Chemical Science International Journal

Volume 33, Issue 2, Page 1-10, 2024; Article no.CSIJ.112261
ISSN: 2456-706X
(Past name: American Chemical Science Journal, Past ISSN: 2249-0205)

Flexible Pressure Sensor Based on Carbon Black/PVDF Nanocomposite

Victor K. Samoei [a], Ahalapitiya H. Jayatissa [a*] and Keiichiro Sano [b]

[a] Nanotechnology and MEMS Laboratory, Mechanical Industrial and Manufacturing Engineering Department, The University of Toledo, Toledo, OH 43606, USA.
[b] Department of Symbiotic Design,1-50-1, Mutsuura-Higashi, Kanazawa, Yokohama 236-8503, Japan.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CSJI/2024/v33i2885

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/112261

Original Research Article

Received: 27/11/2023
Accepted: 01/02/2024
Published: 07/02/2024

ABSTRACT

A piezoresistive flexible pressure sensor was fabricated using carbon black and Poly (vinylidene fluoride) (CB/PVDF) composite. The conductive CB/PVDF composite was prepared by a wet-cast method and deposited onto a flexible polyethylene (PE) substrate. The surface morphology, crystal structure, and material properties were studied using SEM and X-ray diffraction methods. This flexible pressure sensor was tested in a wide pressure range of about 0 - 76 kPa, and its response time was less than 0.43 s. The sensitivity, response time, and recovery time were studied for different pressures and vibration modes. The repeatability and reproducibility characteristics of the sensors were studied, and it was found that the sensors exhibited excellent characteristics. The sensor was subjected to different loading and unloading pressures, and the resistance of the sensor remained stable, indicating that the sensor had a high degree of reproducibility. Owing to its flexible properties and the materials used, the proposed device can be applied in the next generation of smart sensors for biomedical, robotic, and automotive sensing applications.

Keywords: Flexible pressure sensor; carbon black; PVDF; composite, solvent; piezoresistive.

**Corresponding author: E-mail: ahalapitiya.jayatissa@utoledo.edu;*

1. INTRODUCTION

Sensors with distinct characteristics such as lightweight, high flexibility, and high sensitivity are attracting a wide range of applications. In particular, flexible pressure sensors are increasingly applied in different fields such as electronic skin, health monitoring, robotics, advanced prosthetics, virtual reality entertainment technology, and sports [1-7]. Novel materials such as conductive polymers, carbon nanomaterials, and carbon black (CB) are mainly used in these flexible pressure sensors because they possess excellent electrical conductivity, chemical stability, and low toxicity, and are widely available [8-12]. These novel materials are deposited on polymeric substrates such as polyimide (PI), polydimethylsiloxane (PDMS), polyethylene terephthalate, and PE for flexible pressure sensor applications [3,13-15]. These novel materials replace the metal foils and semiconductors that were traditionally used as the sensing platform. The rigidity and high cost of the old materials make them inefficient for current practical applications.

The sensing mechanism of the pressure sensors can be divided into different categories. The four main categories are piezoresistive, piezoelectric, capacitive, and transistor [16-18]. Piezoelectric pressure sensors have high sensitivity and stability but have limited applications in pressure measurements because they cannot measure static pressure. The surface charge produced by the applied force in the piezoelectric materials can be neutralized easily by current leakage, charges from the environment, or the resistance from the connected electronics making them require high pass filters. [14,19-22]. Another disadvantage of these sensors is that they are sensitive to temperature, most piezoelectric materials are pyroelectric, therefore they are temperature sensitive, and the temperature may induce crystal deformation, which may in turn produce unwanted forces [22]. The piezoelectric pressure sensors are the most utilized sensors due to their remarkable advantages including simple fabrication, stability, and reliability, and they have high pixel density to measure large pressure ranges [23]. The conductive sensing material is an important parameter in evaluating the variation rate of the resistance in these resistive sensors. To improve their sensitivity, porous materials such as porous elastomers and electrospun nanofiber membranes have been used to increase the deformation of the piezoresistive sensors. Polymer materials are suitable polymer nanomaterials, including carbon nanotubes, graphene, nanowires, and other metal nanomaterials.

Various publications on piezoresistive materials, using different binders, and nanoparticles on different substrates, have been reported in the past on their sensitivity, hysteresis, reproducibility, and resistance performance. For instance, Zhang et al. experimented on CB/silver nanoparticles (CB/AgNPs) based strain sensors on polyuarethane substrate. They found that the sensitivity improved by 18 times for CB/AgNPs composite compared with bare carbon-based strain sensors [24]. Chang et al. developed a flexible resistive-type pressure sensor using carbonized cotton fabric (CCF). The sensors showed a large measurement range (~0.16 kPa), a low detection limit (~0.70 Pa), and excellent durability (>4000 cycles) [25]. For fluid pressure sensing on a curved microtube, Yao et al. developed a piezoresistive flexible sensor using micropatterned conductive carbon nanotube as the sensing element. A high sensitivity (0.047 kPa^{-1} in gas sensing and 5.6 × 10^{-3} kPa^{-1} in liquid sensing) and low consumption (<180 μW) were reported [26]. Kweon et al. fabricated PVDF-HFP/ PEDOT composited-based pressure sensors using 3D electrospinning. These samples indicated higher pressure sensitivity compared with conventional electrospinning (13.5 kPa^{-1} for 3D electrospinning whereas 5.1 kPa^{-1} for conventional). The sensors also showed a minimum detection of 1 Pa and were resilient up to 10,000 compressive cycles [27].

