INTRODUCTION

In recent years, due to the increasing depletion of fossil energy, energy harvesting from the environment has become a widely discussed topic in industry and academia. Since the wasteful vibration energy can be harvested and converted into usable electrical energy, piezoelectric energy harvesting technology has been increasingly regarded as a key point in the development of self-sustaining micropower electronic devices. For example, the wireless sensors in the existing Internet of things mainly use chemical batteries for power supply, which have a limited life span and the recycling process is not conducive to environmental protection. In such cases, piezoelectric energy harvesters (PEHs) that replace chemical batteries are an excellent green energy supply mode. Because the common vibration frequency in the environment is located in the low frequency region (<100 Hz), the PEHs need to work in an off-resonant state, far away from the resonant frequency (>1 KHz) of the piezoceramic itself. In the off-resonant state, the energy density (u) of the piezoceramic can be calculated according to the following equation:

\[ u = \frac{1}{2} (d \times g) \left( \frac{F}{A} \right)^2 \]  

(1)

Abstract

The construction of fine-grained piezoceramics with large transduction coefficient \((d_{33} \times g_{33})\) and mechanical properties is the key to the development of high-quality piezoelectric energy harvesters (PEHs). In this work, samarium doping strategy is used to optimize the properties of Pb(Zn\(_{1/3}\)Nb\(_{2/3}\))\(_{0.20}\)(Zr\(_{1/2}\)Ti\(_{1/2}\))\(_{0.80}\)O\(_3\) (0.2PZN-0.8PZT) piezoceramics. The results show that Sm\(_2\)O\(_3\) additive can effectively refine the grain size accompanied with the enhanced mechanical properties. Meanwhile, the Sm\(_2\)O\(_3\) addition induced the formation of local structural heterogeneity accompanied by the reduced domain size, which boosts the transduction coefficient. A cantilever beam type PEH was further assembled from the preferred samarium modified material, and the power density was up to 489 \(\mu\)W/cm\(^3\) at 1 g acceleration. Excitingly, its relative charging ability to commercial electrolytic capacitor has a relative enhancement of ~91% compared to the undoped counterpart. This work not only provides a piezoceramic with excellent energy harvesting characteristics, but also demonstrates a new important paradigm for the development of fast-charging microelectronic storage devices in wireless sensor networks.

KEYWORDS

domain structure, local structural heterogeneity, mechanical properties, piezoelectric energy harvesters, power generation
Where $d$ is the piezoelectric charge constant, $g$ is the piezoelectric voltage constant, $F$ is the applied force, and $A$ is the electrode area. In order to obtain excellent power generation characteristics, the piezoceramic for PEHs need to have high transduction coefficient $d \times g$. Considering that $g = d/\varepsilon_0\varepsilon_r$, the transduction coefficient can be expressed as another form $d^2/\varepsilon_0\varepsilon_r\varepsilon_r$. Therefore, it is clear that a piezoceramic with a high transduction coefficient needs to have both a high $d$ and a low $\varepsilon_r$. Among all reported piezoceramics, relaxor ferroelectrics have attracted much attention because of their high $d$ and high coupling coefficient $k_p$. Some studies have revealed that increasing grain size is beneficial to the enhancement of the $d$ value of relaxor ferroelectrics, resulting in the enhancement of the transduction coefficient. For example, Zheng et al. found that when the grain size of NiO-doped PZN-PZT ceramics increased from 0.4 μm to 0.75 μm, the $d_{33}$ increased from 195 to 322 pC/N, and meanwhile, the $d_{33} \times g_{33}$ increased synergistically, from $4297 \times 10^{-15}$ to $1050 \times 10^{-15}$ m$^2$/N. The similar phenomenon has also been observed in PZT-PZN system. When the grain size is 1.66 μm, $d_{33}$ is 320 pC/N and $d_{33} \times g_{33}$ is $7231 \times 10^{-15}$ m$^2$/N. In comparison, when the grain size is decreased to 130 nm, $d_{33}$ and $d_{33} \times g_{33}$ are only 65 pC/N and $291 \times 10^{-15}$ m$^2$/N. The so-called grain size effect was proposed to give reasonable explanation. That is as the grain size increases, the grain boundary phase becomes smaller, which is conductive to the release of the domain wall clamping effect, thereby enhancing the piezoelectric performance and causing an increase in the transduction coefficient.

