Graphene as biomedical sensing element: State of art review and potential engineering applications

[1]Ranvijay Kumar, [1]Rupinder Singh, [2]David Hui, [3]Luciano Feo, [3]Fernando Fraternali

[1]Dept. of Production Engineering, Guru Nanak Dev Engineering College, Ludhiana (India)

[2]Dept. of Mechanical Engineering, University of New Orleans, Louisiana (USA)

[3]Dept. of Civil Engineering, University of Salerno (Italy)

[1]ranvijayk12@gmail.com, [1]rupindersingh78@yahoo.com
[2]DHui@uno.edu
[3]l.feo@unisa.it,[3]f.fraternali@unisa.it

Abstract

Nano grephene (Gr) particles are of abundant methodical and scientific interest as having the astonishing prospective to usage as the sensors element in the miniaturized and biomedical sensor device. The nano Gr particles have been appeared on the life science and health platform due to their interesting material performance like; excellent biocompatibility, conductivity, super para magnetism, thermal, chemical, mechanical and metallurgical properties to use as a sensor component. In recent years, Gr as nanoparticles has acquired powerful technological and scientific attention and having potential applications like; for fabrication of super-capacitors, batteries, solar or fuel cells, miniaturized and biomedical sensors. Gr is one of the most influential nano composites with endowment of use in the sensing mechanism like; bio-sensing, bio-imaging and diagnostic of diseases due to stimulating material behavior like; biocompatibility, cell growing properties, excellent surface behavior thermally and chemically etc. The present discussion explores the state of art review and prospective of the Gr in the miniaturized and biomedical sensors. The sensing mechanism for each of the sensors has been discussed for betters understanding of the functionality and prospective of the Gr in the sensors.

Keywords: biomedical sensors, additive manufacturing, physical sensor, biosensors, bio-potential electrode, sensing mechanism

1 Introduction

The broad term sensors is an electronic module, component, subsystem or an element based on the certain detection mechanism to measure the changes in the environmental activities, [1-5]. The biomedical sensors are broadly differentiated upon the basis of sensing mechanism like the gas sensors senses the gaseous particles, optical sensors measure the light changes and similarly various physical, bio-potential electrode and biosensors measures different physical and chemical quantities. There are some of the previous studies which have lightened the prospective and application of different classified sensors in the different areas of applications, [6-12]. A sensor observed the changes in the environment components such as movement, light, temperature, moisture, pressure, flow rate and many more as response/output. The sensors are usually liable to determine the values in electrical, mechanical, optical and electromechanical signals. Blood pressure and flow rate, growth rate of bone, body temperature measurement are some of the applications of physical sensors prospective with use of Gr. Most commonly uses as diagnostics of body issues are externally employed. Use of Gr increases the precision and sensitivity of measurement [13].

The biosensors are the most advanced and intelligent sensors that fit internally to the human living organism for the investigations of internal changes like, enzymes, protein, and DNA etc. Gr are the most important research components due to their activeness even at nano-particle level, enable it to be potential part, [14]. A highly sensitive behavior of Gr in terms of thermal and electrical conductivity made it eligible for its applications in fabrication of bio sensing devices, electronic circuits charge storage devices and medical biosensors [15-17].

The diagnostics of gaseous issue in relation with concentration of chemical in human bodies, their monitoring (chemical activities in the body)is performed by the chemical sensors. High chemically sensitiveness of Gr enables it to be a most desirable component in biomedical devices, [18]. There are some of the considerations such as specifications of sensor devices must be known by a user before working. Sensitivity, operating conditions, accuracy, and response time are few basics of sensors which explain the capabilities of the sensors in numerous applications such as; accelerometer, biosensors, image sensors, motion sensors etc. This excellent material behavior of Gr extracted from graphite has been best applicable to the 3D printing like fused deposition modeling (FDM) of components for high quality sensors, medical devices and precision making mechanical and electrical tools,[19-20]. Gr is two dimensional materials have noteworthy belongings of extraordinary Young's modulus, knack to thermally and electrically superconductive (high kinesis of charge and electron), surface insulating performance and enormous aspect ratio for prototype fabrication. The performance of vertical axis wind turbine can be improved by changing geometrical components design, FDM emerged as specific tool for such analysis by fabricating functional prototypes, [21]. FDM technology covers almost every area of application. For example on medical field, a device called oral pulsatile, release of drugs and patient-tailored tablets have been fabricated by FDM [22-23].

2 Synthesis of Gr for sensing devices

Graphite is a low cost raw source for extraction of Gr. It is generally extracted via different methods of processing like; chemical vapour deposition (CVD), micromechanical exfoliation, and ball milling etc. [24-26]. Previous studies reveals that exfoliation concept can also be used as chemical processing of graphite in water for Gr production by using 1-pyrenesulfonic acid sodium salt, [27]. Graphite is the best and economical source for extraction of Gr material. The previous literature highlighted that oxidative treatment of graphite resulted in formation of graphite oxide (GO) for extraction of Gr, [28-29]. Oxidation and exfoliation mechanisms for GO production were explained by [30-32]. Synthesis of Gr through exfoliation of natural graphite in ortho-dichloro benzene (ODCB) has been achieved by process called “sonication”, [33]. All Gr extraction technique contributed to achieve specific mechanical, optical and thermal properties, as chemical vapor deposition (CVD) led to Gr sheet production with high mechanical strength, [34-35].

Most of the studies related to the FDM with different feedstock filament materials (like polymer reinforced Gr particles) highlighted the pre-processing, production and post-processing of prototypes,[36-43].Graphite is semi-metallic characterized allotropes of carbon which is available in crystalline and considered as most stable form of carbon. Mechanical exfoliation, chemical exfoliation, chemical synthesis, pyrolysis, epitaxial growth, CVD are some of the processes which are used for Gr synthesis from graphite (Figure 1).

The solid phase method is based upon the principle of mechanical exfoliation and synthesis of silicon carbide (SiC). The Gr is extracted by the use of taping method for mechanical exfoliation (Figure 1^{1-3}). The Gr extracted from the graphite by the mechanical exfoliation are of excellent charge carrier mobility characteristics, [44-47].

The solution phase method is consisting of the extraction of Gr by exposing to the chemical reagent or exposing the graphite oxide to chemical consisting mechanical setup. The new technique for Gr extraction has been introduced by the use of laser for reduction of graphite oxides (See Figure 1^{1-7}). The chemical exfoliation is the economical extraction technique which can have the potential to use in the different areas of application for the sensor fabrication, [48-51]. A process procedure has been shown in Figure 1(7), the mixing of graphite in organic solvent contributed to mixing of graphite dissolution. Treating in ultrasonic bath followed by centrifugation provide separation of graphite flakes from Gr. Aging of Gr dissolution contributed for stabilization of Gr layers in solutions then graphite flakes are removed to extract the Gr through pipetting. Chemical exfoliation method midst all the synthesis processes is termed as the informal and furthermost cost-effective one with foundation of pureness of ultimate artifact [49], 51-52]. Exfoliation is a chemical approach for removal of GO from graphite dissolution to achieve Gr extraction,[33]. Exfoliation process forms chemically converted stable Gr from graphite powder with very less production cost [53-55]. There are some most common organic chemical like; benzene, toluene, nitrobenzene have been reported as catalyst for chemical exfoliation of graphite. N, N-dimethyl- formamide (DMF) and N-methylpyrrolidone (NMP) have been used to form homogeneous dispersion of graphene, [56-59]. Except chemical exfoliation some studies have been reported for exfoliation through electrochemical, water dispersion and other mode of dispersion, [25, 27, 60-62].

The Gr for sensor application and other manufacturing processes required large surface area and effective mechanical and thermal and electronic properties which are generally not achieved with either solid phase method or solution phase method. The CVD method has been emerged as the most effective technique for the manufacturing of high yield Gr. [35, 63-69]. The Gr by the CVD methods are extracted with the use of the substrate used, the nature of substrate is resulted into the yield of the extracted graphene. Fig. 1^{8-9} shows the process of chemical vapor deposition for extraction of graphene.

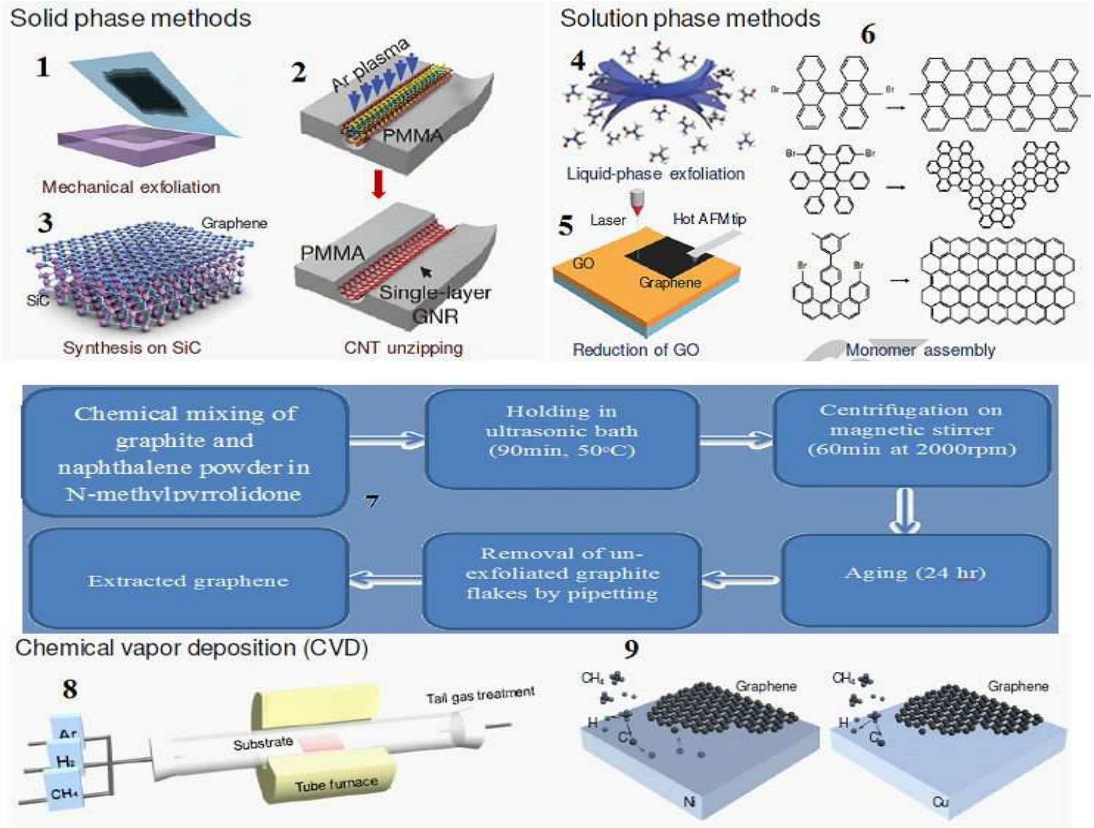


Figure 1 Grsynthesis techniques, Mechanical exfoliation[1], Synthesis on SiC[2], Plasma etching[3], Solution Phase technique[4], Liquid phase exfoliation[5], reduction of GO induced by hot AFM (atomic force microscope) tipor laser[6], Chemical Exfoliation Method[7] Chemical Vapor deposition method[8&9], [47, 70-72].

Table 1 shows the comparative study for charge carrier mobility of Gr processed by different synthesis technique. The mechanical exfoliation resulted in the highest charge carrier mobility of Gr.

Table 1 Charge carrier mobility resulted by different processes of synthesis, [72]

Properties	Mechanical exfoliation	Chemical exfoliation	Chemical exfoliation by graphene oxide	Chemical vapor deposition (CVD)	Synthesis on SiC
Sample size(mm)	>1	Infinite because of	Infinite because of	Approx.1000	100

		overlapping flakes	overlapping flakes		
Crystallite size(μm)	>1000	≤0.1	Approx. 100	1000	50
Charge carrier mobility (at 25^{o}C) ($cm^2V^{-1}S^{-1}$)	$>10^6$	100	1	10000	10000

3 Specifications of biomedical sensors

A sensor observed the changes in the environment components such as movement, light, temperature, moisture, pressure, flow rate and many more as response of output. The sensors are usually liable to determine the values in electrical, mechanical, optical and electromechanical signals. There are some of the considerations such of specifications of sensor devices must be known by a user before working. Sensitivity, operating conditions, accuracy, and response time are few basics of sensors which explain the capabilities of the sensors in numerous applications such as; Accelerometer, Biosensors, image sensors, motion sensors etc (Table 2).