This paper reports the experimental results of a simple, low-cost, and highly sensitive piezoresistive flexible pressure sensor using CB/PVDF composite as the sensing element. The composite was prepared through the wet casting process and deposited on a flexible polyethylene substrate. The pressure vs resistance response was recorded, resulting in good stability, sensitivity, and repeatability. The details of the experimental process and the obtained results will be covered in the subsequent sections.

2. MATERIALS AND METHODS

The materials used for the preparation of the sensing element are CB nanoparticles, PVDF powder, and DMF. The material properties of these components were extracted from the manufacturer's literature. Table 1 provides a summary of the material properties of CB and

PVDF. CB served as the conductive phase, PVDF acted as a binder, and DMF was employed as the solvent to create the composition.

The process of fabricating the film and preparing the CB/PVDF nanocomposite is illustrated in Fig.1. First, CB nanoparticles were blended in DMF solvent, followed by mechanical stirring and sonication to attain a thoroughly dispersed CB suspension. A PVDF solution was prepared by dissolving 50 mg of PVDF powder in the DMF solvent. The solution was thoroughly stirred using the magnetic stir bar until the powder was completely dissolved in DMF solvent. The dispersed CB solution was then combined with PVDF solution in a mass ratio of 1:1 as shown in the schematic in Fig. 1 (a-c). This ratio was chosen in order to have a high carbon: binder ratio and to provide clarity on the analysis. The binder also helps in forming a uniform film that is mechanically stable when loading and unloading pressure is applied. The solution was vigorously stirred to ensure homogenous dispersion of the conductive nanocomposite. This composition was also ultrasonicated for 1 hour with a constant interruption of 20 min to avoid the agglomeration of nanocomposites. The PE substrate was then prepared according to standard practice for the preparation of surfaces of plastics to enable adhesive bonding of the CB/PVDF composition. The physical surface preparation of the substrate involved wiping with methanol, sanding, wiping with a clean dry wipe, and then wiping with the methanol wipes again [28].

Table 1. Properties of CB and PVDF used for the preparation of the sensing Element

	Specific surface area (m^2/g)	Resistivity (Ω.cm)	Young's Modulus (MPa)	Dielectric constant
Carbon Black (CB)	780	0.2	$1.5 X10^5$	
PVDF	3.76 - 6.61	$> 10^{14}$	2450	7.5-13.2

