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Ayman Mahmoud Mohamed; Yao, Kui; Yasmin Mohamed Yousry; Wang, Junling;
Ramakrishna, Seeram

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Ayman M. Mohamed,^{1,2} Kui Yao,^{1,a)} Yasmin M. Yousry,^{1,3} Junling Wang,² and Seeram Ramakrishna³

AFFILIATIONS

¹Institute of Materials Research and Engineering, A*STAR (Agency for Science, Technology and Research), 2 Fusionopolis Way, Singapore 138634

²School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Ave., Singapore 639798

³Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575

^{a)}Author to whom correspondence should be addressed: k-yao@imre.a-star.edu.sg

ABSTRACT

Open-cell nanocomposite foams of poly(vinylidene fluoride-co-trifluoroethylene) [P(VDF-TrFE)] and multi-walled carbon nanotubes (MWCNTs) were investigated for airborne sound absorption. When MWCNTs were well dispersed in the P(VDF-TrFE) matrix, the degree of crystallinity of the polar phase of the polymer was enhanced, and hence, the local piezoelectric effect and the electrical conductivity varied by nearly seven orders of magnitude dependent on the amount of MWCNT loading. The measurements in a standard acoustic tube showed that introduction of an appropriate amount of MWCNTs significantly enhanced the airborne sound absorption coefficient of P(VDF-TrFE) foam without poling, particularly in the lower and intermediate frequency range (below 2 kHz), which is attributed to the local piezoelectric effect in the polar polymer matrix and charge dissipation through the conductive MWCNT interfacing the polar phase. The experimental results and data analysis indicate that the open-cell nanocomposite foam with an optimal combination of local piezoelectric effect and electrical conductivity is promising for noise mitigation applications with enhanced passive airborne sound absorption.

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I. INTRODUCTION

Noise is one of the vitally important environmental issues that significantly affect life quality and liveability, particularly for people living in high-density urban environments.^{1,2} As it is well known, exposure to a high noise level can cause hearing loss. Even at a low noise level, noise disturbances have a significant negative effect on psychological health. Research has been conducted to investigate and develop various materials and techniques for airborne noise mitigation under three major categories: passive, active, and hybrid.^{3,4} The passive noise mitigation is realized by using porous sound absorbing materials, which are easy to be implemented without complicated control algorithms as required in the active and hybrid methods.⁵ Methods using passive sound absorbing materials are effective for mid- and high-frequency airborne noise mitigation, in which the acoustical energy can be substantially absorbed and converted into heat.^{6,7} Based on their microscopic structure, sound absorbing

materials are categorized into cellular, fibrous, and granular. They can also be classified based on their pore configurations of open- and closed-cells.⁵ Open-cells have interconnected and continuous channels connected to the ambient environment, while closed-cells have pores isolated from their neighbors. Open-cell porous materials usually exhibit superior sound absorption performance in comparison to the closed-cell counterparts.⁶

In a passive approach that uses porous materials, sound waves are dissipated through three different phenomena: visco-inertial dissipation, thermal dissipation, and structural dissipation damping.^{8–10} The visco-inertial dissipation occurs from the friction of air particles with the material frame walls while the sound waves propagate into the foam.^{11,12} The thermal dissipation results from thermal exchanges between air particles and the frame,¹⁴ while the structural effects are associated with the deformation of the porous materials' structure.^{11–13}

Piezoelectric materials have been introduced into the field of structure borne vibration control a long time ago. Piezoelectric ceramics have been employed as films,¹⁵ beams,¹⁶ and shell¹⁷ structures for sensing and active control of structure borne mechanical vibration. Piezoelectric shunt damping has also been used in structural vibration damping technologies.¹⁸ However, very limited efforts are made to investigate the effectiveness of the piezoelectric property on passive airborne sound absorption. Caused by low mechanical impedance, porous polymeric piezoelectric materials offer better mechanical matching to air than ceramics.

