Recent Advances in Piezoelectric Materials for Electromechanical Transducer Applications

FERROELECTRICITY has made a huge impact on science and technology since Joseph Valasek (then a Ph.D. student at the University of Minnesota) discovered it in 1920, a little longer than 100 years ago. Whereas Dr. Valasek's original research was motivated by the need to develop seismic sensors, at present ferroelectric materials have been extensively studied for applications in high-energy capacitors, energy harvesting systems, night vision sensors, and electrocaloric solid cooling, and, of particular significance, the ferroelectrics are the material-of-choice for numerous electromechanical devices, including underwater acoustic transducers, medical diagnostic and therapeutic transducers, piezoelectric actuators, and ultrasonic motors, to name a few. The progress over the past 100 years has been enormous and it is ongoing: for example, the piezoelectric coefficient d of ferroelectrics has increased from a few pico-Coulomb per Newton to several thousand pico-Coulomb per Newton, which benefits all piezoelectric sensing and actuation devices.

To celebrate the 100th anniversary of the discovery of ferroelectricity, the IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL (UFFC TRANSACTIONS) launched a spotlight issue focusing on the piezoelectricity of ferroelectrics and their ever-expanding applications. We have collected six review articles and eight original research articles, which are briefly discussed in the following.

The properties of ferroelectric materials directly affect the output performance of the piezoelectric devices. Several reviews and research papers have proposed some approaches to improve the properties of ferroelectric materials. In [A1], Yu et al. reviewed the effects and underlying mechanisms of various sintering aids on the sintering behaviors of (K, Na)NbO_3 (KNN) ceramics. In [A2], Uchino reviewed the electrostrictive effects in complex-perovskite "relaxor" ferroelectrics, which exhibit superior performance in comparison with the simple-perovskite normal ferroelectrics. In [A3], Kim et al. reviewed recent research progress and perspectives in alternating current poling (ACP) on relaxor-$PbTiO_3$ (PT) single crystals, which has been actively studied in the last few years, showing a great advantage of the ACP over traditional direct current poling (DCP) in enhancing the piezoelectric properties of the ferroelectric single crystals. In addition, in [A4], Liu et al. reported a complete set of material constants for [001]-poled $0.72Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.28PbTiO_3$ (PMN-0.28PT) single crystals poled by the ACP approach, and made a detail comparison with that of DCP poled crystals, further corroborating the clear benefit of ACP in improving the piezoelectric and dielectric properties. In [A5], Sun et al. reported that much higher piezoelectric and dielectric properties could be achieved in AC poled PMN-PT single crystals, which have been confirmed in the sliver mode of the crystals to meet the cardiac probes fabrication requirement. The reported results have important implications for the commercial application of ACP technology to medical imaging ultrasound probes.

A major driving force of relaxor ferroelectric single crystals (SCs) has been the mass production of ultrasound transducers and array probes for medical diagnostic systems since the early 2000s. In [A6], Yamashita et al. reviewed the lead perovskite ferroelectric SCs and their medical transducer application. The authors believe that the direction of research in the next decades will be 1) the development of growth technology for high d_{33} single crystals with a high composition uniformity at low-energy-consumption single crystal growth technology, such as solid-state crystal growth, 2) the low-loss single crystal transducer manufacturing technique, and 3) the improved poling processes. In [A7], Sun et al. proposed to use <001> textured $Pb(Mg_{1/3}Nb_{2/3})O_3$–$Pb(Zr,Ti)O_3$ ceramics to fabricate medical ultrasound transducers with high image resolution with a central frequency of 15 MHz and a fractional bandwidth of 67%, demonstrating that this low-cost material fabrication technology can also lead to high-performance ultrasound transducer.

This Spotlight Issue also collects reviews and research papers on ferroelectric materials for actuators, resonators, and filters. In [A8], Jin et al. reviewed the recent progress in high-performance ferroelectric materials, the development of piezoelectric actuators, and the relationship between the figures-of-merit of ferroelectric materials and the performance of piezoelectric actuators; the authors also provided an outlook and challenges for piezoelectric materials and actuators. In [A9], Yang et al. reported on piezoelectric accelerometers fabricated based on high Curie temperature $(1\text{-}x)BiFeO_3$–$xBaTiO_3$–$0.0035MnO_2$–$0.001Li_2CO_3$ (BF-xBT) ceramics, showing a high sensitivity of about 40 pC/N with an excellent stability up to 400 ^{o}C. In [A10], Yin et al. reviewed the progress of using the thermal spray method for fabricating piezoelectric ceramic coatings and their values for structural health monitoring (SHM) applications. The scalable thermal spray processing method opens substantial application opportunities, especially in ultrasonic structural

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health monitoring technology, exhibiting the competitiveness and commercial values. In [A11], Luo et al. presented the design, fabrication, and characterization of 500-nm-thick aluminum scandium nitride (AlScN) contour mode resonators (CMRs), which take advantage of the optimized stress control of co-sputtered AlScN thin films and a vertical inductively coupled plasma etching profile to achieve an electromechanical coupling factor k_t^2 of 5.24% and a loaded quality factor of 1219 at an operating frequency of 300 MHz. In [A12], Xu et al. reported a large range spurious mode suppression/elimination for the $LiNbO_3$(LN)/SiO_2/Si wideband SAW filters. They theoretically and experimentally addressed this problem by modulating the cut angle (θ) of LN, providing a simple and feasible route to meet the requirements for filters satisfying high-performance and high-volume data communication in the 5G technology.

