Materials Today Nano 20 (2022) 100275

Contents lists available at ScienceDirect

Materials Today Nano

journal homepage: https://www.evise.com/profile/#/MTNANO/login

Morphotropic phase boundary in pure perovskite lead titanate at room temperature

Z. Zhang [a, 1], X. Chen [a, 1], X. Shi [b, 1], Y. Hu [d, e], J. Huang [d, e], S. Liu [d, e], Z. Ren [c, ***], H. Huang [b, **], G. Han [c], G. Van Tendeloo [f], Z. Zhang [a, c], H. Tian [a, c, g, *]

[a] Center of Electron Microscope, School of Materials Science and Engineering, Zhejiang University, 310027, China
[b] Advanced Research Institute of Multidisciplinary Science, Beijing Institute of Technology, Beijing, 100081, China
[c] State Key Laboratory of Silicon Materials, School of Materials Science and Engineering, Zhejiang University, Hangzhou, 310027, China
[d] Key Laboratory for Quantum Materials of Zhejiang Province, Department of Physics, School of Science, Westlake University, Hangzhou, Zhejiang 310030, China
[e] Institute of Natural Sciences, Westlake Institute for Advanced Study, Hangzhou, Zhejiang 310024, China
[f] EMAT, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium
[g] School of Physics and Microelectronics, Zhengzhou University, Zhengzhou, 450052, China

ARTICLE INFO

Article history:
Received 4 August 2022
Received in revised form
6 October 2022
Accepted 7 October 2022
Available online 18 October 2022

Keywords:
Morphotropic phase boundary
Uniaxial pressure
Phase transition
Pure perovskite lead titanate
Piezoelectric response

ABSTRACT

For many decades, great efforts have been devoted to pursue a large piezoelectric response by an intelligent design of morphotropic phase boundaries (MPB) in solid solutions, where tetragonal (T) and rhombohedral (R) structures coexist. For example, classical $PbZr_xTi_{1-x}O_3$ and $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ single crystals demonstrate a giant piezoelectric response near MPB. However, as the end member of these solids, perovskite-structured $PbTiO_3$ always adopts the T phase at room temperature. Here, we report a pathway to create room temperature MPB in a single-phase $PbTiO_3$. The uniaxial stress along the *c*-axis drives a T-R phase transition bridged by a monoclinic (M) phase, which facilitates a polarization rotation in the monodomain $PbTiO_3$. Meanwhile, we demonstrate that the coexistence of T and R phases at room temperature can be achieved via an extremely mismatched heterointerface system. The uniaxial pressure is proved as an efficient way to break the inherent symmetry and able to substantially tailor the phase transition temperature *Tc*. These findings provide new insights into MPB, offering the opportunity to explore the giant piezoelectric response in single-phase materials.

1. Introduction

A morphotropic phase boundary (MPB) is a coexistent region of T and R structure in the phase diagram, which has been well established in $PbZr_xTi_{1-x}O_3$ from the 1950s and subsequent relaxor $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ single crystals [1,2]. Near such regions, a large piezoelectric response is usually found [2–4]. To understand such response, a polarization rotation mechanism has been developed, where the energetically favorable rotation from a $[001]_T$ direction to a $[111]_R$ direction generates a pronounced strain by costing a low electric field [3,5–7]. This mechanism can also be mediated via the creation of an M phase, as a structural bridge between the T and R phase [4,7,8]. These findings make the concept of MPB highly attractive for exploring high-performance piezoelectric materials from an experimental design [9–11]. However, the empirical tuning of the exact structure of the solid solutions remains very complex. The realization of MPB in a single-phase material would be of great interest for both the understanding of the fundamental mechanism of the electromechanical response and the design and optimization of the giant piezoelectric effect [11–13].