Table 2 Specification of Gr sensors, [73-78]

Key	Description
Extent range	The ranges of sensor for measurement of bio-characteristics must be detailed the maximum and minimum measurable information. For example of pressure sensors, the pressure must be in range of 0-10MPa.
Sensitivity	Sensitivity of a sensor is defined as the changes of output over the input under the controlled specific environment. For pressure sensors it should be equal to the 0.4V/Pa. 0.4 Volt will change over 1Pa pressure.
Operating temperature	The operating temperature ranges of sensor must be optimum for great performance. Operating beyond temperature range may cause the losses in accuracy and performance. For graphene based NO_2 sensors the operating range suggested 20-150^{o}C.
Accuracy	The accuracy is the measure of the exactness upon the true values output. The accuracy must be detailed to minimize the rejections.
Reproducibility	Reproducibility of the sensor is the measure of the closeness in output over keeping the same operating conditions and same sensors. For temperature sensor the reproducibility of ±0.1V/℃ in temperature range of 20-80℃.
Response time	Response time is the measure to reach a sensor on calibrated values upon changes in the input. For pressure sensor the response time should be 10 second to reach the 95% of the maximum output.
Drift	$D_{zero} = (\blacktriangle Y_0/Y_{FS}) \times 100\%$, drift is defined as the changes in the output value when input keep constant. The zero drift can be expressed as above expression. Where $\blacktriangle Y_0$ is the output changes and Y_{FS} is the reference input.

4 **Prospective of Gr in bio-medical sensing devices**

4.1 Classification of biomedical sensors

The biomedical sensors are broadly classified in the 4 basic subgroups based upon the nature of sensing such as; physical sensors, chemical sensors, bio-potential electrode and biosensors [74]. Physical sensors are those sensors which senses the changes in the physical factors like; pressure, force, velocity, momentum, capacitance, depth and level etc. the chemical sensors are liable to measure the any changes in the chemical composition of environment, food and other bodies, the most common used chemical sensor is gas sensors but now a days with prospect of efficient the other type of chemical sensors have been emerged like; electrochemical sensor, photometric and physiochemical sensor. Bio-potential electrodes are those sensors which measure the change in the factor by a electrode in form of some graphs or plots, the ECG, EOG and EMG are some of the bio-potential electrode which commonly used in the biomedical fields. Biosensors are the advanced sensors which can fit internally to the human body for sensing purpose of protein, DNA, glucose etc. Figure 2 shows the detailed classification of miniaturized and biomedical sensors.

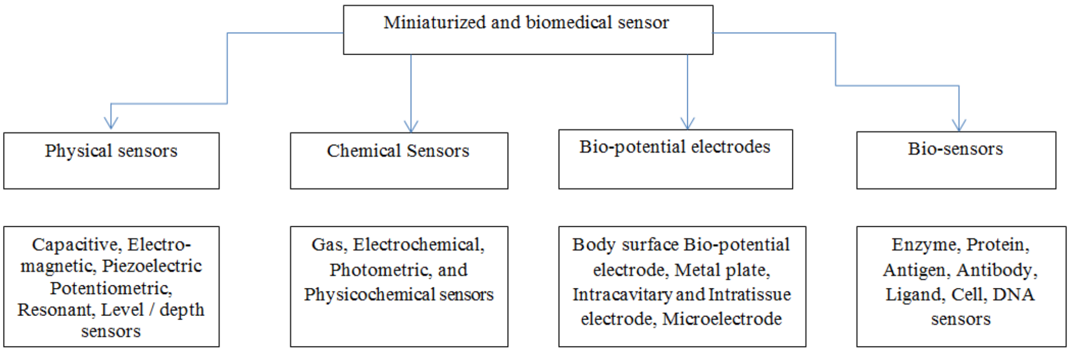


Figure 2 Classification of miniaturized and bio-medical sensors

4.2 Physical sensors

Some of the applications of physical sensors are for geometric, mechanical, thermal, hydraulic, electrical and optical measurements. Blood pressure and flow rate, growth rate of bone, body temperature measurement are some of the applications of physical sensors prospective with use of graphene. Most commonly uses as dignostics of body issues externally. Use of graphene increases the precision and sensitivity of measurement [13].Physical sensors are composed of nanochemical resonator and pressure membrane for measurement of force, pressure, temperature, flow rate, bone growth rate in biomedical fields, [79]. All the touch screen device, oil and pressure regulating system in automobile industries, digital blood pressure monitoring, evaluation of gases and their partial pressure, to keep balance between control system and atmosphere in aviation field and to measure the depth of submarine in marine industries, [80] The Gr in the miniaturized sensors is the need of hour to improve the efficiency in physical sensors. Gr is the most desirable material for fabrication of nonchemical resonator and pressure membrane to use in miniaturized biomedical sensing devices, [81]. The pressure sensors are the most commonly used sensor in biomedical and miniaturized sensors. The ordinary sensors are used to low efficient measurement. Composite sensors with use of Gr can be used as the attachment to the ordinary sensors as the secondary measurand shown in Figure 3 will improve the efficiency and precision.

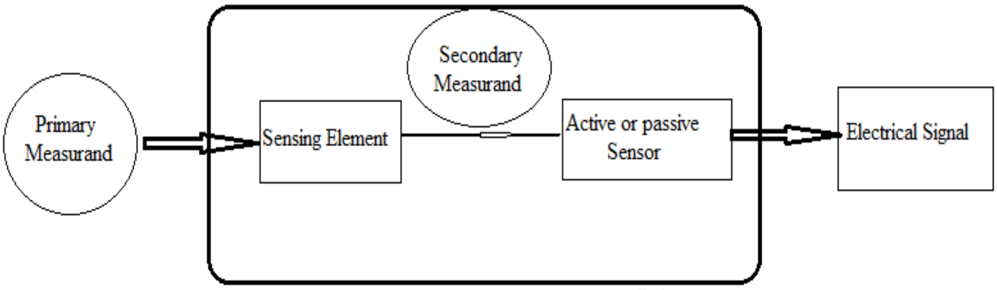
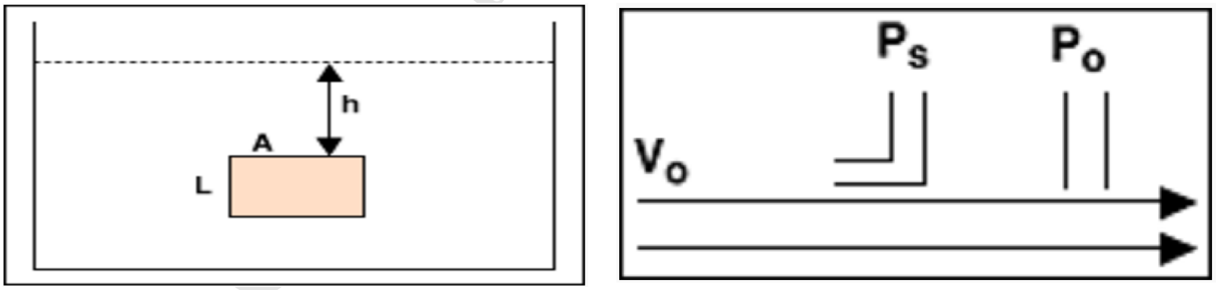


Figure 3 Gr based composite sensor elements

Pressure Sensors: The pressure in pressure sensing devices can be measure statically (Figure 4(a)) and dynamically (Figure 4(b)), the pressure exerted to the system can be understood from the given source described below [82]. For improvement in sensitivity Gr blended sensors may be employed.

Static pressure sensing

Dynamic pressure sensing



4(a)

4(b)

Figure 4 Pressure sensing mechanism in static and dynamic conditions

The upward pressure exerted (P_U) can be calculated by expression given below

$$P_U = (h + L)\,\rho g$$

Where, h= distance between pressure point to the surface, A&L= area and length of the bock in container, $\rho$and g are the density and acceleration due to gravity.

The pressure in a moving fluid exerted parallel to the flow direction is called the impact pressure, P_s. This is due to the kinetic energy of the fluid:

$$P_s = \rho V_O^2/2$$

Vo = fluid velocity

Light sensors: The photo-detector is one of the physical sensors which measure the environmental quantity like; incident of light. Photo-detecting sensors measure incident of light or photon flux or optical power by converting the absorbed photon energy into electrical current. They are widely used in a range of devices, such as remote controls, televisions and DVD players. The sensing mechanism of photo-detectors is works on the photo thermoelectric effect principle based upon the Motto's formula,[83]. The photo-detection is the measure of the change in the thermoelectric power also called thermo power (s) related to the electrical conductivity (σ) and can be calculated by the given equation, [84].

$$S = -\frac{\pi^2 K_{.}^{2} T_{ef}\,\delta\,\sigma}{3q\,\sigma\,\delta\mathcal{E}}$$

The proposed equation leads to the sensing mechanism as change in output of the σ . Where K is the Boltzmann's constant, q is the electronic charge (1.60217662×10^{-19} coulombs), k is Boltzmann's constant (1.38064852×10^{-23} m^2 kg s^{-2} K^{-1}),$\mathcal{E}_0$is the standard permittivity of free space (8.85 x 10^{-12} farad per meter (F/m)),T_{ef} is effective temperature and can be calculated as;

$$T_{ef} = \sqrt{T_0} + T^2$$

T is the sample temperature and T_0 is the fitting parameter related to Dirac point associated with random potential fluctuations. Here also Gr blended samples will improve the sensitivity of measurement.

4.2.1 Prospect of Gr in physical sensors

Capacitive sensors use carbon nano-platelets with polymeric material to reduce the cost, easily implemented and rapid prototyped of physical and chemical sensors. The prospective of Gr in biomedical sensor is wide because change of resultant value with very small changes in the strain (≤0.2%). The humidity changes measurement are the key goal to use the Gr in the miniaturized sensors. The typical mechanically or chemically extracted GO can achieve high sensitivity and fast response. The capacitive pressure sensors use dielectric permittivity materials as graphene for high performance [85-87]. Electromagnetic interference (EMI) shielding properties are the key element in electromagnetic sensors to know the efficiency and capability of the sensing materials. The Gr aerogels (GAs) are prepared under the chemical process by GO reveals the potentiality of the graphene in the electromagnetic sensors. The EMI shielding effectiveness (SE) has been noted significantly changes by varying Go under hydrazine vapor. The surface-enhanced Raman scattering (SERS) characteristics can be enhanced by the using hybrid blend of Gr/Ag-nanoparticles. The unique blending of Gr/Ag-nanoparticles enhances sensitivity of electromagnetic sensor up to the ultra-sensitivity level,[88-89]. Bi-Gr sheets/piezoelectric (BGP) was exposed to the moving particle medium of certain gases, ensured the potential application of Gr reinforced laminates for the future prospective of Gr. The viscoelastic behavior of piezoelectric layer decreases the nonlinear dynamic amplitude of BGP laminated films only. The difference between linear and nonlinear solutions depends on the speed of moving particles. The obtained new features and interesting results about the nonlinear viscoelastic dynamic responses of BGP laminated films under moving particles, [90], The potentiometric sensors are the resistive sensors which changes the resistance exposing to the different environmental pressure conditions (by following LVDT, Hall Effect, or by eddy current principle). Recently with prospect of use of Gr studies reported for polymer-based potentiometric nano-Gr/ionic liquid/carbon paste electrode for the determination of in changes in the pharmaceutical products. The acetone detection through ultraviolet (UV) illumination has been promised the better and high level application of potentiometric sensors with Gr sensors, [91-92]. The variation in resonant frequency under different loading conditions used to measure the changes over stress, gas density and applied pressures. The Gr based resonant can leads to the absorption on terahertz (THz) frequency range. Most of the studies highlighted the use of other micro or nano molecules but Gr will certainly be one of the best replacements of sensing element, [93-95]. The depth/level sensors are calculated the volume, depth of the chemical tank, water reservoir, and large dam. Some of the studies have highlighted the propspective of Gr as Gr/polyethylene-based nanocomposites by depth-sensing indentation. It is obvious that Gr has the excellent and outstanding properties of sensitivity like, thermally, electrically, mechanically and good resonant properties. The depth sensors need to be a good sensing element carrying all round material properties. The graphene may be the best available option among the entire nanocomposite to be a part of level/depth sensing device, [96-98].

