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Antiferroelectric capacitor for energy storage: a review from the development and perspective

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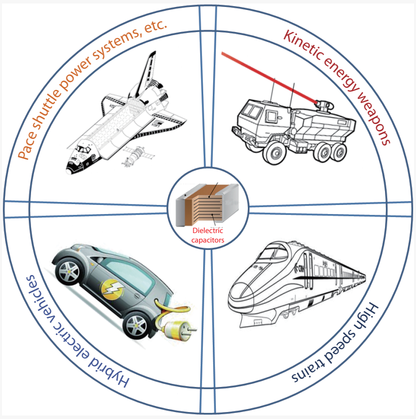
With the fast development of the power electronics, dielectric materials with large power densities, low loss, good temperature stability and fast charge and discharge rates are eagerly desired for the potential application in advanced pulsed power-storage system. Especially, antiferroelectric (AFE) capacitors which have been considered as a great potential for electric device applications with high energy density and output power are widely concentrated recently. To propel the development of dielectric capacitors marketization, in this view, we comprehensively summarized the development process of energy storage density and efficiency, improving strategy, raw materials cost and thermal steadily of the typical AFE capacitors, including Pb(Zr, Ti)O_3, $AgNbO_3$, (Bi, Na)TiO_3, and $NaNbO_3$ AFE systems. Moreover, the advantages and disadvantages of these AFE energy-storage ceramics are compared and discussed, which lay the foundation for the AFE energy storage capacitor early realization of marketization.



With the rapid development of electronics industry, the demand for dielectric energy storage devices is becoming more and more urgent, such as hybrid electric vehicles, laser weapons, space vehicle power systems, and cardiac defibrillators as shown in Fig. 1[1–3], because they have fast charging/discharging speed, high power density and excellent fatigue resistance[4]. Various types of dielectric materials can be potential candidates for energy storage, including antiferroelectrics (AFEs)[5–7], relaxor ferroelectrics (RFEs)[8,9], normal ferroelectrics (FEs)[10], and linear nonpolar dielectric materials[11]. Among these dielectrics, AFE dielectrics, characterized by a double hysteresis loop, are favored for energy storage due to their relatively high maximum polarization (P_{max}) and particularly low remanent polarization (P_r) compared with other types of dielectrics. In this paper, we summarized the energy storage density (U_{rec}) and efficiency (η) of AFE dielectrics systems in recent 10 years as shown in Fig. 2, and reviewed their industrialization application potential from the properties, economics, and environment.

Lead-based antiferroelectrics

Lead-based AFE ceramics that possess excellent U_{rec} and η, like (Pb,La)(Zr,Ti)O_3 system[5,6,12–14], have been the mainstay energy storage materials. Even so, the U_{rec} of lead-based AFE ceramics is just about 0.55 J cm^{-3} in the early days, and increases to 13.9 J cm^{-3} at present, along with $\eta > 90$ %. From the whole development process as shown in Fig. 2a[15–26], the improvement of energy storage performances can be summarized in the following three aspects. Firstly, increasing the electric field of AFE-FE phase transition, such as phase transition electric field of AFE-to-FE (E_F) and FE-to-AFE (E_A)[27]; Secondly, designing a core shell[28] or laminated composite structure[26] to improve the breakdown strength (BDS); Thirdly, building a multiple phase transition[22,29,30]. All these measures not only improve the U_{rec} of lead-based AFE ceramics, but also make their η significantly increased. Except for above bulk ceramics, multilayer capacitors (MLCCs) technique also is a great way to achieve high U_{rec} and η. For example, Hao et al.[31,32] achieved a variety of ultrahigh $U_{rec} > 15$ J cm^{-3} and excellent $\eta > 90\%$ in lead-based MLCCs. However, with increasing environmental concerns, the adverse effect of lead oxide on the environment and human health will gain more and more attention, and the development of lead-free AFE energy storage capacitors have necessitated.

$Bi_{0.5}Na_{0.5}TiO_3$ based antiferroelectrics

Lead-free antiferroelectric materials have attracted increasing attention for environmentally friendly energy-storage applications in recent years[33]. As one of the earliest studied lead-free energy storage ceramics $Bi_{0.5}Na_{0.5}TiO_3$ (BNT)-based AFE have a series of attractive features, including relatively large and tunable spontaneous polarization and high Curie

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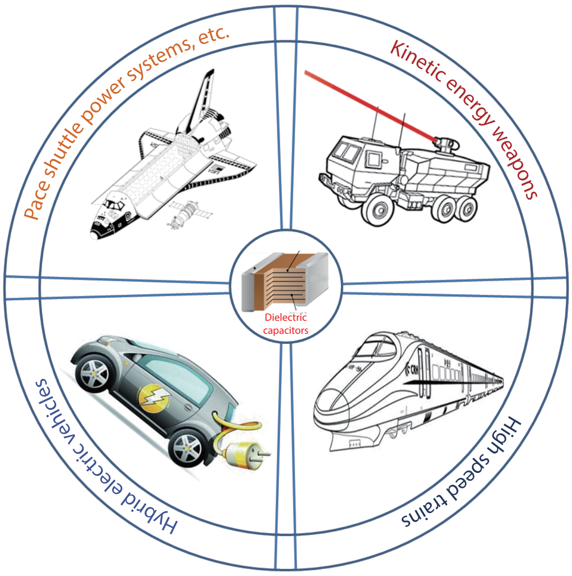

Fig. 1 The application of dielectric energy storage materials in pulsed-discharge and power conditioning electronic devices.

