

Effect of PbTiO_3 Content Variation on High-power Performance of PMN-PT Single Crystal

WANG Xiaobo¹, ZHU Yuliang¹, XUE Wenchao¹, SHI Ruchuan¹, LUO Bofeng², LUO Chengtao¹

(1. School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China;
2. Southern Power Grid Digital Grid Research Institute Co., Ltd., Guangzhou 510000, China)

Abstract: Lead magnesium niobate-lead titanate (PMN-PT) piezoelectric single crystals are widely utilized due to their outstanding performance, with varying compositions significantly impacting their properties. While application of PMN-PT in high-power settings is rapidly evolving, material parameters are typically tested under low signal conditions (1 V), and effects of different PT (PbTiO_3) contents on the performance of PMN-PT single crystals under high-power conditions remain unclear. This study developed a comprehensive high-power testing platform using the constant voltage method to evaluate performance of PMN-PT single crystals with different PT contents under high-power voltage stimulation. Using crystals sized at 10 mm×3 mm×0.5 mm as an example, this research explored changes in material parameters. The results exhibit that while trend of the parameter changes under high-power excitation was consistent across different PT contents, degree of the change varied significantly. For instance, a PMN-PT single crystal with 26% (in mol) PT content exhibited a 25% increase in the piezoelectric coefficient d_{31} , a 13% increase in the elastic compliance coefficient s_{11}^E , a 17% increase in the electromechanical coupling coefficient k_{31} , and a 73% decrease in the mechanical quality factor Q_m when the power reached 7.90 W. As the PT content increased, the PMN-PT materials became more susceptible to temperature influences, significantly reducing the power tolerance and more readily reaching the depolarization temperatures. This led to loss of piezoelectric performance. Based on these findings, a clearer understanding of impact of PT content on performance of PMN-PT single crystals under high-power applications has been established, providing reliable data to support design of sensors or transducers using PMN-PT as the sensitive element.

Key words: piezoelectric single crystal; PMN-PT; high-power testing; constant voltage method; material parameter

Piezoelectric materials, due to their unique ability to convert mechanical stress into electrical signals and *vice versa*, play a pivotal role in various applications including sensors, actuators, and high-precision positioning systems^[1-4]. As an emerging piezoelectric material, PMN-PT single crystals exhibit superior piezoelectric properties compared to traditional polycrystalline piezoelectric materials. They demonstrate higher piezoelectric coefficients, electromechanical coupling coefficients, and mechanical quality factors, leading to

their increasingly widespread use in both research and industrial applications^[5-7].

The general properties and applications of PMN-PT have been extensively measured and documented, yet its performance under high-power conditions remains less explored^[8-9]. Previous studies have primarily focused on low-power scenarios, often involving small signal conditions (1 V), which do not fully represent the operational environments encountered in high-power applications such as transducers or high-intensity

Received date: 2024-11-07; **Revised date:** 2024-12-07; **Published online:** 2024-12-16

Foundation item: Research and Development Project on Voltage Sensors by China Southern Power Grid Digital Research Institute (210000KK5220017)

Biography: WANG Xiaobo (1995–), male, PhD candidate. E-mail: 022035910015@sjtu.edu.cn

王晓波(1995–), 男, 博士研究生. E-mail: 022035910015@sjtu.edu.cn

Corresponding author: LUO Chengtao, associate professor. E-mail: cluo1989@sjtu.edu.cn; LUO Bofeng, engineer. E-mail: mrlcsg@foxmail.com
罗骋韬, 副教授. E-mail: cluo1989@sjtu.edu.cn; 骆柏锋, 工程师. E-mail: mrlcsg@foxmail.com

