Sensors International 3 (2022) 100183

Contents lists available at ScienceDirect

Sensors International

journal homepage: www.keaipublishing.com/en/journals/sensors-international

Graphene-based temperature, humidity, and strain sensor: A review on progress, characterization, and potential applications during Covid-19 pandemic

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ARTICLE INFO

Keywords:
Graphene
Temperature
Humidity
Strain
Covid-19

ABSTRACT

Graphene's potential as material for wearable, highly sensitive and robust sensor in various fields of technology has been widely investigated until now in order to capitalize on its unique intrinsic physical and chemical properties. In the wake of Covid-19 pandemic, it has been noticed that there are various potentials roles that can be fulfilled by graphene-based temperature, humidity and strain sensor, whose roles has not been widely explored to date. This paper takes the liberty to mainly highlight the progress layout and characterization technique for graphene-based sensor while including a brief discussion on the possible strategy of sensing data analysis that can be employed to minimize and prevent the risk of Covid-19 infection within a living community. While majority of the reported sensor is still in the in-progress status, its highlighted role in this work may provide a brief idea on how the ongoing research in graphene-based sensor may lead to the future implementation of the device for routine healthcare check-up and diagnostic point-care during and post-pandemic era. On the other hand, the sensitivity and response time data against working temperature, humidity and strain range that are provided could serve as a reference for benchmarking purpose, which certainly would help enthusiast in the development of a graphene-based sensor with a better performance for the future.

1. Introduction

The development of graphene-based sensor, which is able to rapidly react and convert the miniscule changes in the open system for easier monitoring of selected condition while staying highly durable remains as one of the major aims of researchers and enthusiasts in the field of sensor technology. A wide variety of measurable quantity such as temperature, humidity, light, strain, and vibration can be processed in the form of analog signal with the existing vast network of microprocessor that would allow a cyclic trigger-response from these quantities to be reflected in the output devices such as computer and smartphone. A combination of multiple sensors would increase the complexity of the produced circuit and possibly introduce multiple composite signals in the reading of the data. In the machine learning and artificial intelligence dawn of era, the capability of sensor to sense millions of dynamic environmental data would certainly bring an advantage for the database assembly, which forms one of the major criteria for Big Data. With the assistance of graphene-based sensor as a tool for machine learning and A.I., certain patterns in the routine motion or work can be unhidden and be further modelled for optimization in the sensing system.

In the design of graphene incorporated sensor, most reported works employ piezoresistive approach for powering up the sensor, as the electrical energy supplied by DC/AC source will be used to provide source for resistance/impedances changes under different stimulants level [1–5]. Provided that the stimulant quantity is known, a series of the generated electrical resistance values would be used for calibration of the sensor

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https://doi.org/10.1016/j.sintl.2022.100183
Received 25 November 2021; Received in revised form 19 May 2022; Accepted 19 May 2022

prior to the actual data measurement. Meanwhile, an actuation of sensor under the introduction of stimulant is considered as a new strategy direction for sensing system as the sensor itself requires no battery and is to visually demonstrate the reaction at different stimulant levels. The sensor will either bend or twist to indicate the condition changes in the measured humidity [6,7], temperature [8], light [9] and solvent vapor [10] system.

In the selection of graphene class for the application as a material for sensing purpose, certain properties of graphene such as defect or ratio O/C must be considered prior to the fabrication of the sensor. In describing the defect of graphene, whose level certainly can be reflected from I_D/I_G value of Raman spectrum, a high defect level especially in the basal plane region, could affect the electrical conductivity of graphene and impede the sensitivity of the later produced sensing system [11]. On the other hand, a lower O/C value can affect the sensitivity of sensor towards moisture or infrared and will not fulfil the criteria for humidity sensing of the device. With this knowledge, a balance between defect and C/O must be strived for a better design of sensing device. From a wide selection of graphene synthesis method available nowadays, a proper selection graphene size, thickness, defect and O/C ratio protocol design for sensor application certainly would benefit many.

Besides the characteristic of graphene itself, a selection of substrate or matrix for the prepared sensor such as SiO_2/Si, polymethyl methacrylate (PMMA), polyimide (PI), polyethylene terephthalate (PET), and polyurethane (PU)would affect the robustness or the flexibility of the sensing system. An elastomer class of polymer such as styrene-ethylene-butylene-styrene (SEBS) and ethylene-propylene-diene (EPDM) rubber or even polydimethylsiloxane (PDMS) commonly employed as matrix material for the graphene due to the elasticity enables a longer strain range values as compared to that of the soft or brittle polymer. Meanwhile, a coating of graphene film on flexible/softs substrates such as fabric [12], polymer [13] and paper [14] is another novel strategy that can be applied to prevent an inhomogeneous or poor dispersion of graphene flakes during the preparation of polymer/graphene composite for sensing application. The use of inkjet printing [15], vacuum filtration [16], dip coating [17] or spray method [18] further allows a systematic control of graphene ink distribution on the substrate during the fabrication stage.

In this paper, a set of graphene-based sensor class (temperature, humidity, and strain) that is potentially useful for monitoring and reporting the health status of the user while assisting in the safety standard protocol regulation throughout daily activities in Covid-19 pandemic are discussed in detail. The outbreak of Covid-19 pandemic ever since the first recorded patient zero in 2019 [19] has reported to seriously impede the human's mental health [20] and economic progress of many countries and business [21,22] while combating the spreading of Covid-19 associated sars-2 viruses through vaccination remains of the best option until now [23]. As the virus itself is easily transmitted to other people from the discharge of infected respiratory droplets by sneezing and coughing into the air [24], a preventive measure for rapid screening of potential Covid-19 through the application of graphene sensor for detection of common symptoms certainly would be beneficial. Thus, the progress for the selected sensor class has been systematically highlighted in this paper with the aim for a complete overview of the potential role of the graphene-based sensing system in improving the diagnostic quality of Covid-19 symptom while data performance has also been provided for comparison purpose against the existing sensors.

2. Progress in graphene-based sensor

Generally, a human brain works by filtering and differentiating between an important and insignificant information from mundane/routine motion of human activities such as walking, running, and talking, where the articulately designed body parts are tasked for collection of signals to brain for processing prior to rapid actuation of muscle for response. Similar in concept to the operating principle of electromechanical sensor, a sensing circuit will record a series of data as a function of time and later transmitting the data to processor for the activation of programmable response to the designated meet condition. In real life application of sensor, where a unit of data will be clustered together in the vast sea of information from the ambient surrounding, a sensing selectivity through data filtration is becoming crucially important as the data from measured body temperature for example, must be exclusive from strain or humidity signals as the resulting misleading data may impede the accuracy and quality of the measured data. As the application of sensor for human activities monitoring may not only be limited to body temperature monitoring but possibly also for pulse, breath or cough variation examination, a sensor that is not only sensitive but potentially flexible and wearable gradually become one of the potential features in the current and future daily activities by human during the pandemics. While the presence of sensor does not completely guarantee the prevention of Covid-19 disease among community members, a real-time monitoring of human activities during the daily life may allow a rapid screening of potential Covid-19 patient, whose common symptom such as a higher body temperature, coughing and sore throat may be able to be detected from the early stage by wearable sensor [25]. Thus, the following subsection describes the progress of sensor class that may play a major role for Covid-19 prevention and self-regulation of health status during and beyond the pandemic era.