Ferroelectric poly(vinylidene fluoride) (PVDF) and its copolymers with trifluoro ethylene (TrFE) exhibit excellent piezoelectric properties. Both of them have mainly five known crystalline phases with different molecular conformations; they are designated as all-trans (TTT) for β phase, TGTG for α phase and δ phase, and T3GT3G for ϵ and γ phases.^{19–21} Among them, the β phase possesses the highest electrical polarity and piezoelectric performance due to its polar dipole configuration perpendicular to the chain direction.²² It should be noted that, for PVDF homopolymer, the nonpolar α phase is the most favorable thermodynamic stable phase.²³ Thus, post-treatments during manufacturing are required to achieve polar β phase to obtain the desired piezoelectric properties.²³ In contrast, P(VDF-TrFE) copolymer can form the β -phase structure spontaneously without any post-treatment processes, as confirmed by theoretical calculation in which the β phase is the most thermodynamically favored phase.²⁴

In our previous work, a concept of hybrid local piezoelectric and electrically conductive functions has been proposed for improving airborne sound absorption, where a composite foam made of porous PVDF mixed with conductive single-walled carbon nanotubes (SWCNTs) was used.^{25,26} We improved the local piezoelectricity of open-cell PVDF foam by thermal annealing treatment to yield a high content of polar phase to improve passive airborne noise mitigation.²⁷ We also investigated how the KNN ($\text{K}_{0.5}\text{Na}_{0.5}\text{NbO}_3$) fillers with much stronger and opposite local piezoelectric effect affect the airborne sound absorption behaviors in the PVDF/KNN-nanofiber composite foams.²⁸ Moreover, a polyurethane/PVDF/MWCNTs (multi-walled carbon nanotubes) foam was also fabricated for airborne sound absorption purpose.²⁹ While the currently common applications of using piezoelectric polymeric materials as electromechanical devices for energy harvesting, sensing, actuation, and transducer applications,³⁰ the work here is about utilization of the local piezoelectric effect for energy dissipation and in related airborne noise mitigation applications.

In this work, piezoelectric open-cell foams of P(VDF-TrFE) and its nanocomposites with cost-effective MWCNTs were fabricated for airborne sound absorption investigations. P(VDF-TrFE) was selected because of its enhanced piezoelectricity with higher polar β -phase content in comparison to the PVDF homopolymer. Analyses on the structure of the nanocomposite and hybrid local piezoelectric and conductive effects were conducted to understand the obtained outstanding airborne sound absorption performance.

II. EXPERIMENTAL

The materials and chemicals used in this work were poly(vinylidene fluoride-co-trifluoroethylene) [P(VDF-TrFE)] polymer

with MW $\sim 534\,000$ (Sigma Aldrich); *N,N*-dimethylformamide (DMF) (Merck); acetone (Merck); sugar; and MWCNTs (Mknano), with a carbon purity of >95 wt. %, outer diameter of 8–15 nm, and length of 10–30 μm .

Open-cell P(VDF-TrFE) foams were prepared by a sugar template method. The solutions were prepared by dissolving the P(VDF-TrFE) polymer powder in mixed organic solvent of DMF and acetone (50:50 in volume). MWCNTs (with concentrations of 0 wt. %, 3 wt. %, 5 wt. %, 7 wt. %, and 9 wt. %) were dispersed in mixed DMF and acetone solvent and sonicated in ultrasonic bath. After that, both solutions were mixed, sonicated, and heated at 50 °C to obtain a homogeneous precursor solution. The foams were prepared by mixing the P(VDF-TrFE) or P(VDF-TrFE)/MWCNT precursor solution with commercially available sugar to form a mixture dough. The mixture was formed using homemade molds that had a suitable geometrical shape and immediately dried in an oven at 100 °C to remove excess solvent and ensure complete drying. Then the samples were removed from the mold and leached (rinsed) in repeating cycles of hot water immersion to remove the sugar and obtain the foam with a porous structure. The foam samples were then dried at 100 °C for 12 h in an oven. Figure S1 in the [supplementary material](#) presents photographs of two obtained open-cell foam samples prepared through the sugar template method, a white PVDF foam and a black PVDF/MWCNT composite foam.

