Piezoelectric and pyroelectric properties of Mn-doped $0.36\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3$ - $0.36\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.28PbTiO_3 ceramics

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Piezoelectric and pyroelectric properties of Mn-doped $0.36\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3$ - $0.36\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.28PbTiO_3 ceramics

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Abstract:

Piezoelectric and pyroelectric properties as well as strain behavior of 0.5 mol% Mn-doped $0.36\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3$ - $0.36\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.28PbTiO_3 (Mn-PIMNT) ceramics were studied. High piezoelectric coefficient of $d_{33} = 235$ pC/N, planar electromechanical coupling factor of $k_p = 43.1\%$ and the high-power Figure of Merit ($\text{FOM} = 60160$ pC/N) were achieved in Mn-PIMNT ceramics. Furthermore, the ceramics exhibited high pyroelectric coefficient of $p = 4.8 \times 10^{-4}$ Cm⁻²K⁻¹, figures of merit for the current responsivity of $F_i = 1.92 \times 10^{-10}$ mV⁻¹, the voltage responsivity of $F_v = 0.028$ m²C⁻¹, and the detectivity of $F_d = 2.317 \times 10^{-5}$ Pa^{-1/2} at room temperature. The excellent piezoelectric and pyroelectric properties together with high ferroelectric rhombohedral to tetragonal phase transition temperature of $T_{rt} = 146$ °C and ferroelectric tetragonal to cubic phase transition temperature of $T_C = 188$ °C make the Mn-PIMNT ceramics suitable for high-temperature piezoelectric and pyroelectric devices.

Keywords: Mn-PIMNT ceramics; Phase structures; Piezoelectric; Pyroelectric

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1 Introduction

The first-generation relaxor ferroelectrics, which are represented by $(1-x)\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - $x\text{PbTiO}_3$ (PMNT) and $(1-x)\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - $x\text{PbTiO}_3$ (PZNT) single crystals, have been widely used in sonar transducers, actuators, energy harvesting and resonators, due to their excellent piezoelectric performance (electromechanical coupling factor $k_{33} \sim 92\%$, piezoelectric coefficient $d_{33} \sim 2500$ pC/N) [1-7]. However, the relatively low rhombohedral to tetragonal phase transition temperature ($T_{rt} \sim 60\text{-}95$ °C) and Curie temperature ($T_C \sim 130\text{-}170$ °C) limit their usage temperature range [8-11].

In order to improve the temperature stability, the second-generation relaxor ferroelectrics represented by $y\text{PIN}-(1-x-y)\text{PMN}-x\text{PT}$ (PIMNT) having higher T_C and coercive field (E_C) than PMNT and PZNT systems were developed, nevertheless, the global piezoelectric and pyroelectric performances were inferior [7]. In comparison, the following third-generation relaxor ferroelectrics represented by Mn-doped PIMNT (Mn-PIMNT) were further reported and simultaneously possess much better temperature stability over a wide temperature range and high performance [11,12]. The Mn ions doping in PIMNT are Mn^{2+} or Mn^{3+} , which can be called a “hard dopant”. They enter the crystal lattice and replace the high-valent cations of *B*-site (for example Ti^{4+} , Mg^{2+} , Nb^{5+} , and In^{3+} ions) [13]. As a result, oxygen vacancies are created to keep the system electrically neutral. The defect dipoles formed by the oxygen vacancies can decrease the mobility of charge carriers on the domain wall and disrupted the stability of the ferroelectric domain [14,15]. This led to a substantially decreased dielectric and mechanical loss, and meanwhile enhanced piezoelectric and pyroelectric properties were achieved [12,15,16].