As a typical ferroelectric material with a simple perovskite structure, $PbTiO_3$ has been identified to adopt a T phase below the ferroelectric phase transition temperature (~490 °C) [14,15]. Owing to its simple structure, $PbTiO_3$ is an ideal model to explore the origin of ferroelectricity [16–18] and therefore, it triggered many research efforts on exploring the existence of MPB and the large

* Corresponding author.
** Corresponding author.
*** Corresponding author.
E-mail addresses: renzh@zju.edu.cn (Z. Ren), hbhuang@bit.edu.cn (H. Huang), hetian@zju.edu.cn (H. Tian).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.mtnano.2022.100275
2588-8420/

piezoelectricity near MPB [7,10,11,19]. Nevertheless, the existence of room temperature MPB for pure $PbTiO_3$ has not been achieved so far, neither theoretically nor experimentally. As anisotropic stress, the uniaxial pressure has been wildly proved as a unique and efficient way to involve an inherent symmetry breaking [20,21], bypass the extreme and harsh conditions to achieve a phase transition, such as dramatically increasing the critical temperature T_c of superconductivity in Sr_2RuO_4 [22,23]. Meanwhile, the R phase has a pseudo-cubic structure with a smaller volume of the unit cell and *c*/*a* ratio than the T phase [6,11]. We performed first-principles density functional theory calculations and found that a uniaxial compressive strain applied along the *c*-axis can drive the T phase of $PbTiO_3$ to gradually transform into M-like and R-like phases (details in Fig. S1). These findings provided us with a possible clue for achieving MPB at room temperature. Herein, we report a facile uniaxial pressure is an efficient way to break inherent symmetry to drive a single-component ferroelectric to MPB at room temperatures, not necessitating the extreme and harsh conditions, such as low temperature and high pressure. Furthermore, we designed an extremely mismatched (010) $SrTiO_3/PbTiO_3$ heterostructure, in which we achieved a stable co-existence of T and R phases by inducing the interfacial c-axis compressive strain. Our findings pave a simple and facile way to obtain an MPB situation in pure phase perovskites; the triggering conditions that reach MPB are significantly reduced and confirmed the possibility of achieving the giant piezoelectric effect by an actual example of interface engineering, which certainly will trigger particular interest in designing MPB for a giant piezoelectric effect.

2. Experiment section

2.1. Materials

Single-crystal and monodomain $PbTiO_3$ bulk samples were synthesized by a two-step hydrothermal method as follows: $Pb(NO_3)_2$ and tetrabutyl titanate were used as starting materials. Potassium hydroxide was used as a mineralizer. Potassium hydroxide was first dissolved in deionized water, tetrabutyl titanate was then added in the aqueous solution, and $Pb(NO_3)_2$ solution was finally dropwise added under vigorous stirring. The resultant products were washed with water and ethanol several times and subsequently dried at 60 °C in air for 12 h $PbTiO_3$ nanoplates were first prepared under hydrothermal condition [24]. $SrTiO_3/PbTiO_3$ heterostructures were synthesized by a facile hydrothermal method as follows: Mixing tetrabutyl titanate and strontiumnitrate in aqueous solution as precursor, and sodium hydroxide was used as crystallographic controlling agent. $PbTiO_3$ nanoplates were added in the solution after stirring. The reaction was performed in an autoclave at 200 °C for 10 min to 24 h.

2.2. Characterizations

Transmission electron microscope (TEM) samples are prepared using a focus ion beam (Quanta 3D FEG, FEI). High-angle annular dark field-scanning transmission electron microscope (HAADF-STEM) experiments were performed on an aberration-corrected TEM (FEI Titan G2 80–200 Chemi STEM). The integrated differential phase contrast (iDPC-STEM) was conducted on an aberration-corrected TEM (FEI Titan Themis). The in-situ loading experiment was performed on a TEM (FEI Tecnai G2 F20 S-TWIN) with a nanoindentation system (Hysitron PI95). The synchrotron X-ray diffraction was carried out at the beamline 15U1, Shanghai Synchrotron Radiation Facility, China. The X-ray wavelength was 0.6199 Å. The monodomain structure of $PbTiO_3$ was characterized by the piezoelectric force microscope (BRUKER DIMENSION ICON).