However, the negative effect brought by the increased grain size is the deterioration of the mechanical properties of piezoceramics, which is very detrimental to the working stability of PEHs, especially in the severe vibration environment. According to the Hall-Petch theory, the decreased numbers of grain boundaries in large grain sized ceramics weaken the effect of dislocation blocking, which reduces the difficulty of slip plane movement and leads to the deterioration of mechanical properties. Therefore, it is very urgent to find a new material design strategy to achieve the fine-grained relaxor ferroelectric ceramics while ensuring excellent electrical and mechanical properties.

The dopants are known to be important factors influencing the electrical properties of piezoceramics. By introducing various additives into the matrix of piezoceramics, piezoelectric properties can be tailored to a wide extent. For example, Chang et al. investigated the CuO doping effect in PIN-PMN-PT ceramic and found that excellent electrical properties could be obtained with the addition of 0.125 wt% of CuO. Zheng et al. found that the introduction of CoCO$_3$ into a PZN-PZT matrix can increase $d_{33}$ from 215 to 310 pC/N when the addition amount is 0.8 wt%. Especially, Li et al. recently made a breakthrough in doped piezoceramics and the record $d_{33}$ value of 151 pC/N has been obtained in Sm$_2$O$_3$-doped PMN-PT system. The local structural heterogeneity theory has been proposed with respect to Sm doping. However, the adjustment effect of Sm doping on the grain size was not obvious in PMN-PT, and the obtained samples were still coarse-grained ceramics (the average grain size is about 11 μm) without energy harvesting report.

As we known, PZN-PZT is a widely studied ternary high-performance relaxor piezoceramic. If it is used to replace the PMN-PT binary system as a matrix, can Sm doping effectively boost transduction coefficient while refine grain size simultaneously? This is a subject worth exploring. In this work, we conducted a systematic research on Sm$_2$O$_3$-added 0.2PZN-0.8PZT system. The doping mechanism boosting transduction coefficient and mechanical behavior was investigated and correlated with the microstructural evolution. In addition, a cantilevered PEH was assembled using the optimal materials to evaluate its real power generation capacity.

## EXPERIMENTAL

The components prepared by the traditional solid-phase method in this study are as follows: Pb$_{(1-x)}$Zn$_{1/3}$Nb$_{2/3}$O$_3$ (Zn$_{1-x}$Ti$_{1/2}$)$_{0.5}$O$_{1+x}$Sm$_{3}$O$_{5}$, where $x = 0.0-0.7$ wt%. Reagent-grade oxide powders of PbO$_3$ (99.9%; Fuchen), ZnO (99%, Fuchen), ZrO$_2$ (99.5%; Fuchen), Sm$_3$O$_5$ (99.9%, Sinopharm Chemical Reagent Co., Ltd.), Nb$_2$O$_5$ (99.9%, Zhuzhou Cemented Carbide Group Co., Ltd.), and TiO$_2$ (99%, Beijing Chemical Works) were used as raw materials. Firstly, the raw materials were weighed according to stoichiometric ratio and then mixed by ball milling in absolute ethanol for 24 hours. After drying, the mixture was calcined at 850°C for 2 hours. The calcined powders were remilled for 24 hours and then pressed into a disk with a diameter of 11.5 mm and sintered at 1200°C for 2 hours. During the sintering process, PbZrO$_3$ powder is placed around the green disks to reduce the loss of PbO. After sintering, the thickness of disks is about 1 mm.

The crystal structures of the samples were examined by an X-ray diffractometer (XRD; Bruker D8 Advance) in the $\theta$-$2\theta$ configuration using Cu-$K_\alpha$ radiation. The micromorphology was characterized by scanning electron microscopy (SEM; S4800; Hitachi), and the mean grain size was measured by the nano measurer software. In order to ensure accuracy, for one specimen, more than 200 grains are selected for counting the grain size. Vickers indentation hardness of the materials was carried out on a Digital Microhardness Tester (HXD-1000TM/ LCD). To characterize domain structures, a transmission electron microscope was carried out using an instrument (TEM; S4800; FEI) operated at an accelerating voltage of 200 kV.