From these previous works, it can be noted that the pyroelectric study on the third-generation relaxor ferroelectrics were mainly focused on the single-crystal form, few reports on pyroelectric properties of Mn-PIMNT ceramic systems were available, which are much easier to be commercialized with low cost [12]. Under these considerations, the purpose of this article is to explore ferroelectric materials having piezoelectric

and pyroelectric properties as well as high T_{rt} for piezoelectric and pyroelectric devices. We focus on studying phase and domain structure, dielectric, ferroelectric, piezoelectric and pyroelectric properties as well as strain behavior of 0.5 mol.% Mn-doped $0.36\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3$ - $0.36\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - 0.28PbTiO_3 (Mn-PIMNT) ceramics. The results show that the Mn-PIMNT ceramics have excellent piezoelectric and pyroelectric performance as well as thermal stability.

2 Experimental procedures

Mn-PIMNT ceramics were prepared by a two-step precursor method. All the reagent grade raw materials of In_2O_3 (99%), Nb_2O_5 (99.99%), PbO (99%), TiO_2 (98%) and MnO_2 (97.5%) were commercially supplied from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). MgO was obtained by heating $4\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2 \cdot 5\text{H}_2\text{O}$ at 1000°C for 2 h. InNbO_4 was synthesized by In_2O_3 with Nb_2O_5 at 1100°C for 6 h. MgNb_2O_6 was synthesized by MgO with Nb_2O_5 at 1000°C for 4 h. The powders of PbO , MgNb_2O_6 , InNbO_4 , TiO_2 , and MnO_2 were ball-milled with alcohol for 6 h, then dried and calcined at 850°C for 2 h to form the Mn-PIMNT pure perovskite phase. The calcined powders were pressed to pellets with using polyvinyl alcohol and heated at 600°C for 2 h. The sintering temperature of pellets ranges from 1225°C to 1265°C for 2 h. From the shrinkage, density and electrical properties of Mn-PIMNT ceramics, the optimal sintering temperature was determined to be 1245°C . The samples were polished and then thermally etched at 900°C for 2 h to release the surface stresses. In order to test electrical properties, the samples were covered with silver electrodes. The samples were poled in silicone oil at room temperature for 15 min with 40 kVcm^{-1} .

The crystallographic structures of Mn-PIMNT ceramics were conducted by X-ray diffractometer (XRD, D8-Advanced, $\text{CuK}\alpha$ radiation). The microstructure was observed by field emission scanning electron microscopy (FESEM, S4800, Hitachi). The domain structures were observed by piezoresponse force microscope (PFM, MFP-3D, Asylum Research, America). The dielectric constant (ϵ_r) and dielectric loss ($\tan\delta$)

were determined using a precision impedance analyzer (HP4294A, Agilent, America). The P - E hysteresis loops and S - E behavior were examined by ferroelectric analyzer (TF2000, aixACCT, Germany). Piezoelectric coefficients (d_{33}) were measured by the quasi-static d_{33} meter (ZJ-4AN, Institute of Acoustics of the Chinese Academy of Sciences, China). The pyroelectric coefficient (p) was measured by a charge integral method using a Keithley 6517A electrometer [12].

3 Results and discussion

Fig. 1 shows the XRD patterns of Mn-PIMNT ceramics. Pure perovskite phase and sharp diffraction peaks can be observed. The radii of the B -site cations In^{3+} , Mg^{2+} , Nb^{5+} , and Ti^{4+} ions in PIMNT were 0.80 Å, 0.72 Å, 0.78 Å and 0.60 Å [17], respectively, and the radii of Mn^{2+} and Mn^{3+} were 0.67 Å and 0.72 Å, respectively [18,19]. The Mn ions entered the crystal lattice and replaced the high-valent cations of the B -site. The reason was attributed to these ions' radii similar.

Fig. 2 shows the SEM image of Mn-PIMNT ceramics. The image revealed that homogeneous grain size distribution could be observed and an average grain size was about 3.15 μm , which was calculated from the software of Nano Measurer. Furthermore, the dense microstructure was formed and the ceramics had well-defined grains.

Fig. 3 shows the PFM images of the Mn-PIMNT ceramics at room temperature with a scanning size of $8 \times 8 \mu\text{m}^2$. Two different colors in the vertical PFM phase images represented the upward and downward polarization directions, respectively. At the grain boundaries, strip domains were observed to nucleate, which may reduce activation energy due to defects (e.g., grain boundaries) and can be observed in Fig. 2 of the SEM surface image [20]. The domain across the grain boundary may be affected by the internal residual stress and electric field [21,22]. Furthermore, nano-sized domain structures can greatly increase the domain wall density, which is beneficial to polarization rotation and domain conversion, thereby enhancing piezoelectric response.