focused ultrasound systems^[10-13]. Recent studies have shown that the PT content in PMN-PT significantly affects their energy storage performance. By adjusting the fabrication process, the growth of PMN-PT crystals with varying PT contents is achieved, followed by further observation of their *P-E* curves. However, these test results were obtained under a low-voltage excitation of 1 V, not considering the real-world high-power application scenarios, and performance testing under a high-power excitation was not been conducted^[14]. Additionally, Jiang *et al.*^[15] researched PMN-PT single crystals with PT contents of 29%, 29.5%, 30%, 30.5%, and 31% (in mol) within the morphotropic phase boundary (MPB) and the performance of corresponding ultrasonic transducers. They measured related piezoelectric parameters and changes in the relative permittivity at a free state, and by using simulation software combined with circuit analysis, they were able to model the performance of the sensors. However, these materials were also not tested under high-power excitation conditions^[15]. In 1999, Wada^[16] conducted experimental research on the nonlinear dynamic behavior of piezoelectric ceramic vibrators using a constant voltage method, meticulously documenting and analyzing phenomena such as jumping and dropping. This study aided in understanding and predicting the nonlinear response of piezoelectric materials in high-power applications, but their complexity and reliance on specific experimental equipment limited the model's general applicability^[16]. In 2002, Gonnard *et al.*^[17] employed impedance spectroscopy and high-power testing systems to study the nonlinear behavior of soft and hard PZT materials. This research provided a deep understanding of the nonlinear response of PZT materials in high-power applications^[17]. In 2021, Stevenson *et al.*^[18] used impedance spectroscopy and high-power characterization systems to study PZT piezoelectric ceramics composed of different components. This study characterized material properties under small-signal and high-power excitation, using custom software written in LabVIEW to collect impedance data^[18]. This method allowed the research team to evaluate the nonlinear behavior of PZT piezoelectric ceramics under large electric fields. However, these studies focused on PZT piezoelectric ceramics and did not verify the piezoelectric performance of PMN-PT single crystals with varying PT contents. This research gap underscores the urgent need to assess the performance of PMN-PT under actual application conditions.

This study aims to address the issues mentioned by establishing a systematic evaluation method to explore the performance trends of PMN-PT single crystals with varying PT contents under high-power conditions. Utilizing the constant voltage method, this research has developed a comprehensive high-power testing platform

to assess material parameters and their variations thoroughly. This approach not only explores the fundamental piezoelectric properties but also provides aids in understanding how changes in PT content affect the thermal stability and power tolerance of PMN-PT single crystals. By systematically analyzing performance at different power levels, this study aims to provide robust data to support the design and optimization of piezoelectric devices.

1 Experimental

1.1 Constant voltage method test system

Currently, there are three main high-power testing systems: the constant voltage method^[19], the constant current method^[20], and the transient pulse method^[21]. This study employs a testing method based on an improved constant voltage method. By modifying the triggering mechanism, the piezoelectric single crystals do not need to operate under high electric field excitation for extended periods, which reduces self-heating and prevents depolarization of the piezoelectric materials. Fig. 1 illustrates the flowchart of the testing system based on the improved constant voltage method.

As illustrated in Fig. 1, the signal generator (Tektronix AFG-1022) produces a sweep frequency signal that is amplified by a high-voltage amplifier (Aigtek ATA-3080) and fed into the piezoelectric material. The piezoelectric material is clamped at the central point, leaving the surroundings free. An oscilloscope is connected with voltage and current probes to monitor the circuit's voltage and current, collecting data that is then output to a computer for analysis.

The sweep frequency method records the current and voltage across the piezoelectric transducer. Due to the impedance characteristics of the material, there is a proportional relationship between the impedance and the current values. Consequently, the corresponding current curve can be used to plot the impedance curve, which in

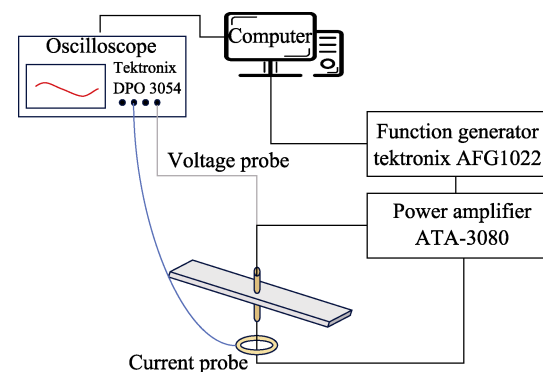


Fig. 1 Constant voltage method test system

turn helps identify the resonant and anti-resonant frequencies. These frequencies are crucial for further calculation of the material parameters.