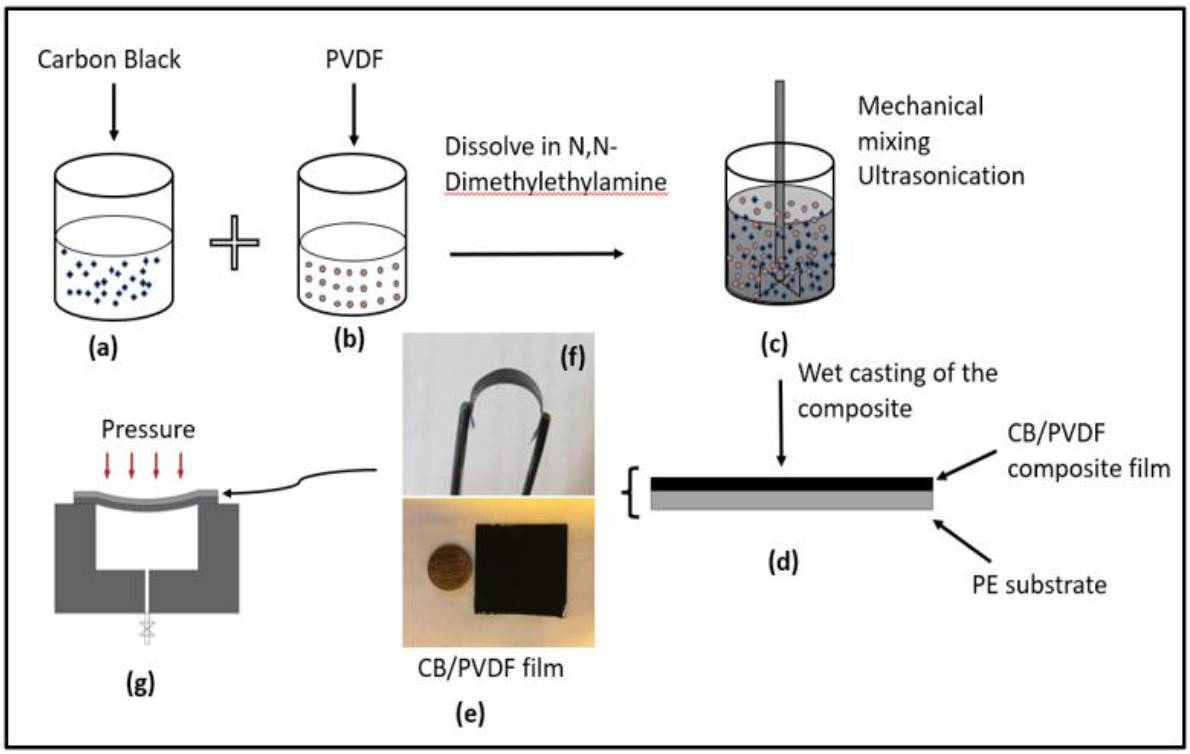

Fig. 1. The schematic illustration for the preparation of CB/PVDF composite film for the fabrication of pressure sensor

The CB/PVDF composite was wet-casted onto a flexible PE substrate to form a thin CB/PVDF film of about 0.1 mm (Fig. 1.d). Subsequently, the film was placed on a warm plate at 30°C for 20 minutes to evaporate the excess DMF solvent. Furthermore, the film was left to air dry in the room for 12 hours. A sensitive thin film of CB/PVDF, approximately 30 microns thick, was formed and then etched to create a thin strip about 2 mm in thickness. The dried nanocomposite film was integrated into a (20 × 20 × 10) mm acrylic PMMA cube with an opening at the center, forming a sensing device. The center diameter measured 5 mm with a depth of 5 mm (Fig.1.g). The CB/PVDF conductive film was then affixed to the surface containing the 5 mm hole in the acrylic PMMA cube (Fig.1.g). A high-pressure compressor was connected to the acrylic PMMA fixture through the valve attached to the 5 mm hole. Pressure gauges were mounted to regulate the applied pressure on the CB/PVDF film. When gauge pressure was applied through a valve, the thin CB/PVDF membrane deformed into a dome-shaped structure. The radius of the dome was a function of pressure, and thus, the strain experienced by the film gave rise to resistance in the material, which changed with the applied pressure. The resistance of the film was recorded using a Keithley multimeter connected to a computer through a custom-made LabVIEW interface. The response graphs obtained represent the relationship between resistance and time.

3. RESULTS AND DISCUSSION

3.1 Characterization of Microstructure

The surface morphology of the fabricated film was investigated using scanning electron microscopy (SEM). Here, small magnification (Fig.2(a)) and large magnification (Fig.2(b)) are given to understand the microstructure of CB/PVDF films. The SEM images in Fig.2 indicate a good dispersion of CB/PVDF particles. The uniform distribution of the conductive and binder matrix plays a key role in determining the piezoresistive property of the composite film. The uniform dispersion is influenced by the particle size, shape, and orientation of the particles. The XRD pattern has been carried out on CB/PVDF composite in the ratio by mass percentage is shown in Fig. 3. It is clear from the Fig that there were peaks of PVDF corresponding to a 2 θ angle of 20.16 and 39.84. The presence of a dominant peak at 20.16 confirms the presence of beta-phase in PVDF material. The XRD pattern confirms the semi-crystalline nature of PVDF polymer film [29]. The crystalline size for the PVDF-110 peak was found to be approximately 0.89 nm using the Scherrer equation. The diffused peak of CB was observed at an angle of 23.8^0 (002) plane, this diffused peak may be caused by the lack of crystallinity of CB and polymer mixture at this angle. The PVDF restricts the diffract of the film at this angle due to its polymeric structure, the peaks of PVDF dominated the CB as indicated by the XRD spectra [30-32].

3.2 Characterization of Pressure Sensing Mechanism

Fig. 4 shows the time response for CB/PVDF film when vacuum pressure was applied. It was noted that when pressure was applied the film resistance decreased. This decrease in resistance was because the film diaphragm deformed causing compressive stress on the film, the uniaxial pressure causes the gaps between two adjacent conductive particles to be smaller and it leads to a decrease in the film's electrical resistance [33]. The PVDF binder helps the active material to mitigate the stresses of contraction and to maintain the adhesion of the CB to the conductive network. The compression destroys the conductive paths of CB by causing the transverse slippage of CB, which contributes to an increase in composite resistance [33]. The electrical resistance of a single conductive path can be described by the equation below [34]:

$$R = \frac{2h^2 sL}{3a^2 e^2 \sqrt{2m\varphi}} exp\left(4\pi\sqrt{2m\varphi}\,\frac{s}{h}\right). \quad (1)$$

Where, *R, L, m, e, h, s, φ, a^2* are the resistance of the single conductive path, the number of particles forming the conductive path, the electron mass, the electron charge, the Plank's constant, the thickness of insulating film, the height of potential barrier between adjacent particles, and the effective cross-sectional area respectively.