Fig. 4(a) shows the temperature dependence of the ε_r and $\tan\delta$ of Mn-PIMNT ceramics from 25 °C to 250 °C at different frequencies. The values of ε_r and $\tan\delta$ were 790 and 0.01 at 100 Hz at room temperature, which was lower than that of undoped PIMNT ceramics [7,13]. It can be observed that two dielectric anomalies, corresponding to the ferroelectric rhombohedral to tetragonal phase transition temperature of $T_{rt} = 146$ °C and ferroelectric tetragonal to cubic phase transition temperature of $T_C = 188$ °C that was 63 °C higher than that of the binary Mn-PMNT single crystals [23]. The ceramics had good temperature stability for high-temperature ferroelectric devices over a broad temperature usage range. The ε_r increased with increasing temperature and reached a maximum at T_C , then began to decrease.

The modified Curie-Weiss law as the following equations can obtain the degree of diffuse [24], which can be used to analysis the diffuse of the phase transition,

$$\frac{1}{\varepsilon} - \frac{1}{\varepsilon_m} = \frac{(T - T_m)^\gamma}{C^*} \quad (1)$$

where the ε , ε_m , T_m , γ , C^* are the relative permittivity, the dielectric permittivity peak at $T = T_m$, the degree of diffuse and the Curie-Weiss constant, respectively. To study the relaxation characteristics of Mn-PIMNT ceramics, $\ln(1/\varepsilon - 1/\varepsilon_m)$ and $\ln(T - T_m)$ are shown in Fig. 4(b). The fitted values represented that γ at 0.1, 1 and 10 kHz were 1.927, 1.939 and 1.997, respectively. The value of γ ranges from 1 to 2 by calculation. It is known that if the fitted value of γ is 1, it stands for a normal ferroelectric system. While the fitted value of γ is 2, it represents an ideal relaxor ferroelectric system [14,24,25]. So, the results suggested that they had strong relaxor characteristic. The figure that γ increased with increasing frequency, which indicated that the diffuse behavior of the medium depended on the frequency. The reason was that the dipole deflecting could not keep up with the external field and further lag behind with increasing the frequency.

Fig. 5 shows the P - E hysteresis loops of Mn-PIMNT ceramics at 10 Hz. At room temperature, the values of remnant polarization P_r , and coercive field E_C were 34.57 μCcm^{-2} and 12.97 kVcm^{-1} , respectively. Compared to PMNT ceramics [16], they had high values of E_C , making Mn-PIMNT appropriate to be the

materials using in high power applications. With the increasing electric field amplitude (E_0), the P_r , E_C , and hysteresis area $\langle A \rangle$ all increased gradually, indicating that domain motions and polarization switching became completely. Due to “hard” Mn-doping, the ceramics exhibited significantly enhanced P_r and E_C , compared to the pure PIMNT ceramics ($P_r = 27.3 \mu\text{Ccm}^{-2}$ and $E_C = 8.2 \text{ kVcm}^{-1}$) [7]. The values of P_r and E_C changed with the electric field and comparatively saturated at 50 kVcm^{-1} . In addition, we further studied temperature-dependent the P - E hysteresis loops at 40 kVcm^{-1} . However, the polarization axis is slightly asymmetric and therefore the internal bias field is calculated by the following equations,

