

电介质材料的多维度进展

吴迪¹, 雷文², 马名生³

(1. 南京大学 现代工程与应用科学学院, 南京 210023; 2. 华中科技大学 光学与电子信息学院, 武汉 430074;
3. 中国科学院 上海硅酸盐研究所, 上海 201800)

电介质材料是一类重要的功能材料, 从 5G/6G 通信的高速传输到智能传感器的精准感知, 都离不开电介质材料独特的介电、压电与铁电特性。随着材料设计从宏观尺度深入到原子层面, 性能优化从经验积累转向数据智能驱动, 电介质材料研究领域已迈入新阶段。

通过精确调控电介质材料中的晶体缺陷、畴结构和界面特性, 可以使电介质材料性能获得进一步突破。例如, 采用织构化技术显著提升了铅基压电陶瓷的性能; 通过调整 Ruddlesden-Popper 结构的维度发现了新型铁电态; 微波介质陶瓷在保持介电常数的同时提高了温度稳定性, 为高频器件发展提供了新可能。这些研究进展表明, 材料微结构的精确设计和多维度调控已成为电介质材料发展的主要方向之一。

本专刊汇集了国内电介质材料领域的最新研究成果。王轲研究员和李飞教授分别从不同角度深入剖析了铅基织构压电陶瓷的进展; 刘小强教授详细解析了 Ruddlesden-Popper 结构铁电体的非常规铁电性物理机制; 李恩竹教授通过 P-V-L 键理论, 为微波介质陶瓷的性能优化提供了分子层面的设计指导; 周迪教授重新评估了 $\text{Ba}(\text{Nd}_{1/2}\text{Nb}_{1/2})\text{O}_3$ 陶瓷的价值; 李玲霞教授则在 MgNb_2O_6 陶瓷太赫兹介电性能方面有了新的突破, 推进了微波介质陶瓷的研究进展。

在具体技术突破方面, 方亮教授发现了 Rattling 效应新机制, 为改善微波介质陶瓷的温度稳定性提供了新的思路; 雷文研究员和张博研究员分别采用离子掺杂策略提升了微波介质陶瓷的性能; 朱建国教授和周志勇研究员分别通过自掺杂策略, 提升了无铅压电材料的性能; 汪尧进教授通过调控相界与畴工程, 优化了 PZT 基陶瓷的压电性能, 进一步验证了“结构决定性能”的基本规律。

制备技术和表征方面的进展同样值得关注。郑木鹏团队总结的低温烧结技术, 以及刘志甫研究员和马名生研究员开发的复合氧化物烧结助剂, 都有效降低了陶瓷的烧结温度; 温峥教授与许钊钊研究员分别利用压电力显微镜(PFM)与电子能量损失谱(EELS)技术, 分析了超薄膜的弛豫特性与多层陶瓷电容器(MLCC)元素的精准结构, 为微型化电介质器件的研发奠定了基础。这些突破不仅推动了科研成果的产业化, 也为开发新型、高性能材料体系提供了支持。

展望未来, 电介质材料将呈现三个主要发展趋势: (1) 理论研究将由经验模型转向多尺度计算, 结合机器学习实现材料设计的智能化; (2) 材料性能研究将由单一特性向光电-力-热多场耦合发展, 开发出具有环境适应能力的新型材料; (3) 制备技术将从宏观加工迈向原子级制造, 通过外延生长、拓扑组装等技术制造新型功能材料。这些技术将推动电介质材料在量子计算、太赫兹通信、人形机器人等领域发挥关键作用。

最后, 向所有致力于电介质材料研究的科研工作者致敬。期待通过学科交叉与产学研合作, 电介质材料领域能持续产出创新成果, 为科技进步和社会发展作出更大贡献。

Multidimensional Advances in Dielectric Materials

WU Di¹, LEI Wen², MA Mingsheng³

(1. College of Engineering and Applied Sciences, Nanjing University, Nanjing 210023, China; 2. School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China; 3. Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China)

As a vital category of functional materials, dielectric materials underpin advancements ranging from the high-speed transmission in 5G/6G communications to the precise sensing capabilities of intelligent sensors, all enabled by their unique dielectric, piezoelectric, and ferroelectric properties. As material design advances from macroscopic scale to atomic-level precision, and performance optimization shifts

from empirical accumulation to data-driven intelligence, research on dielectric materials has entered a new phase characterized by transformative innovation.