temperature, which enables BNT to maintain large polarization over a wide temperature range. Yet, the U_{rec} of pure BNT ceramic is limited because of their high P_r and relatively low BDS. Therefore, from 2011 to 2020, researchers have been working on reducing the P_r and increasing the BDS by increasing relaxor behavior and decreasing the grain size [34–37]. Especially the strategies, such as defect engineering,[38] field-induced structure transition[39], multiscale polymorphic domains[41], were adopted in recent years, making U_{rec} and η of BNT system markedly increased as shown in Fig. 2b[35,38–44]. Besides, the feature of thin dielectric layer thickness also makes BNT based MLCCs possess an ultrahigh *BDS* and U_{rec}, especially for the <111>-textured $Na_{0.5}Bi_{0.5}TiO_3$-$Sr_{0.7}Bi_{0.2}TiO_3$ (NBT-SBT) MLCCs, which possess an ultrahigh *BDS* ~ 103 MV m^{-1} and U_{rec}~21.5 J cm^{-3} because it has a greatly low tensile electro-strain[45]. However, it is still not mature to be used to marketization, due to the complicated chemistry structure and high process cost for the texture.

$AgNbO_3$ based antiferroelectrics

The characteristic of double P-E hysteresis loops for $AgNbO_3$ (AN) was first reported in 2007, suggesting the practical possibility of its application in energy storage[46]. However, the U_{rec} of pure AN ceramic is only about 2 J cm^{-3} [47,48], far lower than that of lead-based AFE systems [45,49,50]. The main reasons are that there have a non-zero P_r value and poor breakdown strength (BDS) at room temperature for pure AN ceramic. Enormous efforts [51–58] have been made as to solve these questions as following three aspects. One is using oxide dopants for compositional modification to suppress the ferroelectricity characteristic and boost the AFE one. Typical examples include AN+0.1wt%MnO_2 [51] and AN+0.1wt%WO_3[47] systems, where the U_{rec} reaches 2.5 J cm^{-3} and 3.3 J cm^{-3}, respectively. Another is ion substitutions, e.g., replacement of Ag^+ by La^{3+}[48], Sm^{3+}[59], Ba^{2+}[60], Lu^{3+}[61], Gd^{3+}[62], etc., and/or Nb^{5+} by Ta^{5+} [52]. The U_{rec} can be effectively increased to 3.2 J cm^{-3} in $Ag_{1-3x}La_xNbO_3$ system at x=0.02[48], 4.5 J·cm^{-3} in $Ag_{1-3x}Sm_xNbO_3$ system at x=0.02[59], 2.3 J cm^{-3} in $Ag_{1-2x}Ba_xNbO_3$ system at x=0.02[60], and 4.2 J cm^{-3} in $Ag(Nb_{1-x}Ta_x)O_3$ system at x=0.15[52], and so on. Reducing

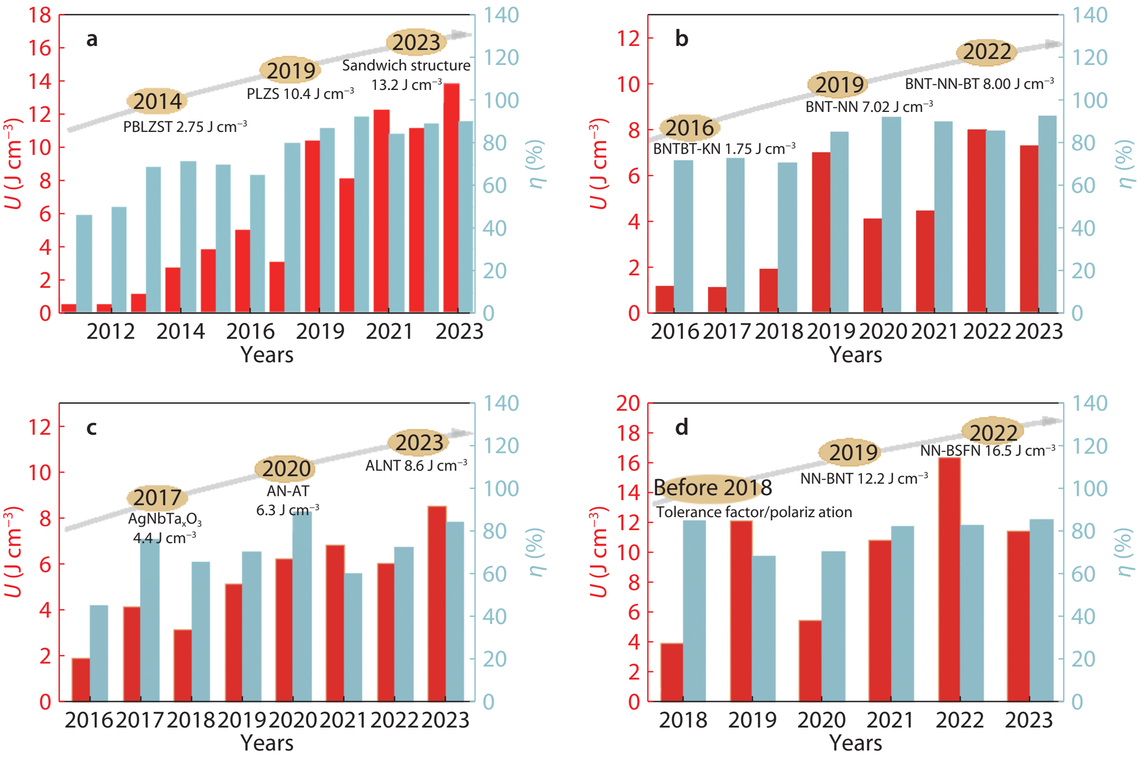

Fig. 2 Comparison of energy-storage properties among four typical anti-ferroelectric ceramics in recent 10 years.