1.2 Piezoelectric material

In this study, the piezoelectric material used is $(1-x)\text{PMN}-x\text{PT}$, where x represents the PT content. The PT contents are 26%, 29%, and 33% (in mol), respectively, representing low, medium, and high component levels of PT content and their impact on piezoelectric performance. The dimensions of the samples are $10\text{ mm}\times 3\text{ mm}\times 0.5\text{ mm}$, configured to operate in thickness-mode excitation and length-mode vibration, known as the 31-mode. As shown in Fig. 2(a), image is displayed for the three different PT contents of PMN-PT materials. The polarization direction is [001], and the (001) face is sputtered with Cr/Au layers of 0.03 and 0.3 μm , respectively.

As illustrated in Fig. 2(b, c), d_{33} of the materials are measured using a d_{33} meter (ZJ-6BN) and their fundamental material parameters under small signal conditions (1 V) are further evaluated using an impedance analyzer (Keysight-4294A). The results of these measurements are summarized in Table 1.

According to the material characteristics under the small signal above, the changing trend of the material parameters under the high-power excitation can be determined.

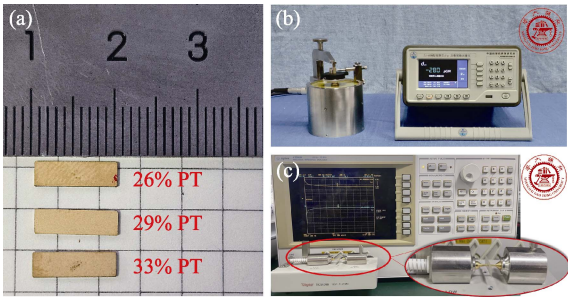


Fig. 2 PMN-PT samples and test equipments
(a) PMN-PT samples; (b) d_{33} instrument; (c) Impedance analyzer

Table 1 Small-signal material parameters of PMN-PT with different PT contents

PT content/%	Dielectric constant/kHz	Capacitance/nF	Loss tangent/%	d_{33}^* / (pC·N ⁻¹)
26	4518	2.4	0.9	1170
29	5082	2.7	0.9	1500
33	6776	3.6	1.6	2200

2 Results and discussion

By utilizing the established constant voltage method in the high-power testing system, the piezoelectric material parameters such as d_{31} , s_{11}^E , k_{31} and Q_m are measured and calculated. Accurately determining these parameters is crucial for designing efficient piezoelectric devices, as it ensures that the materials can perform optimally under the specific operational conditions expected in their final applications.

2.1 Impedance curve

The impedance curve of piezoelectric materials contains critical information that is essential for determining the material's characteristic frequencies, assessing its piezoelectric coupling coefficient and mechanical quality factor, as well as providing a comprehensive evaluation of the material's electrical and mechanical properties.

Fig. 3 depicts the impedance curves of three PMN-PT single crystals with different PT compositions under various power excitations. In Fig. 3, f_r and f_a represent the resonant and anti-resonant frequencies of the piezoelectric materials, respectively.

As the excitation voltage increases, the resonant and anti-resonant frequencies of the single crystal materials with three different PT contents exhibit the same trend of shifting towards lower frequencies. The impedance value

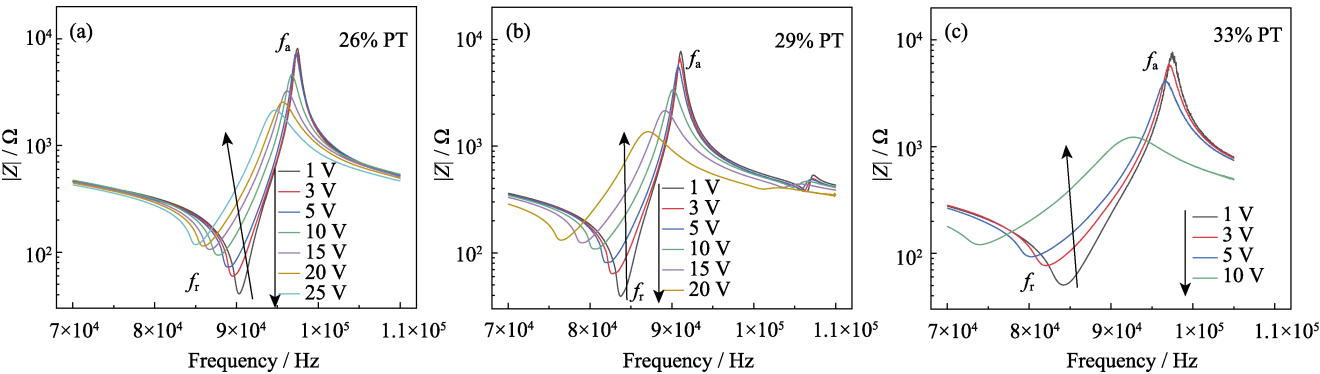


Fig. 3 Impedance curves of PMN-PT with different PT contents
(a) 26% PT; (b) 29% PT; (c) 33% PT