3. Results and discussions

To verify the suggestion that a simple uniaxial stress might break the inherent symmetry and reach an MPB at room temperature, an in-situ experiment of uniaxial pressure is loaded on a single-crystal and monodomain $PbTiO_3$ at room temperature (characterization in Fig. S2). As shown in Fig. 1a, a pillar of T phase $PbTiO_3$ with a size of 1 μm was prepared for in-situ pressure loading analysis [16]. The electron diffraction patterns of the initial state and the compressed state are shown in Fig. 1b. As the pressure increases, the intensity of the 001 spot significantly decreases, and the shift of the 002 spot implies a dramatic reduction of *c* value (Fig. 1c). This variation of the *c* parameter is consistent with the phase transition from T to R. This transition is reversible, and spots recover to their initial state when the pressure is unloaded.

To further clarify the dynamical aspect of the phase transition, the evolution of the lattice parameters and diffraction patterns was monitored as a function of time (Fig. 1c–g). In the initial stage, there is elastic deformation (red background); the *c* value gradually decreases while *a* increases. When the compressive stress reaches 1.63 ± 0.30 GPa, the evolution of both lattice parameters and *c*/*a* reaches a platform (gray background), corresponding to a *c*/*a* of 1.030; this can be interpreted as an intermediary region in the phase transition sequence. With the pressure further increasing, the *c* value abruptly drops to about 0.385 Å, and the *c*/*a* ratio also changes abruptly from ~1.030 to ~0.98. After transforming into the R phase, the lattice parameters and *c*/*a* ratio reach another platform (blue background). When the compressive pressure is gradually unloaded, the abrupt change and the platform are similar to the loading process. This confirms that the two platforms, in loading and unloading, are related to the existence of an intermediate phase in the phase transition sequence.

Based on the above results, it is reasonable to conclude that the T to R phase transformation in $PbTiO_3$ can be realized at room temperature through the application of a uniaxial pressure. Previous reports [4,7,8] also mention that there may exist a low symmetry phase connecting T and R phases. Ahart reported [11] that pure $PbTiO_3$ goes through a T→M→R phase transition under a huge hydrostatic pressure (20 GPa) at ultra-low temperature (10 K). The emergence of the M phase is accompanied by an abrupt change in the β angle of the unit cell in the vicinity of the T-M transition. With this in mind, we analyzed the evolution of the β-90° angle to verify the existence of this T-M phase transition (Fig. 1f). These measurements show that in the initial T phase, R phase, and recovery stage, the deviation from 90° remains stable at (0.0 ± 0.43)°, whereas at the onset of the transition stage, there is a jump in both the loading and the unloading directions. The β-90° angle approaches 1.2° at both transition stages, indicating the existence of a monoclinic (M) phase. Moreover, we further compared experimental and simulated diffraction patterns; both the position and the intensity ratio of diffraction spots show an excellent agreement for all three phases (Fig. 1g and Fig. S3). This provides proof for the existence of a T-M-R phase transition sequence induced by the application of an in-situ uniaxial stress along $[001]_T$.

Our experimental results are further confirmed by calculations with the phenomenological thermodynamic theory and recalculated the low-temperature hydrostatic pressure results in Ahart's work [11] to verify the accuracy and feasibility of the calculation (Fig. S4). The stress and temperature phase diagram of bulk $PbTiO_3$ under uniaxial *c*-axis compressive stress is shown in Fig. 1h (Methods). Both experiments and calculations reflect a fact that a facile uniaxial pressure is an efficient way to drive the T-*M*-R phase transition at room temperature, not necessarily the extreme and harsh conditions. All conditions for this approach can be realized in practical applications, such as interface engineering.