the thickness of the dielectric layer is the other efficacious strategy to enhance the BDS and U_{rec} of the AN system. For example, Zhu et al.[63] indicates that an ultrahigh $U_{rec} > 14$ J cm^{-3} and excellent $\eta > 85$ % were achieved in $Sm_{0.05}Ag_{0.85}Nb_{0.7}Ta_{0.3}$ MLCCs. All these results suggest that AN AFE materials have a great application potential in pulsed-discharge and power conditioning electronic devices. However, it is difficult to meet the low-cost market requirement because of its high price for raw materials in AN system.

$NaNbO_3$ based antiferroelectrics

Sodium niobate ($NaNbO_3$, NN) system has also been attracted intensive interest because it has similar with AN system's AFE perovskite structure. Different with the AN system, lead-free NN AFE ceramics has a raw material with low cost, simple sintering process, high band gap, and so on, which was considered the most promising dielectric capacitors. However, it is difficult to get double P-E hysteresis loops at room temperature, because its metastable FE phase (P21ma) and AFE phase (Pbma) can coexist at room temperature and the electric field induced FE phase can still be preserved after the electric field is removed, exhibiting a ferroelectric P-E hysteresis loop[64–71]. An idea which was to stabilize the antiferroelectric phase and exploits its potential for AFE energy storage was achieved in $NaNbO_3$-$CaZrO_3$[72,73], $NaNbO_3$-$CaHfO_3$[74], and $NaNbO_3$-$CaSnO_3$[75] systems, and so on with applying the strategy of reducing the tolerance factor and average B-site polarization. However, their U_{rec} are still very low because of low BDS and large P_r. For example, the U_{rec} and η of AFE $NaNbO_3$-$CaZrO_3$ system are just about 0.55 J cm^{-3} and 63% [76]. To further improve the U_{rec} and η, many of the strategies were adopted, such as breaking long-range ferroelectric order which is the benefit to build relaxation characteristics and improve BDS, decreasing the grain size or reducing the dielectricpropertiestoenhancethebreakdownfield,andsoon[77–87]. The U_{rec} and η of NN-based ceramics have gotten an obviously improvement as shown in Fig. 2d [76–79,84,88–90]. For example Qi et al.[77] have reported that an 0.76$NaNbO_3$-0.24$(Bi_{0.5}Na_{0.5})TiO_3$ relaxor antiferroelectric (AFE) ceramic was designed, which shown an ultrahigh energy-storage density U_{rec} = 12.2 J cm^{-3}, which is higher that of other lead-free system and most of lead ceramic. Xie et al.[78] have shown that the fine grain for 0.83$NaNbO_3$-0.17$SrTiO_3$ ceramics prepared by the two-step sintering method is the benefit to improve the U_{rec} and η, which are 1.60 J cm^{-3} and 50%, respectively. Besides, Shi et al.[48] have reported that a *PC*-phase 0.78NN-0.22$Bi(Mg_{2/3}Ta_{1/3})O_3$ ceramics has ultrahigh breakdown field about 627 kV cm^{-1}, which conduce to achieving high U_{re}= 5.01 J cm^{-3}. Although the U_{rec} and η of NN-based ceramics have achieved a big breakthrough, they still have some shortcomings, such as the volatilization of Na ions at high temperature, complex phase transitions and sample poor stability, which is not conducive to its practical application.

Other properties

Except the U_{rec} and η, the cost of raw materials for dielectric capacitors is also another critical factor in whether it can be used to industrialization application. Herein, the prices of