It is known that sound absorption properties are related to materials' porous morphology and various properties. To assess the local piezoelectric and conductive effects on sound absorption performance, all open-cell porous P(VDF-TrFE)/MWCNT nanocomposite foams with similarity in their porous morphology were fabricated under the same conditions using a sugar templating method with the mass ratio of P(VDF-TrFE):sugar = 1:9.

The crystalline phases of the P(VDF-TrFE) and P(VDF-TrFE)/MWCNT foams were analyzed with Fourier transform infrared spectroscopy (FTIR Spectroscopy Spectrum 2000; Perkin Elmer), with scan recorded over a range of 1600–600 cm^{-1} at 4 cm^{-1} resolution. The crystalline structure analysis was performed at room temperature using an x-ray diffraction (Bruker 2D Micro XRD Cu K(alpha) system D8-ADVANCE, Bruker AXS GmbH, Karlsruhe, Germany). The morphology of P(VDF-TrFE) foam was examined with a scanning electron microscope (SEM 6360LA, JEOL). The samples' porosity was calculated using ethanol saturation method, with more details given in Sec. III. The dielectric and electrical resistivities of the samples were measured with an impedance analyzer (Agilent 4294 A). The standard impedance tube (4206 A, Bruel & Kjaer) was used to measure the sound absorption coefficients of all the porous materials. This test was done according to ASTM E1050-98 standard test method for the absorption of acoustic materials. Thermal studies of P(VDF-TrFE) and its composite foams were performed by differential scanning calorimetry (DSC, Mettler Toledo) under dry N_2 environment.

III. RESULTS

Figure 1(a) shows the attenuated total reflection–Fourier transform infrared (ATR-FTIR) spectra for the obtained P(VDF-TrFE) foams with different concentrations of MWCNTs. The

FIG. 1. (a) ATR-FTIR spectra and (b) XRD patterns of open-cell P(VDF-TrFE) and P(VDF-TrFE)/MWCNT nanocomposite foams. The unmarked peaks are common for both α and β phases.

characteristic vibration bands designated to the polar β phase are at 840 cm^{-1} (CH_2 rocking and CF_2 asymmetrical stretching), 1288 cm^{-1} (C-F stretching vibration), and 1400 cm^{-1} (CH_2 wagging vibration), while the characteristic bands associated with the non-polar α phase are at 766 cm^{-1} (CH_2 in-plane or rocking) and 976 cm^{-1} (CH_2 twisting).^{31,32} As shown in Fig. 1(a), both β and α phases co-exist in the open-cell P(VDF-TrFE) and its nanocomposite foams, whereas it is clear that the β phase is dominant in P(VDF-TrFE)/MWCNT foams comprising 3–9 wt. % MWCNTs, and the amount of β phase increases with the MWCNTs. Furthermore, the FTIR spectra show that the crystallinity of P(VDF-TrFE) is slightly enhanced besides the increase of the β -phase content.

X-ray diffraction (XRD) analysis at room temperature over a scan range of $2\theta = 10^\circ\text{--}40^\circ$ was also conducted to examine the crystalline phases of the obtained P(VDF-TrFE)/MWCNT foams. The characteristic peaks of the polar β phase in the XRD patterns shown in Fig. 1(b) are at 20° and 35° , which correspond to the (110)/(200) and (020)/(101) reflections, respectively. The peak at 18.3° is attributed to a reflection plane (100) of the non-polar α phase.³³ The diffraction intensity of the crystalline peaks at 20° increases with adding more MWCNTs, which indicates that MWCNTs promote the formation of a polar β phase, which is in good agreement with the FTIR results presented in Fig. 1(a). In contrast, the peak intensity of the non-polar α phase at 18.3° was reduced with increasing MWCNTs in the nanocomposites. The results here show that the MWCNTs with large specific surface areas dispersed in the polymer matrix can enhance the degree of crystallinity of the β phase, which could be attributed to the crystallization nucleation occurring at the interfaces between P(VDF-TrFE) and the MWCNTs. The local polarization and piezoelectric effects are expected to improve in the open-cell nanocomposite foams with increasing MWCNTs highly dispersed in the P(VDF-TrFE) matrix.

