Design and Fabrication of a Graphene/Polyvinylidene Fluoride Nanocomposite-Based Airflow Sensor

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ABSTRACT: In recent years, flexible and stretchable sensors have been a subject of intensive research to replace the traditional sensors made up of rigid metals and semiconductors. In this paper, a piezoresistive airflow sensor was designed and tested to measure the speed of air inside a pipe. Graphene/polyvinylidene fluoride nanocomposite films were prepared using a solvent-cast technique on a flexible polyethylene substrate as a piezoresistive material. Three different solutions were studied as a function of graphene concentration. The microstructure of the nanocomposite was characterized by X-ray diffraction, scanning electron microscopy, and optical microscopy. The effect of temperature on electrical conductivity was investigated by heating and cooling the sample between the room temperature and 150 °C. The stretchability of the nanocomposite film was studied with a tensile test, and the same procedure was employed to determine the breakdown point of the electrical conductivity. The sensor response was measured in terms of the resistance change caused by air pressure and found to increase with the concentration of graphene in the composite. The sensing characteristics were simulated using the COMSOL Multiphysics software, and the modeled data were compared favorably with the experimental result. The sensitivity of the sensor was found to be 1.21% kPa⁻¹ in the range of 0–2.7 kPa. This piezoelectric sensor possesses unique characteristics such as being lightweight, flexible, and exhibiting fast response; hence, it can have potential applications in various sectors such as ventilators, commercial HVAC, and automotive industries.

1. INTRODUCTION
Flexible conductive polymers with distinct characteristics such as high flexibility, stretchability, high sensitivity, lightweight, and miniature size have been the subject of emerging studies because of their wide range of applications in sensors and electronic devices including human motion detection, electronic skin, robotics, human–machine interface, personal health care, and flow measurement. Conventional sensor devices made of metals and semiconductors possess brittle and rigid nature, low fatigue life, low sensitivity, and poor biocompatibility, limiting their applications at high strain levels or integration with irregular surfaces. Flexible sensor devices can address such challenges. Sensors can be distinguished based on their sensing mechanisms such as piezoresistive, piezoelectric, capacitive, triboelectric, and field-effect transistors, which showcase versatile applications. These differences are inherently important for the development of the best functioning sensors as one kind of sensor can provide more desirable results than the others. One of the most common sensors is the piezoresistive type, which converts mechanical stimuli into electrical signals. The piezoresistive-based flexible conductive polymer exhibits many advantages such as straightforward fabrication, high flexibility, a simple read-out system, and a simple sensor configuration. During the designing of flexible sensors, one of the most important factors to be considered is materials handling, including a substrate that meets the mechanical, structural, and sensing requirements to ensure reliable and durable application. Carbon-based micro-/nanophase materials such as carbon nanotubes, carbon black, graphene, conductive polymers, and metal nanowires have been used as conductive materials. Apart from sensing materials, commonly used flexible substrate polymers are polydimethylsiloxane, thermoplastic polyurethane, polyolefin elastomer, natural rubber, polyethylene (PE), polyimide, and polyethylene terephthalate.

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Graphene is a two-dimensional crystal structure of sp²-hybridized carbon atoms. Since the discovery of graphene in 2004, extensive research has been performed to take advantage of its excellent physical, chemical, electrical, and mechanical properties, such as the very high specific surface area (2300 m²/g), electrical conductivity (6 × 10⁴ S/cm), light transmittance (97.7% for a single layer), thermal conductivity (5000 W/mK at the room temperature), and tensile strength and shear modulus (130 GPa and 1.0 TPa, respectively). Such unique properties of graphene can be implemented in the graphene/polymer nanocomposites. The fluorine atoms of polyvinylidene fluoride (PVDF) possess a high affinity to carbon atoms; hence, it is more suitable as a binder for graphene. On the other hand, it also has a high dielectric constant, resistance to chemicals, and unique pyroelectric and piezoelectric properties.

Many studies have been performed on the manufacturing of graphene and its applications in graphene/polymer composites. Li et al. reported that the electrical conductivity and dielectric properties of PVDF/graphite nanocomposites exhibited a strong frequency dependence, particularly in the vicinity of the percolation threshold (Øvol = 6 vol %). Stankovich et al. studied the electrical conductivity of the graphene/polystyrene nanocomposite and found that only 1.0 vol % of graphene addition enhanced the conductivity up to ~0.1 S/m. Zhao et al. fabricated the graphene/polyvinyl alcohol composite by the solution-blending method and found that the tensile strength and Young’s modulus improved up to 150% and 10 times, respectively, at 1.8 vol % of graphene.