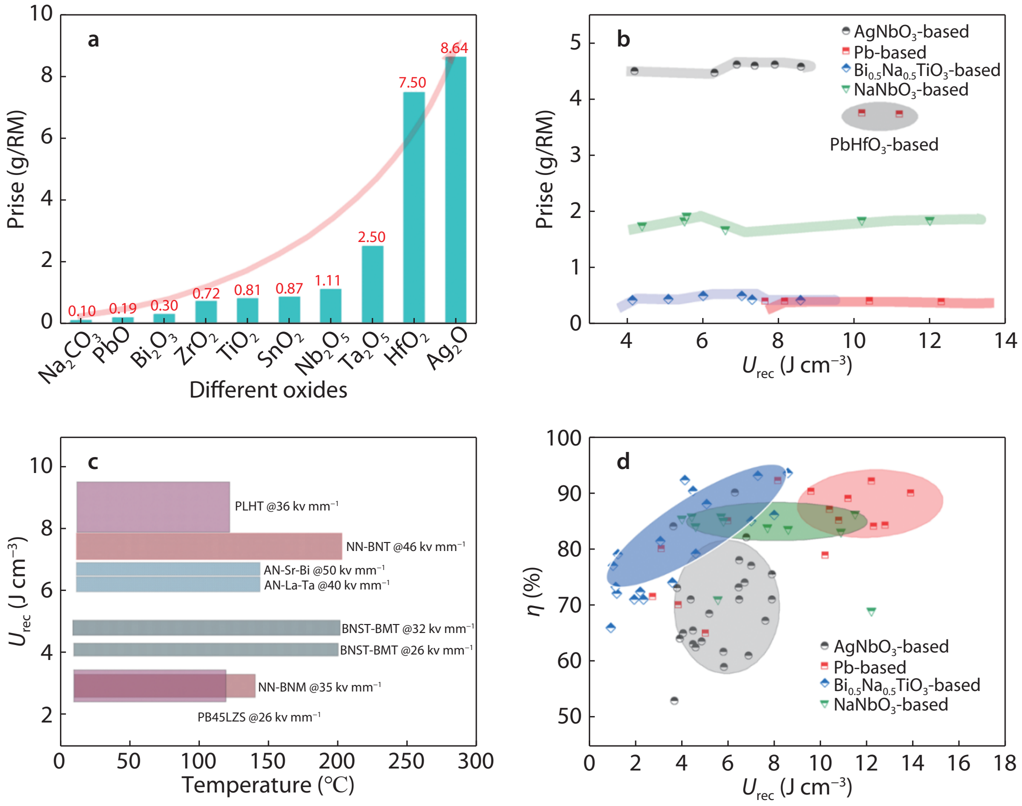

Fig. 3 **a** The prices of commonly used oxides. Comparison of **b** raw material price, **c** temperature stability and **d** energy storage performance of four typical antiferroelectric ceramics reported recently.

main four typical antiferroelectric raw materials (data from McLean and Aladdin website) are listed in Fig. 3a. Ag_2O and HfO_2 are the most expensive than others in these raw materials, which lead to the $AgNbO_3$-based and $PbHfO_3$-based AFE ceramics exhibited high raw material cost as shown in Fig. 3b [22–24,32,37,40,43,55,56,77,91–95] that is not conducive to their practical application. Besides, the temperature stability is also the crucial parameters to make sure the practical application of dielectric capacitor. The temperature stability of $Bi_{0.5}Na_{0.5}TiO_3$-based and $AgNbO_3$-based systems is better than that of $NaNbO_3$-based and Pb-based capacitors as shown in Fig. 3c [30,40,58,92,94,96,97]. This result suggests that $Bi_{0.5}Na_{0.5}TiO_3$-based and $AgNbO_3$-based ceramics can be used in more complex environments conditions. Fig. 3d presents the comparison of U_{rec} and η of these typical AFE ceramics [19–24,26,27,29,30,35,37,39,40,48,54–56,59,77,88–90,92,94,98–127]. The Pb-based capacitor possesses the highest U_{rec} than others, and an excellent η. In addition, the U_{rec} and η of $Bi_{0.5}Na_{0.5}TiO_3$-based and $NaNbO_3$ ceramics are higher than that of $AgNbO_3$-based systems.

Outlook and perspective

To meet the practical applications, the energy storage capacitors are needed to possess not only the high U_{rec} and η values, but also the excellent temperature stability and the low cost as well as environment friendly, and so on. The advantages and disadvantages of four typic antiferroelectric systems were shown in Table 1. Although the Pb-based AFE capacitors have a significant advantage in U_{rec} and η, its widespread adoption will be restricted because the hazardous element exists. In addition, $AgNbO_3$-based ceramic has an ultrahigh BDS, high U_{rec} and η, as well as excellent temperature stability, but it is also difficult to be used to marketization due to high cost for raw materials. However, for $NaNbO_3$-based and $Bi_{0.5}Na_{0.5}TiO_3$-based AFE systems, due to low cost for the raw materials, eco-friendly, high $U_{rec} > 10$ J cm^{-3} and $\eta > 85$ %, as well as excellent temperature stability, they have a great potential in pulsed-discharge and power conditioning electronic devices as the energy storage capacitors.

Table 1. The advantages and disadvantages of four typic antiferroelectric systems.

	Pb-based	$Bi_{0.5}Na_{0.5}TiO_3$-based	$AgNbO_3$-based	$NaNbO_3$-based
U_{rec}	excellent	poor	well	well
η	well	excellent	poor	well
Materials price	low	low	high	midium
Human health	poor	excellent	excellent	well

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The manuscript was drafted by Dong Liu and revised by Ting Tang and Prof. Li-Feng Zhu. All authors had approved the final version of the manuscript.