The average crystal size of the polar β phase of P(VDF-TrFE) can be calculated using Scherrer's equation.³⁴ β -phase crystallite size of pure P(VDF-TrFE) foam is about 1.22 nm, while the crystallite size of composite foams with 3, 5, 7, and 9 wt. % MWCNT is about

3.38, 4.00, 4.60, and 6.00 nm. These results indicate that the introduction of MWCNT increases the crystallite size in addition to the content of the polar β -phase of the P(VDF-TrFE) polymer matrix.

It should be noted that the addition of natural sugar as a sacrifice material could possibly contribute to the enhancement of polar β phase of the obtained open-cell P(VDF-TrFE) nanocomposite foam due to the polarity existence in the sugar structure.³⁵

Figure S2 in the [supplementary material](#) (a, b, c, d, and e) present the morphology and the pore size distribution histograms of the P(VDF-TrFE)/MWCNT nanocomposite foams with different amount of MWCNTs. The SEM micrographs and pore size distribution histograms reveal that all the foams are highly porous with open cell configuration, with pore size around $500\text{ }\mu\text{m}$ and below. The incorporation of MWCNTs does not substantially affect the morphology and pore size of the P(VDF-TrFE) foams. The porosity of the P(VDF-TrFE)/MWCNT nanocomposite foams was determined using the solvent saturation method.³⁶ In this approach, a dry sample was immersed in a solvent, ethanol, and the change in the original weight was observed until a constant weight is reached. Then, the porosity was calculated using the following equation:

$$\phi(\%) = \left(\frac{(m_{\text{sat}} - m_d)/\rho_{\text{solvent}}}{V_a} \right), \quad (1)$$

where m_{sat} is the weight of the sample saturated with solvent, m_d is the dry weight, ρ_{solvent} is the density of solvent, and V_a is the apparent volume. The porosity was adjusted by controlling the mass ratio of P(VDF-TrFE) and sugar to be approximately 88% in all the prepared foams.

To gain insight into the effect of MWCNTs on the structure and properties of P(VDF-TrFE) foams, differential scanning calorimetry (DSC) measurements were conducted. Figure 2(a) shows DSC curves during heating of P(VDF-TrFE)/MWCNT nanocomposites. Endothermic peaks at 106.7°C and 146.3°C for P(VDF-TrFE) are attributed to the ferroelectric–paraelectric phase

FIG. 2. DSC (a) heating and (b) cooling curves of the open-cell P(VDF-TrFE) and P(VDF-TrFE)/MWCNT nanocomposite foams.

transition at Curie temperature (T_c) and melting temperature (T_m), respectively. The melting temperature T_m of P(VDF-TrFE)/MWCNT nanocomposite foam is continuously increased from 146.3 °C for the pristine P(VDF-TrFE) foam to about 153.5 °C with 9 wt. % MWCNTs. Moreover, Fig. 2(b) shows DSC cooling curves for P(VDF-TrFE)/MWCNT nanocomposites with different amount of MWCNTs. For the pristine P(VDF-TrFE) foam, three exothermal peaks are observed at 123.8 °C, 65.3 °C, and 58.8 °C, correlated to crystallization temperature (T_{cr}), and two phase transition temperatures due to the coexistence of two ferroelectric phases, respectively. The crystallization temperature increases with increasing MWCNTs or crystallization occurs earlier during cooling of the melt with MWCNTs, which well supports that crystallization nucleation occurs at the interfaces between P(VDF-TrFE) and the MWCNTs. The effect of the added MWCNTs on the consistent

shift of the peaks whether in heating or cooling curves and the intensity increase of peaks indicate that the MWCNTs are well dispersed in nanocomposites and promote the crystalline structure, which is consistent with the FTIR and XRD results.