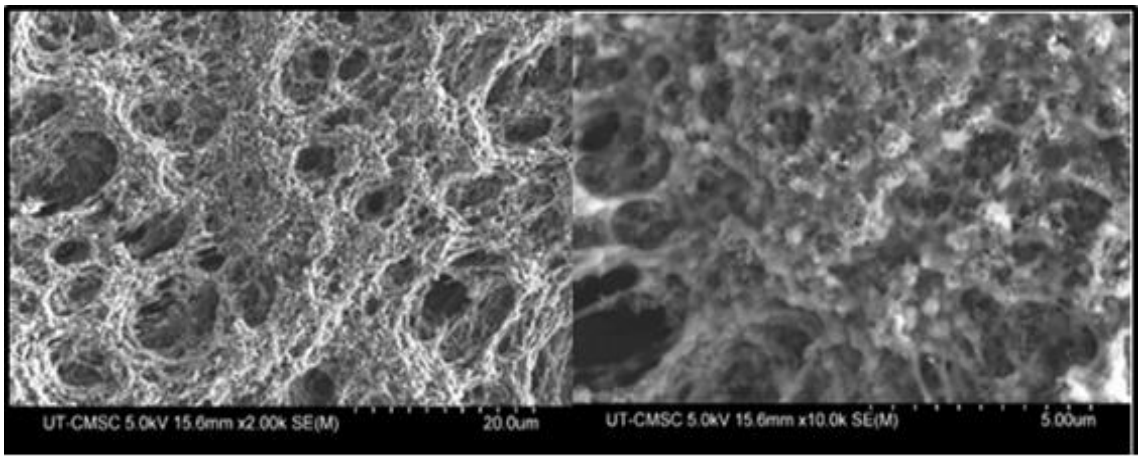

Fig. 2. Scanning electron microscopy (SEM) image of the CB/PVDF composite

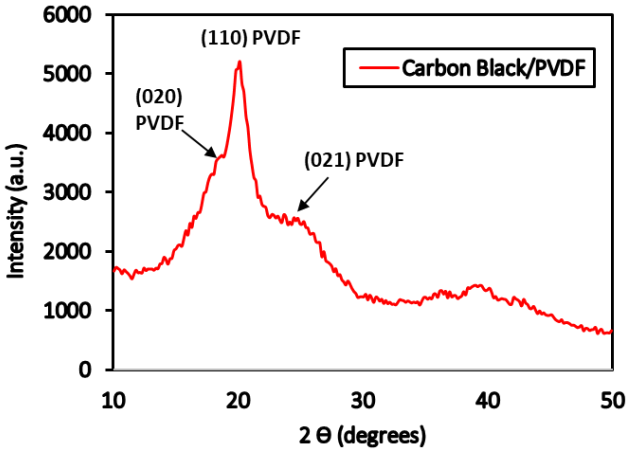

Fig. 3. X-ray diffraction patterns of CB/PVDF composite

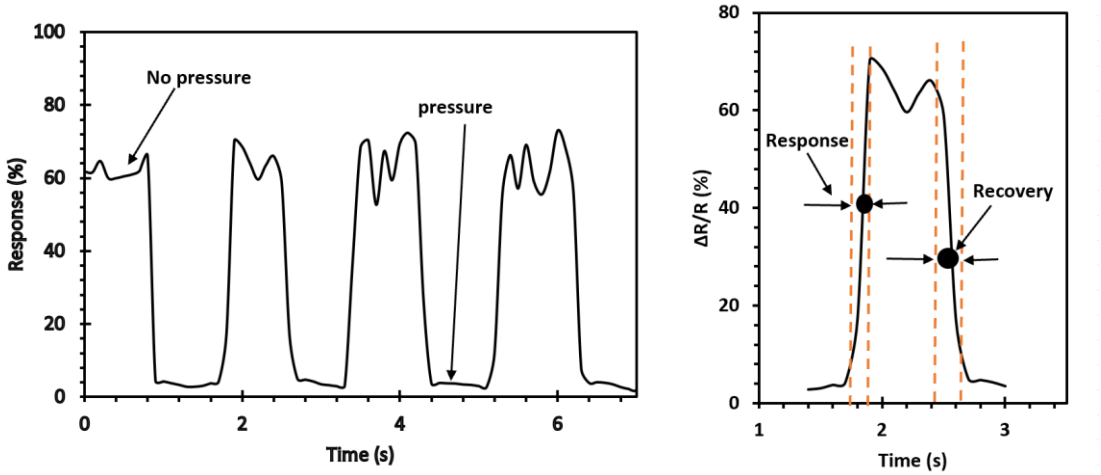

Fig. 4. Performances of the pressure sensor with a thin CB/PVDF membrane under a pressure of 76 kPa. The right indicates an enlarged view of the response to see the clarity of the response and recovery of the sensor.

