and relevance of polymer nanocomposites reinforced with carbon nanotube and graphite fillers. *Polym Plast Technol Engineer* 55(2): 171-198. https://doi.org/10.1080/03602559.2015.1055504
38. Ambrosi A, Pumera M. 2010. Stacked graphene nanofibers for electrochemical oxidation of DNA bases. *Phys Chem Chem Phys* 12(31): 8943-8947. https://doi.org/10.1039/C0CP00213E
39. Ali W, Kausar A, Iqbal T. 2015. Reinforcement of high performance polystyrene/polyamide/polythiophene with multi-walled carbon nanotube obtained through various routes. *Compos Interfac* 22(9): 885-897. https://doi.org/10.1080/09276440.2015.1076251
40. Du D, Wang L, Shao Y, Wang J, Engelhard MH, et al. 2011. Functionalized graphene oxide as a nanocarrier in a multienzyme labeling amplification strategy for ultrasensitive electrochemical immunoassay of phosphorylated p53 (S392). *Analytical Chem* 83(3): 746-752. https://doi.org/10.1021/ac101715s
41. Shen J, Zhu Y, Yang X, Li C. 2012. Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis and photovoltaic devices. *Chem Communicat* 48(31): 3686-3699. https://doi.org/10.1039/C2CC00110A
42. Wang Y, Shao Y, Matson DW. 2010. Nitrogen-doped graphene and its application in electrochemical biosensing. *ACS Nano* 4(4): 1790. https://doi.org/10.1021/nn100315s
43. Shan C, Yang H, Song J. 2009. Direct electrochemistry of glucose oxidase and biosensing for glucose based on graphene. *Anal Chem* 81(6): 2378-2382. https://doi.org/10.1021/ac802193c
44. Kang X, Wang J, Wu H. 2009. Glucose oxidase-graphene-chitosan modified electrode for direct electrochemistry and glucose sensing. *Biosens Bioelectron* 25(4): 901-905. https://doi.org/10.1016/j.bios.2009.09.004
45. Qiu JD, Shi L, Liang RP. 2012. Controllable deposition of a platinum nanoparticle ensemble on a polyaniline/graphene hybrid as a novel electrode material for electrochemical sensing. *Chem A Eur J* 18(25): 7950-7959. https://doi.org/10.1002/chem.201200258
46. Geim AK. 2009. Graphene: status and prospects. *Science* 324(5934): 1530-1534. https://doi.org/10.1126/science.1158877
47. Dikin DA, Stankovich S, Zimney EJ, Piner RD, Dommett GHB, et al. 2007. Preparation and characterization of graphene oxide paper. *Nature* 448(7152): 457-460. https://doi.org/10.1038/nature06016
48. Li D, Muller MB, Gilje S, Kaner RB, Wallace GG. 2008. Processable aqueous dispersions of graphene nanosheets. *Nat Nanotechnol* 3(2): 101-105. https://doi.org/10.1038/nnano.2007.451
49. Schedin F, Geim AK, Morozov SV, Hill EW, Blake P, et al. 2007. Detection of individual gas molecules adsorbed on graphene. *Nat Mater* 6: 652-655. https://doi.org/10.1038/nmat1967
50. He Q, Wu S, Yin Z, Zhang H. 2012. Graphene-based electronic sensors. *Chem Sci* 3(6): 1764-1772. https://doi.org/10.1039/C2SC20205K
51. Ristein J, Zhang W, Speck F, Ostler M, Ley L, et al. 2010. Characteristics of solution gated field effect transistors on the basis of epitaxial graphene on silicon carbide. *J Phys D: Appl Phys* 43(34): 345303. https://doi.org/10.1088/0022-3727/43/34/345303