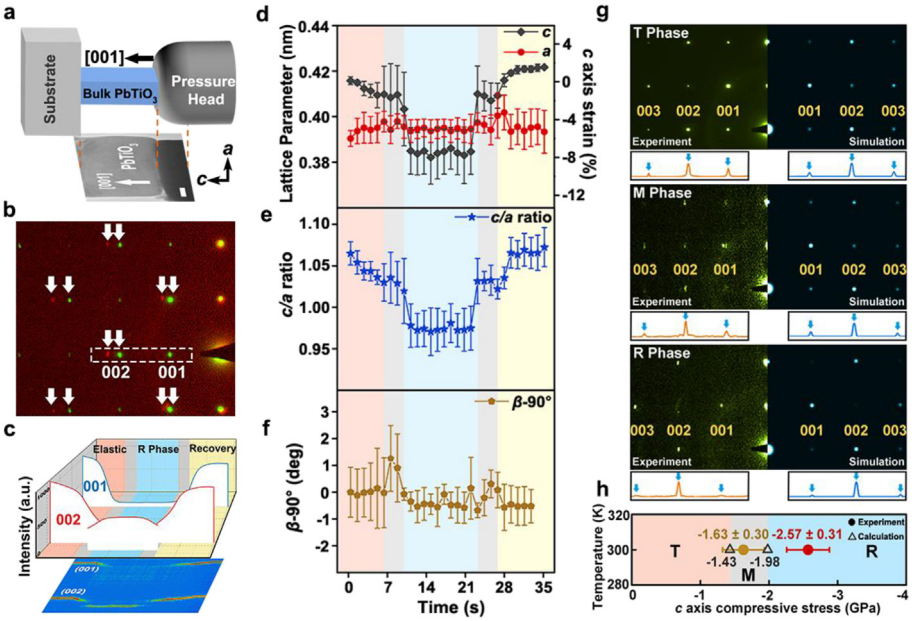

Fig. 1. In-situ pressure loading analysis results of single-crystal and monodomain $PbTiO_3$ when applying a uniaxial stress along [001]. (a) Schematic of the experimental setup. Scale bar 200 nm. (b) [010] zone axis selected area diffraction pattern of the initial state (green) and compressed state (red). (c) Evolution of the 001 and 002 diffraction spot intensity versus time. (d–f) Evolution profiles of lattice parameters, *c*-axis strain, *c*/*a* ratio, and *β*-90° angle of the unit cell in $PbTiO_3$. (g) Evolution of experimental and simulated diffraction patterns of the T, M, and R phases. (h) Phase diagram of bulk $PbTiO_3$ under uniaxial stress along the *c*-axis. Circles and triangles indicate experimental and calculated phase transition points at 300 K, respectively.

To realize the uniaxial strain needed for room-temperature MPB in $PbTiO_3$, we designed a (001) $SrTiO_3$/(100) $PbTiO_3$ epitaxial heterostructure, where various stress can be introduced by a huge lattice mismatch (a mismatch of up to 6.4% can theoretically introduce a maximum tensile and compressive stress of +12.6 GPa and −5.25 GPa). Such heterointerface is an ideal platform to further explore whether the R phase can stably exist in pure $PbTiO_3$ at room temperature, and what *c*-axis pressure can drive the T-R phase transition at room temperature [25]. Taking advantage of the electrostatic force-driven oxide heteroepitaxy [24,26], (010) $SrTiO_3$/$PbTiO_3$ heterostructures have been prepared (Methods). Fig. 2a shows a HAADF-STEM image of the (010) $SrTiO_3$/$PbTiO_3$ interface.

According to the results of a geometric phase analysis for Fig. 2b and c, nearby each dislocation core in $PbTiO_3$, there is a particular region that shows the *c*-axis compressive strain is around −2.3%, and the *a*-axis tensile strain is around +0.7% (Fig. S5), leading to a decrease in the *c*/*a* ratio approaching 1, which is favorable for the formation of the R phase.