When the pressure was applied on the thin CB/PVDF film, the resistance (response) decreased with time, and when the gauge valve was turned off the response increased abruptly. Eq. 2 was used to calculate the recovery time on the exponential curve of this pressure response [35]:

$$R = R_0 + A_1\, exp\left(-\frac{t}{t_1}\right). \quad (2)$$

Where, R_O and A_1 are constants, while t and t_1 are the time response and time constants, respectively. The calculated average time constants (t_1) are 0.43 s when the valve was turned off (recovery) and 0.138 s when pressure was initially applied to the film. The time response values were estimated from the linear fit of the exponential curves. The higher recovery time t_1 can be attributed to a slow air intake on the valve but the rapid increase of the air in the chamber resulted in a small t value.

The sensor was then subjected to different pressures as shown in Fig. 5, this test was used to study the repeatability and reproducibility of the sensor. The sensing element was subjected to loading and unloading for several cycles and the response at different pressures was recorded. The mean response at different pressures was recorded and marked as shown in Fig. 6. The sensor exhibited a linear response to applied pressure, as indicated by a high coefficient of determination (R^2 = 0.97), which signifies the consistent and predictable relationship between the applied pressure and the sensor's output. This linearity is important for the calibration of the pressure sensor. The trendline closely aligning with the error bars enhances the credibility of the sensor's measurements, indicating minimal deviation from the expected values. The linear curve of the CB/PVDF nanocomposite pressure sensor is a critical characteristic that highlights the sensor's precision and reliability. This characteristic is important in applications where accurate and proportionate pressure sensing is needed.

The sensitivity of the CB/PVDF pressure sensor to applied pressure was defined within the range of 0 – 76 kPa. The sensor exhibited a high sensitivity of 0.96% kPa^{-1}, indicating its capacity to detect small variations in pressure and convert them into proportional changes in electrical output. The ability to detect small changes in pressure is important, especially in applications where accuracy and responsiveness are critical, such as in the development of piezoresistive pressure sensors. The reported sensitivity indicates the potential of the CB/PVDF nanocomposite as a key component in advanced sensing technologies, promising reliable and accurate pressure measurements across a broad pressure spectrum.

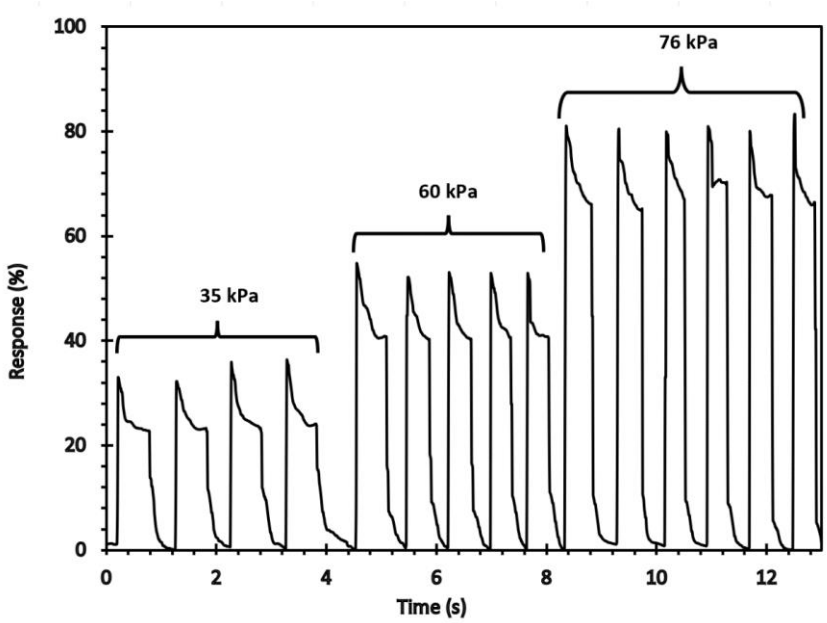

Fig. 5. Time response and repeatability test for CB/PVDF composite at different vacuum pressures.

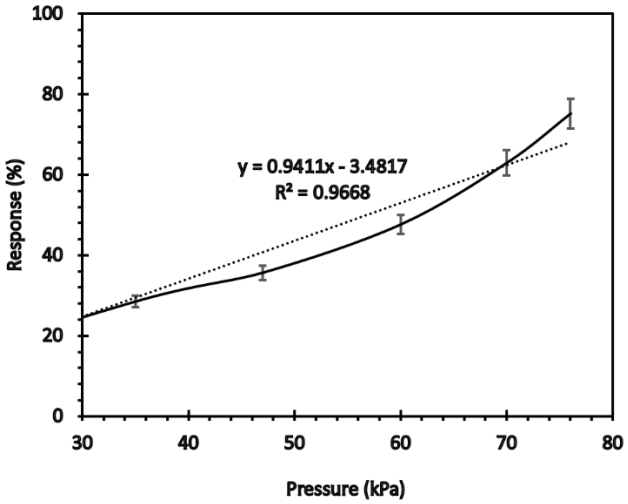

Fig. 6. Dependence of piezoresistive response on the pressure with error bars for the experimental data.

