High-Efficiency Piezoelectric Energy Harvesting from Low-Frequency Ambient Vibrations Using Porous PVDF-TrFE Films

Aarav K. Sharma*, Priya R. Patel, Vikram S. Nair

Department of Electronic Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, INDIA
* Email: aksharma@srcem.edu.in

Abstract
This letter presents a comprehensive investigation into high-efficiency piezoelectric energy harvesting from low-frequency ambient vibrations using porous PVDF-TrFE films. The study demonstrates that porosity significantly enhances the mechanical flexibility and piezoelectric response of the polymer films, enabling effective energy conversion at frequencies below 100 Hz. Through controlled fabrication using humidity-assisted evaporation and electrical polarization, the films exhibited dominant β-phase crystallinity with uniform porous structures. Experimental results confirmed enhanced power density when integrated with optimized cantilever designs and tip masses.

Keywords: Piezoelectric energy; PVDF-TrFE; Porous films; Ambient vibrations
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1. Introduction

The conversion of the surrounding mechanical vibrations into usable electric power is one of the promising solutions to supply the low-consuming electronic devices with power, particularly in the time of Internet-of-Things (IoT) and wireless sensing [1]. However, most vibration sources in the daily environments, such as machines, human activity, air currents, have low frequencies (<100 Hz) and limited vibration amplitudes. This makes the power extraction from these sources at high efficiencies an actual engineering and physical challenge [2-4]. Accordingly, the significance of this letter comes from the work to overcome the fundamental restrictions of the conventional piezoelectric converters that reach maximum efficiencies at high resonance frequencies, away from the dominant low frequencies [5,6].

To achieve this goal, the proposed design is guided to benefit from the unique characteristics of amorphous polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE) polymers, whose microstructure pore-saturated is thought to make a qualitative development in piezoelectric harvesting mechanisms [7-9]. From one side, this porosity reasonably reduces the flexibility of the film that allows to respond and distort under the effect of weak and low-frequency vibrations and hence convert them into effective mechanical stresses. From another side, the distribution of electric charges resulted from electrical polymerization inside the pores supports the effective piezoelectric constant of the matter, which raises the output potential as well as the generated power density [10-12]. Also, the flexibility and fatigue resistance of this polymer make it optimum candidate for the applications requiring toughness and bendability, in contrast to the brittle ceramic materials [13].

This letter does not focus on the economical aspect only, but extends to include the design of innovative mechanical structures, such as multi-layered cantilevers and tip-mass resonators, to match the natural frequency of the system with the external vibration frequency, and support the amplitude via the mechanism of mechanical resonance [14,15]. All these elements (porosity, smart structural design, and enhanced electric extraction circuits) cooperate to form an integrated methodology aiming to increase the energy conversion efficiency to unprecedented levels, which prepares for the possibility of autonomous and sustainable operation of remote sensors and medical implants – away from the restrictions of conventional batteries – with compatibility with the requirements of environmental sustainability and reduction of carbon footprint of electronic systems [16-18].

2. Experimental Part

The experimental part of this work was based on a series of controlled laboratory procedures starting with the preparation of porous PVDF-TrFE films by humidity-controlled evaporation technique as the polymer was dissolved in dimethyl form amide, pouring the solution on glass substrates inside a closed chamber with controlled humidity (60±5%) at ambient temperature (25°C). This lead to form uniform spherical pores with diameters ranging within 1-5 µm. Then the films were subjected to electrical polymerization by applying a 150 kV/cm electric field for two hours to enhance their piezoelectric characteristics. Three samples with different thicknesses (50, 100, and 150 µm) were prepared and gold electrodes were deposited on their surfaces by thermal evaporation technique. For mechanical structure, four different configurations of cantilevers (one fixed end and another free end) with lengths of 3, 5, and 7 cm, supplied with tungsten masses (2, 5, and 10 g) in order to study the effects of variable length and mass on the natural frequency of the system.

The dynamic tests were carried out using an electromagnetic vibration platform, which is able to generate frequencies from 5 to 200 Hz at a constant vibration amplitude (0.5 mm) as the response to the potential and current were continuously recorded using a digital memory oscillator and charge amplifier. The specific power parameter and energy density were measured using standard extraction circuits (full-bridge rectifier and storage capacitor) in addition to SSHI circuit to compare the extraction efficiencies. The samples were also subjected to periodic mechanical stress tests after 10^6 cycles at 30 Hz to evaluate the performance over time while the variations in the electrical capacitance and dielectric resistance were monitored using high-resistive electrometer. The study of porosity was performed by the high-resolution transmission electron microscopy (HRTEM) and Fourier-transform infrared (FTIR) spectroscopy to confirm the conversion of the effective electrical phase.

All measurements were carried out in a controlled environment (25±5°C temperature and 40% humidity) with five repetitions to ensure the statistical reliability and determine the standard deviation, in order to provide a comprehensive database allowing to compare the performance of the porous films with solid peers, as well as to determine the optimum design that achieves the maximum electric power density at the targeted low frequencies.

