Polar Microstructure and Nanoscale Electromechanical Behavior of Lead-Free Piezoelectric Ceramics

Abstract

Within the plethora of energy converters, piezoelectric materials are highly recognized due to their ability of linear, bidirectional translation of mechanical and electric energy. The piezoelectricity of these materials is, as such, employed for countless high-tech applications from piezoelectric actuators, fuel injectors, transducers to piezoelectric motors, micro- and nanopositioning systems, and many others. In order to mitigate the adverse effect of prevalent, high-performance lead zirconate titanate and its compounds on human health and environment, a rapid growth of research efforts has been encouraged in the field of lead-free piezoelectric materials, resulting in an improvement of already existing and the development of a variety of new non-toxic piezoelectric materials.

The present work focuses on the investigation of the salient properties of KNN- and BNT-based piezoelectric materials, performed on the sub-micron scale. The underlying, fundamental physical mechanisms were assessed by means of piezoresponse force microscopy for three distinct material classes: First, a ferroelectric, represented by $0.95(Na_{0.49}K_{0.49}Li_{0.02})(Nb_{0.8}Ta_{0.2})O_3$-$0.05CaZrO_3$; second, a relaxor ferroelectric, namely $Bi_{1/2}Na_{1/2}TiO_3$-$0.19Bi_{1/2}K_{1/2}TiO_3$-$yBiZn_{1/2}Ti_{1/2}O_3$; third, a composite material that comprises nonergodic phase fraction of $Bi_{1/2}Na_{1/2}TiO_3$-$0.07BaTiO_3$ along with an ergodic phase $Bi_{1/2}Na_{1/2}TiO_3$-$0.06BaTiO_3$-$0.02K_{0.5}Na_{0.5}NbO_3$. This comprehensive approach includes the investigation of the macroscopic constitutive behavior by means of various electric characterization methods, contrasted against the sub-microscopic investigations performed via piezoresponse force microscopy.

Their structural, microstructural, and electrical properties, as well as their mutual interrelation are examined as a function of composition, temperature, and electric field. The conducted research is based on the interrelated observations of the materials' electromechanical behavior on different length scales, ranging from a submicroscopic to a macroscopic perspective. Within the framework of this work, the former one is achieved by means of piezoresponse force microscopy, a state-of-the-art scanning probe microscopy technique. The direct comparison of properties on multiple length scales affords deep insight into the fundamental mechanisms responsible for the enhanced electromechanical behavior of the investigated material systems. Novel, advanced data analysis methods are introduced, aiming at a quantitative description of the complex domain microstructures witnessed in the materials in question. Moreover, a distinction of local polarization switching character is sought.