2.1. Temperature sensors

Temperature sensor acts like a thermometer, where the warm body of human is measurable from the contact between sensor electrodes with the skin. A change of electrical resistances from the difference in recorded temperature would reflect the actual body temperature after careful calibration. As temperature regulation of body can be affected by the health status of the user, a constant monitoring of temperature by wearable sensor would allow early detection of fever, which is one of the early signs for Covid-19 viruses infection. However, in many realities of Covid-19 cases, the patient may or may not exhibit fever symptom, which crucially force the combination of temperature sensor with another type of sensor such as humidity or strain sensor for the detection of Covid-19 associated symptoms such as coughing and respiration/breathing difficulty. In the worst case, in a situation where the Covid-19 patient is asymptotic, a multifunctional graphene-based temperature sensor that is able to detect the sar-2 virus from breath vapor [26] or visually force the changes in sensing fabric color such as mask [27] may becoming necessary for alarming and facile tracing asymptotic covid-19 patient apart from relying on conventional body temperature measurement alone. In this case, a mandatory wearing of mask is not only useful for protection against the airborne Covid-19 virus but also could serve as a tool for rapid screening of Covid-19 patient.

The application of graphene for temperature sensing is attributed to the excellent in-plane thermal conductivity possesses by this material [28]. The preparation of graphene either by chemical vapor deposition (CVD) [29], reduction of graphene oxide [30] or direct liquid-phase exfoliation of graphite [31] are some of the commonly used strategies for the synthesis of graphene for temperature sensor. The coating of graphene can be further achieved via deposition of the graphene flakes onto the targeted substrate by screen printing [32], lithography [33], inkjet printing [34] and in the latest trend, by 3D printing technique [35] prior to drying. Besides coating-substrate assembly, fabrication of graphene-based temperature sensor can also be achieved through the incorporation of graphene flakes as fillers for polymer matrix [36]. The resulting temperature sensor from polymer/graphene composite is reported to be more mechanically robust, is not easily cracked or scratched like graphene coating-based sensor and have a higher sensitivity towards temperature.

Meanwhile, the characterization of graphene-based temperature sensor can be completely performed through the measurement of current/resistance changes by varying temperature. As show in Fig. 1a, an increment of the current value upon contact of the sensor with the skin of

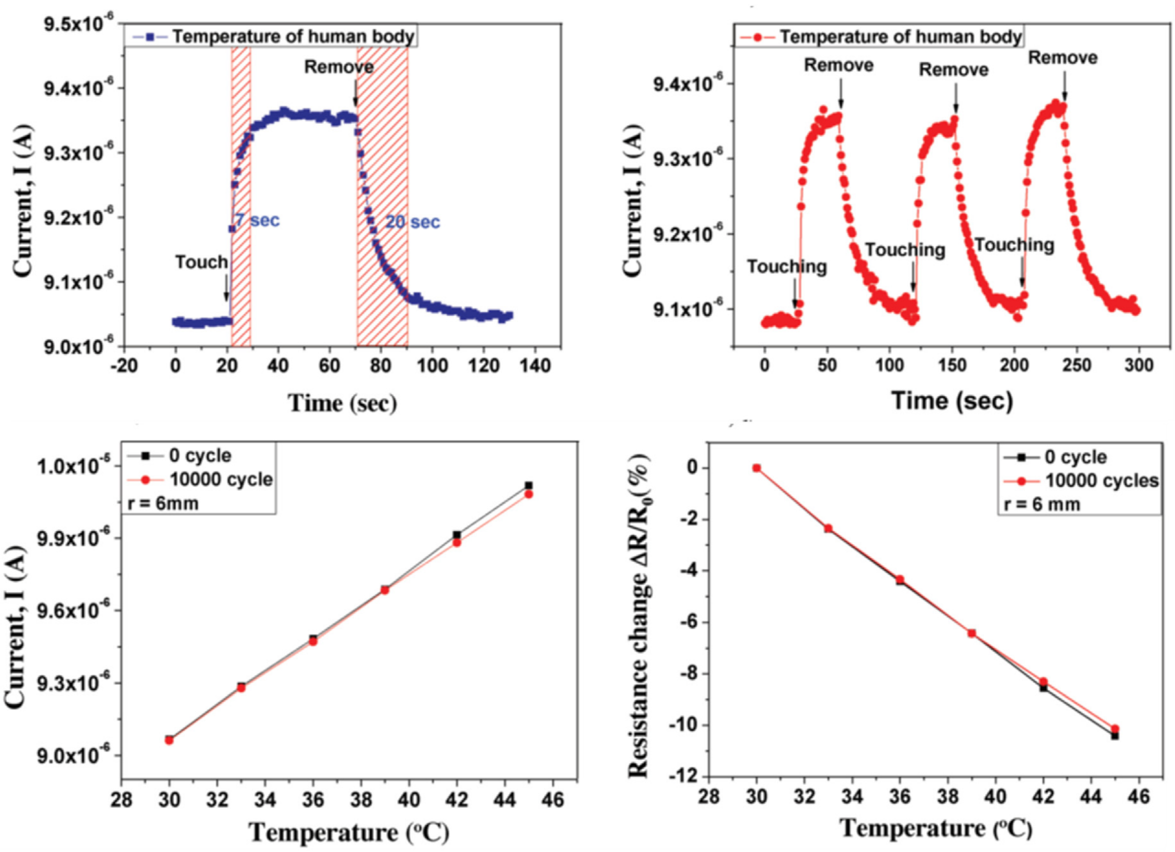

Fig. 1. Investigation on the response time and temperature sensitivity for graphene sensor (a)Response-recovery time measurement (b) stability of sensor reading is evaluated from the continuous cyclic of signal (c) and (d) represents linear relationship between current/resistance changes and temperature in °C. Reproduced with permission [37]. Copyright 2018, Wiley.

the finger is indicating the sensitivity of the temperature sensor towards human body's temperature [37].