To measure the electrical properties of the samples, sintered disks were polished to a thickness of 0.6 mm, and then, silver paste was coated on both sides and fired at 560°C. A multifrequency inductance capacitance resistance (LCR) analyzer (Agilent E4980A) with an automatic temperature controller was used to measure the temperature dependent dielectric properties. The polarization-electric field ($P-E$) loops and strain-electric
field (S-E) curves were measured using a ferroelectric tester (PremierII; Radiant Technologies) at 1 Hz. Specimens for piezoelectric property measurements were poled in a silicone oil bath at 120°C by applying a DC field of 40 kV/cm for 30 minutes and cooled to room temperature under electric field. After aging for 24 hours, the piezoelectric charge constant $d_{33}$ was measured using a quasi-static piezoelectric $d_{33}$ meter (ZJ-6A, Institute of Acoustics, Academic Sinica) at 100 Hz. The electromechanical coupling factor $k_p$ was determined by a precision impedance analyzer (4294A; Agilent Technologies) through the resonance-anti-resonance method. In order to directly evaluate the power generation capacity of piezoceramics in this study, the poled ceramics were attached to stainless steel substrates (120 mm x 12 mm x 0.9 mm) using epoxy (353ND; Epoxy Technology). The specific test method with regard to the cantilever beam PEH can be seen elsewhere.

3 | RESULTS AND DISCUSSION

Figure 1A-H show SEM images of the fractured surfaces of 0.2PZN-0.8PZT ceramics with different Sm$_2$O$_3$ additive. The images indicate that all the samples have a dense structure and the grains are well-grown. Interestingly, with increasing Sm$_2$O$_3$ addition, the average grain size of the ceramics decreased remarkably from approximately 2.50 to 1.59 μm as shown in Figure 1I. This phenomenon is different from previous observation in transitional metal ion (ie, Cr$^{3+}$, Mn$^{2+}$, Fe$^{3+}$, Co$^{2+}$) doped 0.2PZN-0.8PZT systems. In those works, as the additive amount increases, the grain size continues to increase. This difference is mainly due to the different substitution positions of doping elements in perovskite matrix. For transitional metal ions such as Cr$^{3+}$, Mn$^{2+}$, Fe$^{3+}$, and Co$^{2+}$, they mainly enter the B-site to replace the high valence Zr$^{4+}$ or Ti$^{4+}$ ions. For maintaining electrical neutrality, this type of doping normally leads to the generation of a large number of oxygen vacancies, which in turn enhances the transfer of mass and energy during the sintering process, and eventually results in grain growth. However, considering that the 12-coordinate Sm$^{3+}$ ion radius (1.24 Å) is more close to Pb$^{2+}$ (1.49 Å), it mainly replaces the A-site, not B-site in perovskite matrix. In this case, lead vacancies appear for charge compensation. The negatively charged lead vacancies may have an inhibition effect on migration of the

![FIGURE 1](image-url) SEM micrographs of specimens with different Sm$_2$O$_3$ additions: (A) 0.0 wt%; (B) 0.1 wt%; (C) 0.2 wt%; (D) 0.3 wt%; (E) 0.4 wt%; (F) 0.5 wt%; (G) 0.6 wt%; (H) 0.7 wt%, and (I) the average grain size of 0.2PZN-0.8PZT ceramics with different Sm$_2$O$_3$ additions
positively charged oxygen vacancies, which is not conducive to the transfer of mass and energy, in turn leading to the refinement of ceramic grain size.

In order to evaluate the effect of grain size changes on mechanical properties, the Vickers indentation hardness ($H_v$) and fracture toughness ($K_{IC}$) of different Sm doped samples were tested. Here, the $H_v$ values were measured using a load of 1.96 N for 10 s in general. The $K_{IC}$ was calculated using the following equation:\(^{34}\)