Figure 3(a) presents the sound absorption coefficient in the frequency range of 500–6400 Hz for open-cell P(VDF-TrFE)/MWCNT nanocomposite foams with different MWCNT concentrations with a thickness of 20 mm. The sound absorption measurements were conducted using the standard impedance tube. The sound absorption coefficient shows a significant increase with the introduction of the increasing MWCNTs, while the porous morphology is maintained substantially as shown in Figure S2 in the supplementary material. The zoom-in plots in the low frequency range of 500–2000 Hz, as presented in Fig. 3(b), show clearly that the MWCNTs in the open-cell P(VDF-TrFE)/MWCNT foams

FIG. 3. Sound absorption coefficient of the open-cell P(VDF-TrFE) and P(VDF-TrFE)/MWCNT nanocomposite foams with different amount of MWCNTs (a) from 500 Hz to 6400 Hz and (b) from 500 Hz to 2000 Hz.

enhance sound absorption in the relatively low frequency range below 2000 Hz, which is highly valuable as it is usually challenging to absorb low frequency noise with a passive approach. However, it is further noted that the sound absorption coefficient drops significantly with excess MWCNTs. The sound absorption coefficient of open-cell P(VDF-TrFE)/7 wt. % MWCNT nanocomposite foam is the highest among all the P(VDF-TrFE) nanocomposite foams with 0, 3, 5, 7, and 9 wt. % MWCNTs.

A small resonance peak is noted at 680 Hz for the foam with 7 wt. % MWCNTs, which has the largest sound absorption coefficient. Smaller resonance peak around this frequency is also noted in the sample with the second largest sound absorption coefficient (5 wt. % MWCNT) but not significant in other compositions with relatively lower absorption. Our analysis shows that this small peak is related to a longitudinal mechanical resonance of the skeleton of the solid part of the P(VDF-TrFE) foam, with the frequency of 670 Hz for the foam with 7 wt. % MWCNTs as estimated according to the following equation:

$$f_s = \frac{1}{4e} \sqrt{E((1-\nu)/(1+\nu)(1-2\nu))/\rho_s}, \quad (2)$$

where f_s is the skeleton resonance frequency, e is the thickness of the foam sample, E is the modulus of elasticity (35 MPa), ν is Poisson's ratio of skeleton (0.33), and ρ_s is the density of the solid material (1.78 g/cm³).

Furthermore, the first large broad absorption peak occurring at 3950 Hz for the P(VDF-TrFE) foam matches well with the first acoustic resonance mode at 3969 Hz of the porous foam, as calculated according to the following equation:

$$f_r = \frac{nv}{2(L + 0.8d)}, \quad (3)$$

where n is a positive integer (1, 2, 3, ...) representing the resonance mode; L (20 mm) and d (29 mm) are the length and diameter of the foam, respectively; and v is the speed of sound in air (which is approximately 343 m/s at 20 °C). The position of the first acoustic resonance absorption peak could be affected by many factors such as mechanical and electrical impedances and dimension of the porous foams. The effects of all these parameters and the shift of the acoustic resonance peak will be discussed in detail below.

The acoustic impedance was measured for the open-cell P(VDF-TrFE) samples with 0 and 7 wt. % MWCNT using an impedance tube, as shown in Figure S3 in the [supplementary material](#). The acoustic impedance did not show substantial change with the additional MWCNT annealing process. The observed improvement in the sound absorption coefficient should be attributed to other extra energy dissipation mechanisms that are highly relevant to the local piezoelectric effect in combination with the appropriate matching electrical conductivity of the open-cell P(VDF-TrFE)/MWCNT nanocomposite foams.

Furthermore, an efficient way to examine the homogeneity of the fabricated samples was done by testing the sound absorption coefficient of the sample from both sides (front and back). The measured sound absorption results for both sides of the foams are presented in Figure S4 in the [supplementary material](#), which show

FIG. 4. Volume electrical conductivity and noise reduction coefficient of the open-cell P(VDF-TrFE)/MWCNT nanocomposite foams.

a high degree of homogeneity with the matching results from the front and back surfaces of the foams.