4.3 Chemical sensors

Gas, Electrochemical, Photometric, and other physicochemical sensor are some of the chemical based biomedical sensors. Diagnostic of gaseous issues in relation with concentration of chemical in human body is one of the important concerns. The monitoring of chemical activities in the body can be performed by the chemical sensors. High chemically sensitiveness of Gr enables it to be a most desirable component in biomedical devices. [18].The interpretation of gas sensing mechanism is governed by the two models, (i) Oxygen ionosorption and (ii) Oxygen vacancies, [99]. The steps involves to exposing the sensors to as air or reducing gas (Like, CO) media.

The responses mechanism are defined upon exposure to oxygen by an adsorptions reactions, at elevated temperatures, reactive oxygen species such as , O_{2-} and O_{-} are adsorbed on the surface of metal oxide semiconductor. The sequence of processes involved in the adsorption of oxygen on the metal oxide surface [100].

O_2 (gas) + $e^- \leftrightarrows O_2^-$ (adsorbed)

O_2^- (adsorbed) + $e^- \leftrightarrows O_2^{2}$ (adsorbed)$\leftrightarrows$ $2O^-$ (lattice)

When the sensing element exposed to O_2environment, the O_2 adsorbed by the sensing surfaces resulted of decrease in the charge carrier concentration (e^-) which leads to increase in the resistance of the sensing material. The change in the resistance is termed as the sensibility of the sensor upon exposure to O_2. The similar mechanism also governed for the reducing gases like; CO_2, [99, 101-102].

The sensing of gas sensors upon exposing to a reducing gas environment (e.g. CO), the reactions delivered as;

CO + O^- (adsorbed) $\longrightarrow$ CO_2+ e^-

2CO + O_2^-(adsorbed) $\longrightarrow$ CO_2 + e^-

The monitoring purposes of chemical activities in the body are measured by the chemical sensors. High chemically sensitiveness of Gr enables it to be a most desirable component in biomedical devices.Photochemical and photometric are the most commonly used chemical sensors that fulfill the need for examining the concentration and changes in the chemical reactions with most precision, [103-106]. Conventionally nanacomposite like silicon nanowire is the one of the most desirable materials for application in chemical sensors, [107].

The electrochemical sensors are liable to respond the changes in the PH value of the solutions. A relation has been suggested by [108] for oxide-on-graphene field effect bio- sensors for electrochemical sensing devices. The PH value can be measure of the solution gate capacitance (Csg) change as shown by equation given below.

$$C_{sg} = \frac{C_{DL}\cdot C_{ox}\cdot}{C_{DL}\cdot + C_{ox}\cdot}$$

The Csg is the combination of the series connected capacitance of the solution (C_{DL}) and capacitance of double oxide layer (Cox) as the sensing material.

Semiconductors are the key for fabricating chemical sensors; study highlighted the image correction for chemical sensors by changing material characteristics [109]. The semiconductor reported as less efficient and produced lesser image sensing, conductive polymers are the replacement of semiconducting polymer due to high stability in image sensing, [110]. Metal oxide nanowires are emerged as the one of the stable material for the stable image sensing. The metal oxide as chemical sensors proposed as ease of rapid prototyping, integration to other devices and fabrication purposes, [111].

The sensing mechanism for graphene-based quantum capacitance wireless vapor sensors has been demonstrated. The change in the resonant frequency of metal oxide graphene capacitive (varactor) sensor is liable to change in the vapor concentration as relative humidity (RH). A model has been suggested to calculate the varactor capacitance (C_V) as sensing mechanism to vapor, [112]

$$C_V = A.\left(\frac{1}{C_{oc}} + \frac{1}{C_q}\right)^{-1}$$

Cv is the varactor capacitance, A is the active area of the metal oxide Gr capacitor, Coc is the oxide capacitance per unit area and Cq is the quantum (Gr capacitance per unit area, and the C_{oc} and C_q can be calculated as;

$$Coc = \frac{3.9\mathcal{E}_0}{EOT}$$

EOT is the equivalent oxide thickness of dielectric of metal oxide graphene, $\mathcal{E}_0$is the standard permittivity of free space.

$$Cq = \frac{2}{\pi}\left(\frac{qkT_{eff}}{hV_F}\right)^2 ln\left(2 + 2cosh\left(\frac{E_f}{KT_{eff}}\right)\right)$$

Where q is the electronic charge, k is Boltzmann’s constant, h is the plank constant,Fermi velocity $V_F = 1100000$ cm/sec, E_f is the Dirac point energy, T_{ef} is effective temperature.

The adsorption capacity is the main key to select the sensor material, [113-114]. Most of the chemical sensors exposes to the water, gas or other fluid media to calculate the changes in the adoptions. The Gr in the chemical sensor widely used because of their excellent adsorption nature exposing to certain gases and liquid. The sensing mechanism by adsorption can be suggested as;

$$Q = \frac{m_1 - m_2}{m_2}$$

Q is the adsorption capacity and can be calculated as knowing the m_1 which is the mass of sensing element before exposure to fluid and m_2 is the mass after exposure to fluid.

Figure 5 shows the sensing mechanism of a biosensor system

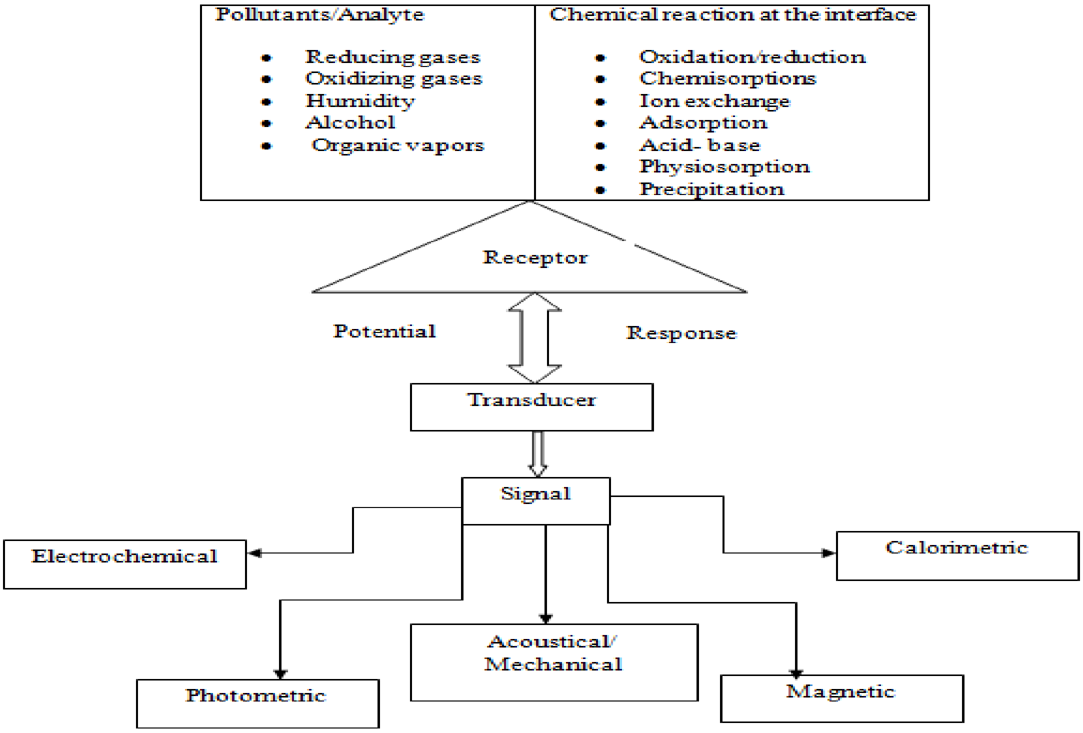


Figure 5 Principle of chemical sensor based mechanism, [115]

4.3.1 Prospect of Gr in biomedical chemical sensors

Gas adsorption is the key of sensitivity towards the selection of sensor materials. The more is the gas adsorbed sensitive characteristics of the material higher will be the preference to use as sensing material. Gr proposed the good adsorption characteristic to ensure the reliability of the chemical sensors. Study highlighted the use of microwave irradiation technique synthesis of zinc oxide semiconductor using Gr for chemical sensors. Fluorinated graphene oxide has been studies experimentally for sensing of NH_3 gas. The advancement in the field of sensor fabrication can be a best applied by the blend of Gr/titanium dioxide hybrid material. Blend of Gr-TiO2 resulted in excellent NH3 gas sensing, [116-119]. Potentiometric, amperometric and conductometric are some of the electrochemical sensors which provide the continuous information about the changes in the environment. Detectability, experimental simplicity and low cost are some of the remarkable characterizes of the electrochemical sensors enable it to apply potentially in different areas. The Gr can be best applying to the electrochemical sensor for advances the sensing ability. Determinations of daphnetin, preparations of Hydrophilic graphene surface are some of the achievement after use of graphene as an electrochemical sensing element,[120-122]. Photodetectors are recent advancement of sensors used to response the changes in luminous flux, illuminance, luminous intensity and luminance for application in different fields. Photo-resistors, photodiodes or photomultipliers are the sensing element t in photometric sensors. There is a need to explore the use of Gr for sensing element for photometric sensor. It has been explored that Gr has excellent adsorbent ability that is the reason it should be apply as photometric sensors, [123-124]. The recent development in the chemical based sensors has been targeted for the sensing of local magnetic fields, magnetic particle characteristics, viscosity and chemical binding. The graphene will be the future material for the physiochemical sensing as having great electrical, thermal and chemical characteristic,[125-128]**.**

4.4 Bio-potential electrode

Body surface bio-potential electrode, metal plate, Intracavitary and intratissue electrode, microelectrode are some of the classifications of bio-potential electrodes. The little changes in activities of muscle, brain, eye retina, nerves and skin can be measure by the use of the bio potential electrode such as; ECG (Electrocardiogram),EMG (Electromyogram), EOG (Electrooptigram). ESR (Galvanic skin reflex) etc.[129].The bio-potential electrodes are the transducer used in the sensing devices for converting the bodies' ionic current into electronic current. The responses can be explored in the form of some signals or other representations. The uses of high conductive bio-potential electrode are the key element in the sensors uses for carries the charges. The ECG/EEG/EMG Systems are some of the potentially applied devices that give the very precise output in the form of signal for any changes in the human body. The bio potential electrodes are the greatly applied biomedical and miniaturized sensors, [129]. The transducing function is being able to be applicable as the excellent electrical conductivity of the electrode. Graphene is the most accepted material because of its extraordinary electrical conductivity. The sensing mechanism of the electrode in aqueous solution for charge carrier can be governed by the given equation, [130].

$$C \leftrightarrows C^{n+} + n^{e-}$$

$$A^{m-} \leftrightarrows A + m^{e-}$$

Where n is the valence of positively charged material(C), and m is the valence of negatively charged material (A). In the genetral, the cations in solution and the metal of the electrodes are the same, so the atoms C are oxidized when they give up electrons and go into solution as cations. Figure 6 shows the different configurations.