$$K_{IC} = 0.0624P/dl^{1/2} \quad (2)$$

Where $P$ is the load, $d$ is the diagonal length of the indentation, and $l$ is the crack's vertical length measured from the tip of indentation, as marked in Figure 2A. Figure 2B gives the composition dependent $H_v$ and $K_{IC}$ values. For pure 0.2PZN-0.8PZT sample, $H_v$ and $K_{IC}$ are about 4.03 GPa and 1.05 MPa·m$^{1/2}$, respectively. With the addition of Sm$_2$O$_3$, both $H_v$ and $K_{IC}$ value gradually increase. When the content of Sm$_2$O$_3$ is 0.4 wt%, excellent mechanical properties are obtained, that is, $H_v$ of 4.44 GPa and $K_{IC}$ of 1.23 MPa·m$^{1/2}$, which are significantly higher than unadded counterpart. In this case, the Vickers hardness and the fracture toughness are satisfied, and the $H_v$ value and the $K_{IC}$ value are better than other report in lead-based relaxor ferroelectric ceramics,\(^{35}\) which is conducive to the stable operation of PEHs under cyclic vibration environment. The enhancement of the mechanical properties of PZN-PZT ceramics doped with Sm$_2$O$_3$ may be related to the increase in the number of grain boundaries caused by the decrease in grain size. The increased number of grain boundaries will provide additional obstacles to the movement of lattice dislocations in adjacent grains.\(^{15,36-39}\) In addition, the mechanical failure of piezoceramics generally starts with the largest pore defect or the most dangerous crack in the region of tensile stress. The reduction of the grain size is beneficial to reduce the porosity of the material and the size of the microcracks, thereby improving the mechanical properties of piezoceramics.\(^{14,40,41}\)

In order to investigate the effect of Sm doping-induced grain size changes on the phase structure, the XRD patterns of 0.2PZN-0.8PZT compounds with different Sm$_2$O$_3$ contents were tested, and the results are shown in Figure 3A. It can be seen that all samples have a well-crystallized pure perovskite structure, and no detectable pyrochlore phase or other impurities are observed.\(^{31}\) To detailed study phase evolution with respect to Sm doping, fine scanning was carried out in the diffraction angle range of $2\theta = 43^\circ - 46^\circ$. Here, the tetragonal phase content of investigated compositions was calculated according to the method described elsewhere,\(^{42}\) and the results are shown in Figure 3B. It can be seen that the content of the tetragonal phase ($TP$) is almost independent of the composition change, although the grain size has changed greatly. It has been revealed in previous literature that the reduced grain size contributes to the phase transition of the relaxor ferroelectric from the tetragonal structure to the rhombohedral structure, and a stress relaxation model of grain size was proposed to explain the phase transition phenomenon.\(^{43-45}\) However, our work shows a different trend: As the grain size decreases, the tetragonal phase content remains essentially unchanged. Therefore, the grain size-dependent stress relaxation mechanism is not suitable for the existing

![Figure 2](image_url)

**Figure 2** A. The Vickers indentation images of undoped and 0.4wt% Sm$_2$O$_3$-added 0.2PZN-0.8PZT ceramic; B. Comparison of Vickers hardness and fracture toughness values of undoped and 0.4wt% Sm$_2$O$_3$-added 0.2PZN-0.8PZT ceramic
PZN-PZT + Sm$_2$O$_3$ wt% system. It should be noted that for the previously studied system, the main method of adjusting the grain size is to change the sintering temperature, while the material composition remains unchanged. However, in this work, the grain size is adjusted by doping different amounts of Sm$^{3+}$, not varying the sintering temperature, so it is speculated that the doping effect may weaken the stress relaxation effect and cause the phase composition to remain stable. To clarify this speculation, more detailed structure analysis is needed.

On the other hand, many works revealed that although grain refinement is advantageous for the improvement of mechanical properties, it usually leads to a reduction in the transduction coefficient. However, the results of this experiment show a completely different phenomenon. The electrical properties of 0.2PZN-0.8PZT ceramics with different Sm$_2$O$_3$ additive were given in Figure 4. It can be seen that all measured parameters, that is, $d_{33}$, $\varepsilon_r$, $d_{33} \times g_{33}$, and $k_p$, show similar increasing trends as the grain size decreases, and the peak values ($d_{33} \times g_{33} = 9609 \times 10^{-15}$ m$^2$/N, $d_{33} = 413$ pC/N, $\varepsilon_r = 2006$, $k_p = 0.63$) are obtained when the content of Sm$_2$O$_3$ is 0.4 wt%. It should be addressed here that in this case, the high transduction coefficient mainly comes from the contribution of high $d_{33}$. Since the phase composition maintains a certain stability within the doping range (Figure 3), its influence on the piezoelectric properties is excluded. Herein, the mechanism of $d_{33}$ enhancement is analyzed mainly from the intrinsic and extrinsic factors.

It is known that, for the intrinsic contributions, $d_{33}$ can be estimated using the following derived equation:

$$d_{33} = 2\varepsilon_0\varepsilon_r P_r Q_{33}$$  \( (3) \)

Where $P_r$ is the remanent polarization and $Q_{33}$ is the electrostrictive coefficient.

