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Optimization and Functional Characterization of Ferroelectric-Based Materials and Composites: From Solid Solutions to Porous Systems for Advanced Applications

Habilitation Thesis

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Summary

The habilitation thesis, titled *Optimization and Functional Characterization of Ferroelectric-Based Materials and Composites: From Solid Solutions to Porous Systems for Advanced Applications*, is structured into two principal sections. The first section outlines my research contributions to ferroelectric-based materials, focusing on $BaTiO_3$ (BT)-based solid solutions and composite systems. The second section presents my career development plan, which aims to strengthen academic and industrial collaborations in materials science.

Section I: Scientific and Professional Results provides a comprehensive investigation into the development and optimization of ferroelectric materials, with a focus on BT-based solid solutions and composite structures. It includes an in-depth study of preparation methods, compositional modifications, structural characteristics, and microstructural tuning, analyzing the impact of these variables on functional properties. The research addresses:

1. **Ferroelectric-based solid solutions**: Key contributions to understanding the relaxor-ferroelectric behavior in $Ba(Zr,Ti)O_3$ (BZT) ceramics include a detailed study of the compositionally induced crossover from ferroelectric to relaxor states, phase transitions through Landau theory, and the effects of oxygen vacancies on dielectric response. Advanced characterization techniques reveal the impact of Zr substitution in BT, providing insights into switching properties and grain boundary effects that enhance functional behavior in BT-based applications.
2. **Ferroelectric-based composite systems**:

(i) **Ferroelectric-ferrite magnetoelectric composites**: This research examines both lead-based ($Pb(Zr,Ti)O_3$) and lead-free (BT-based) magnetoelectric composites, exploring the relationships between preparation methods, composition, structure, and microstructure on their functional properties. The focus is on volume-surface effects, interconnectivity, and percolation phenomena, detailing how these factors influence electric and magnetic properties. The work includes designing composites suitable for miniaturized microwave devices with magnetic tunability, highlighting their potential for microelectronic and environmentally friendly applications.

(ii) **Other Ferroelectric-based composites** include studies on $SrTiO_3$@$BaTiO_3$ nanocomposites and Ag-doped $BaTiO_3$ ceramics. The thesis explores $SrTiO_3$@$BaTiO_3$

nanoceramics fabricated via high-pressure field-assisted sintering, producing materials with stable permittivity, low dielectric losses, and linear tunability suitable for high-frequency electronic applications. Through microstructural engineering and optimized sintering conditions, the research enhances dielectric properties and energy storage capabilities, demonstrating the significant impact of additives and processing techniques on the functional performance of these materials.

(iii) **Ferroelectric-polymer composites**: These composites combine the properties of polymers and inorganic fillers. I have investigated and emphasized the incorporation of BT nanofillers or silver (Ag) nanoparticles into polymer matrices such as poly(ε-caprolactone) (PCL), gelatin, and polyvinylidene fluoride (PVDF). Optimizing particle size, volume fraction, and filler distribution, including adding Ag nanoparticles, results in composites with improved dielectric, piezoelectric, and energy storage capabilities. These materials have promising applications in flexible electronics, energy harvesting, and biomedical devices due to their multifunctionality, environmental sustainability, and adaptability.

(iv) **Porous $BaTiO_3$-based composites**: This section explores the transformative role of porosity in $BaTiO_3$-based composites, impacting key functional properties such as dielectric, ferroelectric, and piezoelectric responses. The research emphasizes how engineered porosity can enhance energy harvesting by optimizing dielectric constants, improving tunability, and tailoring microstructural effects to influence polarization behaviors. Integrating theoretical modeling with experimental data, this work demonstrates how strategically introduced porosity—controlled in size, shape, and distribution—supports the creation of efficient, sustainable energy-harvesting materials suitable for advanced electronic applications.

Section II: Career Development Plan outlines my career trajectory, targeting academic advancement through teaching, mentorship, and research. The plan includes objectives such as attaining doctoral advisor status, expanding courses in advanced materials, establishing a dedicated lab for 3D-printed functional ceramics, and fostering industry collaboration. Through active networking, publishing, project proposals, and the integration of new additive manufacturing techniques, I aim to contribute to sustainable energy solutions and cutting-edge research in functional materials, bridging academic and industrial applications.

This thesis highlights significant advancements in ferroelectric-based materials, contributing to both scientific understanding and practical applications while establishing a structured path for continued academic and professional growth in advanced materials research.