at the resonant frequency increases, while it decreases at the anti-resonant frequency. Similarly, as the PT content increases, the power tolerance of the piezoelectric materials decreases, leading to depolarization phenomena. The characteristic frequencies extracted from the impedance curves can be used to calculate relevant material parameters.

2.2 Elastic compliance coefficient s_{11}^E

The elastic compliance coefficient s_{11}^E is the ratio of the strain in the material's longitudinal direction (direction 1) to the stress it experiences, measured under a constant electric field. It describes the material's elasticity, representing an essential mechanical performance indicator. The calculation formula is:

$$s_{11}^E = \frac{1}{4\rho l^2 f_r^2} \quad (1)$$

where ρ represents the density of the material, and l denotes the length of the material. The calculation results are shown in Fig. 4.

According to the curves shown in Fig. 4, the elastic compliance coefficient s_{11}^E of the piezoelectric material increases with the rising excitation voltage and power. The change is particularly noticeable in the PMN-PT single crystal with 33% PT content, which increases by 30%. The PMN-PT single crystals with 26% and 29% PT contents are relatively stable, but s_{11}^E still increases by 13% and 19%, respectively.

As the elastic compliance coefficient s_{11}^E increases, it implies that the material becomes softer, which can lead to higher deformability. However, it is also important to consider the potential decline in mechanical properties and limitations in applicability that this may bring. When designing and selecting materials, these factors should be weighed according to the application's specific requirements.

2.3 Electromechanical coupling coefficient k_{31}

The electromechanical coupling coefficient k_{31}

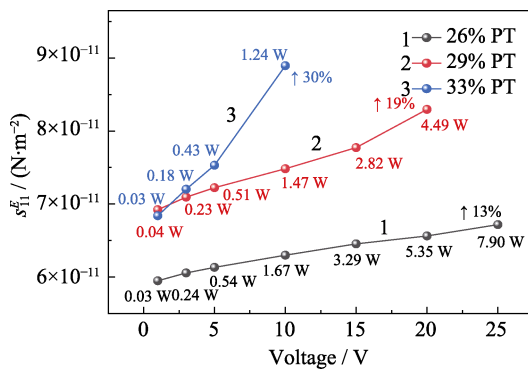


Fig. 4 s_{11}^E curves of PMN-PT with different PT contents

describes the efficiency of energy conversion between mechanical and electrical energies in the material. A dimensionless coefficient characterizes the ratio of mechanical energy that can be converted into electrical energy by the piezoelectric effect in a specific mode. The calculation formula is:

$$\frac{k_{31}^2}{1-k_{31}^2} = \frac{\pi}{2} \cdot \frac{f_a}{f_r} \cdot \tan\left(\frac{\pi}{2} \cdot \frac{f_a - f_r}{f_r}\right) \quad (2)$$

The calculation results are shown in Fig. 5. Under various excitation voltages and power levels, the electromechanical coupling coefficient k_{31} of PMN-PT single crystals with different PT contents exhibits a consistent trend. The electromechanical coupling coefficients of PMN-PT single crystals with low, medium, and high PT contents increased by 17%, 21%, and 20%, respectively.

An increase in the electromechanical coupling coefficient k_{31} can enhance the material's energy conversion efficiency and improve output performance, which may be beneficial for enhancing the response speed and sensitivity of sensors. However, it also introduces issues with thermal stability, a challenging problem for the application of piezoelectric materials, as the performance of PMN-PT single crystals is highly susceptible to temperature influences. Therefore, in practical applications, while pursuing a high electromechanical coupling coefficient, it is necessary to employ appropriate material cooling methods, such as liquid cooling.