In this research, a graphene/PVDF nanocomposite was prepared by the solvent cast technique with PVDF as a binder material. The solution was then coated on a flexible PE substrate to make a flexible piezoresistive flow sensor. The electrical conductivity of composite films was investigated as a function of graphene concentration. The flow sensor was fabricated as a cantilever, and its performance was assessed at different airflow speeds in a pipe. The response was recorded in terms of resistance change. It was found that the proposed sensor showed a high performance in terms of durability, repeatability, and accuracy.

2. SENSING MECHANISM

The sensing principle of a piezoresistive sensor can be described as the change in the resistance under structural deformation. There are two modes of resistance change when the device is subjected to deformation or strain; one is due to a physical change in dimensions such as length (l) and area (A), and the other is due to resistivity (ρ). The resistance is expressed by ρl/A. The change in resistance due to resistivity is dominant over the change in resistance due to physical dimensions for a piezoresistive material. The relative change in resistance, which is also known as the sensor response, is expressed by eq 1

\[ \frac{\Delta R}{R} = \frac{1}{\varepsilon} + \frac{\Delta \rho}{\rho} \]  

where ρ and ε are the Poisson’s ratio and strain of the nanocomposite, respectively. The change in resistivity under structural deformation or upon stretching of a flexible conductive polymer depends upon different factors such as the breaking of conductive pathways while stretching, a decrease in charge carriers, or charge carriers travelling longer paths.

The schematic illustration of the piezoresistive airflow sensor in normal conditions under no loading and deflection under stressed conditions are shown in Figure 1a,b, respectively. A force or pressure on the surface of the sensor due to airflow inside the pipe causes the sensor to deflect at the sensor legs, increasing the resistivity of the thin film made up of the graphene/PVDF nanocomposite. This mechanism leads to the increase in the resistance of the sensor. This phenomenon can be explained as the stretching of graphene layers during deformation, providing less conductive paths for electrons to transport.

3. EXPERIMENTAL PROCEDURE

3.1. Materials and Sample Preparation. The sensor was fabricated by coating a thin layer of conductive nanocomposites on a flexible substrate. A PE sheet having a thickness of 0.1 mm was chosen as the substrate due to its flexibility and stretchability. The sensor was designed in CAD software with a dimension of 25 mm × 14 mm, as shown in Figure 1a. Graphite particles of 1.0 μm (purity of 99.9%) were mixed with acetonitrile in a ratio of 1.0 g of graphite to 20.0 mL of acetonitrile as recommended by Wang & Jayatissa. The solution was then stirred with a glass rod for approximately 30 min to breakdown the large flakes of graphite, followed by sonicated the mixture for 40 min. Exfoliation of graphite occurred during this process, forming graphene layers. The solution was left for a few hours to achieve stable multilayer graphene suspension. The top portion of the graphene solution was carefully taken as 1.5, 2.0, and 2.5 mL in three separate beakers. An amount of 50.0 mg of PVDF powder (99.999%, M<sub>w</sub> = 534,000 g/mol, Alfa Aesar) was added to each of the graphene solutions. The corresponding volume concentrations of graphene were 3.23, 2.44, and 1.96 vol/vol %, respectively. The graphene/PVDF nanomposites were then sonicated for 20 min. These solutions were named C1, C2, and C3, respectively. The volume concentration (Øvol) of PVDF can be expressed with the following eq 2.

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Figure 1. Schematic diagram of a sensor in (a) normal condition and (b) deflection under stressed condition.
\[ \mathcal{Q}_{\text{vol}} = \frac{m_p/\rho_p}{m_p/\rho_p + m_G/\rho_G} \times 100\% \]  

(2)

Here, \( m_G \) and \( m_p \) are the mass of graphene and PVDF in the solution, respectively, and \( \rho_G \) and \( \rho_p \) represent the density of graphene and PVDF, respectively. It is important to determine the thermodynamic compatibility of graphene and PVDF. For this purpose, we used the Flory–Huggins interaction parameter to understand the interaction parameter (X12). In this case, PVDF is highly soluble in acetonitrile and the nanoparticles of graphene are also mixable in this solution owing to their 3D structure. As such, we expect X12 < 0.5 for our material system due to the high solubilities of both graphene and PVDF in the acetonitrile solvent. The physical properties of graphene and PVDF are presented in Table 1.