We further recorded iDPC-STEM images [27] to determine the polarization distribution near the interface (Fig. 2d). The polarization direction, far from the dislocation, is along [001], corresponding to the T phase (Fig. 2e). In the region where the *c*/*a* ratio is approaching 1, the polarization direction rotates from horizontal [001] to 45° anticlockwise, which matches the projection of the [111] polarization in the R phase (Fig. 2f). Meanwhile, as shown in

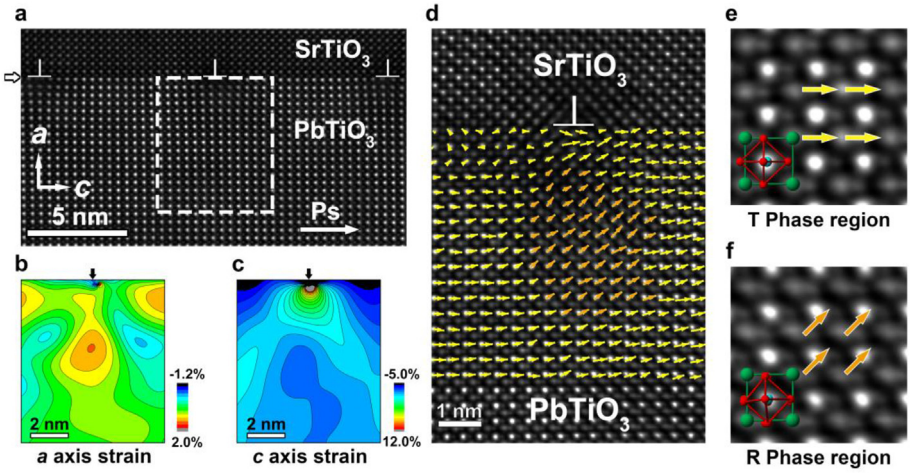

Fig. 2. Atomic-level STEM characterization of the (010) $SrTiO_3$/$PbTiO_3$ heterointerface. (a) Cross section of HAADF-STEM image along the [010] zone axis. (b–c) GPA results for *a*-axis and *c*-axis strain contour mapping of a dislocation region, indicated in (a) by a white-dashed square. (d) iDPC-STEM image superimposed with the corresponding polarization direction of each unit cell in $PbTiO_3$. (e–f) Magnified iDPC images of ordinary and rotated polarization regions.

Fig. 3a and b, we calculated the unit-cell *c/a* ratio around a single dislocation region. These data reveal that beneath the dislocation core, the *c/a* ratio reaches about 1.03, whereas away from the dislocation, the ratio is 1.065 ± 0.003, matching well with that of the T phase (Fig. S8b). By statistically evaluating the lattice parameters and displacement of Ti atoms, we can confirm the existence of an M phase in $PbTiO_3$ as a bridge between T and R phases, and the R phase symmetry is confirmed as *R3c* (Figs. S6–7 and Table S1). It can therefore be concluded that a uniaxial compressive strain along the *c*-axis is favorable to reduce the *c/a* ratio and to induce a stable R phase.

To investigate the 'phase boundary' (or MPB), we quantitatively analyzed the statistical strain distribution of the T and R regions (Fig. 3c–e). Both in the *a*-axis and *c*-axis strain projection planes, there is an obvious boundary or overlap region between R and T phases (Fig. 3c). According to the results in Fig. 3d and e, the maximum of the frequency locates at the R region with negative *c*-axis strain and positive *a*-axis strain, and the corresponding values are ~ −1.4% and +0.5%, respectively, whereas both the *c*-axis and *a*-axis strains of the T phase are almost zero. Moreover, the average values for the *c/a* ratio and cell volume of the T and R regions have been determined (Fig. S8). All the above results are consistent with the existence of the R phase. However, in ferroelectrics, a polarization rotation may also originate from a flexoelectric effect, which is a coupling effect between a strain gradient and an electric polarization [28,29]. The strain gradient distribution along the *c*-axis is calculated; it is obvious that the gradient value is close to zero, implying that a flexoelectric effect is negligible (Fig. S9). Therefore, the boundary of T and R phases can be reasonably confirmed, based on the statistical data in Fig. S10a. Meanwhile, the phase diagram of the biaxial strain of *c* and *a* for bulk $PbTiO_3$ was calculated and shown in Fig. S10b, matching well with the experimental phase diagram in Fig. S10a.