Our experimental results show that the electrical conductivity of the P(VDF-TrFE)/MWCNT nanocomposite foams increases significantly with the increasing concentration of the conductive MWCNT filler, as presented in Fig. 4. From 0 to 9 wt. % of MWCNTs in the composite foam, the conductivity increases from 3.3×10^{-11} to 3.0×10^{-4} S/cm, nearly seven orders of magnitude. A percolation behavior in electrical conductivity with the MWCNT content is observed, with the percolation threshold around 7 wt. % of MWCNTs. According to the percolation theory, when the concentration of the MWCNTs is high enough to satisfy the percolation threshold, the conductive MWCNTs in the foam are connected with each other, forming a long-range three-dimensional conducting network, in which conductivity could be realized effectively with the electron transport via hopping and migration among the MWCNTs.³⁷ Thus, electrical charges in the foam can be steadily dissipated near or above the percolation threshold. Furthermore, with the addition of MWCNTs affecting the conductivity of the P(VDF-TrFE)/MWCNT nanocomposite foams and even the crystallinity of P(VDF-TrFE), it is found that the dielectric constant and loss of the P(VDF-TrFE)/MWCNT nanocomposite foams increase with increasing the MWCNT concentration, as presented in Figs. S5(a) and S5(b) in the [supplementary material](#), and some reports in the literature.³⁸

We further calculated the noise reduction coefficient (NRC) to identify a clear relationship between sound absorption performance and MWCNT concentration. The noise reduction coefficient is an average rating of how much sound energy a sound absorber can absorb at 250, 500, 1000, and 2000 Hz, which is calculated using the following equation:

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4}. \quad (4)$$

As shown in Fig. 4, increasing the concentration of MWCNTs until 7 wt. % significantly enhances NRC, while it drops significantly with increasing concentration of MWCNTs beyond 7 wt. %.

IV. DISCUSSION

To summarize the investigation results above on the structure, morphology, and strong correlation between electrical conductivity and airborne sound absorption, a model on the P(VDF-TrFE)/MWCNT nanocomposite foam and its airborne sound absorption mechanism is schematically illustrated in Fig. 5.

As shown in Figs. 5(a) and 5(b), P(VDF-TrFE)/MWCNT nanocomposite has an open-cell porous structure, and the polar β phase of P(VDF-TrFE) forms with interfaces to the MWCNTs. Our XRD and FTIR results showed that the MWCNTs promote crystallization of the polar β phase with the local piezoelectric effect. The effect of the added MWCNTs on the thermal analysis peaks indicated that the MWCNTs are well dispersed in the nanocomposites for promoting the crystalline structure, which is consistent with the FTIR and XRD results.

The airborne sound pressure wave can penetrate deeply into the open-cell porous structure for realizing effective vibration interactions between the air and solid with mechanical energy transfer from the air to the thin solid structure. Here, the thin struts of the P(VDF-TrFE) polymer matrix are polar and possess a substantial local piezoelectric effect, particularly when they crystallize into the β phase. Thus, in addition to the well-known sound absorption mechanisms, such as fluid viscous and thermal losses, and viscoelastic structural damping effect, which commonly exist in porous foams, the mechanical vibration or strain of P(VDF-TrFE) excited by the airborne acoustic wave can be converted to electrical charges through the local piezoelectric effect in the polar phase. Electrical discharge can happen through the conductive MWCNTs adjacent to the polar phase, so that the electrical energy can be converted into thermal dissipation. Figure 5(c) schematically illustrates the proposed additional noise absorption mechanism with the combined functions of the local piezoelectric response of P(VDF-TrFE) and the electrical conductivity of the adjacent MWCNT filler in the

open-cell P(VDF-TrFE)/MWCNT nanocomposite foams. Additional enhancement in sound absorption performance could be possible with the formation of electrical charges with the presence of polar β phase at the fluid–solid interfaces with potentially increased friction loss.