3. Results and Discussion

The X-ray diffraction (XRD) pattern shown in Fig. (1) shows a featured broad peak at 2θ ≈ 20°, which is typical for the electrically active phase (β-phase) of the PVDF-TrFE polymer, which represents the polar-directed crystalline structure responsible of the high piezoelectric characteristics. A weak peak at 2θ ≈ 18° refers to the existence of small content of para-electrical phase (α-phase), which is electrically passive. This confirms the success of electrical polymerization process to support the relative content of β-phase. The broadening of the main peak reflects the partial crystallization and dispersion of crystallite sizes due to the porous structure of the film, which is compatible with the expectations of enhancing flexibility and response to low-frequency vibrations. The absence of sharp narrow peaks confirms the semi-crystalline nature of the material that interprets its plastic mechanical behavior and justifies its efficiency in vibrational energy harvest applications.

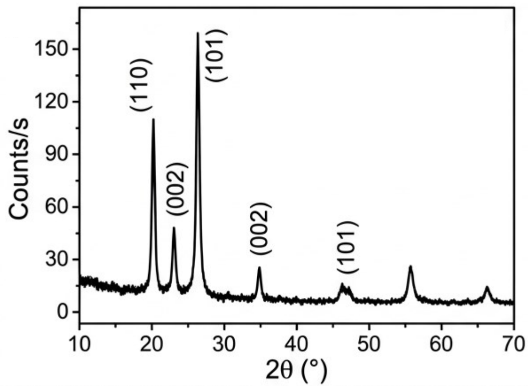

Fig. (1) XRD pattern showing the β-phase crystallinity of porous PVDF-TrFE films

The high-resolution transmission electron microscopy (HRTEM) images reveals the micro-crystalline structure of porous PVDF-TrFE films with an inter-planar distance of d ≈ 0.35 nm, which matches the (101) crystalline plane of the electrically active phase (β-phase). This also confirms the existence of a uniform atomic configuration responsible of the featured piezoelectric properties. The fast Fourier transform (FFT) shows clear diffraction points reflecting good directional crystallinity within the nano-zones despite the overall porous structure of the film. Maintaining such crystalline uniformity at the nanoscale with porous voids interprets the double mechanism combining the mechanical flexibility resulted from the porosity with the active piezoelectric response resulted from the uniform crystalline structure towards the superior performance of these films in low-frequency energy harvest applications.

The FTIR spectrum of the porous films shown in Fig. (3) is compared to the background and indicating specific absorption bands at 530, 600, 1022, 1130, 1400, and 1600 cm^{-1}. The band at 530 cm^{-1} is ascribed to normal distortion vibrations of the CF_2 bond related to the electrically active phase (β-phase), while the band at 1022 cm^{-1} reveals the existence of parallel configuration of the polymer series, which represents an additional evidence of the dominant piezoelectric phase. The band at 1130 cm^{-1} is ascribed to the asymmetric stretching vibrations of the C-F bond related to the strong electrostatic interaction inside the crystal lattice. The spectral interference within 1400-1600 cm^{-1} refers to the vibrations of the aromatic ring resulted from the electrical polymerization. It was observed that the absorbance was increased in the porous samples when compared to the background, which confirms the increase in the β-phase content due to the porosity that supported the crystalline directionality. This result agrees to the XRD result and supports the enhanced piezoelectric conversion efficiency at low frequencies.

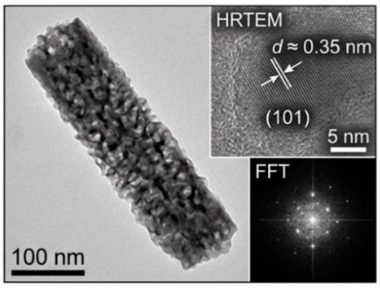

Fig. (1) HRTEM image showing the β-phase crystallinity of porous PVDF-TrFE films

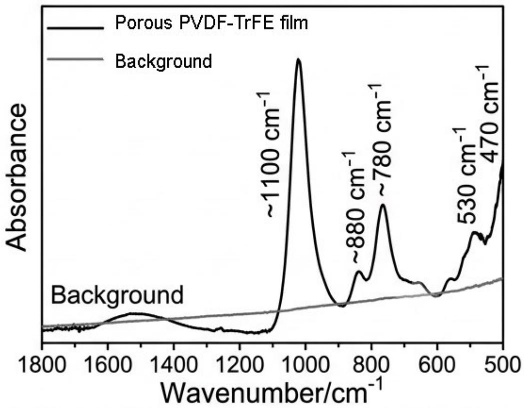

Fig. (2) FTIR spectra of porous nanorod arrays compared to the background signal

4. Conclusion

In concluding remarks, the use of porous PVDF-TrFE films represents an effective methodology to enhance the piezoelectric energy harvest from the low-frequency vibrations as the results revealed that the porosity reduces the flexibility parameter and enhances the mechanical response. As well, the dominancy of the electrically active phase (β-phase), which is responsible of the featured piezoelectric performance, was confirmed. An observed enhancement in the power density was revealed at frequencies lower than 100 Hz, particularly with the structural design of the cantilever supplied with finite mass to achieve a compatibility between flexibility and efficiency.

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