Based on the above results, it is reasonable to speculate that uniaxial pressure along the *c*-axis is able to significantly reduce trigger conditions of the T-M-R phase transition. As reported theoretically, the superior piezoelectricity near MPB is mainly attributed to the large shear piezoelectric response [30–32]. In this work, a new pathway to the superior piezoelectricity was explored. The profile of piezoelectric coefficient d_{33} to the *c*-axis stress was calculated by involving the modified coefficients of the Landau potential. Interestingly, an abrupt increase of d_{33} at the T-M phase boundary at 300 K has been found (Fig. S11), suggesting the existence of optimum piezoelectric efficiency near the MPB.

4. Conclusion

In summary, a combination of in-situ experimental investigations, verification in the interface system, and theoretical calculations revealed that a facile uniaxial pressure is an efficient way to break inherent symmetry to drive a single-component ferroelectric to MPB at room temperatures, not necessitating the extreme and harsh conditions, such as low temperature and high pressure. This phase is crucial for exploring and understanding the high piezoelectric response in this simple perovskite at room temperature. Furthermore, we designed an extremely mismatched (010) $SrTiO_3/PbTiO_3$ heterostructure, in which we achieved a stable coexistence of T and R phases by inducing the interfacial c-axis compressive strain. Our findings pave a simple and facile way to obtain an MPB situation in pure phase perovskites. Complex solid solutions or under extremely critical conditions are no longer the only path to MPB.

Credit author statement

The project was conceived and designed by H.T. and Ze Zhang; Z.R. and G.H. prepared the single-phase $PbTiO_3$ and (010) $SrTiO_3/PbTiO_3$ heterostructure samples; Z.Z. and C.X. performed TEM experiments; Y.H., J.H., and S.L. did first-principles calculations; X.M. and H.H. did phase-field simulations; Z.Z. and C.X. wrote the manuscript. All authors were involved in the analysis of the results and contributed to writing the paper.