A time taken by the sensor to achieve about 90% percentile of the maximum value is known as response time and it is a useful indicator on how fast the sensor can response to any applied temperature under stimulation. Once the heat source (finger) is removed from the sensor, a gradual decrement of the current to the steady state within 20 s, which is regarded as recovery time for the sensor can be observed. The reliability of the temperature sensor can be further investigated by subjecting the sensor to cyclic temperature changes for monitoring any variation in the resulting current/resistance peaks. In Fig. 1b, there is only a slight difference in value between peaks after periodic contact between sensor and finger skin, which is suggesting a good replicability of the reported temperature sensor. Finally, the sensitivity of graphene-based sensor towards temperature variation after a specific cycle number of strain can further be represented from a linear relationship between electrical current/resistance and temperature (see Fig. 1c and d). A highly responsive temperature sensor will produce a significant deviation in current/resistance from the original steady state flow upon sensing minute temperature changes in the measured ambient. Since heat absorption/dissipation rate of the device can influence the sensing effectiveness of the active layer towards temperature variation, various assembly technique, material type and substrate have been employed to secure good sensitivity and a wide working temperature range for the graphene-based temperature sensor (see Table 1).

Fig. 2a shows that most reported works produced temperature sensor with working temperature range between 10 and 80 °C with the best sensitivity recorded so far being 21.4%/°C for a sensor with graphene nanowalls as sensing material [43]. Lack of works reporting on the temperature sensing ability of graphene beyond 120 °C range is possibly because of the limitation in thermal properties of the selected substrate such as PI, PDMS, PET, PU or even cellulose since most of them will thermally be degraded within this temperature value. On the other hand, it is clear from the data pattern presented in the figure that most researches on the role of graphene as active material for temperature sensor are mainly focusing on the applicability of the device for monitoring human body temperature or during exercising as the sensitivity is moderate (<5%/°C) while working range is just between 5 and 70 °C. In terms of response time (see Fig. 2b), most works' reported value is below 50 s with the fastest response time recorded to date is 0.2 s for temperature sensing.

Table 1
Summary on the method and sensing performance for graphene-based temperature sensor.

Process	Substrate	S/T (%/°C)	T_{range} (°C)	References
Casting	Cellulose, PET	1.09	75	[36,38,39]
Printing	PET, PDMS, silk fibroin, PU	2.1	30	[32,34,35, 40]
Coating	PU, yarn, PDMS	1.343	35	[30,41,42]

2.2. Humidity sensors

Humidity sensor works by sensing the amount of water moisture in air while the measured value is accurately represented from the relative percentage difference between water and air concentration. When the sensing system is attached near to the human body, various novel applications such as observation of the skin dryness [44], sweating [45] or breathing rate [46] and even regulation of baby diaper wetness [47] can

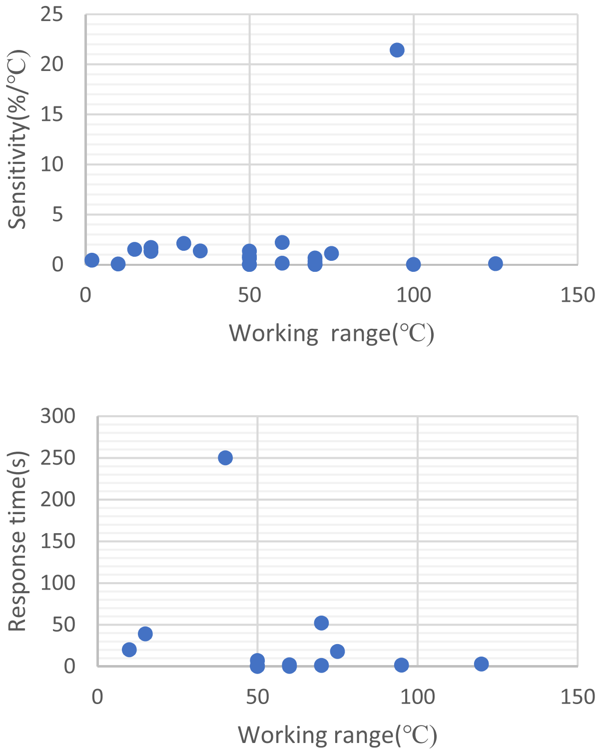

Fig. 2. Performance indicator for temperature sensor with incorporated graphene (a) Sensitivity per temperature ratio and (b) response time is compared against the studied working range. Designing of a temperature sensor with similar sensitivity performance for strain and working temperature beyond 120 °C remains as challenge until now.

be impressively, achieved. Since patients of Covid-19 may suffer from breathing difficulty after prolong exposure to the viruses, an attachment of wearable humidity sensor may assist them in reporting the abnormality in breathing during the daily life activities while preventing late detection of the symptom. Due to heavy skin contact requirement for humidity sensor and frequent swelling-de-swelling of the humidity active material, a selection of substrate and graphene class are both equally crucial. The selected graphene flakes should be biocompatible with human and should trigger no allergy reaction between the skin and graphene while also possess a higher sensitivity to water moisture. While graphene oxide is known to be highly hydrophilic and suits the purpose of sensing of moisture well, a lower electrical conductivity may introduce an electrical signal delay during the practical application of the sensor. On the other hand, chemical reduction of graphene oxide may be useful in improving the C/O ratio, although this step could introduce heavy defect concentration in basal plane region of graphene later. Hybridization of graphene with water-based stabilizer/polymer or even by nanoparticles may require another necessary step for residue removal and the resulted dispersion stability may not be as good as the supernatant obtained by liquid-phase exfoliation of graphite to graphene. For graphene oxide, an intense washing for cleaning against the toxic solvent residue after the post-oxidation stage is also a must. As for major selection criteria of the substrate/matrix used in the humidity sensing system, mainly, it should be strongly resistant and inert against water while remaining flexible. As shown in Table 2, various materials that are including PET [48], PI [49], polyvinyl chloride (PVC) [50], and alumina [51] have been used as a supporting layer for graphene with casting [52], coating [53] and printing [54] are frequently employed for the deposition of graphene during the fabrication of humidity sensor.

In another strategy for improving the moisture sensitivity of graphene, a combination of graphene with hydrophilic natural polymer had also been utilized for the preparation of moisture-sensitive polymer/graphene composite film. A commercial cellulose paper which is hydrophilic had been utilized as the supporting layer for graphene as it can work as secondary humidity sensing layer while providing enough stiffness for tensile/bending loading [57]. Meanwhile, the application of protein albumin as chemical modifier for improved attachment between GO and non-woven layer has also recently reported [57]. Fig. 3 shows a fabrication strategy of graphene-based humidity sensor on non-woven fabric, whose material is commonly used as an inner coating layer for face mask. An interdigitated electrode was first created on the substrate using magnetron sputtering and later leading wires for signal output with

Table 2
Overview on the best performance and humidity range for graphene-based humidity sensor with respect to fabrication method.