REFERENCES

1. F. Z. Yao, Q. Yuan, Q. Wang, H. Wang, *Nanoscale*, 2020, 12, 17165
2. L. Qi, F. Z. Yao, Y. Liu, G. Z. Zhang, H. Wang, Q. Wang, *The Annual Review of Materials Research*, 2018, 48, 219
3. H. Palneedi, M. Peddigari, G. Hwang, D. Jeong, J. Ryu, *Adv. Funct. Mater.*, 2018, 28, 1803665
4. G. Zhang, S. Zhang, Q. Wang, *J. Materiomics.*, 2022, 8, 1287
5. P. Gao, Z. Liu, N. Zhang, H. Wu, A. Bokov, W. Ren, Z. Ye, *Chem. Mater.*, 2019, 31, 979
6. X. K. Wei, C. L. Jia, H. C. Du, K. Roleder, J. Mayer, R. Dunin-Borkowski, *Adv. Mater.*, 2020, 32, 1907208
7. J. Li, F. Li, Z. Xu, S. Zhang, *Adv. Mater.*, 2018, 30, 1802155
8. P. Zhao, H. Wang, L. Wu, L. Chen, Z. Cai, L. Li, X. Wang, *Adv. Energy Mater.*, 2019, 9, 1803048
9. N. Liu, R. Liang, Z. Zhou, X. Dong, *J. Mater. Chem. C*, 2018, 6, 10211
10. L. Zhu, X. Lei, L. Zhao, M, Hussain, G. Zhao, B. Zhang, *Ceram. Inter.*, 2019, 45, 20266.
11. B. Luo, X. Wang, E. Tian, H. Song, H. Wang, L. Li, *ACS Appl. Mater. Interfaces*, 2017, 9, 19963
12. S. I. Shkuratov, J. Baird, V. G. Antipov, S. Zhang, J. B. Chase, *Adv. Mater.*, 2019, 31, 1904819
13. L. Chen, N. Sun, Y. Li, Q. Zhang, L. Zhang, X. Hao, *J. Am. Ceram. Soc.*, 2018, 101, 2313
14. Q. Zhang, Y. Dan, J. Chen, Y. Lu, T. Yang, Y. He, *Ceram. Int.*, 2017, 43, 11428
15. H. Zhang, X. Chen, F. Cao, G. Wang, X. Dong, Z. Hu, T. Du, *J. Am. Ceram. Soc.*, 2010, 93, 4015
16. Y. Wang, X. Hao, J. Yang, J. Xu, D. Zhao, *J. Appl. Phys.*, 2012, 112, 034105
17. S. Jiang, L. Zhang, G. Zhang, S. Liu, J. Yi, X. Xiong, Y. Yu, J. He, Y. Zeng, *Ceram. Int.*, 2013, 39, 5571
18. S. Chen, X. Wang, T. Yang, J. Wang, *J. Electroceram.*, 2014, 32, 307
19. X. Yang, Y. Liu, C. He, H. Tailor, X. Long, *J. Eur. Ceram. Soc.*, 2015, 35, 4173
20. X. Yang, C. He, Y. Liu, X. Li, Z. Wang, S. Han, S. Pan, X. Long, *Ceram. Int.*, 2016, 42, 10472
21. L. Xu, C. He, X. Yang, Z. Wang, X. Li, H. M. Tailor, X. Long, *J. Eur. Ceram. Soc.*, 2017, 37, 3329
22. H. Wang, Y. Liu, T. Yang, S. Zhang, *Adv. Funct. Mater.*, 2019, 29, 1807321.
23. K. Huang, G. Ge, F. Yan, B. Shen, J. Zhai, *Adv. Electron Mater.*, 2020, 6, 1901366.
24. X. Liu, T. Yang, W. Gong, *J. Mater. Chem. C*, 2021, 9, 12399.
25. L. Chen, J. Zhou, L. Xu, J. Ding, Z. Sun, Q. Bao, X. Hao, *Chem. Eng.*