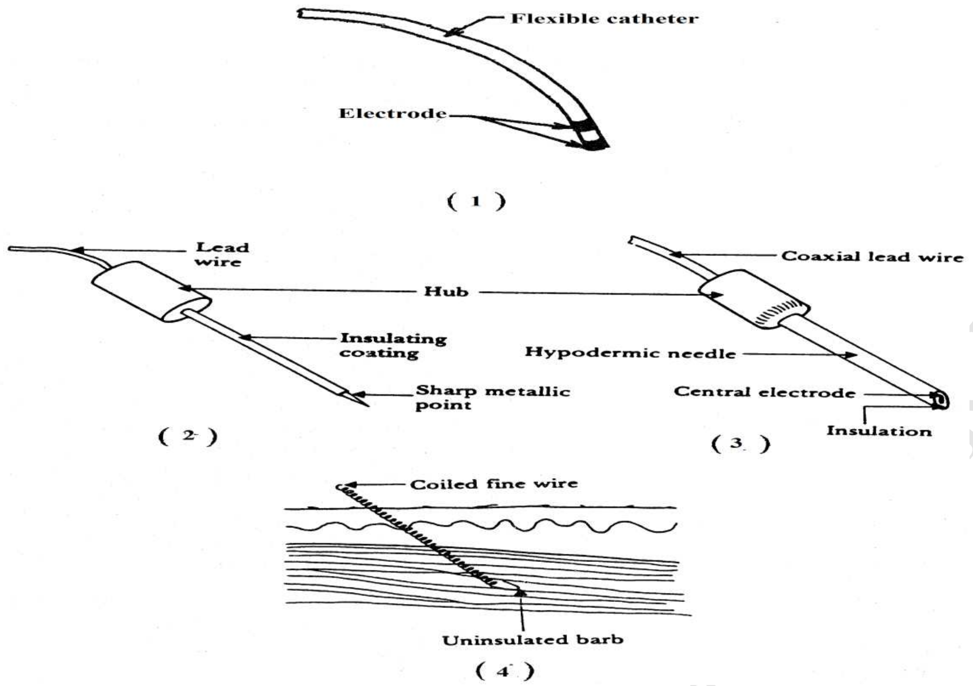


Figure 6 Different types of electrodes used in the bio-potential sensors, (a) probe type (2) needle type (c) cosxial needle typeand (4) coiled wire electrode, [130]

4.4.1 Prospect of Gr in bio-potential electrodes

Gold, silver and copper are the conventional material for the body surface electrode for sensing. Gr is the need of hour to use as the body surface electrode due to its positive features like; excellent electrical, thermal and surface properties. Recent studies have reported on direct electrochemical and electro-catalytic characterization of hemoglobin on palladium-Gr modified electrode. The experimental studies have been suggested that polymer reinforced with the Gr has a wide potential for the fabrication of body surface electrode with provision of rapid prototyping, [131-133].Intracavitary and intratissue electrode are using from the years to cure the internal body issues rather than to diagnose the problem. Use of nanomaterial in the intracavitory and intratissue can greatly improve the performance of the biopotential electrode. the studies reveals the application of Intracavitary electrode in the dog's internal body parts to minimize risk of ventricular fibrillation, [134-135]. Chemically reduced graphene oxide (CRGO) is largely replacing the conventional electrode material in ECG/EOG/EMG system as the sensing material. Studies reported for the dry electrodes as touch sensor for electrocardiograph measurement fabricated by CRGO and Graphene-clad textile electrodes for electrocardiogram monitoring, [136-139].

4.5 *Bio-analytic or biosensors*

Bio-analytic or biosensor is a intelligent analytic device that best applies for detection of analyte that integrate biological component with a physicochemical detector. The biosensors are eligible to observe and analyses the level of enzymes, protein, DNA and microorganism concentrations in the bodies, [140-141]. The main sensing element or transducer attached physiologically, optically or electrochemically convert the signal obtained by integrating the bio-analytic with the sensitive biological element to measurement and quantification. The typical bio-analytic setups consisting of a bio-recognition site, a signal receiver and a signal amplifier to display the processed observations.

Field-effect transistors shortly known as FET are among the most applicable sensors for biosensors. An FET contains input and output electrodes, a semiconducting channel and a gate electrode. The working mechanism of a FET biosensor based upon the Electrical transport through the semiconductor channel which becomes modulated by the applied gate voltage, [142-143]. FET is a typical transistor that uses electrical field to control the functionality of a device. The conductivity between the input and output source is controlled by the electric fireld of the device. The electric field in FET is generated by considering the voltage difference between the body and the gate of the device. The detection mechanism as a biosensor, the transport mechanism is governed by the defining the voltage difference between the two parameter (V), [144].

$$V = I|Z|e^{j\phi}$$

$|Z|$is the magnitude of impedance, I is the current, $e^{j\phi}$ is the phase factor which is the delay in the voltage w.r.t I by a phase ϕ, j=$\sqrt{-1}$.

Biosensing mechanism based on surface plasmon resonance (SPR) is is the most common and known technique to examine the biochemical reactions in scientific, food research, and medical diagnostics, [145]. In particular, SPR provides biosensing without need of fluorescent, radioactive material, which could interfere with the biosensing process, sensitivity, and real-time monitoring of biomolecule binding. The sensitivity is a liable of the performance for any biosensors. For SPR biosensors, the sensitivity(S) is governed by the given expression, [146].

$$S = \frac{\Delta P}{\Delta C} = \frac{\Delta \mathrm{P}}{\Delta \mathrm{n}}\frac{\Delta \mathrm{n}}{\Delta \mathrm{C}} = S_{R1}E$$

P is the output of the SPR sensor as SPR angle for analyte concentration (C), Δnis the refractive index can be taken as 0.005. Therefor the senility is termed as the product of refractive index change (S_{R1}) and Efficiency (E).

A bio-receptor in the bio-analytic is the main element which interacts with antibody/antigen, Artificial binding protein, enzymes, DNA, epigenetics, organelles, cells and tissues for signal processing, [147]. There are 6 types of bio-transduces are commonly uses in the bio-analytic such as; optical, piezoelectric, electronic, gravimetric, electrochemical and pyro-electric types. Figure 7 shows the working mechanism of bio-potential based sensors.

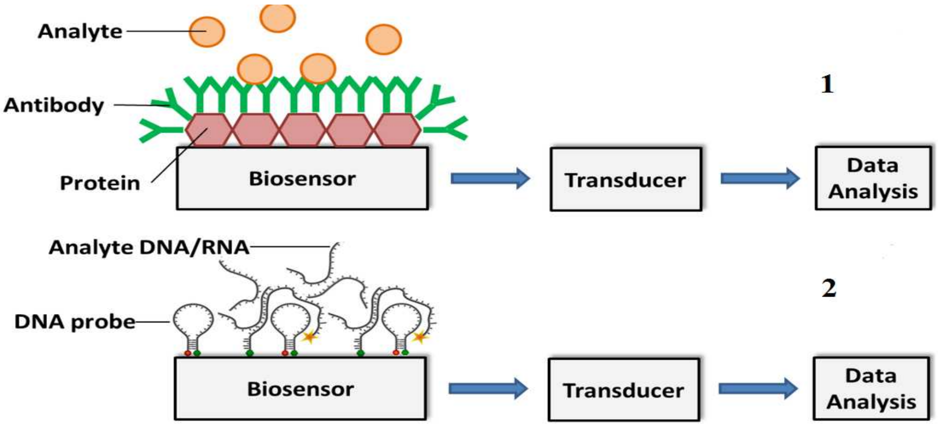


Figure 7Mechanism of sensing for (1) Antibody based biosensor (2) DNA/RNA based biosensors, [148].

4.5.1 Prospect of Gr in Bio-analytic or biosensors

The studies highlighted the triple particle nanoparticle for the biosensor for the glucose response. This type of biosensor was fabricated using the polypyrrole as liking agent through dispersing the nanosized gold particle on the surface of reduced graphene oxide, [149-150]. The cancer biomarker detection is one of the greatest achievement in the biosensor fabrication, the multimaterial electrochemical biosensor was fabricated using graphene surface enhanced with magnetic beads (MBs) and enzyme-labeled antibody-gold nanoparticle, [151]. Polymer based graphene nanocomposite sensor has been demonstrated for the cholesterol detection, high conductivity of graphene based nanocomposite has potential to be a part of biosensors, [152-153] has explained the synthesis of the graphene by chemical vapor deposition method for the fabrication of Nickel nnaosheet/ graphene based composites for biosensing. A study reported to detect the dangerous pesticide residue in the water or food using the sensor fabricated from functionalized GO, [154-155] have developed the graphene based potentiometric biosensor for the detection of the bacterial. Graphene can be lead to the enhancement in the sensitivity, detection accuracy and quality factor, the study reported for the application of GO for the biosensor functionality for explosive detection, [156]. As GO exhibit the excellent dispersibility, biocompatibility to potentially use in the biomedical and Nano-electric biosensors [1, 129]. Dopamine is an organic chemical of the catecholamine and phenethylamine families that plays several important roles in the brain and body, detection were achieved developing a graphene based biosensor, with stusy suggested 3D printing of graphene based biosensor, [157-158]. One of the most recent studies having the potential for the detection of Zika virus infection, the sensor developed for Zika virus detection was cost effective as use of graphene, [159]. Development of Hall Effect based biosensor for DNA detection have been promises the future of the graphene to be best use for miniaturized and biomedical applications, [160].

5 Case study forfabrication of sensor component by additive manufacturing

The FDM feedstock filament with an ABS–Gr (90-10 and 75-25 wt.%) matrix has been successfully prepared by exfoliation of graphite at the lab scale [43, 161]. The blending of Gr in ABS has been processed by two methods, mechanical mixing and chemical + mechanical mixing. Finally, the feedstock filament has been successfully used for preparing functional prototypes. The results of the present case study suggest that the electrical and thermal conductivity and mechanical properties of the functional prototypes have been improved. The proportion of Gr in the ABS matrix is the significant parameter which influences the electrical conductivity, followed by the in-fill density and the process used for blending. Whereas for thermal conductivity, the process used for blending (chemical and mechanical mixing), followed by in-fill density and proportion of Gr in the ABS matrix are significant parameters. The Gr-blended ABS specimens with improved mechanical, thermal, and electrical properties can be used for a number of engineering applications. Their association with recycled materials for the manufacturing of innovative, sustainable composites awaits attention.Investigations have been made to calculate the thermal and electrical conductivities of the Gr blended ABS function surface obtained by 3D printing [161]. The ABS was initially calculated as thermal conductivity of 0.1 W/m.K, after blending of Gr to ABS by twin screw extrusion followed by 3D printing resulted in the improvement in the thermal conductivity of ABS polymer up to 176.6 times (See Figure 8). The thermal conductivity (K) of graphene blended fictional prototypes with 3D printing has been evaluated by the given formula using Lee's disk method;

$$K = \frac{mc\left(\frac{dT}{dt}\right)x}{A(t_2 - t_1)}$$

Where A is the cross sectional area of 3D printed part, t2-t1 is the temperature gradient across sample, x is the thickness of the 3D printed part, m is the mass of Lee's disk and c is the specific heat of capacity of disk. The rate of cooling/temperature gradient (dT/dt) has been calculated by plotting the graph of temperature and time. The thermal conductivities have been calculated using the said expressions and it is plotted as function of infill density and proportions of graphene content against thermal conductivity.

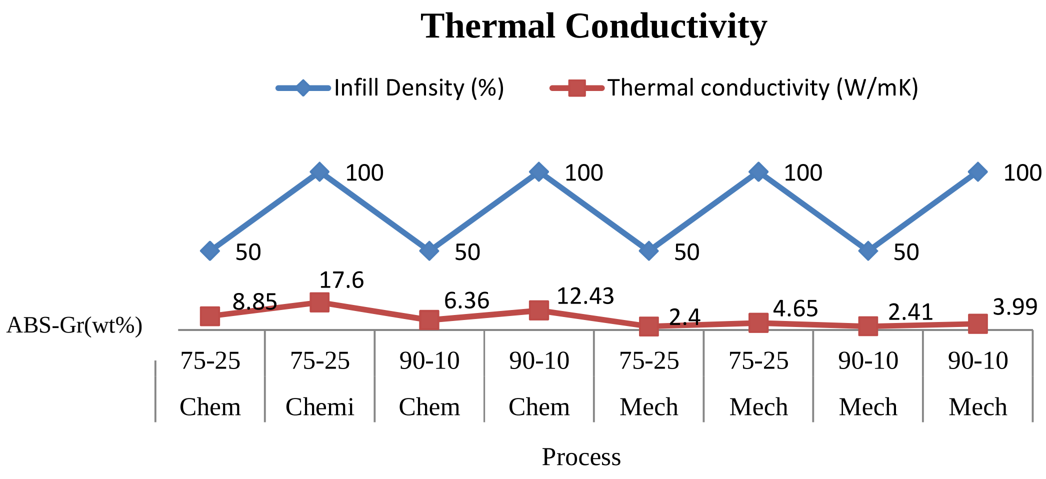


Figure 8 Thermal conductivity of different sample

Similar operations have been performed using the Ohm's law.

The electrical conductivity (σ) for different fictional prototypes has been investigated by the given relations;

$$\sigma = \frac{1}{\rho} \text{in S/m (Siemens/meter)}$$

Where ρ is the resistivity of the sample, the resistivity of the 3D printed part can be calculated as;the inverse of conductivity is called resistivity.

$$\rho = \frac{RA}{l}$$

Where l is the length of the sample and R is the resistance of the 3D printed part and it can be calculated using Ohm's law

$$I = \frac{V}{R} \quad \text{In Amperes}$$

Where V is the voltage and I is the current flow across the samples. Upon this basis the electrical conductivity for each samples have been determined and plotted to see the changes in their values according the other factor variations (See Figure 9).