### Table 1. Physical Properties of Graphene and PVDF

| properties                        | graphene | PVDF  |
|-----------------------------------|----------|-------|
| density (g/cm\(^3\))              | 2.25     | 1.78  |
| melting point (°C)                 | 3650     | 155–160|
| resistivity (Ω-cm)                 | 10^-6    | 2 \times 1014 |
| glass transition temperature (°C)  | -35      |       |

Before coating a thin layer of the graphene/PVDF nanocomposite, the surface of the substrate polymer was cleaned with a sandpaper (grit # 600+) and washed with isopropanol so that unwanted particles were removed. This process was also beneficial to coat composite films on the substrate with better adhesion to the surface. Two wire terminals were connected to the sensor legs (Figure 1a) to measure the electrical resistance. A pipe with a length of 1.5 m and an internal diameter of 7.7 cm was used to measure the airflow parameters. The sensor was attached to the surface of the pipe at an angle of 30° with respect to the pipe axis, as shown in Figure 2.

To analyze the stretchability of the nanocomposite films, three rectangular samples of the same dimension (25 mm \( \times \) 12 mm) for C1, C2, and C3 were prepared, and two wire terminals were connected to measure the change in the resistance of the nanocomposite upon the application of tensile force. Further, the nanocomposite was coated on glass slides to study the characterization of particles and temperature dependence. The average thickness of the nanocomposite coated on the substrate was in the range of 20–22 μm.

### 3.2. Characterization Procedure

An 8-speed manual controller fan (AC Infinity CLOUDLINE S4) was used to flow the air at different speeds inside the pipe. The deformation of the sensor caused by airflow was recorded by a Keithley Multimeter connected to a computer using the LabVIEW 2015 software. The response graphs were plotted as a function of time and resistance. A tensile test was performed by using the ASTM D3039 test machine, as shown in Figure 3. Each sample was stretched at a rate of 100 μm/min, and the change in resistance and resistivity of the thin film was recorded by a multimeter. For the characterization of the nanocomposite, X-ray diffraction (XRD), scanning electron microscopy (SEM), and optical microscopy techniques were employed. Samples were scanned under the diffraction angle, 2θ, in the range of 10–50°. The optical images were captured by a Karl Suss PM 5 microscope at a magnification of 400×. The sample was heated from room temperature to 150 °C and then cooled down to room temperature to investigate the effect of temperature on a nanocomposite having a zero-gap metal (graphene) and insulator (PVDF), since the melting point of PVDF is 155–160 °C. The graph of resistance versus temperature was plotted using an Arrhenius equation to understand the effect of temperature on conductivity.

### 4. RESULTS AND DISCUSSION

#### 4.1. Characterization of Graphene/PVDF Nanocomposite

The microstructure of the nanocomposite was examined by the XRD measurements, as shown in Figure 4. PVDF is a polycrystalline polymer known to exhibit several crystallographic forms, namely, α, β, γ, and δ. Two characteristic peaks of the α-phase of PVDF were observed at 2θ angles of 18.24° and 40.32°, which can be assigned to (020) and (002) planes, respectively. The characteristic peak at 2θ angle of 20.48° (110) indicates the presence of the β-phase of PVDF.

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Figure 2. (a) Schematic diagram of the experimental setup to measure the sensor resistance at various speeds and (b) an enlarged view of the sensor attached to the lid at 30°.
which is desirable for piezoelectric characteristics of the polymer and can be implemented in developing piezoelectric-based sensors. The presence of the $\beta$-phase of PVDF in the nanocomposite was also confirmed experimentally by measuring the change in the voltage under external pressure. However, the primary purpose of this paper is the application of PVDF as a binder to graphene sheets and also to improve the adhesion between the nanocomposite and the substrate. The graphene characteristic peak, seen at a 2$\theta$ angle of 26.4° (002), is much broader than that of graphite. The appearance of the exact peak position indicates that the crystal structure of graphene was not changed during the fabrication of the nanocomposite.

Dispersion of graphene in the PVDF binder in the nanocomposite was studied with SEM and optical microscopy. The optical image in Figure 5a and SEM image in Figure 5c do not show aggregation of graphene, indicating a uniform mixing of PVDF and graphene during the fabrication of the nanocomposite film. According to the optical image shown in Figure 5b, the pure PVDF solution possessed a uniform particle distribution. The crack defect in the surface was due to fast evaporation of the solvent after coating the film on the substrate.