$$E_i = \frac{E_{C+} + E_{C-}}{2} \quad (2)$$

the E_i represents the internal bias field and is used here to compensate the charge generated by the acceptor oxygen vacancy charge-defective dipole. The E_{C+} and E_{C-} represent the intersections of P - E hysteresis loops with positive and negative field axis [13]. The E_i was obtained to vary between 0.15 and 0.39 kVcm^{-1} . With increasing temperature, the P_r , E_C , E_i and $\langle A \rangle$ of P - E loops decreased, indicating the shape of a dielectric material and the polarization switching became easier. Furthermore, as the temperature rising to 120°C , P_r and E_C decreased approximately linearly. Due to the structural phase transition or the reduction of the long-term polar order, the slope of P_r changed near T_r and T_C [12]. It was worth noting that when the temperature was much higher than T_C and reached 200°C , a slight hysteresis characteristic could still be detected from the P - E hysteresis loop, which indicated that microdomains still existed where the temperature was much higher than T_C . Similar phenomenon also existed in the Mn-PIMNT single crystals [26].

Fig. 6 shows the S - E behavior measured at 10 Hz . The unipolar strain behavior showed an S -shape in Fig. 6(a) [27-29]. The bidirectional field-induced strain curves exhibited a typical butterfly shape in the inset of Fig. 6(a). The normalized piezoelectric strain coefficient d_{33}^* can be obtained by the following equation,

$$d_{33}^* = \frac{S_{\max}}{E_{\max}} \quad (3)$$

where the d_{33}^* is the normalized strain constant with a unit of pmV^{-1} . It is an important parameter for actuator applications. The electric field dependence of strain and piezoelectric strain d_{33}^* for Mn-PIMNT ceramics are presented in Fig. 6(b). The unipolar strain $S_{\max}$ and d_{33}^* were 0.22% and 355 pmV^{-1} at electric field of 60 kVcm^{-1} , respectively. The d_{33}^* increased first and then decreased with the increasing of the electric field, meanwhile, the strain for Mn-PIMNT increased. The increase in d_{33}^* at low field was ascribed to the contribution of more non-180° domain wall movement [27]. However, at high electric field levels, the electrical domains were partially clamped by the electrical field and the lattice extension may saturate, resulting in a reduction in the unipolar $S_{\max}$ and the d_{33}^* coefficient rate [27,28]. Fig. 6(c) and (d) shows the temperature dependence of unipolar strain curves for Mn-PIMNT at 10 Hz is below 40 kVcm^{-1} . The unipolar $S_{\max}$ and d_{33}^* first increased to a maximum and then followed a decrease instead with increasing temperature. Meanwhile, unipolar $S_{\max}$ and d_{33}^* showed the similar tendency and reached peak value up to $\sim 0.274\%$ and 697 pmV^{-1} at 170 °C.

According to IEEE standard, the equations are used to calculate the performances of Mn-PIMNT [30],

$$k_p = \sqrt{\frac{1}{0.395 \times \frac{f_r}{f_a - f_r} + 0.574}} \quad (4)$$

where k_p is planar electromechanical coupling, f_r represents the resonant frequency and f_a is anti-resonant frequency in radial vibration mode. The parameter k_p was calculated to be 43.1% by impedance spectrum in Fig. 7(a). The mechanical quality factor Q_m was calculated by the equation,

$$Q_m = \frac{f_r}{f_{+\frac{1}{2}} - f_{-\frac{1}{2}}} \quad (5)$$

According to the admittance spectrum as shown in Fig. 7(b), $f_{-\frac{1}{2}}$ and $f_{+\frac{1}{2}}$ represent frequencies at -3 dB down the peak admittance. The parameter Q_m was calculated to be 256. In addition, the Figure of Merit (FOM)

of the output characteristic parameters for high-power piezoelectric applications [16] was also calculated by the formula,

$$\text{FOM} = Q_m \cdot d_{33} \quad (6)$$

the direct piezoelectric effect of d_{33} was tested to be 235 pC/N and then the FOM was calculated to be 60160 pC/N. Table 1 summarized the values of d_{33} , Q_m , k_p and FOM of Mn-PIMNT in this work and some representative rhombohedral ceramics for comparison. The values of d_{33} , k_p and FOM were much larger than the undoped ceramics [7,16]. The reason can be attributed to Mn-doping, which introduced oxygen vacancies and formed the defect dipoles. They disrupted the stability of the ferroelectric domain as well as reduced the mobility of charge carriers on the domain wall, subsequently inducing piezoelectric hardening characteristics [14,15].