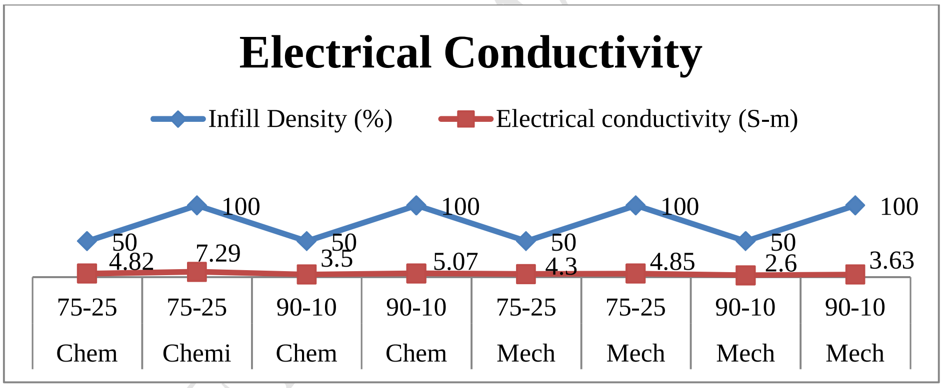


Figure 9 Electrical conductivity of different sample

As observed from literature, the functional component of sensors devices is being fabricated by the 3D printing techniques. The present case study also highlights the potential to fabricate the functionally upgraded parts for sensors devices.

6 Conclusions

Sensors are heart of any measurement, control and diagnostics devices and termed as the critical component. Following conclusions can be made from the present state of art review with prospective of use of Gr in the sensing devices.

- Conventional sensor devices use the sensing element has high cost due to use of expansive nanoparticles. Gr has emerged as one of the most acceptable replacements of nanoparticles used as sensing material. In biomedical applications the Gris replacing the conventional metallic nano particle with provision of reducing cost and improving sensing ability. The 3D printing followed by the extrusion process can be the one of the replacements to fabricate the sensor part blended by particle with nano composites. This novel method of manufacturing the sensor element will be instrumental for reducing the elemental cost of sensor devices.

The employment of composite ABS–Gr FDM feedstock filaments for the rapid prototyping of multi scale innovative materials and structures [162-214] awaits attention.

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References

[1] Park, C. S., Yoon, H., & Kwon, O. S. (2016). Graphene-based nanoelectronic biosensors. Journal of Industrial and Engineering Chemistry, 38, 13-22.

[2] Zhang, X., Li, Z., Zhou, T., Zhou, Q., Zeng, Z., Xu, X., & Hu, Y. (2016). A quantum dot-spore nanocomposite pH sensor. Talanta, 150, 184-189.

[3] Yadav, G. C., Sharma, G., Kumar, S., & Singh, V. (2017). Performance study of metallic clad planar waveguide sensors in presence of graphene layer. Optik-International Journal for Light and Electron Optics. In press.

[4] Nag, A., Mukhopadhyay, S. C., & Kosel, J. (2017). Sensing System for Salinity Testing Using Laser-induced Graphene Sensors. Sensors and Actuators A: Physical. 264,107-116.

[5] Ng, K. L., Tan, G. H., & Khor, S. M. (2017). Graphite nanocomposites sensor for multiplex detection of antioxidants in food. Food Chemistry. 237, 912-920

[6] Wise, K. D., & Weissman, R. H. (1971). Thin films of glass and their application to biomedical sensors. Medical and biological engineering, 9(4), 339-350.

[7] Engin, M., Demirel, A., Engin, E. Z., & Fedakar, M. (2005). Recent developments and trends in biomedical sensors. Measurement, 37(2), 173-188.

[8] Kruss, S., Hilmer, A. J., Zhang, J., Reuel, N. F., Mu, B., & Strano, M. S. (2013). Carbon nanotubes as optical biomedical sensors. Advanced drug delivery reviews, 65(15), 1933-1950.

[9] Salvo, P., Dini, V., Di Francesco, F., & Romanelli, M. (2015). The role of biomedical sensors in wound healing. Wound Medicine, 8, 15-18.

[10] Bona, M., Sardini, E., & Serpelloni, M. (2014). Telemetric model for passive resistive sensors in biomedical applications. Procedia Engineering, 87, 444-447

[11] Kim, J. A., Kulkarni, A., Kim, C., Park, K., & Kim, T. (2016). Fiber Optic Lateral Coupling Force Sensor for Biomedical Applications. Procedia Engineering, 168, 1227-1230.

[12] Ozoemena, K. I., & Carrara, S. (2017). Biomedical electrochemical sensors for resource-limited countries. Current Opinion in Electrochemistry. doi:10.1016/j.coelec.2017.06.002

[13] Serry, M. (2016). Graphene Based Physical and Chemical Sensors. In Next Generation Sensors and Systems (pp. 1-22). Springer International Publishing.

[14] Justino, C. I., Gomes, A. R., Freitas, A. C., Duarte, A. C., & Rocha-Santos, T. A. (2017). Graphene based sensors and biosensors. TrAC Trends in Analytical Chemistry. doi: 10.1016/j.trac.2017.04.003.

[15] Irudayaraja, J. (2012). Graphene for Biosensing Applications. Biomedical Nanosensors, 4, 153

[16] Obeng, Y., & Srinivasan, P. (2011). Graphene: Is it the future for semiconductors? An overview of the material, devices, and applications. The Electrochemical Society Interface, 20(1), 47-52.

[17] Hantel, M. M. (2013). Graphite oxide and graphene oxide based electrode materials for electrochemical double layer capacitors (Doctoral dissertation).

[18] Yavari, F., & Koratkar, N. (2012). Graphene-based chemical sensors. The journal of physical chemistry letters, 3(13), 1746-1753.

[19] Liou, F.W. (2008), “Rapid Prototyping and Engineering Applications, a Toolbox for Prototype Development”, CRC Press, Taylor & Francis Group, London 2008

[20] Kumar, P., Ahuja, I.P.S., and Singh, R. (2012), “Application of fusion deposition modelling for rapid investment casting –a review”, International Journal of Materials Engineering Innovation, Vol. 3, Nos. 3-4, 204–227.

[21] Guerrero-Villar, F., Torres-Jimenez, E., Dorado-Vicente, R. and Jimenez-Gonzalez, J.I. (2015), “Development of Vertical Wind Turbines via FDM Prototypes”, Procedia Engineering, Vol. 132, No. 1, 78-85.

[22] Skowyra, J., Pietrzak, K. and Alhnan, M.A., (2014), “Fabrication of extended-release patient-tailored prednisolone tablets via 4 fused deposition modelling (FDM) 3D printing”, European Journal of Pharmaceutical Sciences, doi.org/10.1016/j.ejps.2014.11.009.

[23] Melocchi, A., Parietti, F., Loreti, G., Maroni, A.,Gazzaniga, A. and Zema, L. (2015), “3D printing by fused deposition modeling (FDM) of a swellable/erodible capsular device for oral pulsatile release of drugs”, Journal of Drug Delivery Science and Technology, doi.org/10.1016/j.jddst.2015.07.016.

[24] Park, S. and Ruoff, R.S. (2009), “Chemical methods for the production of graphenes”, Nature nanotechnology, doi: 10.1038/nnano.2009.58

[25] Su, C. Y., Lu, A. Y., Xu, Y., Chen, F. R., Khlobystov, A. N., & Li, L. J. (2011). High-quality thin graphene films from fast electrochemical exfoliation. ACS nano, 5(3), 2332-2339.

[26] Calderon- Ayala, G., Cortez-Valadez, M., and Mani-Gnzalez, P.G. et al. (2017), “Green synthesis of reduced graphene oxide using ball milling”, Carbon Letters, Vol. 21, No. 1, 93-97

[27] Yang, H., Hernandez, Y., Schlierf, A., Felten, A., Eckmann, A., Johal, S., ...& Palermo, V. (2013). A simple method for graphene production based on exfoliation of graphite in water using 1-pyrenesulfonic acid sodium salt. Carbon, 53, 357-365.

[28] Hummers Jr, W. S., and Offeman, R. E. (1958),”Preparation of graphitic oxide. Journal of the American Chemical Society”, Vol. 80, No. 6, 1339-1339.

[29] Mao, S., Pu, H., and Chen, J. (2012). Graphene oxide and its reduction: modeling and experimental progress. Rsc Advances, 2(7), 2643-2662.

[30] Shao, G., Lu, Y., Wu, F., Yang, C., Zeng, F. and Wu, Q., (2012), “Graphene oxide: the mechanisms of oxidation and exfoliation”, Journal of materials science,Vol. 47, No. 10, 4400-4409

[31] Lopez, M. D. P. L., Palomino, J. L. V., Silva, M. L. S., & Izquierdo, A. R. (2016). Optimization of the Synthesis Procedures of Graphene and Graphite Oxide. In Recent Advances in Graphene Research. InTech

[32] Monajjemi, M. (2017). Liquid-phase exfoliation (LPE) of graphite towards graphene: An ab initio study. Journal of Molecular Liquids, 230, 461-472

[33] Sahoo, S., Hatui, G., Bhattacharya, P., Dhibar, S. and Das, C.K., (2013), “One pot synthesis of graphene by exfoliation of graphite in ODCB”, Graphene,Vol. 2 , No.01, p.42.

[34] Choi, W., Lahiri, I., Seelaboyina, R. and Kang, Y.S., (2010), “Synthesis of graphene and its applications: a review”, Critical Reviews in Solid State and Materials Sciences, Vol. 35, No. 1, 52-71

[35] Zhao, J. G., Xing, B. Y., Yang, H., Pan, Q. L., Li, Z. P., & Liu, Z. J. (2016). Growth of carbon nanotubes on graphene by chemical vapor deposition. New Carbon Materials, 31(1), 31-36

[36] Nunez, P.J., RIwas, A., Garcia-Plaza, E., Beamud, E. and Sanz-Lobera, A., (2015), “Dimensional and surface texture characterization in Fused Deposition Modelling (FDM) with ABS plus”, Procedia Engineering, Vol. 132, No. 1, 856-863

[37] Equbal, A. and Sood, A.K. (2015), “Investigations on metallization in FDM build ABS part using electroless deposition method”, Journal of Manufacturing Processes, Vol. 19, No. 1, 22-31.

[38] Goyanes, A., Chang, H., Sedough, D.,Hatton, G.B., Buanz, A., Gaisford, S. and Basit, A. W. (2015), “Fabrication of controlled-release budesonide tablets via desktop (FDM) 3D printing”, International Journal of Pharmaceutics, doi.org/10.1016/j.ijpharm.2015.10.039

[39] Singh, R. and Singh, S. (2015), “Experimental investigations for statistically controlled solution of FDM assisted Nylon6-Al-Al2O3replica based investment casting”, Materials Today: Proceeding, Vol. 2, No. 1, 1876-1885.

[40] Srivastva, M., Maheshwari, S. and Kundra, T.K. (2015), “Virtual Modelling and Simulation of Functionally Graded Material Component using FDM Technique”, Materials Today: Proceedings, Vol. 2, No. 1, 3471 – 3480

[41] Singh, R., Kumar, R., Feo, L., & Fraternali, F. (2016). Friction welding of dissimilar plastic/polymer materials with metal powder reinforcement for engineering applications. Composites Part B: Engineering, 101, 77-86

[42] Kumar, R, Singh R, Ahuja IPS, (2017). A framework for welding of dissimilar polymers by using metallic fillers, IJMSE , 8(1) 2017 : January-June, 101-105.

[43] Singh, R., Kumar, R., Hashmi MSJ. (2017). Development of graphene blended low cost feedstock filament for FDM. Reference Module in Materials Science and Materials Engineering. In press.

[44] Ma, H., Shen, Z., Yi, M., Ben, S., Liang, S., Liu, L., ...& Ma, S. (2017). Direct exfoliation of graphite in water with addition of ammonia solution. Journal of Colloid and Interface Science, 503, 68-75.

[45] del Río, F., Boado, M. G., Rama, A., & Guitián, F. (2017). A comparative study on different aqueous-phase graphite exfoliation methods for few-layer graphene production and its application in alumina matrix composites. Journal of the European Ceramic Society.37, 3681-3693.

[46] Papageorgiou, D. G., Kinloch, I. A., & Young, R. J. (2017). Mechanical Properties of Graphene and Graphene-based Nanocomposites. Progress in Materials Science. 90, 75-127.

[47] Zhong, Y., Zhen, Z., & Zhu, H. (2017). Graphene: Fundamental research and potential applications. FlatChem, 4, 20-32.