Figure 5A,B shows the $P$-$E$ loops and $S$-$P^2$ curves for Sm$_2$O$_3$-doped PZN-PZT ceramics. The values of $P_r$ and $E_c$ and $Q_{33}$ are extracted from these curves, and the changes of these parameters with Sm$_2$O$_3$ content are given in Figure 5C,D, respectively. It can be seen that changing the composition, $P_r$ reaches a maximum at $x = 0.4$ wt%, while $E_c$ and $Q_{33}$ remain basically unchanged, which is quite different from previous reported composite piezocermics. Further, it is shown in Figure 4 that the dielectric constant increases as the Sm$_2$O$_3$ content increases and reaches a maximum at $x = 0.4$ wt%. Therefore, according to Equation 3 and experimental data of $d_{33}$ and $\varepsilon_r P_r$ (Figure 6), it can be confirmed that from the perspective of the intrinsic contribution, the enhanced $d_{33}$ is partly due to the increase in $\varepsilon_r P_r$.

To further explore the origin of the high dielectricity, the permittivity-temperature ($\varepsilon_r$-$T$) curves of the PZN-PZT + x wt% Sm$_2$O$_3$ ceramics are shown in Figure 7A. The Curie...
temperature ($T_c$) gradually decreased with increasing Sm$_2$O$_3$ content. Generally, the $T_c$ is related to the ferroelectric stability of the material. It is well known that lead is a strong ferroelectric ion because Pb 6s and O 2p states can be strongly hybridized. But unlike Pb$^{2+}$, the outermost electron orbit of Sm$^{3+}$ is 5f. Therefore, the substitution of Sm$^{3+}$ for A-site cation Pb$^{2+}$ is equivalent to reducing the content of strong ferroelectric ion, resulting in the decrease of ferroelectric stability. In addition, the $T_c$ peaks present broadened feature with increasing $x$, indicating an enhancing degree of diffuse-ness. For relaxor ferroelectrics, it is known that the dielectric characteristics deviate from the typical Curie–Weiss behavior and can be described by the Uchino and Nomura function, a modified Curie–Weiss relationship. 

**FIGURE 5** A, P-E loops and B, S-P curves of all samples. The variation in (C) $P_r$ and $E_c$, and (D) $Q_{33}$ values for 0.2PZN-0.8PZT ceramics with different Sm$_2$O$_3$ additions.

**FIGURE 6** $d_{33}$ vs $\varepsilon_r P_r$ of 0.2PZN-0.8PZT ceramics with different Sm$_2$O$_3$ additions.
Where $\varepsilon_{\text{max}}$ is the maximum value of the dielectric constant, $\varepsilon$ is the dielectric constant at temperature $T$, $T_{\text{max}}$ is the temperature at the peak of the dielectric constant, $C$ is the Curie constant, and $\gamma$ is an indicator of the degree of diffuseness that takes a value between 1 and 2. Figure 7B shows the variation in $\gamma$ for the PZN-PZT + $x$ wt% Sm$_2$O$_3$ ceramics. With increasing $x$, $\gamma$ increased almost linearly from 1.83 to 2.00. Generally, the larger the $\gamma$ value, the stronger the diffuseness in the material. It is believed that with the increase of Sm$_2$O$_3$ content, there may be more relaxation elements in the concerned temperature range. These relaxation elements are generally metastable, and their presence can lead to the enhancement of the dielectric response. In this case, the introduction of Sm$_2$O$_3$ in perovskite lattice caused the component and valence fluctuations on the A-site, resulting in the formation of local chemical heterogeneity, which could destroy the long-range ferroelectric order and enhance the relaxation of the PZN-PZT based material.

Compared with the $x = 0.0$ wt% sample, as the content of Sm$_2$O$_3$ increases, the more pronounced dielectric dispersion, together with the larger dielectric constant, eventually resulting in a larger piezoelectric constant (Figure 4).