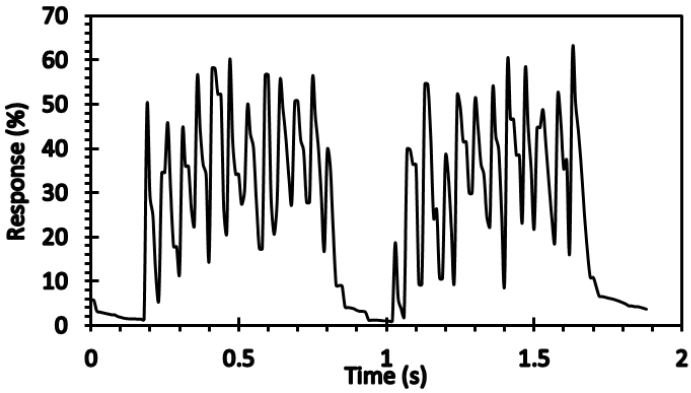

Fig. 7. Vibration response of the sensor when the thin CB/PVDF membrane was mounted to a vibrating device, the frequency was estimated to be about 16 Hz.

The response remained stable after a series of loading-unloading tests at the same pressure. This stability indicated that CB/PVDF exhibited a high degree of repeatability and reproducibility, attributed to the firmness of the CB conductive layer. The sensing element was further evaluated by subjecting it to a vibrating device with various modes suitable for the test, as shown in Fig. 7. The results illustrated that the sensor maintained a high degree of reproducibility and repeatability under vibrational conditions. The calculated frequency for that specific vibration mode was approximately 16 Hz. Subjecting the sensing element of CB/PVDF nanocomposites to a vibrating device with different modes provides a comprehensive assessment of the sensor's performance, reliability, and suitability for applications in dynamic and vibrating environments. This approach aids in optimizing the sensor's design and materials to meet the specific demands of diverse real-world scenarios [36].

Combining CB and PVDF nanocomposites can leverage the strengths of both materials, creating sensors with enhanced properties such as improved sensitivity, selectivity, and response times. CB/PVDF composites exhibit high sensitivity due to the excellent electrically conductive nature of CB and the high surface area, providing a large active area for interactions with analytes. The piezoelectric properties of PVDF also enhance the sensitivity thus resulting in accurate pressure sensing. Kai et al prepared PVDF nanocomposites filled with CNTs and CB by melting them using a small-

scale compounder. They were able to demonstrate that the sensor prepared hard improved conductivity and piezoresistive sensitivity. Their composite combines both a relatively wide strain sensing range as well as a high sensitivity [37].

The flexibility and lightweight nature of the nanocomposite contribute to faster response times compared to some traditional sensors. These properties are crucial for applications where sensors need to be utilized on complex and curved surfaces, such as in biomedical and robotics. The fabrication process and the scale of production are crucial factors in achieving a cost-effective outcome for this sensor. Additionally, the materials used are relatively cost-effective, positioning this sensor as competitive and advantageous when compared to existing sensor technologies [38,39].

The unique combination of properties in CB and PVDF nanomaterial opens avenues for advanced sensing technologies. To fully optimize this sensor's performance, researchers should explore techniques that enhance sensitivity, optimize mechanical properties, employ cost-effective fabrication methods, and promote multifunctionality. Notably, the annealing process has been shown to improve the electrical conductivity of the nanocomposite, further enhancing its overall performance [40]. The nanocomposite can also be integrated with smart materials to explore energy-efficient designs for the sensor. Further work can be done to explore wearable health monitoring devices through improved human-machine interfaces. Additionally, lightweight and fast response time flexible pressure sensors can be integrated into automotive safety systems, such as smart airbags or seat occupancy sensors. Finally, interdisciplinary collaboration and innovative approaches will be instrumental in unlocking the full potential of CB/PVDF nanocomposites.