[48] Parvez, K., Yang, S., Feng, X., & Müllen, K. (2015). Exfoliation of graphene via wet chemical routes. Synthetic Metals, 210, 123-132.

[49] Kamali, A. R. (2017). Scalable fabrication of highly conductive 3D graphene by electrochemical exfoliation of graphite in molten NaCl under Ar/H 2 atmosphere. Journal of Industrial and Engineering Chemistry, 52, 18-27.

[50] Yu, P., Lowe, S. E., Simon, G. P., & Zhong, Y. L. (2015). Electrochemical exfoliation of graphite and production of functional graphene. Current Opinion in Colloid & Interface Science, 20(5), 329-338.

[51] Kintigh, J., Diaconescu, B., Echegoyen, Y., Busnaina, A., Pohl, K., & Miller, G. P. (2016). Hydrogenation and exfoliation of graphene using polyamine reagents. Diamond and Related Materials, 66, 107-112.

[52] Jiang, F., Yu, Y., Wang, Y., Feng, A., & Song, L. (2017). A novel synthesis route of graphene via microwave assisted intercalation-exfoliation of graphite. Materials Letters, 200, 39-42.

[53] Eda, G., Fanchini, G., & Chhowalla, M. (2008). Large-area ultrathin films of reduced graphene oxide as a transparent and flexible electronic material. Nature nanotechnology, 3(5), 270-274.

[54] Xu, Y., Bai, H., Lu, G., Li, C., & Shi, G. (2008). Flexible graphene films via the filtration of water-soluble noncovalent functionalized graphene sheets. Journal of the American Chemical Society, 130(18), 5856-5857.

[55] Li, D., Müller, M. B., Gilje, S., Kaner, R. B., & Wallace, G. G. (2008). Processable aqueous dispersions of graphene nanosheets. Nature nanotechnology, 3(2), 101-105.

[56] Niyogi, S., Hamon, M. A., Perea, D. E., Kang, C. B., Zhao, B., Pal, S. K., ... & Haddon, R. C. (2003). Ultrasonic dispersions of single-walled carbon nanotubes. The Journal of Physical Chemistry B, 107(34), 8799-8804.

[57] Blake, P., Brimicombe, P. D., Nair, R. R., Booth, T. J., Jiang, D., Schedin, F., ...& Geim, A. K. (2008). Graphene-based liquid crystal device. Nano letters, 8(6), 1704-1708

[58] Hernandez, Y., Nicolosi, V., Lotya, M., Blighe, F. M., Sun, Z., De, S., ...&Boland, J. J. (2008). High-yield production of graphene by liquid-phase exfoliation of graphite. Nature nanotechnology, 3(9), 563-568.

[59] Hamilton, C. E., Lomeda, J. R., Sun, Z., Tour, J. M., & Barron, A. R. (2009). High-yield organic dispersions of unfunctionalized graphene. Nano letters, 9(10), 3460-3462.

[60] Zhou, M., Tian, T., Li, X., Sun, X., Zhang, J., Cui, P., ...&Qin, L. C. (2014). Production of graphene by liquid-phase exfoliation of intercalated graphite. Int. J. Electrochem. Sci, 9, 810-820.

[61] He, P., Zhou, C., Tian, S., Sun, J., Yang, S., Ding, G., ...& Jiang, M. (2015). Urea-assisted aqueous exfoliation of graphite for obtaining high-quality graphene. Chemical Communications, 51(22), 4651-4654.

[62] Sharma, V., Garg, A., & Sood, S. C. (2015). Graphene Synthesis via Exfoliation of Graphite by Ultrasonication. International Journal of Engineering Trends and Technology (IJETT), 26, 38-42.

[63] Son, M., & Ham, M. H. (2017). Low-temperature synthesis of graphene by chemical vapor deposition and its applications. FlatChem. In press

[64] Yoshihara, N., & Noda, M. (2017). Chemical etching of copper foils for single-layer graphene growth by chemical vapor deposition. Chemical Physics Letters, 685, 40-46.

[65] Guo, W., Xu, C., Xu, K., Deng, J., Guo, W., Yurgens, A., & Sun, J. (2016). Rapid chemical vapor deposition of graphene on liquid copper. Synthetic Metals, 216, 93-97.

[66] Melios, C., Centeno, A., Zurutuza, A., Panchal, V., Giusca, C. E., Spencer, S., ...&Kazakova, O. (2016). Effects of humidity on the electronic properties of graphene prepared by chemical vapour deposition. Carbon, 103, 273-280.

[67] Kwieciñski, W., Sotthewes, K., Poelsema, B., Zandvliet, H. J., & Bampoulis, P. (2017). Chemical vapor deposition growth of bilayer graphene in between molybdenum disulfide sheets. Journal of Colloid and Interface Science, 505, 776-782.

[68] Pekdemir, S., Onses, M. S., & Hancer, M. (2017). Low temperature growth of graphene using inductively-coupled plasma chemical vapor deposition. Surface and Coatings Technology, 309, 814-819.

[69] Fitri, M. A., Ota, M., Hirota, Y., Uchida, Y., Hara, K., Ino, D., & Nishiyama, N. (2017). Fabrication of TiO 2-graphene photocatalyst by direct chemical vapor deposition and its anti-fouling property. Materials Chemistry and Physics. 198, pp 42-48

[70] Bhuyan, M. S. A., Uddin, M. N., Islam, M. M., Bipasha, F. A., & Hossain, S. S. (2016). Synthesis of graphene. International Nano Letters, 6(2), 65-83.

[71] Singh, R., Kumar, R., Kumar, S. (2017). Polymer Waste as Fused Deposition Modeling Feed Stock Filament for Industrial Applications. Reference Module in Materials Science and Materials Engineering. Oxford: Elsevier; 2017. 1-12.101, 77-86.

[72] Novoselov, K. S., Fal, V. I., Colombo, L., Gellert, P. R., Schwab, M. G., & Kim, K. (2012). A roadmap for graphene. Nature, 490(7419), 192-200.

[73] Tabrizi, M. A., Azar, S. J., & Varkani, J. N. (2014). Eco-synthesis of graphene and its use in dihydronicotinamide adenine dinucleotide sensing. Analytical biochemistry, 460, 29-35.

[74] Zhou, G., Wang, Y., & Cui, L. (2015). Biomedical Sensor, Device and Measurement Systems. In Advances in Bioengineering. InTech.

[75] van de Velde, L., d'Angremont, E., & Olthuis, W. (2016). Solid contact potassium selective electrodes for biomedical applications–a review. Talanta, 160, 56-65.

[76] Kurbanoglu, S., & Ozkan, S. A. (2017). Electrochemical Carbon Based Nanosensors: A Promising Tool in Pharmaceutical and Biomedical Analysis. Journal of Pharmaceutical and Biomedical Analysis.

[77] Kim, H., & Ahn, J. H. (2017). Graphene for flexible and wearable device applications. Carbon, 120, 244-257

[78] http://www.nitride-crystals.com/graphene-gas-sensor.pdf.

[79] Jakoby, B. (2011). Liquid condition monitoring using physical sensors. Procedia Engineering, 25, 657-664.

[80] Stampfer, C., Helbling, T., Obergfell, D., Schöberle, B., Tripp, M. K., Jungen, A., ...& Hierold, C. (2006). Fabrication of single-walled carbon-nanotube-based pressure sensors. Nano letters, 6(2), 233-237.

[81] Jiang, S., Gong, X., Guo, X., & Wang, X. (2014). Potential application of graphene nanomechanical resonator as pressure sensor. Solid State Communications, 193, 30-33.

[82] Bicking, R., E. (1998), Fundamentals of Pressure Sensor Technology, http://www.sensorsmag.com/components/fundamentals-pressure-sensor-technology.

[83] Ashcroft, N. W., & Mermin, N. D. (2005). Solid State Physics (Holt, Rinehart and Winston, New York, 1976). Google Scholar, 403.

[84] Ferrari, A. C., Bonaccorso, F., Fal'Ko, V., Novoselov, K. S., Roche, S., Bøggild, P., ...&Garrido, J. A. (2015). Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems. Nanoscale, 7(11), 4598-4810.

[85] Filippidou, M. K., Tegou, E., Tsouti, V., & Chatzandroulis, S. (2015). A flexible strain sensor made of graphene nanoplatelets/polydimethylsiloxane nanocomposite. Microelectronic Engineering, 142, 7-11.

[86] Guo, R., Tang, W., Shen, C., & Wang, X. (2016). High sensitivity and fast response graphene oxide capacitive humidity sensor with computer-aided design. Computational Materials Science, 111, 289-293.

[87] Wan, S., Bi, H., Zhou, Y., Xie, X., Su, S., Yin, K., & Sun, L. (2017). Graphene oxide as high-performance dielectric materials for capacitive pressure sensors. Carbon, 114, 209-216.

[88] Bi, S., Zhang, L., Mu, C., Liu, M., & Hu, X. (2017). Electromagnetic interference shielding properties and mechanisms of chemically reduced graphene aerogels. Applied Surface Science, 412, 529-536.

[89] Wang, Y., Chen, H., Sun, M., Yao, Z., Quan, B., Liu, Z., ...& Li, J. (2017). Ultrafast carrier transfer evidencing graphene electromagnetically enhanced ultrasensitive SERS in graphene/Ag-nanoparticles hybrid. Carbon, 122, 98-105.

[90] Zhan, H. Z., Yang, F. P., & Wang, X. (2017). Nonlinear viscoelastic dynamic responses of bi-graphene/piezoelectric laminated films under moving particles. International Journal of Mechanical Sciences.

[91] Bagheri, H., Shirzadmehr, A., & Rezaei, M. (2015). Designing and fabrication of new molecularly imprinted polymer-based potentiometric nano-graphene/ionic liquid/carbon paste electrode for the determination of losartan. Journal of Molecular Liquids, 212, 96-102.

[92] Yang, C. M., Chen, T. C., Yang, Y. C., Hsiao, M. C., Meyyappan, M., & Lai, C. S. (2017). Ultraviolet illumination effect on monolayer graphene-based resistive sensor for acetone detection. Vacuum, 140, 89-95.

[93] Hauptmann, P. "Resonant sensors and applications." Sensors and Actuators A: Physical 26.1-3 (1991): 371-377.

[94] Gai, L., Li, J., & Zhao, Y. (2017). Preparation and application of microfiber resonant ring sensors: A review. Optics & Laser Technology, 89, 126-136.

[95] Parvaz, R., & Karami, H. (2017). Far-infrared multi-resonant graphene-based metamaterial absorber. Optics Communications, 396, 267-274.

[96] Flores, A., Ania, F., Salavagione, H. J., Ellis, G., Saurel, D., & Gómez-Fatou, M. A. (2016). Local mechanical properties of graphene/polyethylene-based nanocomposites by depth-sensing indentation. European Polymer Journal, 74, 120-129.

[97] Wei, W., Nong, J., Zhu, Y., Tang, L., Zhang, G., Yang, J., ...& Wei, D. (2017). Cavity-enhanced continuous graphene plasmonic resonator for infrared sensing. Optics Communications, 395, 147-153.

[98] Yu, X., Zhang, W., Zhang, P., & Su, Z. (2017). Fabrication technologies and sensing applications of graphene-based composite films: advances and challenges. Biosensors and Bioelectronics, 89, 72-84.

[99] Chatterjee, S. G., Chatterjee, S., Ray, A. K., & Chakraborty, A. K. (2015). Graphene–metal oxide nanohybrids for toxic gas sensor: A review. Sensors and Actuators B: Chemical, 221, 1170-1181.

[100] Balaguru, R. J. B., & Jeyaprakash, B. G. (2004). Mimic of a Gas sensor, Metal Oxide Gas Sensing Mechanism, Factors Influencing the Sensor Performance and Role of nanomaterials based gas sensors. NPTEL–Electrical & Electronics Engineering–Semiconductor Nanodevices.

[101] Sun, Y. F., Liu, S. B., Meng, F. L., Liu, J. Y., Jin, Z., Kong, L. T., & Liu, J. H. (2012). Metal oxide nanostructures and their gas sensing properties: a review. Sensors, 12(3), 2610-2631.

[102] Shankar, P., & Rayappan, J. B. B. (2015). Gas sensing mechanism of metal oxides: The role of ambient atmosphere, type of semiconductor and gases-A review. Sci. Lett. J, 4, 126.