### 4.2. Measurement of Airflow Speeds

The main application of this graphene/PVDF nanocomposite-based piezoresistive sensor is to assess its performance in an air stream through a pipe. The sensor response is reported in terms of the resistance change. The changes in resistance values at different speeds were compared in Figure 6a for the sensors made with the three graphene concentrations, C1, C2, and C3. Here, the sensor response was calculated with the formula: $\Delta R/R_o = (R_{air} - R_o)/R_o$, where $R_{air}$ and $R_o$ are the resistance of sensor elements with and without the airflow, respectively. For low speeds up to 5.1 m/s, the response is
almost the same for all samples. However, at higher speeds, the response for C3 sensor is stronger than that at other concentrations. In the C3 sample, the PVDF concentration is low, providing more conductive paths for electrons to transport through graphene. Under deformation, graphene layers stretch and conductive particles remain far apart, causing a higher change in resistance. The response was around 0.4% at the speed of 3.4 m/s (lowest air speed), and it increased to 3.3% at the highest air speed of 10.7 m/s for the C3 sample. As shown in Figure 6b, the sensor responded linearly with respect to the imposed pressure (coefficient of determination, $R^2 = 0.995$), and the trendline lies within the error bars. Linearity is an important characteristic of a sensor for its calibration. The sensor was tested in the range of 0−2.7 kPa, and the sensitivity was found to be 1.21% kPa$^{-1}$.

Figure 7 describes the response and repeatability of the sensor over time for the C3 sample. The fan was turned on for 10 s to blow air inside the pipe and then turned off for 10 s. The process was repeated three times for eight different speeds to examine whether the response was repeatable. The result shows good repeatability and distinct response at each speed. From the graph, the average response and recovery time were found to be 550 and 450 ms, respectively.

The sensor was also tested at different angles (30, 45, and 60°). Experimentally, it was found that the threshold angle for the sensor setup is 30° because the sensor response was optimum and also limited to a few airflow ranges. The responses at 45 and 60° were 2.5 and 3.0%, respectively, slightly higher than those at 30° in the intermediate speed range (3.4 m/s < speed < 10.7 m/s). However, the experiments showed the same sensor response at the lowest and the highest air speeds. As the angle of the sensor increases, the laminated pattern of the nanocomposite is prone to delamination. Also, the impact aerodynamic force of the airflow on the sensor is in the high range, which can decrease the lifetime of the sensor. Thus, the test result demonstrates a potential to apply this type of sensor for airspeed measurements.

4.3. Stretchability. Figure 8 presents the experimental result of the tensile test for three concentrations of samples, C1, C2, and C3. The graph of load versus extension justifies the flexibility and stretchability properties of the PE polymer and nanocomposite. The samples were stretched until the breakdown of the electrical connection. The change in resistance followed linear variation up to a strain value of 0.2 and then exponentially increased. This can be explained as the PVDF binder was no longer efficient at holding the graphene layers, causing drastic cracks in conductive paths. Among the three concentrations, C3 possessed maximum stretch of up to 9.6 mm at 12.3 N of applied load before a loss of conductivity. This can be attributed to the more significant number of graphene layers in C3, which slide one over the other during stretching.

The tensile test was also repeated at 35 °C for the C3 sample. As shown in Figure 8C(3b), the conductivity was discontinued at 7.3 mm (lower than that of the room temperature test), and for the same strain value, the response of a higher temperature test was lower than that of the room temperature test. This observation supported the fact that the conductivity of the composite increases with increase in temperature.

4.4. Temperature Dependency of Electrical Conductivity. The resistance dependency on temperature for the graphene/PVDF nanocomposite can be expressed by eq 3

$$R = R_0 \exp \left( -\frac{E_a}{K_B T} \right)$$  (3)

$$\ln R = \left( -\frac{E_a}{K_B} \right) \frac{1}{T} + \ln R_0$$  (4)

where $E_a$ and $K_B$ are the average activation energy and Boltzmann constant, respectively. The samples C1, C2, and C3 were heated from room temperature to 150 °C and then cooled gradually. The graphs of $\ln R$ versus 1000/T were plotted, as shown in Figure 9. It is clear from the plot that the temperature dependency of the conductivity of the graphene/PVDF nanocomposite for the three samples follows eq 4, indicating a decrease in resistance with an increase in temperature. On the other hand, the electrical conductivity
increases with the rise in graphene concentration in the nanocomposite, which can be interpreted as the enhanced number of conductive paths for the movement of electrons.\textsuperscript{13}

The cooling curve also followed an almost similar path as the heating curve. Thus, the results can be interpreted as the semiconductive nature of the graphene/PVDF nanocomposite. This type of sensor can also be used in those regions where the effect of temperature needs to be considered.