Process	Substrate	S/H(%/%RH)	H_{range}(%RH)	References
Coating	SiO_2/Si, alumina, PET, non-woven fabric, paper, PET, glass, coolmax, modal/spandex, quartz crystal, fiber optic	765.1	83	[4,14,51,55–61]
Casting	PET, ceramic, PVA, SiO_2/Si, PI, Si, glass, PVC	1.24	65	[50,52,62–79]
Printing	PET, CMOS hotplate, epoxy, PI, silk fibroin	6.23	50	[32,48,49,54,80–83],

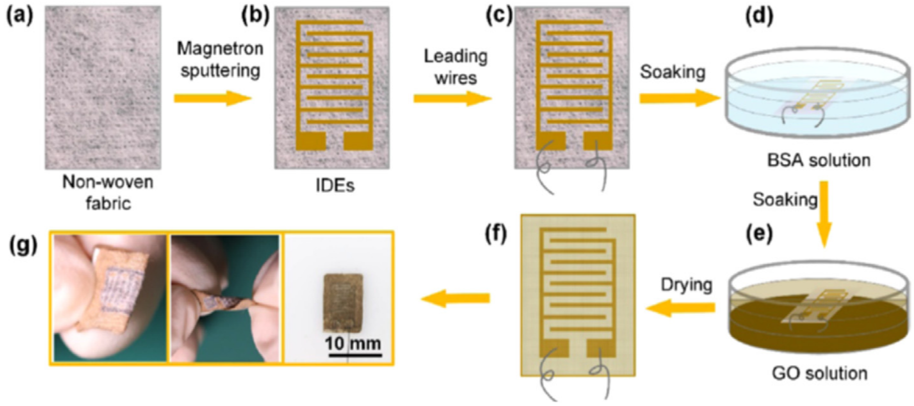

Fig. 3. (a)–(h) Preparation steps for graphene-based humidity sensor with non-woven fabric as substrate after chemical modification of surface with protein albumin. Reproduced with permission [57]. Copyright 2020, American Chemical Society.

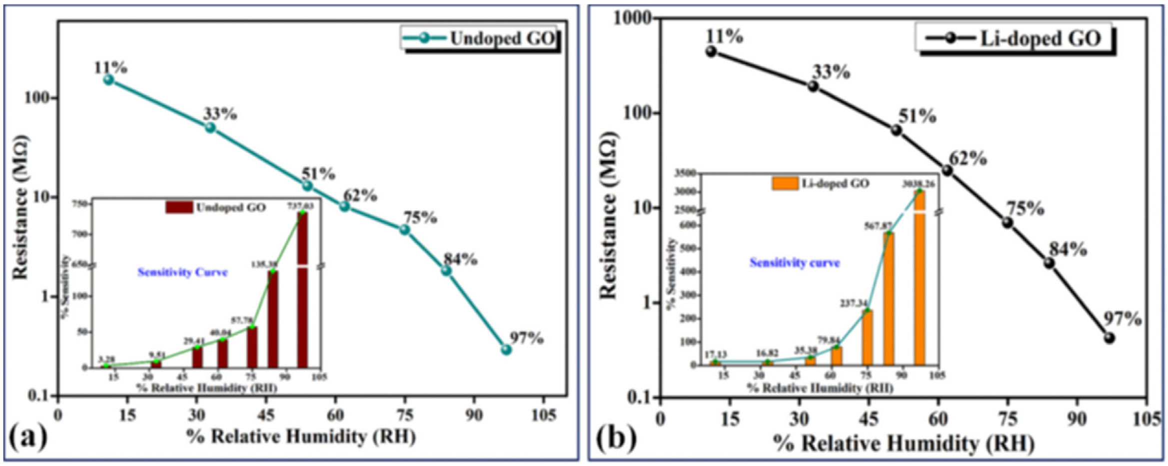

Fig. 4. Decrement rate of electrical resistances at a higher %RH level for both (a) undoped GO and (b) Li-doped GO reflects the sensitivity of graphene-based humidity sensor towards water molecules in air. Reproduced with permission [78]. Copyright 2017, American Chemical Society.

silver adhesive as contact points were installed. Modification of non-woven fabric surface with serum albumin allowed the adsorption of GO flakes on its surface, which finally completed the sensor fabrication process. In this work, compatibility between fabric and GO was highly enhanced by the presence of protein albumin on the cotton surface.

For characterization of graphene-based humidity sensor, an investigation on the performance of the sensor can be performed from the electrical output changes that including voltage [80], current [84], resistance [4], impedance [85], capacitance [86] or even by resonant frequency shift [87]. In the example shown in Fig. 4, a comparison study on humidity sensitivity performance between doped GO and lithium (Li)-doped GO reveals a significant increment in the resistance relative values for Li-doped GO at a higher RH level (737% against 3038%) [78]. It is suggested from this work that the increased hydrophilicity of GO after chemical doping with lithium is due to the adsorption of –OH functional group at the edges of GO and a higher water diffusion rate into/from GO after expansion of GO interlayer. Finally, the loss of electrical resistances at a higher content of moisture is caused by the increasing number of protons that are freely moving between hydroxyl group after the breaking of hydrogen bonding strength in an heavily humid environment.

In a further analysis on the performance of humidity sensor with graphene as an active material, a plot of sensitivity data (%/%RH) against the working range (%RH) in Fig. 5a reveals that a sensor sensitivity for the majority of published works so far stay within operational humidity range that values between 35 and 100 %RH. The best sensitivity for graphene-based humidity sensor is valued at 765.1%/%RH, which was achieved by synergistic combination between rGO, carbonic ink, polyvinyl alcohol (PVA) and spandex fabric as the selected flexible substrate. In terms of sensing mechanics, a modulation of electrical resistance at the presence of humid air is provided through complex network path of highly conductive rGO and carbonic ink while hydrophilicity of PVA is utilized for channeling water molecules into a breakage of energy barricade prior to releasing the mobile protons. For benchmarking purpose, a relationship between response time and working range is presented as well as plotted in Fig. 5b. The fastest response time for humidity sensing of graphene-based device is recorded at 0.198 s, which is not far in value with the best response time for previous temperature sensor. It is presumed that both temperature and humidity sensor rely on the thermal and chemical reaction between graphene and heat/moisture to trigger electrical response, which unsurprisingly may introduce delay in registering input and generating signal for the sensor. The similarity in sensing mechanics for temperature and humidity sensors may explain comparable response time range for both (<300 ms).