Fig. 8 shows the temperature-dependent pyroelectric coefficient (p) of the Mn-PIMNT ceramics. The figures of merit (FOMs) for the current responsivity $F_i = \frac{p}{C_v}$, voltage responsivity $F_v = \frac{p}{C_v \varepsilon_0 \varepsilon_r}$, and detectivity $F_d = \frac{p}{C_v \sqrt{(\varepsilon_0 \varepsilon_r \tan \delta)}}$ are also calculated to assess the performance of pyroelectric materials, where the p , C_v , ε_0 , ε_r and $\tan \delta$ are the pyroelectric coefficient, volume specific heat ($2.5 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$) [23], permittivity of free space ($8.85 \times 10^{-12} \text{ F m}^{-1}$), relative permittivity, and dielectric loss, respectively [12]. At room temperature, the value of p was $4.8 \times 10^{-4} \text{ C m}^{-2} \text{ K}^{-1}$, which was twice as large as that of LiTaO₃ single crystals [31], and increased to $2.3 \times 10^{-3} \text{ C m}^{-2} \text{ K}^{-1}$ with temperature increasing to 130 °C. Furthermore, the values of F_i , F_v and F_d were $1.84 \times 10^{-10} \text{ mV}^{-1}$, $0.028 \text{ m}^2 \text{ C}^{-1}$ and $2.317 \times 10^{-5} \text{ Pa}^{-1/2}$, respectively. A comparison of the pyroelectric properties of the Mn-PIMNT and other ferroelectric ceramics at 1 kHz was summarized in Table 2. Compared to undoped PIMNT ceramics, the Mn-PIMNT ceramics have enhanced F_v and F_d than other ferroelectric ceramics [32,33,34], which are desirable properties for infrared detection applications.

4 Conclusions

In summary, temperature-dependent dielectric, ferroelectric, piezoelectric and pyroelectric properties of Mn-PIMNT ceramics were investigated. The ceramics exhibited high T_{rt} of 146 °C and T_C of 188 °C. The P_r and E_C reached 34.57 μCcm^{-2} and 12.97 kVcm^{-1} , respectively. Compared to undoped PIMNT ceramics, the Mn ions doping formed the defect dipoles and reduced the mobility of charge carriers on the domain wall, enhancing d_{33} , E_C , k_p and FOM. Moreover, high p , F_i , F_v and F_d were achieved in Mn-PIMNT ceramics. The excellent piezoelectric and pyroelectric properties together with high phase transition temperature, indicate that the Mn-PIMNT ceramics possess much better temperature stability over a wide temperature range and are potential candidate materials for piezoelectric and pyroelectric devices.

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Figures

Fig. 1. XRD patterns of Mn-PIMNT ceramics.

Fig. 2. SEM surface image of Mn-PIMNT ceramics.

Fig. 3. (a) Morphology, (b) amplitude and (c) phase images of the Mn-PIMNT ceramics at room temperature by PFM with a scanning size of $8 \times 8 \mu\text{m}^2$.

Fig. 4. (a) Temperature-dependent dielectric properties and (b) plot of $\ln(1/\varepsilon - 1/\varepsilon_m)$ versus $\ln(T - T_m)$ for Mn-PIMNT ceramics at different frequencies.

Fig. 5. P - E hysteresis loops for Mn-PIMNT ceramics measured at 10 Hz (a) at room temperature and (b) temperature dependent at 40 kVcm^{-1} . (c-d) The remnant polarization (P_r) and coercive field (E_c) as a function of electric field and temperature of Mn-PIMNT ceramics.

Fig. 6. (a) Unipolar strain curves and the inset was the bidirectional field-induced strain curves. (b) The maximum bipolar strain $S_{\max}$ and piezoelectric coefficient d_{33}^* as a function of electric field of Mn-PIMNT ceramics at room temperature. Temperature dependence of (c) unipolar strain curves and (d) the unipolar $S_{\max}$ and d_{33}^* of Mn-PIMNT ceramics measured at the 40 kVcm^{-1} at different temperatures.