2.4 Piezoelectric coefficient d_{31}

The d_{31} is a constant that describes the piezoelectric effect, representing the ratio of the strain produced in the direction perpendicular to the electric field to the applied electric field strength. For d_{31} , when the electric field is applied along the polarization direction (typically the 3-direction), the material undergoes linear strain in the perpendicular direction (1-direction).

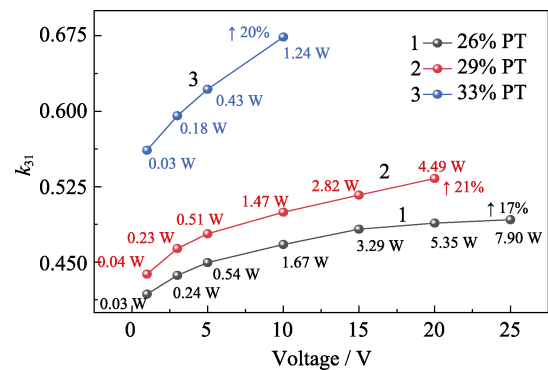


Fig. 5 k_{31} curves of PMN-PT with different PT contents

The calculation formula is:

$$d_{31} = k_{31} \sqrt{\varepsilon_{33}^T s_{11}^E} \quad (3)$$

where ε_{33}^T represents the relative permittivity of the piezoelectric material. The calculation results as shown in Fig. 6 indicate that the electromechanical coupling coefficients of PMN-PT single crystals with low, medium, and high PT contents have increased by 25%, 33%, and 20%, respectively.

This increase is attributed to the movement of domain walls within the PMN-PT single crystals, leading to a reorientation of domain structures, enhancing the material's piezoelectric response. While the piezoelectric properties of the material are indeed improved, this enhancement inevitably introduces non-linear effects, causing self-heating and fatigue in the piezoelectric material. Therefore, in applications seeking high piezoelectric performance, increasing the excitation power is insufficient. Piezoelectric stacking techniques can be employed to enhance the material's piezoelectric performance.

2.5 Mechanical quality factor Q_m

Q_m is the mechanical quality factor of piezoelectric materials in the resonant state, used to describe the energy loss of the material while vibrating at its resonant frequency. High Q_m indicates less energy loss and more sustained vibrations, making it suitable for applications that require long-term stable vibrations. The calculation formula^[10] is:

$$Q_m = \frac{1}{R_l \sqrt{\frac{L_l}{C_l}}} \quad (4)$$

$$C_l = \frac{8l \cdot w \cdot d_{31}}{\pi^2 \cdot t \cdot s_{11}^E} \quad (5)$$

$$L_l = \frac{\rho \cdot l \cdot t}{8w} \left(\frac{s_{11}^E}{d_{31}} \right)^2 \quad (6)$$

$$C_0 = \frac{l \cdot w}{t} \varepsilon_{33}^T (1 - k_{31}^2) \quad (7)$$

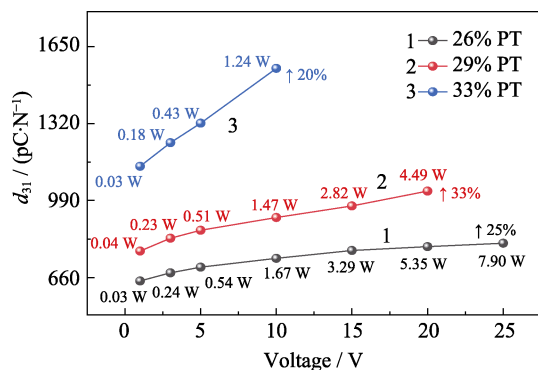


Fig. 6 d_{31} curves of PMN-PT with different PT contents

$$R_l = \frac{|Z|_{\min}}{\sqrt{1 - \omega_r^2 C_0^2 |Z|_{\min}^2}} \quad (8)$$

where w and t represent the width and thickness of the piezoelectric vibrator, respectively; R_l , C_l and L_l represent the dynamic capacitance, resistance, and inductance of the piezoelectric material, respectively; C_0 represents the static capacitance; ω_r represents the angular frequency produced by resonance.