4. CONCLUSION

A flexible pressure sensor was designed based on CB/PVDF nanocomposite and fabricated using the wet-cast technique. The nanocomposite was deposited onto a flexible PE substrate, providing remarkable flexibility. The addition of PVDF into the conductive CB not only enhanced the adhesion of the active material but also provided a crosslink between CB particles. This composite material exhibited a substantial change in resistance during loading, corresponding to film stretching. PVDF also provides excellent mechanical properties essential for generating a sensor signal under loading and unloading cycles. In-depth investigations into the dynamic characteristics revealed that the sensor has high sensitivity, rapid response time, and the ability to measure a wide pressure range. The linear response to the applied pressure (R^2 = 0.97) indicates the sensor's linearity, a crucial feature for calibration. The pressure was applied within a range of 0 – 76 kPa, showing a sensitivity of 0.96% kPa^{-1}. The average response and recovery times were determined to be 0.43 s and 0.138 s, respectively. The reported pressure sensor demonstrates high potential for developing piezoresistive pressure sensors and applications in flexible electronics, such as wearable devices, to monitor the movements of the human body.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Park SJ, Kim J, Chu M, Khine M. Flexible piezoresistive pressure sensor using wrinkled carbon nanotube thin films for human physiological signals. Adv. Mater. Technol. 2018;3:17001508.
2. Li XP, Li Y, Li X, Song D, Min P, Hu C, Zhang HB, Koratkar N, Yu ZZ. Highly sensitive, reliable and flexible piezoresistive pressure sensors featuring polyurethane sponge coated with mxene sheets. J. Colloid Interface Sci. 2019;562:54.
3. Rinaldi A, Tamburrano A, Fortunato M, Sarto MS. A flexible and highly sensitive pressure sensor based on a pdms foam coated with graphene nanoplatelets. Sensors (Switzerland). 2016;16:2148.
4. Itapu, BM, Jayatissa AH. A review in graphene/polymer composites. Chemical Science International Journal. 2018;23.3:1-16.
5. Maharjan S, Jayatissa AH. Application of nanocomposites in the automotive industry. Applications of Nanocomposites. CRC Press. 2022;34-54.
6. Ma Y, Liu N, Li L, Hu X, Zou ZZ, Wang J, Luo S, Gao Y. A highly flexible and sensitive piezoresistive sensor based on MXene with greatly changed interlayer distances. Nat. Commun. 2017;8:1207.

7. Maharjan S, Jayatissa AH, A Review of Flexible Sensors, Nanomaterials for Energy and Sensor Applications. CRC Press, 2024, 137-153.
8. Wu YH, Liu HZ, Chen S, Chu Dong X, Wang PP, Liu S qi, Lin Y, Wei Y, Liu L. Channel crack-designed gold @pu sponge for highly elastic piezoresistive sensor with excellent detectability. ACS Appl. Mater. Interfaces. 2017;9:20098.
9. Choong CL, Shim MB, Lee BS, Jeon S, Ko DS, Kang TH, Bae J, Lee SH, Byun KE, Im J, Jeong YJ, Park CE, Park JJ, Chung UI. Highly stretchable resistive pressure sensors using a conductive elastomeric composite on a Micropyramid array. Adv. Mater. 2014;26:3451.
10. Pang Y, Tien H, Tao L, Li Y, Wang X, Deng N, yang Y, Ren TL. Flexible, highly sensitive, and wearable pressure and strain sensors with graphene porous network structure. ACS Appl. Mater. Interfaces. 2016;8:26458.
11. Wu X, Han Y, Zhang X, Zhou Z, Lu C. Large-area compliant, low-cost, and versatile pressure-sensing platform based on microcrack-designed carbon black @polyurethane sponge for human–machine interfacing. Adv. Funct. Mater. 2016;266246.
12. Huang Y, Fang D, Wu C, Wang W, Guo X, Liu P. A flexible touch-pressure sensor array with wireless transmission system for robotic skin. Rev. Sci. Instrum. 2016;87:065007.
13. Park H, Ra Y, Jeong J, Yun SY, Hong S, Jin SJ, Lee G, Zi, Ha JS. stretchable array of highly sensitive pressure sensors consisting of polyaniline nanofibers and au-coated polydimethylsiloxane Micropillars. ACS Nano. 2015;9:9974.
14. Shin YE, Lee JE, Park Y, Hwang SH, Chae HG, Ko H. Sewing machine stitching of polyvinylidene fluoride fibers: Programmable textile patterns for wearable triboelectric sensors. J. Mater. Chem. A. 2018;6:22879.
15. Pan L, Chortos A, Yu G, Wang Y, Isaacson S, Allen R, Shi Y, Dauskardt R, Bao Z. An ultra-sensitive resistive pressure sensor based on hollow-sphere microstructure induced elasticity in conducting polymer film. Nat. Commun. 2014;5(1).
16. Maharjan S, Samoei VK, Jayatissa AH, Noh JH, Sano K. Knittle pressure sensor based on graphene/polyvinylidene fluoride nanocomposite coated on polyester fabric. Materials. 2023;16.22:7087.
17. Bandodkar AJ, Wang J. Non-invasive wearable electrochemical sensors: A review. Trends in Biotechnology. 2014;32:363.
18. Majumder S, Mondal T, Deen MJ. Wearable sensors for remote health monitoring. Sensors (Switzerland). 2017;17:130.
19. Huang Y, Fan X, Chen SC, Zhao N. Emerging technologies of flexible pressure sensors: Materials, modeling, devices, and manufacturing. Advanced Functional Materials. 2019;29:1808509.
20. Zhao XH, Ma SN, Long H, Yuan H, Tang CY, Cheng PK, Tsang YH. Multifunctional sensor based on porous carbon derived from metal-organic frameworks for real-time health monitoring. ACS Appl. Mater. Interfaces. 2018;10:3986.
21. Cui C, Wang X, Yi Z, Yang B, Wang X, Chen X, Liu J, Yang C. Flexible single-electrode triboelectric nanogenerator and body moving sensor based on porous na2co3/polydimethylsiloxane film. ACS Appl. Mater. Interfaces. 2018;10:3652.
22. Park SH, Lee HB, Yeon SM, Park J, Lee NK. Flexible and stretchable piezoelectric sensor with thickness-tunable configuration of electrospun nanofiber mat and elastomeric substrates. ACS Appl. Mater. Interfaces. 2016;8:24773.
23. Al-Handarish Y, Omisore OM, Igbe T, Han S, Li H, Du W, Zhang J, Wang L. A survey of tactile-sensing systems and their applications in biomedical engineering. Advances in Materials Science and Engineering 2020; 2020).
24. Zhang W, Liu Q, Chen P. Flexible strain sensor based on carbon black/silver nanoparticles composite for human motion detection. Materials (Basel). 2018;11:1836.
25. Chang S, Li J, He Y, Liu H, Cheng B. A high-sensitivity and low-hysteresis flexible pressure sensor based on carbonized cotton fabric. Sensors Actuators, A Phys. 2019;294:4.
26. Yao JL, Yang X, Shao N, Luo H, Zhang T, Jiang WG. A flexible and highly sensitive piezoresistive pressure sensor based on micropatterned films coated with carbon nanotubes. J. Nanomater., 2016. 2016;5.
27. Kweon OY, Lee SJ, Oh JH. Wearable high-performance pressure sensors based on three-dimensional electrospun