2.3. Strain sensors

An excellent sensitivity of graphene towards strain that has been suggested from the shift of D- or G-bands of graphene Raman plot under applied strain during theoretical study makes it a suitable material for strain detection system [88]. A measured type of strain can either be torsion, axial, bending or pressure as the elongation level of graphene film or polymer/graphene composite will lead to the variation of strain magnitude. A wide spectrum of potential applications of graphene-based strain sensor have been reported, including pulse sensing [1,89], human

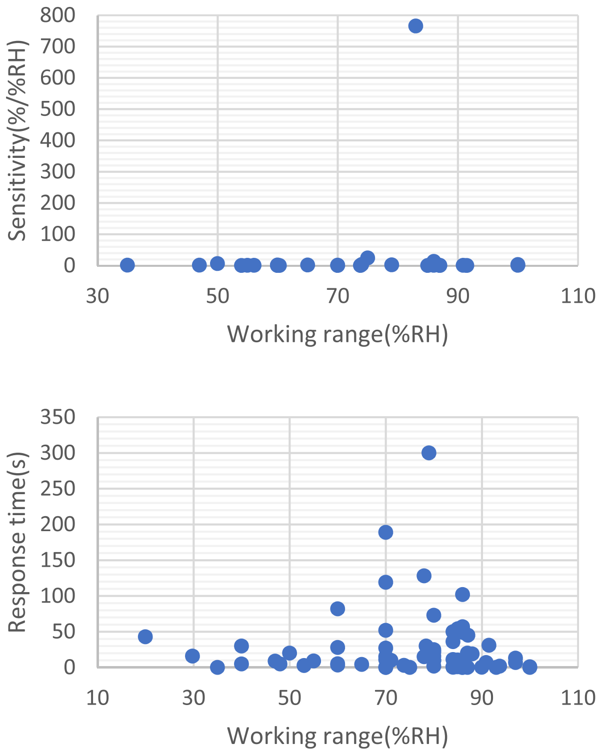

Fig. 5. Performance of humidity sensor versus established working range (a) for sensitivity per humidity range, it is shown that the best value so far is 765%/%RH while most of the works are reporting sensitivity/humidity ratio below 100%/%RH. As for response time, ~50 s or less is the standard operational time.

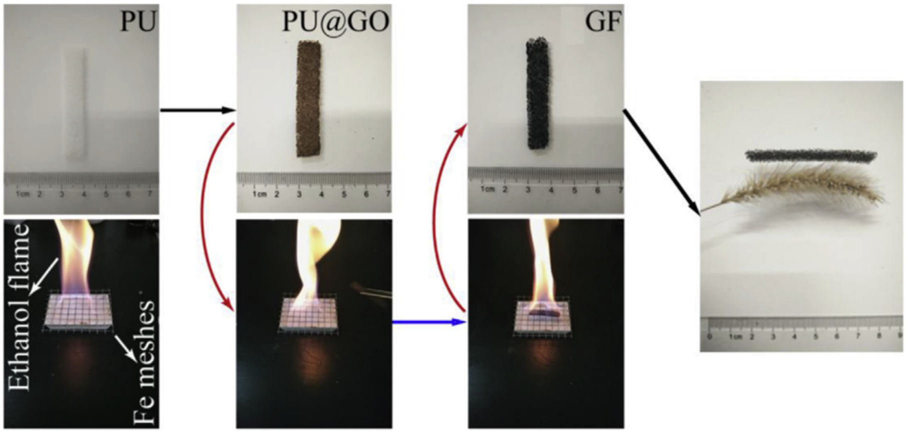

Fig. 6. Facile fabrication of lightweight rGO foam from GO coated PU template through reduction-pyrolysis by ethanol flame. Reproduced with permission [93]. Copyright 2019, Elsevier.

body range detection [90] and words classification [91]. During the pandemic, constant monitoring of heartbeat is crucial as the breathing difficulty, which is one of the major symptoms for Covid-19 may affect the heartbeat rate person. A rapid way to signal an emergency is only possible if the assigned sensor system can recognize the abnormal heartbeat from the normal one. Practically, the sensitivity and working strain range for a strain sensor is affected by the selection of active/passive materials, fabrication method and physical properties of the