J., 2022, 447, 137367
26. X. Liu, T. Yang, B. Shen, L. Chen, *ACS Appl. Energy Mater.*, 2023, 6, 1218
27. L. Zhang, S. Jiang, Y. Zeng, M. Fu, K. Han, Q. Li, Q. Wang, G. Zhang, *Ceram. Int.*, 2014, 40, 5455
28. J. Xie, M. Yao, W. Gao, Z. Su, X. Yao, *J. Eur. Ceram. Soc.*, 2019, 39, 1050
29. G. Ge, K. Huang, S. Wu, F. Yan, X. Li, B. Shen, J. Zhai, *Energy Storage Mater.*, 2021, 35, 114
30. R. Xu, Q. Zhu, Z. Xu, Y. Feng, X. Wei, *Appl. Phys. Lett.*, 2022, 120, 52904
31. X. Meng, Y. Zhao, J. Zhu, L. Zhu, Y. Li, X, Hao, *J. Eur. Ceram. Soc.*, 2022, 42, 6493
32. X. Liu, J. Zhu, Y. Li, T. Yang, X. Hao, W. Gong, *Chem. Eng. J.*, 2022, 446, 136729
33. L. Yang, X. Kong, F. Li, H. Hao, Z. Cheng, H. Liu, J.-F. Li, S. Zhang, *Prog. Mater. Sci.*, 2019, 102, 72
34. Q. Xu, J. Xie, Z. He, L. Zhang, M. Cao, X. Huang, M. T. Lanagan, H. Hao, Z. Yao, H. Liu, *J. Eur. Ceram. Soc.*, 2017, 37, 99
35. Z. Yu, Y. Liu, M. Shen, H. Qian, F. Li, Y. Lyu, *Ceram. Int.*, 2017, 43, 7653
36. X. Zhou, H. Qi, Z. Yan, G. Xue, H. Luo, D. Zhang, *ACS Appl. Mater. Interfaces*, 2019, 11, 43107
37. X. Qiao, F. Zhang, D. Wu, B. Chen, X. Zhao, Z. Peng, X. Ren, P. Liang, X. Chao, Z. Yang, *Chem. Eng. J.*, 2020, 388, 124158
38. L. Zhang, R. Jing, Y. Huang, Q. Hu, D. O. AliKin, V. Y. Shur, J. Gao, X. Wei, L. Zhang, G. Liu, Y. Yan, L. Jin, *J. Materiomics.*, 2022, 8, 527
39. Y. Zhang, A. Xie, J. Fu, X. Jiang, T. Li, C. Zhou, R. Zuo, *ACS Appl. Mater. Interfaces*, 2022, 14, 40043
40. R. Kang, Z. Wang, M. Wu, S. Cheng, S. Mi, Y. Hu, L. Zhang, D. Wang, X. Lou, *Nano Energy*, 2023, 112, 108477
41. Y. Pu, M. Yao, L. Zhang, P. Jing, *J. Alloy Compd.*, 2016, 687, 689
42. B. Hu, H. Q. Fan, N. Li, S. Gao, Z. J. Yao, Q. Li, *Ceram. Int.*, 2018, 44, 10968
43. H. Qi, R. Zuo, *J. Mater. Chem. A*, 2019, 7, 3971
44. T. Wei, K. Liu, P. Fan, D. Lu, B. Ye, C. Zhou, H. Yang, H. Tan, D. Salamon, B. Nan, H. Zhang, *Ceram. Int.*, 2021, 47, 3713
45. J. Li, Z. Shen, X. Chen, S. Yang, W. Zhou, M. Wang, L. Wang, Q. Kou, Y. Liu, Q. Li, Z. Xu, Y. Chang, *Nat. Mater.*, 2020, 19, 999
46. D. Fu, M. Endo, H. Taniguchi, T. Taniyama, M. Itoh, *Appl. Phys. Lett.*, 2007, 90, 252907
47. L. Zhao, J. Gao, Q. Liu, S. Zhang, J.-F. Li, *ACS Appl. Mater. Interfaces*, 2018, 10, 819
48. N. Luo, K. Han, L. Liu, B. Peng, X. Wang, C. Hu, H. Zhou, Q. Feng, X. Chen, Y. Wei, *J. Am. Ceram. Soc.*, 2019, 102, 4640
49. H. Pan, J. Ma, J. Ma, Q. Zhang, X. Liu, B. Guan, L. Gu, X. Zhang, Y.-J. Zhang, L. Li, Y. Shen, Y.-H. Lin, C.-W, *Nan, Nat. Commun.*, 2018, 9, 1813
50. H. Pan, F. Li, Y. Liu, Q. Zhang, M. Wang, S. Lan, Y. Zheng, J. Ma, L. Gu, Y. Shen, P. Yu, S. Zhang, L.-Q. Chen, Y.-H. Lin, C.-W, *Nan, Science*, 2019, 365, 578
51. L. Zhao, Q. Liu, S. Zhang, J.-F. Li, *J. Mater. Chem. C*, 2016, 4, 8380
52. L. Zhao, Q. Liu, J. Gao, S. Zhang, J.-F. Li, *Adv. Mater.*, 2017, 29, 1701824
53. C. Xu, Z. Fu, Z. Liu, L. Wang, S. Yan, X. Chen, F. Cao, X. Dong, G. Wang, *ACS Sustain Chem. Eng.*, 2018, 6, 16151
54. N. Luo, K. Han, F. Zhuo, C. Xu, G. Zhang, L. Liu, X. Chen, C. Hu, H. Zhou, Y. Wei, *J. Mater. Chem. A*, 2019, 7, 14118
55. N. Luo, K. Han, M. J. Cabral, X. Liao, S. Zhang, C. Liao, G. Zhang, X. Chen, Q. Feng, J.-F. Li, Y. Wei, *Nat. Commun.*, 2020, 11, 4824
56. W. Chao, J. Gao, T. Yang, Y. Li, *J. Eur. Ceram. Soc.*, 2021, 41, 7670
57. Y. Xu, Z. Yang, K. Xu, J. Tian, D. Zhang, M. Zhan, H. Tian, X. Cai, B. Zhang, Y. Yan, L. Guo, G. Wang, L. Lin, J. Fan, T. Wang, Y. Tian, *J. Alloy. Compod.*, 2022, 913, 165313