By controlling crystal defects, domain structures, and interfacial characteristics, dielectric materials exhibit smarter responsive behaviors. For instance, texturing techniques have improved lead-based piezoelectric ceramics; new ferroelectric states have emerged in Ruddlesden-Popper structures; and microwave dielectric ceramics have achieved greater temperature stability without sacrificing permittivity. These advances demonstrate the significance of atomic-level design and multidimensional control in advancing dielectric materials.

This special issue compiles cutting-edge research in the field. Prof. Wang Ke and Prof. Li Fei analyzed progress on lead-based textured piezoelectric ceramics. Prof. Liu Xiaoqiang explored unconventional ferroelectric mechanisms in Ruddlesden-Popper structures. Prof. Li Enzhu proposed molecular-level design guidelines for microwave dielectric ceramics based on P-V-L bond theory. Prof. Zhou Di reassessed $\text{Ba}(\text{Nd}_{1/2}\text{Nb}_{1/2})\text{O}_3$ ceramics, and Prof. Li Lingxia advanced terahertz dielectric research with MgNb_2O_6 ceramics.

Notable breakthroughs include Prof. Fang Liang's discovery of a Rattling-effect mechanism to enhance thermal stability in microwave ceramics, and Prof. Lei Wen and Prof. Zhang Bo's researches on performance enhancement in microwave ceramics *via* ion doping. Additionally, Prof. Zhu Jianguo and Prof. Zhou Zhiyong independently developed self-doping strategies for lead-free piezoelectric materials, while Prof. Wang Yaojin demonstrated the "structure determines properties" paradigm by optimizing PZT-based ceramics through phase boundary and domain engineering.

In fabrication and characterization, Prof. Zheng Mupeng's team pioneered low-temperature sintering techniques, and Prof. Ma Mingsheng and Prof. Liu Zhifu designed composite oxide sintering aids to reduce sintering temperatures. Prof. Wen Zheng and Prof. Xu Fangfang utilized PFM and EELS to analyze ultrathin film relaxation and MLCC elemental structures, laying the groundwork for miniaturized dielectric devices. These efforts bridge academia and industry, driving sustainable high-performance materials.

Looking forward, three trajectories will guide future developments: (1) theoretical evolution, with the shift from empirical models to multiscale simulations integrated with machine learning for smart material design; (2) multifunctional integration, aiming to engineer materials with coupled opto-electro-mechanical-thermal responses for adaptive systems; (3) atomic-scale fabrication, leveraging epitaxial growth and topological assembly to create artificial materials with atomic precision. These trends position dielectric materials as crucial enablers in quantum computing, terahertz communications, humanoid robots, and other strategic fields.

We extend the deepest respect to researchers advancing dielectric materials. Through interdisciplinary collaboration and industry-academia partnerships, this field will continue delivering transformative innovations for both technological and societal progress.

文章编号: 1000-324X(2025)06-0561-02



吴迪, 南京大学教授, 南京大学科学技术研究院院长。曾为教育部长江学者特聘教授、基金委杰出青年基金获得者、万人计划科技创新领军人才。长期从事钙钛矿磁电功能氧化物薄膜新材料和相关存储、传感新技术研究, 在国内外学术期刊发表论文 80 余篇, 曾任科技部国家重大科学研究计划项目负责人, 曾获国家自然科学基金二等奖。

E-mail: diwu@nju.edu.cn



雷文, 华中科技大学研究员, 华中科技大学温州先进制造技术研究院副院长, 中国电子材料与元器件产学研协同创新平台理事。长期从事 5G 通信用微波介质材料与 LTCC 集成元件的研究和成果转化工作。在国际权威期刊上发表学术论文 170 余篇, 曾获 2024 年度中国发明协会发明创业成果奖一等奖。

E-mail: wenlei@hust.edu.cn



马名生, 中国科学院上海硅酸盐研究所研究员, 关键陶瓷材料全国重点实验室主任助理, 上海市优秀青年学术带头人, 中国科学院青年创新促进会优秀会员。主要从事 LTCC 及 PTC 热敏材料及功能器件研究, 发表学术论文 50 余篇, 授权专利 18 项, 曾获大飞机先进材料创新联盟优秀成果奖, 上海市优秀技术发明金奖。

E-mail: mamingsheng@mail.sic.ac.cn