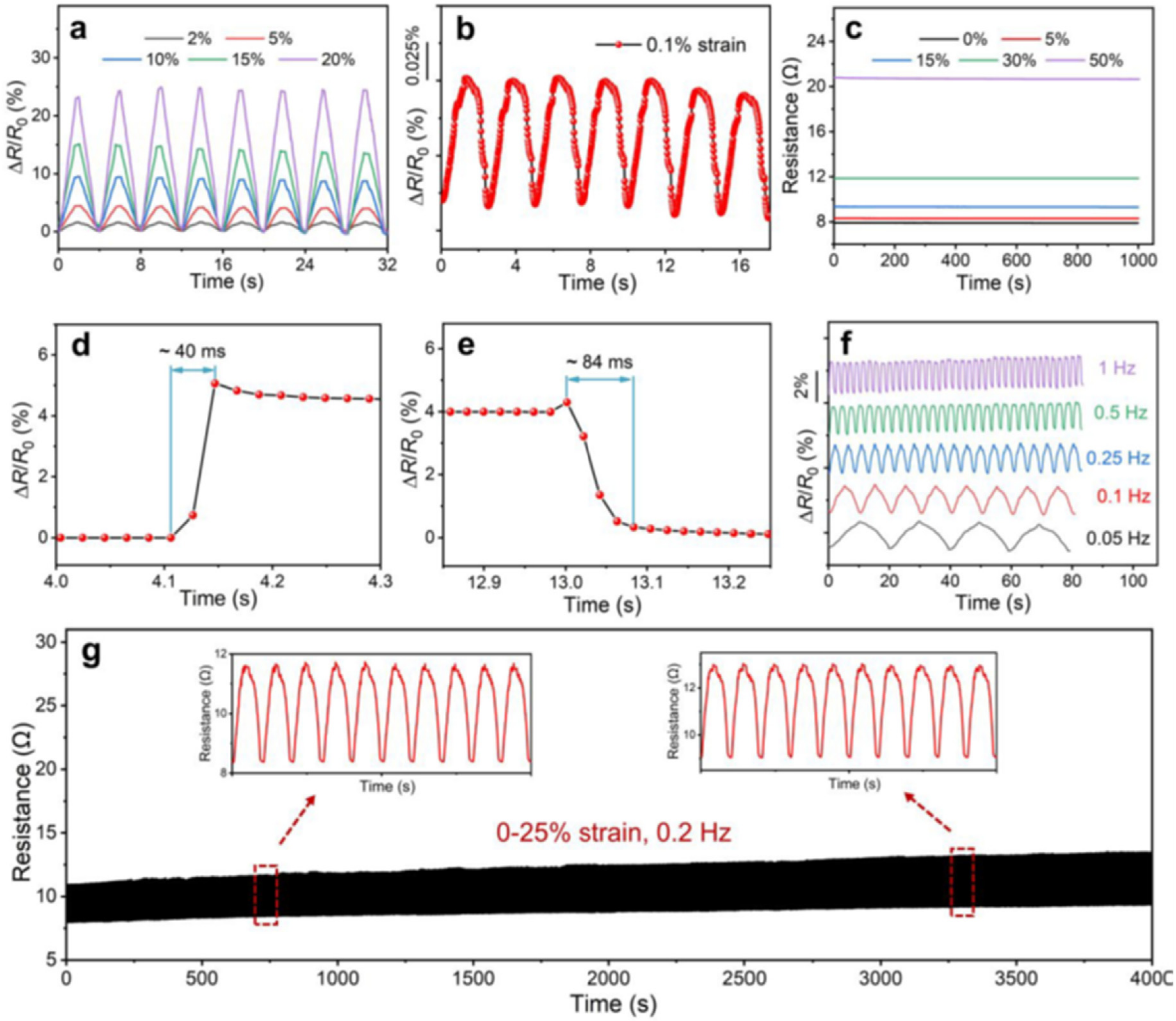

Fig. 7. Further analysis on the performance of strain sensor from (a) effect of sensitivity after variation of strain (b) detection of low strain for establishment of minimum sensing range (c) Stability of resistances at different strain for specific duration (d) and (e) Response time upon cyclic strain initiation (f) Sensitivity dependencies on applied strain frequency and (f) durability of the sensor under cyclic loading. Reproduced with permission [94]. Copyright 2020, American Chemical Society.

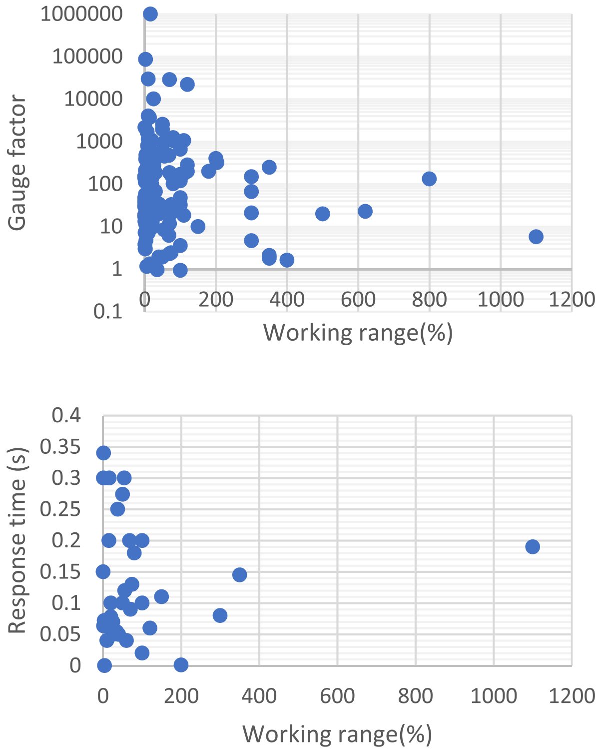

Fig. 8. (a) GF value distribution against the strain working range reveals that most works produced sensor with GF < 10,000 and less than 200% strain. Meanwhile, plot (b) shows that the response time for graphene-based strain sensor is far less than humidity/temperate despite the application of similar sensing material.

assembled system and gauge factor (GF) could be further defined as GF $= (\Delta R/R_0)/\Delta\varepsilon$, where R_0 is the initial resistance value prior to the changes of resistances (ΔR) under a specific applied strain ($\Delta\varepsilon$). For graphene coated-based sensor, the electrical conductivity of graphene can be impeded by the formation of cracks on the surface of graphene film since the percolation electrical network path in the active sensing layer will be hindered by the creeping crack strain. On another hand, there is also a new variation of strain sensor, where the cracks are specifically and systematically engineered and produced to impose strain measurement technique that was considered as a bio-inspired design [92].

Table 3
Summary of progress for graphene-based strain sensor.

Process	Matrix/substrate	GF_{max}	ε(%)	References
Casting/ curing	PET, PDMS, Dragon skin, silicon rubber, Ecoflex, SEBS, epoxy, PVDF, PU, microfiber, paper, natural rubber, EPDM rubber, PI,	28,752	400	[96–99] [92, 100–126],
2D/3D Printing	Stainless steel, PU, polyetherimide, natural rubber, polyester fabric, medical tape, paper	88,443	350	[127–134]
Coating	PDMS, polyester fabric, rubber, spandex/nylon, cotton, paper, PU, lycra fabric, PI, PET, silicon elastomer, Ecoflex, wool fabric, nylon filament	3667	57	[12,18, 135–160]
Laser heating	PI, PDMS, paper	1242	37.5	[5, 161–166],
Template assist + infiltration	PDMS, nickel, PU, PET, Ecoflex, rubber,	10^6	6	[90,93–95, 167–176],
Vacuum Filtration	Silk, oil control film, PDMS, PVA, PET fabric, Ecoflex, paper,	4000	1	[16,91, 177–182],

In the presence of humid air, the swelling of graphene due to high diffusion of water molecules from air into the graphene interlayer will influence the measurement of resistances and therefore, hydrophobic graphene may produce more accurate data as compared to the hydrophilic one. The assembly type of strain sensor can be either bilayer/trilayer consisting of active/passive combination of materials or sandwich arrangement type, where the graphene electrodes are positioned on both sides of the sensor while elastic electrically conducting active material or dielectric material (for capacitive effect) will be sandwiched between the electrodes. A change of distance between electrodes will affect the resulting electrical resistance and capacitances and thus, can be used to indicate the level of applied mechanical pressure strain. In one of the examples for facile preparation of graphene-based strain sensor, a complete pyrolysis of PU foam template at 550 °C through ethanol-flame [93] had successfully been used to induce deoxygenation of GO for fabrication of lightweight rGO foam (see Fig. 6). An infiltration of this rGO coated foam with natural rubber latex later allow it to be used as strain sensor for the sensing of compression stress. With a working strain ranged between 10 and 40%, this strain sensor certainly demonstrating a good flexibility that is commonly required for wearable sensor while the reported GF of 210 is already adequate for the detection of human step and bending/unbending of fingers.