New nonlinear equivalent circuit models and test systems for piezoelectric devices are under continuous development. In [A13], Yu et al. derived nonlinear equivalent circuit and nonlinear resonance frequency equation for the loss-dependent high-power sandwich piezoelectric ultrasonic transducer. In [A14], Kos et al. proposed a new measurement system for piezoelectric resonance impedance spectroscopy under combined ac and high-voltage dc loading.

Over the past 100 years, people have witnessed the great impact of ferroelectricity on our everyday life; numerous ferroelectric materials have been designed and developed to enable the advancement of diverse applications. The UFFC TRANSACTIONS hereby pay tribute to all pioneers and current researchers for their significant contributions to the field of ferroelectrics, including the ferroelectric theory, material design and fabrication, microstructure and property, and ferroelectric applications.

The Guest Editors would like to take this opportunity to thank all the contributing authors for their excellent work. The Guest Editors hope this Spotlight Issue can serve to prompt further innovations in ferroelectric materials for electromechanical transducer applications, focusing on the emerging phenomena and emerging applications.

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APPENDIX: RELATED ARTICLES

[A1] Y. Yu, T. Zheng, N. Zhang, and J. Wu, "Review of sintering aids in lead-free (K,Na)NbO_3-based ceramics," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3003–3012, Nov. 2022, doi: 10.1109/TUFFC.2022.3152412.

[A2] K. Uchino, "Electrostrictive and piezoelectric effects in relaxor ferroelectrics—Historical background," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3013–3036, Nov. 2022, doi: 10.1109/TUFFC.2022.3165002.

[A3] H.-P. Kim et al., "A review on alternating current poling for perovskite relaxor-$PbTiO_3$ single crystals," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3037–3047, Nov. 2022, doi: 10.1109/TUFFC.2022.3181236.

[A4] M. Liu et al., "Complete sets of material constants of [001]-poled $0.72Pb(Mg_{1/3}Nb_{2/3})O_{3-0.28}PbTiO_3$ single crystals using alternating current poling," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3081–3086, Nov. 2022, doi: 10.1109/TUFFC.2022.3141461.

[A5] Y. Sun et al., "Enhanced properties of 3-MHz sliver-mode vibrators for cardiac probes with alternating current poling for $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ single crystals," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3087–3094, Nov. 2022, doi: 10.1109/TUFFC.2022.3199741.

[A6] Y. Yamashita, T. Karaki, H.-Y. Lee, H. Wan, H.-P. Kim, and X. Jiang, "A review of lead perovskite piezoelectric single crystals and their medical transducers application," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3048–3056, Nov. 2022, doi: 10.1109/TUFFC.2022.3160526.

[A7] Y. Sun et al., "Design and fabrication of 15-MHz ultrasonic transducers based on a textured Pb $(Mg_{1/3}Nb_{2/3})O_3$-Pb (Zr,Ti)O_3 ceramic," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3095–3101, Nov. 2022, doi: 10.1109/TUFFC.2022.3145882.

[A8] H. Jin et al., "Review on piezoelectric actuators based on high performance piezoelectric materials," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3057–3069, Nov. 2022, doi: 10.1109/TUFFC.2022.3175853.

[A9] H. Yang et al., "Lead-free BF-BT ceramics with ultrahigh Curie temperature for piezoelectric accelerometer," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3102–3107, Nov. 2022, doi: 10.1109/TUFFC.2022.3143575.

[A10] J. Yin, S. Chen, V.-K. Wong, and K. Yao, "Thermal sprayed lead-free piezoelectric ceramic coatings for ultrasonic structural health monitoring," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3070–3080, Nov. 2022, doi: 10.1109/TUFFC.2022.3176488.

[A11] Z. Luo, S. Shao, and T. Wu, "$Al_{0.78}Sc_{0.22}N$ Lamb wave contour mode resonators," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3108–3116, Nov. 2022, doi: 10.1109/TUFFC.2021.3136337.

[A12] H. Xu et al., "Large-range spurious mode elimination for wideband SAW filters on $LiNbO_3/SiO_2$/Si platform by $LiNbO_3$ cut angle modulation," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3117–3125, Nov. 2022, doi: 10.1109/TUFFC.2022.3152010.

[A13] J. Yu and L. Xu, "Nonlinear equivalent circuit of high-power sandwich piezoelectric ultrasonic transducer," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 69, no. 11, pp. 3126–3136, Nov. 2022, doi: 10.1109/TUFFC.2022.3208619.

[A14] T. Kos, M. Slabki, J. Petrovčič, D. Vrančič, G. Dolanc, and J. Koruza, "Measurement system for piezoelectric resonance impedance spectroscopy under combined AC and high-voltage DC loading," vol. 69, no. 11, pp. 3137–3144, Nov. 2022, doi: 10.1109/TUFFC.2022.3185534.

Fei Li (Senior Member, IEEE) was born in Shaanxi, China, in 1983. He received the B.Eng. and Ph.D. degrees in electronics science and electronic materials from Xi'an Jiaotong University, Xi'an, China, in 2006 and 2012, respectively.

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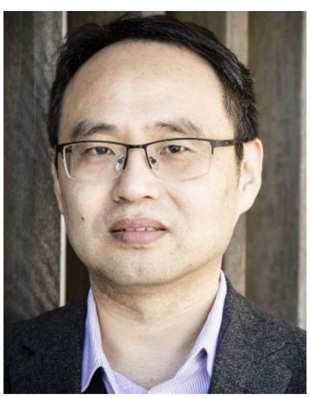

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