The calculation results for Q_m are shown in Fig. 7, revealing significant differences under small signal conditions across the three different PT contents in PMN-PT. The increase in PT content alters the domain structure of PMN-PT, that is crystal structure and phase boundaries, thereby affecting the freedom of domain wall movement. A reduction in Q_m signifies a substantial increase in energy loss during the movement of the piezoelectric material, further leading to a decrease in the vibration stability and efficiency of piezoelectric devices. In applications that require sustained vibrations, such as transducers and very low frequency sonars, this can lead to a continuous decline in device performance. It also implies a reduction in the energy conversion efficiency of the piezoelectric material, causing energy to dissipate as heat rather than being effectively converted. Additionally, low Q_m indicates broadening of the material's resonance peak, and if sensors or devices operate at a specific frequency, high-power excitation may lead to performance that does not meet design specifications, potentially resulting in sensor failure.

3 Conclusions

This study explores the impact of PT content on the performance of PMN-PT piezoelectric single crystals under high-power excitation scenarios. A high-power testing platform based on the constant voltage method was constructed to test material parameters, simulating real-world applications of piezoelectric materials and

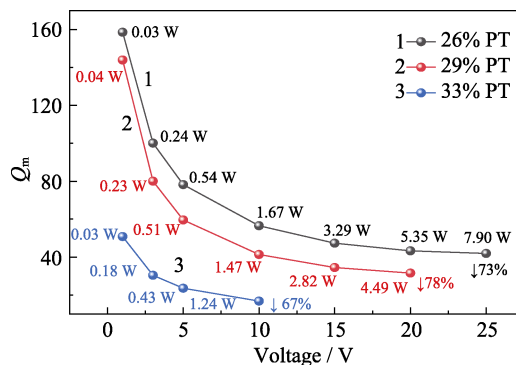


Fig. 7 Q_m curves of PMN-PT with different PT content

providing reliable data support for sensors and transducers operated under high-power stimulation.

The results show that increased PT content significantly alters the properties of piezoelectric materials, causing phase transitions. For a PMN-PT single crystal with 26% PT content under 7.90 W power stimulation, the piezoelectric coefficient increased by 25%, the elastic compliance coefficient by 13%, the electromechanical coupling coefficient increased by 17%, and the mechanical quality factor decreased by 73%. For a PMN-PT single crystal with 29% PT content under 4.49 W power stimulation, the piezoelectric coefficient increased by 33%, the elastic compliance coefficient increased by 19%, the electromechanical coupling coefficient increased by 21%, and the mechanical quality factor decreased by 78%. For a PMN-PT single crystal with 33% PT content under 1.24 W power stimulation, the piezoelectric coefficient increased by 20%, the elastic compliance coefficient increased by 30%, the electromechanical coupling coefficient increased by 20%, and the mechanical quality factor decreased by 67%. These results indicate that higher PT contents make PMN-PT single crystals more susceptible to temperature effects in high-power applications, thus reducing power tolerance and increasing the risk of depolarization. This study is the first to detail the performance of PMN-PT single crystals under different PT contents in high-power applications, presenting significant differences from previous research and filling existing gaps in the literature.

This study's theoretical and practical significance lies in providing essential data support and performance prediction for the design and application of PMN-PT single crystals in high-power sensors or transducers. Despite the findings obtained, the issue of depolarization due to temperature increases under high-power excitation in PMN-PT single crystals remains unresolved. Future research should delve deeper into how material processing optimizations can mitigate this phenomenon and how new material designs or the use of composite materials can enhance power tolerance and temperature stability. This will help advance the development of high-performance piezoelectric materials in a broader range of high-power applications. A potential application direction involves combining piezoelectric materials with semiconductor piezoresistive materials to form sensitive elements, based on the inverse piezoelectric effect and the piezoresistive effect, achieving non-contact measurement of excitation voltage or electric fields.

Supporting materials

Supporting materials related to this article can be found at <https://doi.org/10.15541/jim20240469>.