For electromechanical characterization of graphene-based strain sensor, a sensitivity (R/R_0/%) function of tensile/compressive strains ($\Delta\varepsilon$/%) has been commonly used for GF investigation and the linear/nonlinear region range representation of the studied sensor. However, the mentioning of GF and working strain range alone may not be enough to accurately describe the performance of the reported sensor. In an example work shown in Fig. 7, additional characteristic of strain sensor had been studied in detail to enhance the understanding on the response of the sensor towards static and dynamic applied strain for robustness evaluation of the self-healing strain sensor in silver nanowires/graphene/functionalized PU assembly [94]. As demonstrated in Fig. 7a and b, a highly sensitive and stable reading of the data by the sensor has been directly confirmed from the consistent increment/decrement of sensitivity peaks at a similar rate during stretching and release of the sensor at 2,5,10,15, 20% strains and the sensor's ability to detect low range strain (0.1%) with continuous periodic peak for ~16 s at 7 cycles. As for Fig. 7c, a consistent electrical resistance had been generated for each of the applied strain (0,5,15,30 and 50%) within 1000 s, which is implying the excellent sensing stability of the fabricated sensor under the prolonged exposure to strain. Meanwhile, a fast response/recovery time for the sensor under cyclic mechanical strain is reflected from both the measured value of 40 ms and 84 ms, respectively (see Fig. 7d and e). Finally, it is revealed from Fig. 7f that the performance of the prepared strain sensor is not highly frequency-dependent due to the stabilized sensitivity (2%) even after rigorously applied cyclic strain rate with steady resistance values after 800 strain cycles, and this further demonstrated the durability of the sensor (see Fig. 7g).

Since GF and response time are considered to be major criteria for graphene-based strain sensor with respect to the association of both parameters with sensor sensitivity, about 136 literature data has been plotted as a function of GF and working strain range and presented in Fig. 8a. It is clear from the data pattern that most of the work until now on the graphene strain sensor has produced sensor with 100% range while the GF value is maintained mainly below 10,000. The best reported value ever for GF is 1000000, which was obtained through the utilization of PMDS infiltrated graphene woven fabric as a sensing material [95]. However, the working strain range is quite limited (6%) and future optimization design may be required to improve the original detection limitation for this sensor. As for response time performance (see Fig. 8b), it is discovered from the available data that the recorded response range is extremely small

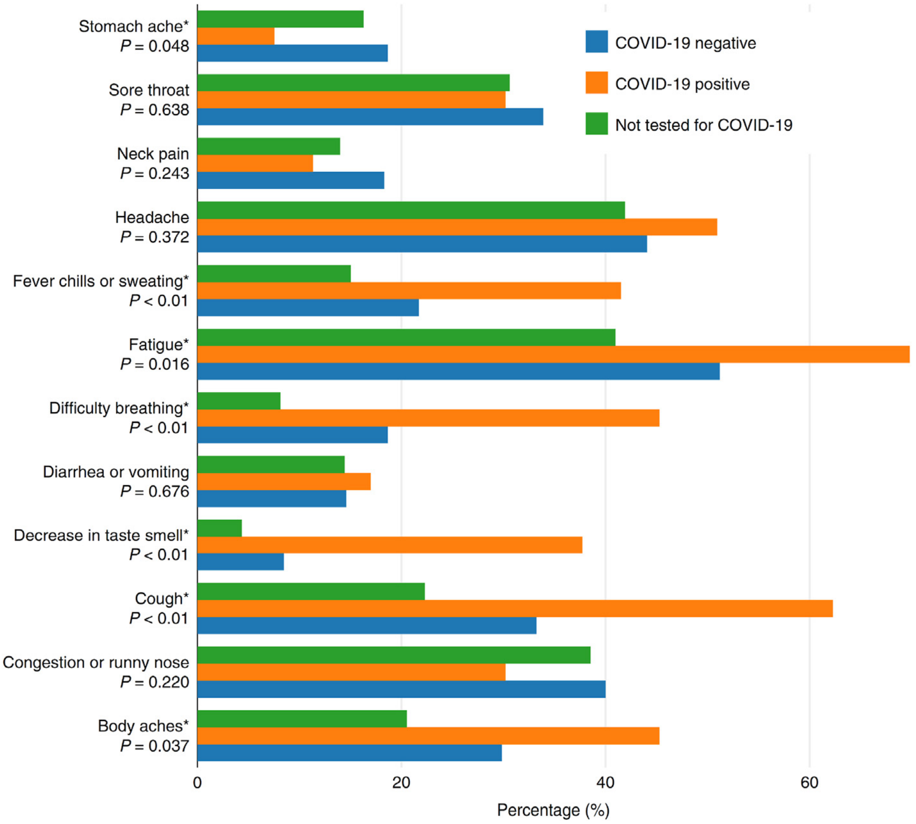

Fig. 9. Common symptoms among patient with positive indicator for Covid-19 are highlighted with asterisk (P-value < 0.05). The result suggests that stomachache, fever chills/sweating, fatigue, difficulty breathing, loss of taste smell, cough, and body aches are a major sign for the infection. Reproduced with permission [191]. Copyright 2021, Springer Nature.

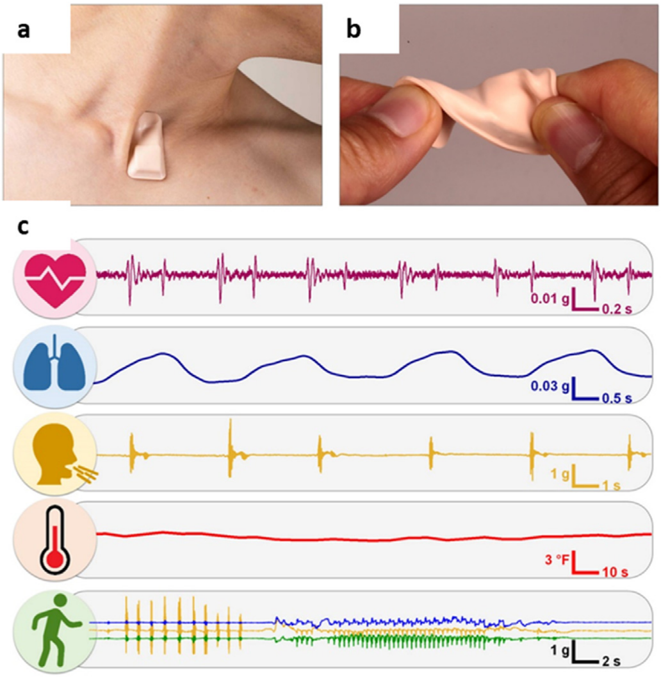

Fig. 10. (a) Wearable and wireless patch sensor attaches well to the neck while (b) the robustness of the sensor against mechanical deformation is evaluated for defect and (c) Real-time monitoring of heartbeat, breathing rate, body temperature and human activity for Covid-19 patient is demonstrated from the presented ongoing plots. Reproduced with permission [195]. Copyright 2020, American Association for the Advancement of Science.