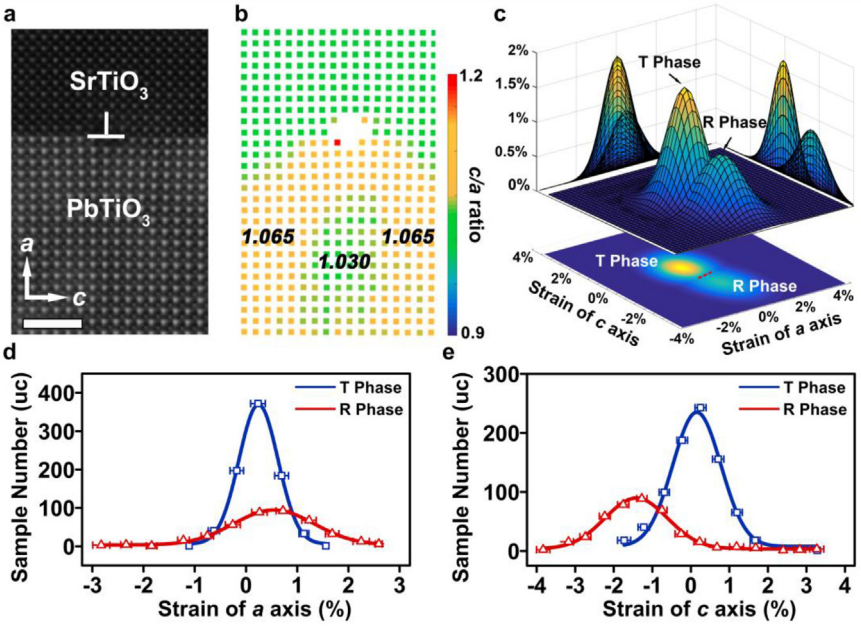

Fig. 3. Unit cell by unit cell strain analyses of the highly strained region. (a) HAADF-STEM image of a single dislocation region. Scale bar 2 nm. (b) Unit-cell mapping of the *c/a* ratio in the region of (a). (c) Statistical histogram of *c*-axis and *a*-axis strain of R and T phase regions, the height represents the frequency of the strain values. (d–e) Statistical profiles of *a*-axis and *c*-axis strain of the R and T phase regions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors acknowledge the National Natural Science Foundation of China (12125407, 11474249, 52272129), National Key Research and Development Program of China (2017YFB0703100, 2021YFA1500800), Joint Funds of the National Natural Science Foundation of China (U21A2067), the Natural Science Foundation of Zhejiang Province, China (Grant No. LD21E020002, No. LR21E020004) and the 111 Project (Grant No. B16042).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mtnano.2022.100275.