Considering the influence of domain structure on the piezoelectric properties of relaxor ferroelectrics, the domain wall motion as an extrinsic contribution has been studied. Figure 8A,B shows the TEM images of the $x = 0.0$ wt% and $x = 0.4$ wt% samples, respectively. Clearly, the doped sample exhibits fine domain structure, and the average domain size is about 15-20 nm, which is about four times smaller to the undoped counterpart. The significant decrease in the domain size can be attributed to two factors. One is the grain size. In general, the domain size is related to grain size through the expression:

$$\text{Domain size} \propto (\text{Grain size})^m$$

Where, the coefficient $m$ is related to the grain size. Therefore, for Sm$_2$O$_3$ doped specimens, with the reduction of the grain size, the domain size also gradually decreases. Another factor is local structural heterogeneity. The Sm$^{3+}$ ions replaced the partial A-site Pb$^{2+}$ ions in perovskite lattice, forming a local structural heterogeneity. The resulting random field disturbance promotes the formation of nanodomains with respect to a stable energy state. Since the domain size is proportional to the square root of the domain wall energy, with reduced domain wall energy is easy to respond to extrinsic excitation, which in turn contributes to the enhancement of piezoelectric properties.

Piezoelectric materials with high transduction coefficient and excellent mechanical properties are conducive to the construction of high-quality PEHs. To directly evaluate the power generation capacity of the Sm$_2$O$_3$ doped specimens, the optimal composition of $x = 0.4$ wt% was selected to fabricate the PEHs. For comparison, PEH counterpart with $x = 0.0$ wt% has also been assembled. The schematic
of experimental setup is presented in Figure 9. Figure 10A shows the frequency response of output voltage for the $x = 0.0$ wt% and $x = 0.4$ wt% PEHs at 1 g acceleration. The results revealed the mechanical resonance phenomena of the two PEHs near 80 Hz, and the low resonance frequency is suitable for recycling the vibration energy in the environment ($<100$ Hz). Figure 10B-D shows the relationship between the load resistance and output voltage, output current, and output power of two PEHs, which was measured at a fixed resonance frequency and 1 g acceleration. It can be seen that in the range of load variation, all the power generation parameters of the $x = 0.4$ wt% PEH are better than $x = 0.0$ wt% PEH. In particular, under the best load matching situation, the $x = 0.4$ wt% PEH’s output power is more than three times that of the reference $x = 0.0$ wt% PEH, showing a huge technical advantage. The power density of the $x = 0.4$ wt% PEH is as high as 489 $\mu$W/cm$^3$, which can be attributed to the large transduction coefficient of Sm$_2$O$_3$ doped specimens. Figure 11A,B further gives the open circuit output voltage and short circuit current of

![Figure 9: The schematic of energy harvesting test system](image)

![Figure 10: A1, A2, The output voltage as a function of frequency for the $x = 0.0$ wt% and 0.4 wt% piezoelectric energy harvesters (PEHs); B, the output voltage; C, output current; and D, output power as a function of extrinsic load resistance for the $x = 0.0$ wt% and 0.4 wt% PEHs](image)
the $x = 0.0$ wt% and $x = 0.4$ wt% PEHs. At 1 g acceleration, the open circuit voltage (20 V) of $x = 0.4$ wt% PEH is about 51% higher than that of $x = 0.0$ wt% PEH (13.2 V), which is related to the high $g_{33}$ value when the Sm$_2$O$_3$ addition amount is 0.4 wt%, as shown in Figure 11C. In addition, the short circuit current has nearly doubled, which is attributed to the high piezoelectric performance caused by the local structure heterogeneity.62 Figure 11D further illustrates an application example of the PEH as an external power source of the microelectronic device. The commercial electrolytic capacitor (10 μF, 25 V) was charged with the electric energy generated by the $x = 0.0$ wt% and $x = 0.4$ wt% PEHs, respectively. It was found that when charging for 150 seconds, the voltage across the capacitor of the $x = 0.4$ wt% PEH reached its saturation value (5.61 V), while the $x = 0.0$ wt% PEH could only obtain 2.94 V, and the charging ability is increased by nearly 91%, which is of great significance for microelectronic devices with fast charging.

4 | CONCLUSIONS

In summary, the rare-earth Sm doping strategy can effectively achieve the construction of fine-grained piezoceramics with outstanding energy harvesting characteristics. The modification mechanism has been proposed based on the analysis of local structural heterogeneity with respect to domain architecture. The optimal transduction coefficient was obtained in $x = 0.4$ wt% specimen, which was further assembled into a cantilever-type PEH to evaluate real power generation capabilities. Excitingly, the generated power density is as high as 489 μW/cm$^3$, showing great application potential in the field of self-powered microelectronic devices.

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