It is known that the optimum piezoelectric damping effect for mechanical structural vibration can be achieved when the external load R matches the condition of $R \sim 1/\omega C$, where C denotes the capacitance of the piezoelectric and ω denotes the frequency.^{39,40} Our previous theoretical model and analysis show the potential of appropriate combination of local piezoelectric and optimal conductive effects for improving sound absorption performance of the porous polymer structure.²⁶ Therefore, we further measured the electrical impedance of the open-cell P(VDF-TrFE)/MWCNT nanocomposite foams to examine the effect of impedance matching on the sound absorption performance. We found that the addition of MWCNTs to the P(VDF-TrFE) polymer matrix significantly decreases the electrical impedance of the foams due to increased conductivity, as shown in Figure S6 in the [supplementary material](#), which potentially in turn affects the impedance matching condition.

Furthermore, analysis revealed that the maximum sound absorption peak constantly shifts toward low frequency with the increase of MWCNT concentration in the P(VDF-TrFE) matrix, which means an improvement of absorption at low frequency. This situation occurs until 7 wt. %, while with further increase in the concentration of MWCNTs beyond the percolation threshold concentration, the first large absorption peak shifts to a higher frequency with a much lower sound absorption coefficient compared to the foam of 7 wt. % concentration of MWCNTs, as shown in Fig. 3. This shift of the first acoustic resonance absorption peak of the foam with 9 wt. % MWCNTs toward higher frequency can be explained from the impedance match and enhanced sound absorption at higher frequency, for smaller $1/\omega C$ to match with the smaller impedance of the foam with 9 wt. % MWCNTs. The shift of the sound absorption peak for the samples with 3, 5, and 7 wt. % of MWCNTs to lower frequency can possibly be understood with the significantly enhanced sound absorption particularly in the

FIG. 5. Schematic illustration of (a) 3D overview of the open-cell porous foam; (b) P(VDF-TrFE)/MWCNT nanocomposite structure; and (c) mechanisms for converting sound energy to electricity with local piezoelectric effect and electrical energy to thermal energy through resistive loss.

lower and intermediate frequency range (below 2 kHz) attributed to the local piezoelectric effect, in contrast to that the conventional sound absorption mechanisms, such as fluid viscous and thermal losses, and visco-elastic structural damping are typically more effective in the high-frequency range. In this work, our study focuses on the effect of material mechanism on sound absorption, and the conclusions as summarized below do not include particular resonance effects that strongly depend on sample geometry.

V. CONCLUSIONS

Open-cell foams of P(VDF-TrFE) and its nanocomposites with different amount of MWCNTs were fabricated for airborne sound absorption investigations. Structural and thermal analyses showed that the MWCNTs were well dispersed in the P(VDF-TrFE) matrix and enhanced the degree of crystallinity of the polar β phase, which improved the local piezoelectric effect with the interfaces between the polar phase P(VDF-TrFE) and MWCNTs. The electrical conductivity of the P(VDF-TrFE)/MWCNT nanocomposite foams increased significantly by nearly seven orders of magnitude with the increasing concentration of the MWCNT up to 9 wt. %, with the percolation threshold in electrical conductivity observed near 7 wt. % of MWCNTs. The measurements in the standard acoustic tube showed that introduction of an appropriate amount of MWCNTs significantly enhanced the airborne sound absorption coefficient of P(VDF-TrFE) foam without poling, particularly in the lower and intermediate frequency range. This is attributed to the electrical energy generation through the local piezoelectric effect of the polar phase of P(VDF-TrFE) foam and charge dissipation through the conductive MWCNTs interfacing the polar phase. The experimental results clearly showed that the optimal sound absorption performance was obtained in nanocomposite foams with conductive or resistive percolation threshold, near 7 wt. % of MWCNTs, which is promising for achieving impedance matching condition for maximizing characteristic piezoelectric damping. Our experimental results and data analysis indicate that the open-cell nanocomposite foam with the polar phase and local piezoelectric effect and the electrically conductive percolation threshold has great potential for enhancing airborne sound absorption at lower and intermediate frequency ranges, which is extending the frequency range of conventional passive sound absorption and thus promising for noise mitigation applications.

SUPPLEMENTARY MATERIAL

See the [supplementary material](#) for experimental details of foam preparation and characterization.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

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