[103] Vergara, A., Muezzinoglu, M. K., Rulkov, N., & Huerta, R. (2010). Information-theoretic optimization of chemical sensors. Sensors and Actuators B: Chemical, 148(1), 298-306.

[104] Zheng, Q., Fu, Y. C., & Xu, J. Q. (2010). Advances in the chemical sensors for the detection of DMMP—A simulant for nerve agent sarin. Procedia Engineering, 7, 179-184.

[105] Katta, N., Meier, D. C., Benkstein, K. D., Semancik, S., & Raman, B. (2016). The I/O transform of a chemical sensor. Sensors and Actuators B: Chemical, 232, 357-368.

[106] Ahmed, K., Paul, B. K., Chowdhury, S., Islam, M. S., Sen, S., Islam, M. I., ...& Miah, M. B. A. (2017). Dataset on photonic crystal fiber based chemical sensor. Data in Brief, 12, 227-233.

[107] Demami, F., Ni, L., Rogel, R., Salaun, A. C., & Pichon, L. (2010). Silicon nanowires synthesis Wang, B., Liddell, K. L., Wang, J., Koger, B., Keating, C. D., & Zhu, J. (2014). Oxide-on-graphene field effect bio-ready sensors. Nano Research, 7(9), 1263-1270 for chemical sensor applications. Procedia Engineering, 5, 351-354.

[108] Wang, B., Liddell, K. L., Wang, J., Koger, B., Keating, C. D., & Zhu, J. (2014). Oxide-on-graphene field effect bio-ready sensors. Nano Research, 7(9), 1263-1270.

[109] Miyamoto, K. I., Sugawara, Y., Kanoh, S. I., Yoshinobu, T., Wagner, T., & Schöning, M. J. (2010). Image correction method for the chemical imaging sensor. Sensors and Actuators B: Chemical, 144(2), 344-348.

[110] Wang, H. H., (2010) Chapter 9 – Flexible Chemical Sensors, Semiconductor Nanomaterials for Flexible Technologies, 247–273.

[111] Comini, E., & Sberveglieri, G. (2010). Metal oxide nanowires as chemical sensors. Materials Today, 13(7), 36-44.

[112] Deen, D. A., Olson, E. J., Ebrish, M. A., & Koester, S. J. (2014). Graphene-based quantum capacitance wireless vapor sensors. IEEE Sensors Journal, 14(5), 1459-1466.

[113] He, Y., Liu, Y., Wu, T., Ma, J., Wang, X., Gong, Q., ...& Gao, J. (2013). An environmentally friendly method for the fabrication of reduced graphene oxide foam with a super oil absorption capacity. Journal of hazardous materials, 260, 796-805.

[114] Tiwari, J. N., Mahesh, K., Le, N. H., Kemp, K. C., Timilsina, R., Tiwari, R. N., & Kim, K. S. (2013). Reduced graphene oxide-based hydrogels for the efficient capture of dye pollutants from aqueous solutions. Carbon, 56, 173-182.

[115] Hahn, Y. B., Ahmad, R., & Tripathy, N. (2012). Chemical and biological sensors based on metal oxide nanostructures. Chemical Communications, 48(84), 10369-10385.

[116] Park, M. S., Kim, K. H., Kim, M. J., & Lee, Y. S. (2016). NH 3 gas sensing properties of a gas sensor based on fluorinated graphene oxide. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 490, 104-109.

[117] Kaur, G., Gupta, S., & Dharamvir, K. (2017). Theoretical investigation of adsorption of gas molecules on Li metal adsorbed at H-site of graphene: A search for graphene based gas sensors. Surfaces and Interfaces, 8, 83-90.

[118] Ye, Z., Tai, H., Guo, R., Yuan, Z., Liu, C., Su, Y., ...&Jiang, Y. (2017). Excellent ammonia sensing performance of gas sensor based on graphene/titanium dioxide hybrid with improved morphology. Applied Surface Science, 419, 84-90.

[119] Kim, H. W., Kwon, Y. J., Mirzaei, A., Kang, S. Y., Choi, M. S., Bang, J. H., & Kim, S. S. (2017). Synthesis of zinc oxide semiconductors-graphene nanocomposites by microwave irradiation for application to gas sensors. Sensors and Actuators B: Chemical, 249, 590-601.

[120] Fu, Y., Wang, L., Huang, D., Zou, L., & Ye, B. (2017). A new calcium germanate-graphene nanocomposite modified electrode as efficient electrochemical sensor for determination of daphnetin. Journal of Electroanalytical Chemistry. Volume 801, 77-83.

[121] Akkarachanchainon, N., Rattanawaleedirojn, P., Chailapakul, O., & Rodthongkum, N. (2017). Hydrophilic graphene surface prepared by electrochemically reduced micellar graphene oxide as a platform for electrochemical sensor. Talanta, 165, 692-701.

[122] Zhang, R., & Chen, W. (2017). Recent advances in graphene-based nanomaterials for fabricating electrochemical hydrogen peroxide sensors. Biosensors and Bioelectronics, 89, 249-268.

[123] Springsteen, G., Ballard, C. E., Gao, S., Wang, W., & Wang, B. (2001). The development of photometric sensors for boronic acids. Bioorganic chemistry, 29(5), 259-270.

[124] Klaudiny, M., & Hilton, A. (2014). Error analysis of photometric stereo with colour lights. Pattern Recognition Letters, 48, 81-92.

[125] McNaughton, B. H., Agayan, R. R., Wang, J. X., & Kopelman, R. (2007). Physiochemical microparticle sensors based on nonlinear magnetic oscillations. Sensors and Actuators B: Chemical, 121(1), 330-340.

[126] Gulzar, A., Yang, P., He, F., Xu, J., Yang, D., Xu, L., & Jan, M. O. (2017). Bioapplications of graphene constructed functional nanomaterials. Chemico-biological interactions, 262, 69-89.

[127] Zheng, D., Hu, H., Liu, X., & Hu, S. (2015). Application of graphene in elctrochemical sensing. Current Opinion in Colloid & Interface Science, 20(5), 383-405.

[128] Rolfe, P. (1988). Review of chemical sensors for physiological measurement. Journal of biomedical engineering, 10(2), 138-145.

[129] Lee, S., & Kruse, J. (2008). Biopotential electrode sensors in ECG/EEG/EMG systems. Analog Devices, 200, 1-2.

[130] Neuman, M. R. “Biopotential Electrodes., (2000) ” The Biomedical Engineering Handbook: Second Edition. Ed. Joseph D. Bronzino Boca Raton: CRC Press LLC.

[131] Ramar, A., Saraswathi, R., Vilian, A. E., Chen, S. M., & Wang, F. M. (2017). Polyisothianaphthene/graphene nanocomposite as a new counter electrode material for high performance dye sensitized solar cell. Synthetic Metals, 230, 58-64.

[132] Chen, W., Niu, X., Li, X., Li, X., Li, G., He, B., ...&Sun, W. (2017). Investigation on direct electrochemical and electrocatalytic behavior of hemoglobin on palladium-graphene modified electrode. Materials Science and Engineering: C. vol. 80, 135-140

[133] Foo, M. E., & Gopinath, S. C. (2017). Feasibility of graphene in biomedical applications. Biomedicine & Pharmacotherapy, 94, 354-361.

[134] Dunbar, D. N., Tobler, H. G., Fetter, J., Gornick, C. C., Benson, D. W., & Benditt, D. G. (1986). Intracavitary electrode catheter cardioversion of atrial tachyarrhythmias in the dog. Journal of the American College of Cardiology, 7(5), 1015-1027.

[135] Brady, L. W., Ardiet, J. M., Heilmann, H. P., Baert, L. V., Camart, J. C., Cetas, T. C., ... & Cosset, J. M. (2012). Interstitial and intracavitary thermoradiotherapy. Springer Science & Business Media.

[136] Yapici, M. K., Alkhidir, T., Samad, Y. A., & Liao, K. (2015). Graphene-clad textile electrodes for electrocardiogram monitoring. Sensors and Actuators B: Chemical, 221, 1469-1474.

[137] Guo, X., Pei, W., Wang, Y., Chen, Y., Zhang, H., Wu, X., ...& Liu, R. (2016). A human-machine interface based on single channel EOG and patchable sensor. Biomedical Signal Processing and Control, 30, 98-105.

[138] Das, P. S., Hossain, M. F., & Park, J. Y. (2017). Chemically reduced graphene oxide-based dry electrodes as touch sensor for electrocardiograph measurement. Microelectronic Engineering.

[139] Xiong, P., Wu, C., Zhou, H., Song, A., Hu, L., & Liu, X. P. (2018). Design of an accurate end-of-arm force display system based on wearable arm gesture sensors and EMG sensors. Information Fusion, 39, 178-185.

[140] Turner, A., Karube, I., & Wilson, G. S. (1987). Biosensors: fundamentals and applications. Oxford university press.

[141] Banica, F. G. (2012). Chemical sensors and biosensors: fundamentals and applications. John Wiley & Sons.

[142] Kuriyama, T., & Kimura, J. (1991). FET-based biosensors. Bioprocess technology, 15, 139-162.

[143] Yuqing, M., Jianguo, G., & Jianrong, C. (2003). Ion sensitive field effect transducer-based biosensors. Biotechnology advances, 21(6), 527-534.

[144] Kurkina, T. (2012). Label-free electrical biosensing based on electrochemically functionalized carbon nanostructures.DISSERTATION , to apply for the degree of „Doctor rerum naturalium“.

[145] Karlsson, R. (2004). SPR for molecular interaction analysis: a review of emerging application areas. Journal of Molecular Recognition, 17(3), 151-161.

[146] Stebunov, Y. V., Aftenieva, O. A., Arsenin, A. V., & Volkov, V. S. (2015). Highly sensitive and selective sensor chips with graphene-oxide linking layer. ACS applied materials & interfaces, 7(39), 21727-21734.

[147] Vo-Dinh, T., & Cullum, B. (2000). Biosensors and biochips: advances in biological and medical diagnostics. Fresenius' journal of analytical chemistry, 366(6), 540-551.

[148] Fang, Y., & Ramasamy, R. P. (2015). Current and prospective methods for plant disease detection. Biosensors, 5(3), 537-561.

[149] Xue, K., Zhou, S., Shi, H., Feng, X., Xin, H., & Song, W. (2014). A novel amperometric glucose biosensor based on ternary gold nanoparticles/polypyrrole/reduced graphene oxide nanocomposite. Sensors and Actuators B: Chemical, 203, 412-416.

[150] Viswanathan, S., Narayanan, T. N., Aran, K., Fink, K. D., Paredes, J., Ajayan, P. M., ...& Demirci, U. (2015). Graphene–protein field effect biosensors: glucose sensing. Materials Today, 18(9), 513-522.

[151] Jin, B., Wang, P., Mao, H., Hu, B., Zhang, H., Cheng, Z., ...& Jin, Q. (2014). Multi-nanomaterial electrochemical biosensor based on label-free graphene for detecting cancer biomarkers. Biosensors and Bioelectronics, 55, 464-469.

[152] Ruecha, N., Rangkupan, R., Rodthongkum, N., & Chailapakul, O. (2014). Novel paper-based cholesterol biosensor using graphene/polyvinylpyrrolidone/polyaniline nanocomposite. Biosensors and Bioelectronics, 52, 13-19.

[153] Guo, W., Li, H., Li, M., Dai, W., Shao, Z., Wu, X., & Yang, B. (2014). Synthesis of nickel nanosheet/graphene composites for biosensor applications. Carbon, 79, 636-645.

[154] Hernández, R., Vallés, C., Benito, A. M., Maser, W. K., Rius, F. X., & Riu, J. (2014). Graphene-based potentiometric biosensor for the immediate detection of living bacteria. Biosensors and bioelectronics, 54, 553-557.

[155] Zhang, H., Li, Z. F., Snyder, A., Xie, J., & Stanciu, L. A. (2014). Functionalized graphene oxide for the fabrication of paraoxon biosensors. Analytica chimica acta, 827, 86-94.

[156] Zhang, Q., Zhang, D., Lu, Y., Yao, Y., Li, S., & Liu, Q. (2015). Graphene oxide-based optical biosensor functionalized with peptides for explosive detection. Biosensors and Bioelectronics, 68, 494-499.

[157] Fritea, L., Tertiș, M., Le Goff, A., Cosnier, S., Săndulescu, R., & Cristea, C. (2017). Graphene-based Biosensors for Dopamine Determination. Procedia Technology, 27, 106-107.