Fig. 7. (a) Impedance and (b) admittance spectrum of Mn-PIMNT ceramics.

Fig. 8. Temperature-dependent pyroelectric coefficient (p) of the Mn-PIMNT ceramics.

Tables

Table 1. A comparison of piezoelectric properties of Mn-PIMNT and other relaxor ferroelectrics.

Ceramics	d_{33}	ϵ_r	$\tan\delta$	k_p	Q_m	P_r	E_C	FOM	Reference
	pC/N			%		$\mu\text{C}\cdot\text{cm}^{-1}$	$\text{kV}\cdot\text{cm}^{-1}$	pC/N	
Mn-0.36Pb(In _{1/2} Nb _{1/2})O ₃ -0.36Pb(Mg _{1/3} Nb _{2/3})O ₃ -	235	790	0.01	43.1	256	34.57	12.97	60160	this work
0.36Pb(In _{1/2} Nb _{1/2})O ₃ -0.36Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.28PbTiO ₃	180	1030	0.01	32.3	260	27.3	8.2	46800	[7]
0.46Pb(In _{1/2} Nb _{1/2})O ₃ -0.26Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.28PbTiO ₃	160	1100	0.022	26.5	240	24.6	8.3	38400	[7]
Mn-0.71Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.29PbTiO ₃	100	1444	0.005	/	500	5	4.1	50000	[16]

Table 2. Room-temperature pyroelectric properties of the Mn-PIMNT and other ferroelectric ceramics.

Ceramics	p	F_i	F_v	F_d	Reference
	$\times 10^{-4} \text{ Cm}^{-2}\text{K}^{-1}$	$\times 10^{-10} \text{ mV}^{-1}$	m^2C^{-1}	$\times 10^{-5} \text{ Pa}^{-1/2}$	
Mn-0.36Pb(In _{1/2} Nb _{1/2})O ₃ -0.36Pb(Mg _{1/3} Nb _{2/3})O ₃ -	4.8	1.92	0.028	2.317	this work
0.30Pb(In _{1/2} Nb _{1/2})O ₃ -0.40Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.30PbTiO ₃	3.7	1.50	0.015	0.998	[32]
0.28Pb(In _{1/2} Nb _{1/2})O ₃ -0.40Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.32PbTiO ₃	4.9	1.98	0.012	1.080	[32]
0.26Pb(In _{1/2} Nb _{1/2})O ₃ -0.40Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.34PbTiO ₃	5.0	2.00	0.009	1.000	[32]
0.24Pb(In _{1/2} Nb _{1/2})O ₃ -0.40Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.36PbTiO ₃	3.8	1.49	0.005	0.689	[32]
0.22Pb(In _{1/2} Nb _{1/2})O ₃ -0.40Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.38PbTiO ₃	3.2	1.26	0.007	0.854	[32]
0.20Pb(In _{1/2} Nb _{1/2})O ₃ -0.40Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.40PbTiO ₃	2.9	1.16	0.006	0.742	[32]
0.68Pb(Mg _{1/3} Nb _{2/3})O ₃ -0.32PbTiO ₃	3.0	1.23	0.007	0.590	[33]
PZT	4.1	1.41	0.008	0.901	[34]

Figures

Figure 1

XRD patterns of Mn-PIMNT ceramics.

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SEM surface image of Mn-PIMNT ceramics.

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(a) Unipolar strain curves and the inset was the bidirectional field-induced strain curves. (b) The maximum bipolar strain and piezoelectric coefficient as a function of electric field of Mn-PIMNT ceramics at room temperature. Temperature dependence of (c) unipolar strain curves and (d) the unipolar and of Mn-PIMNT ceramics measured at the 40 kVcm⁻¹ at different temperatures.

Figure 7

(a) Impedance and (b) admittance spectrum of Mn-PIMNT ceramics.

Figure 8

Temperature-dependent pyroelectric coefficient (p) of the Mn-PIMNT ceramics.