(<0.4 s) as compared to that of the graphene-based temperature and humidity sensor with the fastest ever response time valued at 0.005 s. A narrow response time range for strain type of sensor suggests that graphene may suits perfectly well to detection of mechanicals quantities such as stress, strain, pressure and force than temperature or humidity as no compulsory chemical reaction for chemical activation of the sensor is required prior to electrical response and thus, less signal delay. In Table 3, an overview on the progress of graphene-based strain sensor in term of substrate selection, maximum GF and strain is presented as reference.

3. Opportunities for graphene-based sensor

One of the reported strategies for rapid diagnosing of Covid-19 infections risk is using a detailed analysis of cough/breathing wavelet as it is suggested that there is a distinguished waveform pattern difference between cough/breathing from Covid-19 patient and normal cough/breathing sound [183–186]. A highly sensitive graphene –based strains sensor that is able to capture cough/breathing sound precisely from the movement of throat/chest/abdomen may assist in the discovery of Covid-19 associated traits from the collected sound data with a higher degree of accuracy [187]. Using the knowledge in machine and deep learning, the collected cough/breathing sound data file can be further prepared for a robust prediction model in Covid-19 patient classification by cough/breathing sound [188]. A fully developed Covid-19 detection system from cough certainly is certainly beneficial during the ongoing pandemic era as cough is considered as frequent demonstrated symptom and main source of infection for many due to the potential spreading of sars-2 viruses from cough aerosols and droplets that are present in the air (see Fig. 9). To improve the cough sound diagnosis strategy for Covid-19 patient further, some issues such as validity of the datasets used for training and later validation of the model, potential interference of cough sound from the ambient source, and influence of demographic class such as age, gender and social status or even geographic characteristic on the produced sound data may need to be rectified and addressed [189,190].

Another potential application of graphene for smart health care monitoring is the autonomous skin temperature measurement by graphene-based temperature sensor that is linked with wearable micro-controller system and could be attached on wrist or body [192]. As fever ($T > 39\,^{\circ}C$) is known as one of the early indicators for Covid-19 infection, the monitoring of human body temperature would be on one of the efficient ways for Covid-19 infection as a sudden increment of temperature can be detected by the attached temperature sensor system. In another related opportunity for graphene temperature sensing, a daily human activity such as exercising or normal activity can be recognized from the difference in body temperature recorded by the wearable temperature sensor [193]. This work suggests the applicability of portable temperature sensor for the regulation of human routine activities during quarantine. As for potential Covid-19 patient, an in-situ monitoring of body temperature during quarantine would allow data collection to be performed remotely and further minimizing the risk of sars-2 viruses spreading from hospital workforces and patient during common visit at home. However, it has been reported that fever may after all not be as useful as we think as Covid-19 indicator in younger demographic as only a small number of them suffer from fever while majority of them do not show any Covid-19 associated symptoms at all (asymptotic) [194]. Besides the combination of temperature sensor with vapor sensor for detection of sar-2 virus and visible color changes, an additional sensing system that is able to recognize other Covid-19 associated symptoms such as breathing pattern may be beneficial to enhance the detection accuracy of temperature sensor for a younger person. In this case, a graphene incorporated humidity sensor can be used as a tool for monitoring the breathing rate, whose sensing mechanics is associated with the rate of water vapor release during respiration process. Additionally, an intense body sweating due to Covid-19 fever can also be registered by the same humidity sensor, which further highlights the combination advantage of multiple sensing class in one device as temperature measurement alone may not be enough to identify the potential Covid-19 patient. In a recent work, Fig. 10a and Fig. 10b shows an example of patch sensor that is able to measure respiration rate, heartbeat pulse and body temperature while remains robust and comfortable to be mounted on the skin [195]. The addition of accelerometer into the sensor further allows user to monitor and classify human activity from the signal intensity and frequency for each (see Fig. 10c). With such advanced way of collection of vital data, it is predicted that the screening rate of potential Covid-19 patient could be much easier, faster, and further accelerate the development progress in machine/deep learning estimation model for the disease.

4. Conclusion and outlooks

In this work, we summarize the progress of temperature, humidity, and strain sensor for graphene with a brief visit on the potential role/limitation of these sensors for preventive measure against Covid-19. The fabrication approach, substrate selection, sensitivity factor and working stimulant range have all been discussed strategically to allow a quick but comprehensive overview on the current development stage of each graphene-based sensor class. The sensitivity of graphene sensor towards temperature needs more improvement ($S/T = 21.4\%/^{\circ}C$) while graphene application as sensing material for humidity could be enhanced through the addition of conductive ink and selection of spandex as substrate ($S/H = 765\%/\%RH$). Significantly, we discovered that graphene suits best for the detection of mechanical tensile/bending strain as the GF (10^6) value is far exceeding the sensitivity shown for temperature and humidity sensor. We further showed from the literature data that the response time domain of temperature sensor and humidity sensor is not far in value with each other (<300 s), while strain sensor type produces the fastest measured response time (<0.4 s). Despite the remarkable progress for graphene-based sensor, it is particularly noticed during the performance data analysis that physical limitation of original substrate/matrix material will impede the overall sensitivity/working range of the sensor despite the excellent sensing ability of the graphene. For example, a low thermally resistant substrate may pre-maturely initiate thermal degradation after arriving at a specific temperature even though the accommodated graphene is still able to sense the temperature changes. Meanwhile, chemical reaction between –OH groups in graphene and water molecules that must be triggered for moving protons prior to the sensing of humidity level may ultimately increase the response time for the sensor. In this case, incorporation of another hydrophilic nanomaterials into graphene could potentially accelerate the mobilization of protons upon sensing humidity and haste the response time. From the electronics point of view, a significant presence of signal noise in the background can affect the quality of collected data and thus, an additional pre-processing for cleaning of raw data could become essential prior to the actual wavelets analysis. To conclude this paper, we have proposed several prospective applications for graphene-based temperature, humidity, and strain sensor, which we believe could greatly contribute to the humanities effort against Covid-19 pandemic.

Authors contributions

Z.I, W.F.W.I and A.H.A contributed evenly to this submitted works. The corresponding author states that there is no conflict of interest.

Notes

All used references for plotting of sensor performance against the working range in this work are available as tabulated data in **Supplementary File**.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to the financial assistance provided by the Ministry of Higher Education of Malaysia for this project through the awarded grant of Fundamental Research Grant Scheme (FRGS/1/2019/TK05/UMP/02/16). We also would like to thank all the frontliner workers who have working extremely hard through this challenging pandemic. **Thank You**.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sintl.2022.100183.

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