[158] Song, H. S., Kwon, O. S., Kim, J. H., Conde, J., & Artzi, N. (2017). 3D hydrogel scaffold doped with 2D graphene materials for biosensors and bioelectronics. Biosensors and Bioelectronics, 89, 187-200.

[159] Afsahi, S., Lerner, M. B., Goldstein, J. M., Lee, J., Tang, X., Bagarozzi, D. A., ... & Goldsmith, B. R. (2017). Novel Graphene-Based Biosensor for Early Detection of Zika Virus Infection. Biosensors and Bioelectronics. In-Press.

[160] Loan, P. T. K., Wu, D., Ye, C., Li, X., Tra, V. T., Wei, Q., ...&Lin, C. T. (2018). Hall effect biosensors with ultraclean graphene film for improved sensitivity of label-free DNA detection. Biosensors and Bioelectronics.Vol. 99, 85-91.

[161] Singh, R., Sandhu, G. S., Penna, R., & Farina, I. (2017). Investigations for Thermal and Electrical Conductivity of ABS-Graphene Blended Prototypes. Materials, 10(8), 881.

[162] Feo, L., Fraternali, F., Skelton, R.E. (2017). “Special issue on composite lattices and multiscale innovative materials and structures”. Composites Part B: Engineering, 115, 1-2.

[163] Shirinbayan M., Fitoussi J., Bocquet M., Meraghni F., Surowiec B. &Tcharkhtchi A. (2017). Multi-scale experimental investigation of the viscous nature of damage in Advanced Sheet MoldingCompound (A-SMC) submitted to high strain rates. Composites Part B: Engineering, 115, 3-13.

[164] Bieniek Z. (2017).The self-equilibrium problem of the Class-Theta tetrahedral tensegrity module. Composites Part B: Engineering, 115, 21-29.

[165] Rimoli J.J. & Raj Kumar Pal (2017).Mechanical response of 3-dimensional tensegrity lattices. Composites Part B: Engineering, 115, 30-42.

[166] Colangelo F.& Cioffi R. (2017). Mechanical properties and durability of mortar containing fine fraction of demolition wastes produced by selective demolition in South Italy. Composites Part B: Engineering, 115, 43-50.

[167] Naddeo F., Naddeo A., Cappetti N. (2017). Novel “load adaptive algorithm based” procedure for 3D printing of lattice-based components showing parametric curved micro-beams. Composites Part B: Engineering, 115, 51-59.

[168] Naddeo F., Naddeo A.& Cappetti N. (2017). Novel “load adaptive algorithm based” procedure for 3D printing of cancellous bone-inspired structures. Composites Part B: Engineering, 115, 60-69.

[169] Ermakova A.&Dayyani I.(2017). Shape optimisation of composite corrugated morphing skins. Composites Part B: Engineering, 115, 87-101.

[170] Fraddosio A., Marzano S., Pavone G.&Piccioni M.D. (2017).Morphology and self-stress design of V-Expander tensegrity cells. Composites Part B: Engineering, 115, 102-116.

[171] Amendola A., Benzoni G.& Fraternali F. (2017).Non-linear elastic response of layered structures, alternating pentamode lattices and confinement plates. Composites Part B: Engineering, 115, 117-123.

[172] Castaldo P., Nastri E.& Piluso V. (2017).FEM simulations and rotation capacity evaluation for RHS temper T4 aluminium alloy beams. Composites Part B: Engineering, 115, 124-137.
[173] Khezrzadeh H.(2017). A statistical micromechanical multiscale method for determination of the mechanical properties of composites with periodic microstructure. Composites Part B: Engineering, 115, 138-143.
[174] Magliozzi L., Micheletti A., Pizzigoni A.& Ruscica G. (2017).On the design of origami structures with a continuum of equilibrium shapes. Composites Part B: Engineering, 115, 144-150.
[175] De Tommasi D., Marano G.C., Puglisi G.& Trentadue F. (2017). Morphological optimization of tensegrity-type metamaterials. Composites Part B: Engineering, 115, 182-187.
[176] Monaco A., Minafò G., Cucchiara C., D'Anna J. &La Mendola L. (2017).Finite element analysis of the out-of-plane behavior of FRP strengthened masonry panels. Composites Part B: Engineering, 115, 188-202.
[177] Singh R., Singh R., Dureja J.S., Farina I.& Fabbrocino F. (2017).Investigations for dimensional accuracy of Al alloy/Al-MMC developed by combining stir casting and ABS replica based investment casting. Composites Part B: Engineering, 115, 203-208.
[178] Feo L., Latour M., Penna R.& Rizzano G. (2017).Pilot study on the experimental behavior of GFRP-steel slip-critical connections. Composites Part B: Engineering, 115, 209-222.
[179] Alessi R., Favata A.& Micheletti A. (2017). Pressurized CNTs under tension: A finite-deformation lattice model. Composites Part B: Engineering, 115, 223-235.
[180] Carpentieri G.&Skelton R. E. (2017).On the minimal mass design of composite membranes. Composites Part B: Engineering, 115, 244-256.
[181] Cimmino M.C., Miranda R., Sicignano E., A.J.M. Ferreira, R.E. Skelton& F. Fraternali. (2017). Composite solar façades and wind generators with tensegrity architecture. Composites Part B: Engineering, 115, 275-281.
[182] Ferrante Cavallaro G., Francavilla A., Latour M., Piluso V.& Rizzano G. (2017). Experimental behaviour of innovative thermal spray coating materials for FREEDAM joints. Composites Part B: Engineering, 115, 289-299.
[183] Thorhallsson E.R., Hinriksson G.& Snæbjornsson J.T. (2017). Strength and stiffness of glulam beams reinforced with glass and basalt fibres. Composites Part B: Engineering, 115, 300-307.
[184] Castaldo P., Palazzo B., Ferrentino T.& Petrone G. (2017).Influence of the strength reduction factor on the seismic reliability of structures with FPS considering intermediate PGA/PGV ratios. Composites Part B: Engineering, 115, 308-315.
[185] Genoese A., Genoese A., Rizzi N.L.&Salerno G. (2017).On the derivation of the elastic properties of lattice nanostructures: The case of graphene sheets. Composites Part B: Engineering, 115, 316-329.

[186] Lucantonio A., Tomassetti G.& De Simone A. (2017).Large-strain poroelastic plate theory for polymer gels with application to swelling-induced morphing of composite plates. Composites Part B: Engineering, 115, 330-340.

[187] Bacigalupo A., Gnecco G., Lepidi M.& Gambarotta L. (2017).Optimal design of low-frequency band gaps in anti-tetrachiral lattice meta-materials. Composites Part B: Engineering, 115, 341-359.

[188] Montuori R.& Muscati R. (2017). Smart and simple design of seismic resistant reinforced concrete frame. Composites Part B: Engineering, 115, 360-368, 2017.

[189] Fantilli A.P., Frigo B.& Chiaia B. (2017). Comparing multi-scale cracking mechanisms in man-made composites and natural materials. Composites Part B: Engineering, 115, 369-375.

[190] Fabbrocino F., Farina I.& Modano M. (2017). Loading noise effects on the system identification of composite structures by dynamic tests with vibrodyne. Composites Part B: Engineering, 115, 376-383.

[191] Fantuzzi N., Tornabene F., Bacciocchi M.& Dimitri R. (2017).Free vibration analysis of arbitrarily shaped Functionally Graded Carbon Nanotube-reinforced plates. Composites Part B: Engineering, 115, 384-408.

[192] Singh N., Hui D., Singh R., Ahuja I.P.S. , Feo L. &Fraternali F. (2017).Recycling of plastic solid waste: A state of art review and future applications. Composites Part B: Engineering, 115, 409-422.

[193] Taddei P., Ruggiero A., Pavoni E. & Affatato S. (2017).Transfer of metallic debris after in vitro ceramic-on-metal simulation: Wear and degradation in Biolox® Delta composite femoral heads. Composites Part B: Engineering, 115, 477-487.

[194] Mosallam A. S. & Nasr A. (2017).Structural performance of RC shear walls with post-construction openings strengthened with FRP composite laminates. Composites Part B: Engineering, 115, 488-504.

[195] Ascione L., Fraternali F. (1992). “A penalty model for the analysis of composite curved beams.” Computers & Structures, 45, 985-999.

[196] Fraternali F., Reddy J.N. (1993). “A penalty model for the analysis of laminated composite shells.” International Journal of Solids and Structures, 30, 3337-3355.

[197] Fraternali F., Bilotti G. (1997). “Non-linear elastic stress analysis in curved composite beams.” Computers & Structures, 62, 837-869.

[198] Fraternali F., Spadea S., Berardi V.P. (2014). “Effects of recycled PET fibers on the mechanical properties and seawater curing of Portland cement-based concretes.” Construction and Building Materials, 61, 293-302.

[199] Spadea S., Farina I., Carrafiello A., Fraternali F. (2015). “Recycled nylon fibers as cement mortar reinforcement.” Construction and Building Materials, 80, 200-209.

[200] Farina I., Fabbrocino F., Carpentieri G., Modano M., Amendola A., Goodall R., Feo L., Fraternali F. (2016). “On the reinforcement of cement mortars through 3D printed polymeric and metallic fibers.” Composites Part B: Engineering, 90, 76-85.

[201] Farina, I., Fabbrocino, F., Colangelo, F., Feo, L., Fraternali, F. (2016). “Surface roughness effects on the reinforcement of cement mortars through 3D printed metallic fibers.” Composites Part B: Engineering, 99, 305-311.

[202] Amendola A., Nava E.H., Goodall R., Todd I., Skelton R.E., Fraternali F. (2015). “On the additive manufacturing, post-tensioning and testing of bi-material tensegrity structures.” Composite Structures, 131, 66-71.

[203] Amendola A., Carpentieri G., de Oliveira M., Skelton R.E., Fraternali F. (2014). “Experimental investigation of the softening stiffening response of tensegrity prisms under compressive loading.” Composite Structures, 117, 234-243.

[204] Fraternali F., Carpentieri G., Amendola A. (2015). “On the mechanical modeling of the extreme softening/stiffening response of axially loaded tensegrity prisms.” Journal of the Mechanics and Physics of Solids, 74, 136-157.

[205] Ngo D., Fraternali F., Daraio C. (2012). “Highly Nonlinear Solitary Wave Propagation in Y-Shaped Granular Crystals with Variable Branch Angles.” Physical Review E, 85, 036602-1-10.

[206] Leonard A., Fraternali F., Daraio C. (2013). “Directional wave propagation in a highly nonlinear square packing of spheres.” Experimental Mechanics, 53(3), 327-337.

[207] Fraternali F., Marino A., Elsayed T., Della Cioppa A. (2011). “On the structural shape optimization via variational methods and evolutionary algorithms.” Mechanics of Advanced Materials and Structures, 18, 225-243.

[208] Raney J.R., Fraternali F., Amendola A., Daraio C. (2011). “Modeling and in situ identification of material parameters for layered structures based on carbon nanotube arrays.” Composite Structures 93:3013–3018.

[209] Fraternali F., Lorenz C.D., Marcelli G. (2012). “On the estimation of the curvatures and bending rigidity of membrane networks via a local maximum-entropy approach.” Journal of Computational Physics, 231, 528-540.

[210] Fraternali, F., Amendola, A. (2017). “Mechanical modeling of innovative metamaterials alternating pentamode lattices and confinement plates.” Journal of the Mechanics and Physics of Solids, 99, 259-271.

[211] Amendola A., Smith C.J., Goodall R., Auricchio F., Feo L., Benzoni G., Fraternali F. (2016). “Experimental response of additively manufactured metallic pentamode materials confined between stiffening plates.” Composite Structures, 142, 254-262.

[212] Singh, R., Kumar, R., Hashmi MSJ. (2016). Friction Welding of Dissimilar Plastic-Based Material by Metal Powder Reinforcement. Reference Module in Materials Science and Materials Engineering. vol. 13,2016, pp. 1–16. Oxford: Elsevier.

[213] Verma, A., Prakash, A., & Tripathi, R. (2015). Sensitivity enhancement of surface plasmon resonance biosensor using graphene and air gap. Optics Communications, 357, 106-112.

[214] Kumar, R., Singh, R., Ahuja, I. P. S., Amendola, A., & Penna, R. (2017). Friction welding for the manufacturing of PA6 and ABS structures reinforced with Fe

particles. *Composites Part B: Engineering*. https://doi.org/10.1016/j.compositesb.2017.08.018