References:

- [1] The Institute of Electrical and Electronics Engineers. IEEE Standard on Piezoelectricity: ANSI/IEEE Std 176-1987. New York: American National Standards Institute, 1987.
- [2] KOS T, SLABKI M, PETROVIC J, *et al.* Measurement system for piezoelectric resonance impedance spectroscopy under combined AC and high-voltage DC loading. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 2022, **69(11)**: 3137.
- [3] LI G, TIAN F H, GAO X Y, *et al.* Investigation of high-power properties of PIN-PMN-PT relaxor-based ferroelectric single crystals and PZT-4 piezoelectric ceramics. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 2020, **67(8)**: 1641.
- [4] SAFAEI M, SODANO H A, ANTON S R. A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008–2018). *Smart Materials and Structures*, 2019, **28(11)**: 113001.
- [5] DAVIS M, DAMJANOVIC D, SETTER N. Electric-field, temperature, and stress-induced phase transitions in relaxor ferroelectric single crystals. *Physical Review B*, 2006, **73(1)**: 014115.
- [6] ZHANG S J, LUO J, WESLEY H, *et al.* Characterization of Pb(In_{1/2}Nb_{1/2})O₃-Pb(Mg_{1/3}Nb_{2/3})O₃-PbTiO₃ ferroelectric crystal with enhanced phase transition temperatures. *Applied Physics Letters*, 2008, **104(6)**: 4106.
- [7] IEEE Ultrasonics, Ferroelectrics and Frequency Control Society. IEEE Standard for Relaxor-based Single Crystals for Transducer and Actuator Applications: IEEE Std 1859-2017. New York: American National Standards Institute, 2017.
- [8] KENJI U. Loss mechanisms and high power piezoelectrics. *Journal of Materials Science*, 2006, **41(1)**: 217.
- [9] MORITA T. Evaluation method for high-power piezoelectric materials and devices. IEEE International Ultrasonics Symposium (IUS), Kobe, 2018: 1.
- [10] UCHINO, K, ZHENG J H, JOSHI A, *et al.* High power characterization of piezoelectric materials. *Journal of Electroceramics*, 1998, **2(1)**: 33.
- [11] LEE H J, URAL S O, CHEN L, *et al.* High power characteristics of lead-free piezoelectric ceramics. *Journal of the American Ceramic Society*, 2012, **95(11)**: 3383.
- [12] SOMENO S, NAGATA H, TAKENAKA T. High-temperature and high-power piezoelectric characteristics of (Bi_{0.5}Na_{0.5})TiO₃ based lead-free piezoelectric ceramics. *Journal of the Ceramic Society of Japan*, 2014, **122(1426)**: 406.
- [13] CHEN L, LIU H, QI H, *et al.* High-electromechanical performance for high-power piezoelectric applications: fundamental, progress, and perspective. *Progress in Materials Science*, 2022, **127**: 100944.
- [14] XIA X J. Study on the fabrication and energy storage performance of relaxor ferroelectric thin films. Wuhan: Wuhan University of

- Technology Master's Thesis, 2022.
- [15] JIANG Z B, HOU C X, FEI C L, *et al.* Effects of composition segregation in PMN-PT crystals on ultrasound transducer performance. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 2022, **69**(2): 795.
- [16] WADA T. A study on jumping and dropping phenomena and their hysteresis of ceramic resonator. *IEEJ Transactions on Fundamentals and Materials*, 1999, **119**(3): 246.
- [17] GONNARD P, PETIT L. Nonlinear effects in piezoelectric materials. *Boletin de la Sociedad Espanola de Ceramica y Vidrio*, 2002, **41**(1): 107.
- [18] STEVENSON J, FENU N C, CHILLES J, *et al.* Characterisation of PZTs non-linear behaviour for high-power systems. *IEEE International Ultrasonics Symposium (IUS)*, Xi'an, 2021: 1.
- [19] HIROSE S T. Vibration-level characteristics of lead-zirconate-titanate ceramics. *Japanese Journal of Applied Physics*, 1992, **31**(9S): 3055.
- [20] HIROSE S, YAMAYOSHI Y, TAGA M, *et al.* A method of measuring the vibration level dependence of impedance-type equivalent circuit constants. *Japanese Journal of Applied Physics*, 1991, **30**(S1): 117.
- [21] KENJI U. Piezoelectric actuators and ultrasonic motors. 2nd edition. New York: Springer Science & Business Media, 1996: 38.