5. FINITE ELEMENT ANALYSIS

The simulation model of the piezoresistive sensor is shown in Figure 10a. The model consists of a thin film of thickness 20.0 $\mu$m, made up of graphene/PVDF, which is coated on the PE substrate; a PVC pipe; and a portion of PVC pipe to support the sensor. The simulation was carried out in a model developed based on COMSOL Multiphysics. The first order of magnitude of the force ($F$) and the pressure ($P_x$) exerted on
the sensor due to the airflow can be estimated by using eqs 5 and 6 based on the Newton’s second law of motion.

\[ F = \frac{d(mv)}{dt} \]

\[ = A \rho v^2 \]  

(5)

\[ P_x = \rho \times v^2 \]  

(6)

where, \( A \) is the effective area of sensor, which was estimated as 2.3 cm\(^2\); \( \rho \) is the density of air (1.29 kg/m\(^3\)); \( v \) is the mean airspeed; and \( dm/dt = A \times \rho \times v \). The above assumptions can be further modified based on the speed and flow behaviors such as laminar flow or turbulent flow.

For mechanical analysis, the air was passed in the pipe duct at a speed of 10.7 m/s. The results for velocity profile, displacement, and stress level are shown in Figure 10b–d, respectively. According to the velocity profile, maximum velocity (15 m/s) was obtained at the pipe centerline and was zero at the boundaries as imposed. The velocity of air at the sensor position was approximately 11.0 m/s, which was close to the input velocity. The maximum displacement at the free end of the cantilever sensor was 8.1 mm. Even at the maximum bending, the bent sensor surface does not touch the support, allowing more space for further bending at a higher speed. The bending stress was maximum at the sensor leg and found to be 7.9 MPa, which is less than the yield strength of the substrate material (20 MPa) to ensure failure criteria.

For electrical analysis, the inflow speed was varied from 0 to 10.7 m/s and the corresponding resistance was recorded. The response graph was plotted against the speed and compared with the experimental results in Figure 11. The response of the simulated result was quite higher than that of the experimental result for a speed of up to 8.7 m/s. The sensor did not bend properly at low speeds, showing less response. At a higher speed, the results are close. The patterns for both the results show an increase in response with an increase in speed.

6. CONCLUSIONS

A flexible and stretchable piezoresistive flow sensor was designed based on graphene/PVDF nanocomposite and...
fabricated by the solution-phase mixing technique. This sensor measures the speed of air flowing inside a pipe in terms of the resistance change of the nanocomposite material. Three samples with different concentrations of graphene and PVDF, C1, C2, and C3, were tested, and the response was recorded for each sample, which was found to be higher for the C3 sample. The maximum response recorded was 3.3% at 10.7 m/s. The change in resistance of the nanocomposite during heating and cooling indicates its semiconductor nature and shows promising applications at variable temperatures. The presence of the PVDF binder in a graphene matrix helped the sensor to stretch under loading, and the thin film stretched up to 9.6 mm under an applied load of 12.3 N. The average response and recovery times were 550 and 450 ms at 10.7 m/s, respectively, which is quite impressive for the novel material in the sensor. The sensitivity of the sensor was found to be 1.7 × 10⁻⁴ kPa⁻¹ in the range of 0–2.7 kPa. These findings are quite impressive for the sensor with a novel material. The model was simulated for mechanical and electrical analyses. The graphs of response versus speed for simulated and experimental results are close at higher speeds. This piezoresistive flow sensor based on the graphene/PVDF nanocomposite possesses good electrical conductivity and mechanical properties, favorable response to different pressure ranges or speeds of airflow, and repeatability. Besides its application of flow measurement in various devices, it can be implemented in other applications such as skin-mountable and wearable devices, flexible electronic devices to measure shear stress, and pressure among others.