58. L. He, Y. Yang, C. Liu, Y. Ji, X. Lou, L. Zhang, X. Ren, *Acta Materialia.*, 2023, 249, 118826
59. J. Gao, Q. Liu, J. Dong, X. Wang, S. Zhang, J.-F. Li, *ACS Appl. Mater. Interfaces*, 2020, 12, 6097
60. K. Han, N. Luo, Y. Jing, X. Wang, B. Peng, L. Liu, C. Hu, H. Zhou, Y. Wei, X. Chen, Q. Feng, *Ceram. Int.*, 2019, 45, 5559
61. S. Mao, N. Luo, K. Han, Q. Feng, X. Chen, B. Peng, L. Liu, C. Hu, H. Zhou, F. Toyohisa, Y. Wei, *J. Mater. Sci: Mater. El.*, 2020, 31, 7731
62. S. Li, H. Nie, G. Wang, C. Xu, N. Liu, M. Zhou, F. Cao, X. Dong, *J. Mater. Chem. C*, 2019, 7, 1551
63. L.-F. Zhu, S. Deng, L. Zhao, G. Li, Q. Wang, L. Li, Y. Yan, H. Qi, B.-P. Zhang, J. Chen, J.-F. Li, *Nat. Commun.*, 2023, 14, 1166
64. R. H. Dungan, R. D, *J. Am. Ceram. Soc.*, 1964, 47, 73
65. A. V. Ulinzheyev, O. E. Fesenko, V. G. Smotrakov, *Ferroelectrics Lett.*, 1990, 12, 17
66. A. V. Ulinzheyev, A. V. Leiderman, V. G. Smotrakov, V. Y. Topolov, O. E. Fesenko, *Phys. solid state*, 1997, 39, 972
67. V. A. Shuvaeva, M. Y. Antipin, R. S. V. Lindeman, O. E. Fesenko, V. G. Smotrakov, Y. T. Struchkov, *Ferroelectrics*, 1993, 141, 307
68. T. Arioka, H. Taniguchi, M. Itoh, K. Oka, R. Wang, D. Fu, *Ferroelectrics*, 2010, 401, 51
69. H. Shimizu, K. Kobayashi, Y. Mizuno, Clive A. Randall, *J. Am. Ceram. Soc.*, 2014, 97, 1791
70. Y. Xu, W. Hong, Y. Feng, X. Tan, *Appl. Phys. Lett.*, 2014, 104, 52903
71. D. Fu, T. Arioka, H. Taniguchi, T. Taniyama, M. Itoh, *Appl. Phys. Lett.*, 2011, 99, 012904
72. H. Shimizu, H. Guo, S. E. Reyes-Lillo, Y. Mizuno, K. M. Rabe, C. A. Randall, *Dalton Trans.*, 2015, 44, 10763
73. H. Guo, H. Shimizu, Y. Mizuno, C. A. Randall, *J. Appl. Phys.*, 2015, 118, 054102
74. L. Gao, H. Guo, S. Zhang, C. A. Randall, *J. Appl. Phys.*, 2016, 120, 204102
75. J. Ye, G. Wang, X. Chen, F. Cao, X. Dong, *Appl. Phys. Lett.*, 2019, 114, 122901
76. Z. Liu, J. Lu, Y. Mao, P. Ren, H. Fan, *J. Eur. Ceram. Soc.*, 2018, 38, 4939
77. H. Qi, R. Zuo, A. Xie, A. Tian, J. Fu, Y. Zhang, S. Zhang, *Adv. Funct. Mater.*, 2019, 29, 1903877
78. A. Xie, H. Qi, R. Zuo, *ACS Appl. Mater. Interfaces*, 2020, 12, 19467
79. J. Shi, X. Chen, X. Li, J. Sun, C. Sun, F. Pang, H. Zhou, *J. Mater. Chem. C*, 2020, 8, 3784
80. R. Jing, L. Jin, Y. Tian, Y. Huang, Y. Lan, J. Xu, Q. Hu, H. Du, X. Wei, D. Guo, J. Gao, F. Gao, *Ceram. Int.*, 2019, 45, 21175
81. Y. Fan, Z. Zhou, R. Liang, X. Dong, *J. Eur. Ceram. Soc.*, 2019, 39, 4770
82. H. Qi, R. Zuo, A. Xie, X. Fu, D. Zhang, *J. Eur. Ceram. Soc.*, 2019, 39, 3703
83. M. Zhou, R. Liang, Z. Zhou, S. Yan, X. Dong, *ACS Sustain. Chem. Eng.*, 2018, 6, 12755
84. M. Zhou, R. Liang, Z. Zhou, S. Yan, X. Dong, *J. Mater. Chem. A*, 2018, 6, 17896
85. M. Zhou, R. Liang, Z. Zhou, X. Dong, *Sustain Energ. Fuels*, 2020, 4, 1225
86. N. Qu, H. Du, X. Hao, *J. Mater. Chem. C*, 2019, 7, 7993
87. R. Shi, Y. Pu, W. Wang, X. Guo, J. Li, M. Yang, S. Zhou, *J. Alloy. Compd.*, 2020, 815, 152356
88. A. Tian, R. Zuo, H. Qi, M. Shi, *J. Mater. Chem. A*, 2020, 8, 8352
89. J. Jiang, X. Meng, L. Li, J. Zhang, S. Guo, J. Wang, X. Hao, H. Zhu, S. Zhang, *Chem. Eng. J.*, 2021, 422, 130130
90. T. Pan, J. Zhang, D. Che, Z. Wang, J. Wang, J. Wang, Y. Wang, *Appl. Phys. Lett.*, 2023, 122, 72902
91. P. Qiao, Y. Zhang, X. Chen, M. Zhou, G. Wang, X. Dong, *J. Alloy. Compd.*, 2019, 780, 581
92. H. Yuan, X. Fan, Z. Zheng, M. Zhao, L. Zhao, K. Zhu, J. Wang, *Chem. Eng. J.*, 2023, 456, 141023
93. S. Gao, Y. Huang, Y. Jiang, M. Shen, H. Huang, S. Jiang, Y. He, Q.