PT 含量变化对 PMN-PT 单晶的大功率性能影响

王晓波¹, 朱于良¹, 薛稳超¹, 史汝川¹, 骆柏锋², 罗骋韬¹

(1. 上海交通大学 电子信息与电气工程学院, 上海 200240; 2. 南方电网数字电网研究院股份有限公司, 广州 510000)

摘要: PMN-PT($\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$)压电单晶材料因其优异的性能而得到广泛的应用, 不同组分的配比含量会对 PMN-PT 压电单晶的性能产生较大影响。同时 PMN-PT 在大功率上的应用快速发展, 材料参数都是在小信号 (1 V) 下测试完成的, 而不同 PT 含量对 PMN-PT 单晶在大功率应用下的性能影响尚不明确。本研究基于恒压法搭建了完整的压电材料大功率测试平台, 对比测试不同 PT 含量的 PMN-PT 单晶在大功率电压激励下的性能表现, 以 $10\text{ mm}\times 3\text{ mm}\times 0.5\text{ mm}$ 的 PMN-PT 单晶为例, 探究材料参数变化。结果显示: 不同 PT 含量的 PMN-PT 单晶在大功率激励下的材料参数变化趋势相同, 但变化程度有较大不同。以 PT 含量为 26%(摩尔百分数)的 PMN-PT 单晶为例, 当功率达到 7.90 W 时, 压电系数 d_{31} 增加 25%, 弹性耦合系数 s_{11}^E 增加 13%, 机电耦合系数 k_{31} 增加 17%, 机械品质因数 Q_m 下降 73%。随着 PT 含量增加, PMN-PT 材料更易受温度的影响, 功率耐受性显著降低, 更易达到退化温度, 导致压电性能消失。基于本工作的研究结果, 可以更好地明确 PT 含量对 PMN-PT 单晶在大功率应用下的影响规律, 从而为以 PMN-PT 为敏感元件的传感器或换能器设计提供可靠的数据支持。

关键词: 压电单晶; PMN-PT; 大功率测试; 恒压法; 材料参数

中图分类号: TQ174 文献标志码: A 文章编号: 1000-324X(2025)07-0840-07

Supporting materials

Effect of PbTiO₃ Content Variation on High-power Performance of PMN-PT Single Crystal

WANG Xiaobo¹, ZHU Yuliang¹, XUE Wenchao¹, SHI Ruchuan¹, LUO Bofeng², LUO Chengtao¹

(1. School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China;
2. Southern Power Grid Digital Grid Research Institute Co., Ltd., Guangzhou 510000, China)

During high-power excitation in this study, the temperature of the PMN-PT piezoelectric single crystal materials significantly increases. We monitor the temperature changes using an infrared thermometer (FOTRIC-246 M). The scanning frequency range is 70–120 kHz, with a scanning duration of 120 ms. Although the duration has been greatly reduced compared to traditional constant voltage excitation methods, it still results in a sharp increase in temperature. After the excitation is removed, the temperature rapidly decays, but once it reaches the depolarization temperature of the PMN-PT piezoelectric single crystals, their piezoelectric properties completely disappear.

Fig. S1 displays the infrared temperature probe monitoring image of the piezoelectric materials. Fig. S2 shows the temperature change of the material during high-power excitation.

This method can also be specifically applied to depolarize piezoelectric materials, but the excitation power needs to be specially designed to prevent material fracture and physical damage due to excessive power.

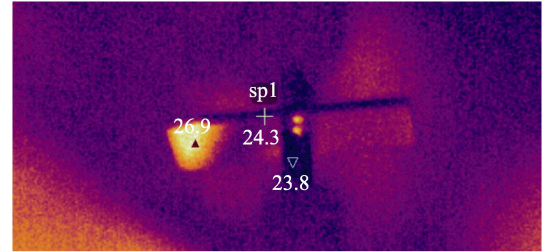


Fig. S1 Infrared temperature probe monitoring image

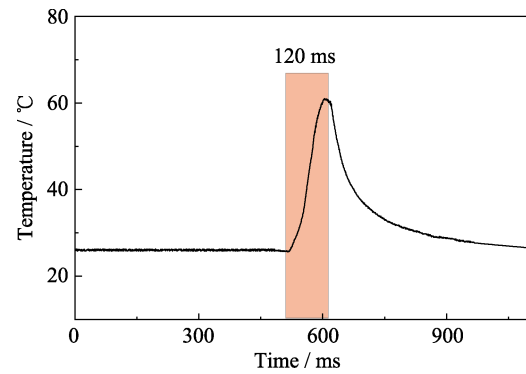


Fig. S2 Temperature curve of the piezoelectric material