conductive nanofibers. NPG Asia Mater. 2018;10:540.
28. Materials EI, Oxide A. <2012010818323103.Pdf>," 08, pp. 4–6.
29. Singh P, Borkar H, Singh BP, Singh VN, Kumar A. Ferroelectric polymer-ceramic composite thick films for energy storage applications. AIP Adv. 2014;4:087117.
30. Pawlyta M, Rouzaud JN, Duber S. raman micro-spectroscopy characterization of carbon blacks: Spectral analysis and structural information. Carbon N. Y. 2015;84:479.
31. Ungár T, Gubicza J, Ribárik G, Pantea C, Zerda TW. Microstructure of carbon blacks determined by X-ray diffraction profile analysis. Carbon N. Y. 2002;40:929.
32. Horibe H, Sasaki Y, Oshiro H, Hosokawa Y, Kono A, Takahashi S, Nishiyama T. Quantification of the solvent evaporation rate during the production of three PVDF crystalline structure types by solvent casting. Polym. J. 2014;46:104.
33. Wang L, Ding T, Wang P. Effects of compression cycles and precompression pressure on the repeatability of piezoresistivity for carbon black-filled silicone rubber composite. J. Polym. Sci. Part B Polym. Phys. 2008;46:1050.
34. Maharjan S, Samoei VK, Jayatissa AH. Graphene/PVDF Nanocomposite-Based Accelerometer for Detection of Low Vibrations. Materials. 2023;16.4:1586.
35. Shi Z, Jayatissa AH, Peiris FC. Fabrication of semiconducting pyrite thin films from hydrothermally synthesized pyrite (FeS2) powder. J. Mater. Sci. Mater. Electron. 2016;27:535.
36. Priyanka R, Ahamed B, Deshmukh K. Dielectric and electromagnetic interference shielding properties of zeolite 13X and carbon black nanoparticles based PVDF nanocomposites. Journal of Applied Polymer Science. 2021:138.13:50107.
37. Xinlei T, Pötschke P, Pionteck J, Li Y, Formanek P, Voit B. Tuning the piezoresistive behavior of poly (vinylidene fluoride)/carbon nanotube composites using poly (methyl methacrylate). ACS Applied Materials & Interfaces. 2020;12.38:43125-43137.
38. Javad P, Mazaheri M, Zeraati AS, Jamasb S, Sundararaj U. Physics-Based Modeling and Experimental Study of Conductivity and Percolation Threshold in Carbon Black Polymer Nanocomposites. Applied Composite Materials. 2023;1-21.
39. Xinlei T, Pionteck J, Pötschke P. Improved piezoresistive sensing behavior of poly (vinylidene fluoride)/carbon black composites by blending with a second polymer. Polymer. 2023;268:125702.
40. Maharjan S, Samoei VK, Jayatissa AH, Noh JH, Sano K. Effect of Annealing on Graphene/PVDF Nanocomposites. ACS omega. 2023;8.15:13876-13883.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/112261