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■ REFERENCES

(1) Geim, A. K.; Novoselov, K. S. The rise of graphene. Nat. Mater. 2007, 6, 183–191.
(2) Novoselov, K. S.; et al. Two-dimensional atomic crystals. Proc. Natl. Acad. Sci. 2005, 102, 10451–10453.
(3) Meyer, J. C.; Geim, A. K.; Katsnelson, M. I.; Novoselov, K. S.; Booth, T. J.; Roth, S. The structure of suspended graphene sheets. Nature 2007, 446, 60–63.
(4) Bolotin, K. I.; et al. Ultrahigh electron mobility in suspended graphene. Solid State Commun. 2008, 146, 351–355.
(5) Kim, K. S.; et al. Large-scale pattern growth of graphene films for stretchable transparent electrodes. Nature 2009, 457, 706–710.
(6) Balandin, A. A.; et al. Superior Thermal Conductivity of Single-Layer Graphene. Nano Lett. 2008, 8, 902–907.
(7) Nair, R. R.; et al. Fine Structure Constant Defines Visual Transparency of Graphene. Science 2008, 320, 1308.
(8) Yee, W. A.; Kotaki, M.; Liu, Y.; Lu, X. Morphology, polymorphism behavior and molecular orientation of electrosprun poly(vinylidene fluoride) fibers. Polymer 2007, 48, 512–521.
(9) Wang, M.; Shi, J.-H.; Pramoda, K. P.; Goh, S. H. Microstructure, crystallization and dynamic mechanical behaviour of poly(vinylidene fluoride) composites containing poly(methyl methacrylate)-grafted multivalved carbon nanotubes. Nanotechnology 2007, 18, 235701.
(10) Li, Y. C.; Tjong, S. C.; Li, R. K. Y. Electrical conductivity and dielectric response of poly(vinylidene fluoride)/graphite nanoplatelet composites. Synth. Met. 2010, 160, 1912–1919.
(11) Li, Y. C.; Li, R. K. Y.; Tjong, S. C. Frequency and Temperature Dependences of Dielectric Dispersion and Electrical Properties of Polyvinylidene Fluoride/Expanded Graphite Composites. J. Nanomater. 2010, 2010, 1–10.
(12) Stankovich, S.; et al. Graphene-based composite materials. Nature 2006, 442, 282–286.
(13) Zhang, H.-B.; et al. Electrically conductive polyethylene terephthalate/graphene nanocomposites prepared by melt compounding. Polymer 2010, 51, 1191–1196.
(14) Rolnick, H. Tension Coefficient of Resistance of Metals. Phys. Rev. 1930, 36, 506–512.
(15) Amjadi, M.; Kyung, K.-U.; Park, I.; Sitti, M. Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review. Adv. Funct. Mater. 2016, 26, 1678–1698.
(16) Hu, N.; et al. Investigation on sensitivity of a polymer/carbon nanotube composite strain sensor. Carbon 2010, 48, 680–687.
(17) Wang, V.; Jayatissa, A. H. Comparison study of graphene based conductive nanocomposites using poly(methyl methacrylate) and poly(pyrrole) as matrix materials. J. Mater. Sci. Mater. Electron. 2015, 26, 7780–7783.
(18) Itapu, B.; Jayatissa, A. A Review in Graphene/Polymer Composites. Chem. Sci. Int. J. 2018, 23, 1–16.
(19) Wang, W.; Jayatissa, A. H. Computational and experimental study of electrical conductivity of graphene/poly(methyl methacrylate) nanocomposite using Monte Carlo method and percolation theory. Synth. Met. 2015, 204, 141–147.
(20) Rana, D.; Bag, K.; Bhattacharyya, S. N.; Mandal, B. M. Miscibility of poly(styrene-co-butyl acrylate) with poly(ethyl methacrylate): Existence of both UCST and LCST. J. Polym. Sci., Part B: Polym. Phys. 2000, 38, 359–375.
(21) Granman, D. M.; Garland, J. C.; Tanner, D. B. Critical Behavior of the Dielectric Constant of a Random Composite near the Percolation Threshold. Phys. Rev. Lett. 1984, 46, 375–378.
(22) Salam, M. A-E.; Elkomy, G.; Osman, H.; Nagy, M.; El-Sayed, F. Structure-electrical conductivity of polypyrrolidylene fluoride/graphite composites. J. Reinf. Plast. Compos. 2012, 31, 1342–1352.