DOI: 10.54227/mlab.20230028

Zhang, *Acta Materialia*, 2023, 246, 118730.
94. M. Wang, Q. Feng, C. Luo, Y. Lan, C. Yuan, N. Luo, C. Zhou, T. Fujita, J. Xu, G. Chen, Y. Wei, *ACS Appl. Mater. Interfaces*, 2021, 13, 51218
95. J. Liu, P. Li, C. Li, W. Bai, S. Wu, P. Zheng, J. Zhang, J. Zhai, *ACS Appl. Mater. Interfaces*, 2022, 14, 17662
96. A. Xie, J. Fu, R. Zuo, C. Zhou, Z. Qiao, T. Li, S. Zhang, *Chem. Eng. J.*, 2022, 429, 132534
97. W. Chao, L. Tian, T. Yang, Y. Li, Z. Liu, *Chem. Eng. J.*, 2022, 433, 133814
98. Y. Zhou, S. Gao, J. Huang, M. Shen, S. Jiang, Y. He, Q. Zhang, *J. Materiomics*, 2023, 9, 410.
99. D. Feng, H. Du, H. Ran, T. Lu, S. Xia, L. Xu, Z. Wang, C. Ma, *J. Solid State Chem.*, 2022, 310, 123081
100. Y. Xu, Y. Guo, Q. Liu, Y. Yin, J. Bai, L. Lin, J. Tian, Y. Tian, *J. Alloy. Compd.*, 2020, 821, 153260
101. J. Ai, X. Chen, L. Luo, R. Zheng, L. Xu, *Ceram. Int.*, 2022, 48, 23630
102. S. Li, T. Hu, H. Nie, Z. Fu, C. Xu, F. Xu, G. Wang, X. Dong, *Energy Storage Mater.*, 2021, 34, 417
103. L.-F. Zhu, L. Zhao, Y. Yan, H. Leng, X. Li, L.-Q. Cheng, X. Xiong, S. Priya, *J. Mater. Chem. A*, 2021, 9, 9655
104. Z. Lu, W. Bao, G. Wang, S.-K. Sun, L. Li, J. Lei, H. Yang, H. Ji, A. Feteira, D. Li, F. Xu, A. K. Kleppe, D. Wang, S.-Y. Liu, I. M. Reaney, *Nano Energy*, 2021, 79, 105423
105. J. Gao, Y. Zhang, L. Zhao, K.-Y. Lee, Q. Liu, A. Studer, M. Hinterstein, S. Zhang, J.-F. Li, *J. Mater. Chem. A*, 2019, 7, 2225
106. M. Shang, P. Ren, D. Ren, X. Wang, X. Lu, F. Yan, G. Zhao, *Mater. Res. Bull.*, 2023, 157, 112008
107. J. Li, L. Jin, Y. Tian, C. Chen, Y. Lan, Q. Hu, C. Li, X. Wei, H. Yan, *J. Materiomics*, 2022, 8, 266
108. M. Zhao, J. Wang, H. Yuan, Z. Zheng, L. Zhao, *J. Materiomics*, 2023, 9, 19
109. P. Shi, X. Wang, X. Lou, C. Zhou, Q. Liu, L. He, S. Yang, X. Zhang, *J. Alloy. Compd.*, 2021, 877, 160162
110. B. Li, Z. Yan, X. Zhou, H. Qi, V. Koval, X. Luo, H Luo, H. Yan, D. Zhang, *ACS Appl. Mater. Interfaces*, 2023, 15, 4246
111. L. Ma, Z. Chen, Z. Che, Q. Feng, Z. Cen, F. Toyohisa, Y. Wei, C. Hu, L. Liu, N. Luo, *J. Eur. Ceram. Soc.*, 2022, 42, 2204
112. K. Han, N. Luo, S. Mao, F. Zhuo, L. Liu, B. Peng, X. Chen, C. Hu, H. Zhou, Y. Wei, *J. Mater. Chem. A*, 2019, 7, 26293
113. L. Ma, Z. Che, C. Xu, Z. Cen, Q. Feng, X. Chen, F. Toyohisa, J.-F. Li, S. Zhang, N. Luo, *J. Eur. Ceram. Soc.*, 2023, 43, 3228
114. P. Ge, X. Tang, K. Meng, X.-X. Huang, Q.-X. Liu, Y.-P. Jiang, W.-P. Gong, T. Wang, *Mater. Today Phys.*, 2022, 24, 100681
115. K. Huang, G. Ge, H. Bai, F. Yan, X. He, Y. Shi, B. shen, J. Zhai, *J. Eur. Ceram. Soc.*, 2021, 41, 2450
116. P. Ge, X. Tang, K. Meng, X.-X. Huang, S.-F. Li, Q.-X. Liu, Y.-P. Jiang, *Chem. Eng. J.*, 2022, 429, 132540
117. X. Meng, Y. Zhao, Y. Li, X. Hao, *J. Am. Ceram. Soc.*, 2021, 104, 2170
118. G. Ge, H. Bai, Y. Shi, C. Shi, X. He, J. He, B. Shen, J. Zhai, X. Chou, *J. Mater. Chem. A*, 2021, 9, 11291
119. Y. Wu, Y. Fan, N. Liu, P. Peng, M. Zhou, S. Yan, F. Cao, X. Dong, G. Wang, *J. Mater. Chem. C*, 2019, 7, 6222
120. P. Ren, Z. Liu, X. Wang, Z. Duan, Y. Wan, F. Yan, G. Zhao, *J. Alloy. Compd.*, 2018, 742, 683
121. X. Wu, H. Liu, J. Chen, *J. Mater. Res.*, 2021, 36, 1153
122. Y. Pu, L. Zhang, Y. Cui, M. Chen, *ACS Sustain. Chem. Eng.*, 2018, 6, 6102
123. D. He, Y. Wang, S. Song, S. Liu, Y. Luo, Y. Deng, *Compos. Sci. Technol.*, 2017, 151, 25
124. Y. Shen, L. Wu, J. Zhao, J. Liu, L. Tang, X. Chen, H. Li, Z. Su, Y. Zhang, J. Zhai, Z. Pan, *Chem. Eng. J.*, 2022, 439, 135762
125. Q. Wang, B. Xie, Q. Zheng, M. A. Marwat, Z. Liu, P. Mao, S. Jiang, H. Zhang, *Chem. Eng. J.*, 2023, 452, 139422
126. R. Kang, Z. Wang, W. Yang, X. Zhu, L. He, Y. Gao, J. Zhao, P. Shi, Y. Zhao, P. Mao, Y. Hu, L. Zhang, X. Lou, *Chem. Eng. J.*, 2022, 446, 137105
127. B. Laubacker, K. Wang, M. Wetherington, N. Wonderling, J. V. Badding, S. E. Mohney, *J. Mater Sci: Mater. Ele.*, 2023, 34, 741

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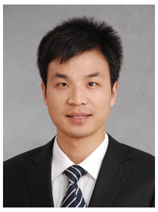

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