1000 at 1000: relaxor ferroelectrics undergoing accelerated growth

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Relaxor ferroelectrics form a peculiar class of ferroelectric materials. Very dissimilar behavior is generally observed in normal ferroelectrics and in relaxor ferroelectrics. The latter are also simply called relaxors or (especially in early literature) ferroelectrics with diffuse phase transition. A comparison of some key features between normal ferroelectrics and relaxors is schematically shown in Fig. 1. Both have a paraelectric phase of nonpolar symmetry at high temperatures, but the normal ferroelectrics transform upon cooling into a polar ferroelectric phase with macroscopic domains, while the canonical relaxors do not undergo structural phase transitions. Instead, they transform to a macroscopically nonpolar relaxor state in which the crystal develops randomly oriented nanosized regions of polar symmetry, commonly

called polar nanoregions. Some properties of relaxors are analogous to those of well-studied magnetic spin glasses, but some others are fundamentally different. Relaxors are used as a component of the high-performance piezoelectric solid solutions and as excellent materials for electromechanical transducers and capacitors due to their unprecedentedly high electrostriction and dielectric constant, respectively. They are also good energy storage materials [2].

Our motivation to write a review on relaxors was mainly driven by the major breakthrough achieved in the piezoelectric performance of single crystals of relaxor-based solid solutions [3]. As we know, development and improvement in the performance of functional materials usually take place gradually. With a few exceptions, it is hardly possible to see a main technical parameter increased sharply by

This editorial is part of our series “1000 at 1000,” highlighting the Journal of Materials Science’s most highly cited publications as part of the journal’s celebration of 1000 issues. This issue features the article: “Recent progress in relaxor ferroelectrics with perovskite structure.” by A. A. Bokov and Z.-G. Ye from Simon Fraser University in Burnaby, British Columbia, Canada [1].

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Figure 1 Similarities and differences between typical normal ferroelectrics and canonical relaxor ferroelectrics in terms of local structure, polarization, domains, and dielectric and ferroelectric properties.

several times without significant deterioration of other parameters.

However, this was exactly what happened with piezoelectric materials in the late 1990s. PZT ceramics (a solid solution of perovskite ferroelectric PbTiO_3 and antiferroelectric PbZrO_3) have been for decades (and still are) a ubiquitously used piezoelectric materials system. The piezoelectric charge coefficient, d_{33} , of doped PZT is typically in the range of 300–700 pC/N. In 1997, an extraordinary value of $d_{33} > 2500$ pC/N was discovered in the solid solutions of PbTiO_3 and relaxor ferroelectrics $\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ or $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$, together with a very high electromechanical coupling factor and very large field-induced strain [3]. Such a sharp improvement in the performance represented the biggest breakthrough in piezoelectrics in the last 50 years or so [4], and it is reminiscent of the discovery of high Curie temperature (T_C) cuprate superconductors [5, 6].

The enhanced piezoelectric performance was later found in some other relaxor-based solid solutions, and it became clear that, as an effective component of the solid solutions, relaxors play an important role in the appearance of the outstanding piezoelectric performance [4]. Many researchers have joined the field trying to answer the emerging questions, in particular, what the microscopic mechanism responsible for the ultrahigh piezoelectric effect in relaxor-based materials is, why piezoelectric constants in relaxor crystals are much higher than in ceramics of the same composition, how to increase the operating temperatures (often limited by the T_C), whether it is possible to design high-performance materials using environmentally friendly lead-free relaxors, etc. All these research activities have resulted in a rapid growth of the field, as shown in Fig. 2 which presents the number of publications on relaxor ferroelectrics by the year.

Motivated by this fast development, we felt there were urgent needs for a comprehensive review on the recent developments in relaxor ferroelectrics of perovskite structure. Thus, our review paper [1] was written to meet the needs of the ferroelectric community for a thorough overview of modern research achievements associated with relaxor ferroelectric materials. The article reviewed the structure, physical properties, and theories, rather than technological aspects of materials fabrication and applications, and for this reason it can be interesting not only for

Figure 2 Statistical data retrieved from Web of Science Core Collection: (i) the number of articles on relaxor ferroelectrics published per year (search criteria: relaxor* or “diffuse phase transition*” in Topic) (black), (ii) the number of citations per year received by our review [1] (red), and (iii) the total number of citations per year received by all other reviews on relaxors published since 1998 (search criteria: relaxor* or “diffuse phase transition*” in Title and review in Document Types) (blue), in the period from 1980 to 2019.

materials scientists, but also for physicists, chemists, and crystallographers.

Our article was published as a part of the special issue of Journal of Materials Science (JMS) entitled “Frontiers of Ferroelectricity” (edited by Sidney Lang and Helen Chan). A year later, Springer published this special issue in the form of a book [7]. This year, for the third time, this review was reprinted by another publisher, World Scientific [8]. According to Web of Science as of July 24, 2020, our 2006 review has received more than 1370 citations in the form of journal article and 20 citations as book chapter.

We aimed to present information in a concise manner, gathering significantly relevant results from different references and omitting less important details. We have tried to discuss all existing theoretical models, to analyze their pros and cons from our point of view, but not to impose our opinion to the reader. Looking back, we can say that this approach of presentation has been well received and the review has raised considerable interest. In particular, it is gratifying for us to see from Fig. 2 that, after a slight

setback, the number of publications on relaxor ferroelectrics has been undergoing an accelerated growth since 2000, while the citation number of our review follows a similar trend: It has been cited in every fourth article on relaxors published in the last decade and the amount of citations does not drop after almost 15 years. Therefore, we are proud that, to some extent, our article has contributed to the accelerated development of the field of relaxor ferroelectrics in the last decade and a half.

There have been many reviews exclusively devoted to relaxors that have appeared so far: Web of Science lists 33 other such articles since 1998 (obtained by searching the words relaxor* or “diffuse phase transition*” in Title and “review*” in Document Types). However, most of those reviews have not received many citations (Fig. 2). We think this is partly because many reviews were not aimed at discussing the full range of theoretical, experimental, and technological problems, but rather focused only on some of those aspects. Another possible reason is that the authors often advocated a specific theoretical model (in particular, the one they personally proposed or agreed upon) and did not pay much attention to, or did not want to accommodate, alternative views.

Finally, with the number of related publications growing sharply in the last decade or so, a lot of exciting new developments have happened. It is perhaps time for us to contemplate a new comprehensive review on relaxor ferroelectrics and related materials, and there is no doubt that JMS will be an ideal venue for the publication of such an article.

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