References

[1] G. Shirane, S. Hoshino, K. Suzuki, X-ray study of the phase transition in lead titanate, Phys. Rev. 80 (1950) 1105–1106, https://doi.org/10.1103/PhysRev.80.1105.
[2] S.E. Park, T.R. Shrout, Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals, J. Appl. Phys. 82 (1997) 1804–1811, https://doi.org/10.1063/1.365983.
[3] H.X. Fu, R.E. Cohen, Polarization rotation mechanism for ultrahigh electromechanical response in single-crystal piezoelectrics, Nature 403 (2000) 281–283, https://doi.org/10.1038/35002022.
[4] R. Guo, L.E. Cross, S.-E. Park, B. Noheda, D.E. Cox, G. Shirane, Origin of the high piezoelectric response in $PbZr_{1-x}Ti_xO_3$, Phys. Rev. Lett. 84 (2000) 5423–5426, https://doi.org/10.1103/physrevlett.84.5423.
[5] B. Noheda, Structure and high-piezoelectricity in lead oxide solid solutions, Curr. Opi. Solid State Mater. Sci. 6 (2002) 27–34, https://doi.org/10.1016/S1359-0286(02)00015-3.
[6] L. Bellaiche, A. Garcia, D. Vanderbilt, Electric-field induced polarization paths in $PbZr_{1-x}Ti_xO_3$ alloys, Phys. Rev. B 64 (2001), 060103. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.64.060103.
[7] Z.G. Wu, R.E. Cohen, Pressure-induced anomalous phase transitions and colossal enhancement of piezoelectricity in $PbTiO_3$, Phys. Rev. Lett. 95 (2005), 037601, https://doi.org/10.1103/PhysRevLett.95.037601.
[8] B. Noheda, D.E. Cox, G. Shirane, A monoclinic ferroelectric phase in the $Pb(Zr_{1-x}Ti_x)O_3$ solid solution, Appl. Phys. Lett. 74 (1999) 2059–2061, https://doi.org/10.1063/1.123756.
[9] S. Rajput, X. Ke, X. Hu, M. Fang, D. Hu, F. Ye, Y. Hao, X. Ren, Critical triple point as the origin of giant piezoelectricity in $PbMg_{1/3}Nb_{2/3}O_3$-$PbTiO_3$ system, J. Appl. Phys. 128 (2020), 104105, https://doi.org/10.1063/5.0021765.
[10] P.-E. Janolin, P. Bouvier, J. Kreisel, P.A. Thomas, I.A. Kornev, L. Bellaiche, W. Crichton, M. Hanfland, B. Dkhil, High-pressure effect on $PbTiO_3$: an investigation by Raman and x-ray scattering up to 63 GPa, Phys. Rev. Lett. 101 (2008), 237601, https://doi.org/10.1103/physrevlett.101.237601.
[11] M. Ahart, et al., Origin of morphotropic phase boundaries in ferroelectrics, Nature 451 (2008) 545–548, https://doi.org/10.1038/nature06459.
[12] A.S. Everhardt, et al., Temperature-independent giant dielectric response in transitional $BaTiO_3$ thin films, Appl. Phys. Lett. 7 (2020), 011402. https://aip.scitation.org/doi/10.1063/1.5122954.
[13] P. Haumont, A. Bouvier, K. Pashkin, S. Rabia, B. Frank, W. Dkhil, A. Crichton, C.A. Kuntscher, J. Kreisel, Effect of high pressure on multiferroic $BiFeO_3$, Phys. Rev. B 79 (2009), 184110. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.79.184110.
[14] S.A. Mabud, A.M. Glazer, Lattice parameters and birefringence in $PbTiO_3$ single crystals, J. Appl. Cryst. 12 (1979) 49–53, https://doi.org/10.1107/S0021889879011754.
[15] L. Zhang, et al., Giant polarization in super-tetragonal thin films through interphase strain, Science 361 (2018) 494–497. https://science.sciencemag.org/content/361/6401/494.
[16] A.M. Glazer, S.A. Mabud, Powder profile refinement of lead zirconate titanate at several temperatures. II. Pure $PbTiO_3$, Acta Cryst. B 34 (1978) 1065–1070, https://doi.org/10.1107/S0567740878004938.
[17] D.D. Fong, G. Brian Stephenson, Stephen K. Streiffer, Jeffrey A. Eastman, Auciello Orlando, H. Paul, Fuoss, carol thompson, ferroelectricity in ultrathin perovskite films, Science 304 (2004) 1650. https://science.sciencemag.org/content/304/5677/1650.
[18] Chun-Lin Jia, Valanoor Nagarajan, Jia-Qing He, Lothar Houben, Zhao Tong, Ramamoorthy Ramesh, Knut Urban, Rainer Waser, Unit-cell scale mapping of ferroelectricity and tetragonality in epitaxial ultrathin ferroelectric films, Nat. Mater. 6 (2007) 64–69, https://doi.org/10.1038/nmat1808.
[19] J. Frantti, Y. Fujioka, R. Nieminen, Pressure-induced phase transitions in $PbTiO_3$: a query for the polarization rotation theory, J. Phys. Chem. B 111 (2007) 4287–4290, https://doi.org/10.1021/jp0713209.
[20] C. Jiang, W. Xiong, C. Li, C. Niu, F. Wang, Uniaxial strain induced symmetry lowering and valleys drift in MoS_2, New J. Phys. 23 (2021), 053007. https://iopscience.iop.org/article/10.1088/1367-2630/abfb09.
[21] L. Fu, C.L. Kane, Topological insulators with inversion symmetry, Phys. Rev. B 76 (2007), 045302. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.76.045302.
[22] A. Steppke, et al., Strong peak in T_c of Sr_2RuO_4 under uniaxial pressure, Science 355 (2017), eaaf9398. https://science.sciencemag.org/content/355/6321/eaaf9398.
[23] S. Kittaka, H. Taniguchi, S. Yonezawa, H. Yaguchi, Y. Maeno, Higher-T_c superconducting phase in Sr_2RuO_4 induced by uniaxial pressure, Phys. Rev. B 81 (2010), 180510. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.81.180510.
[24] C. Chao, Z.H. Ren, Y.H. Zhu, Z. Xiao, Z.Y. Liu, G. Xu, J.Q. Mai, X. Li, G. Shen, G.R. Han, Self-templated synthesis of single-crystal and single-domain ferroelectric nanoplates, Angew. Chem. Int. Ed. 51 (2012) 9283–9287, https://doi.org/10.1002/anie.201204792.
[25] N.A. Pertsev, A.G. Zembilgotov, A.K. Tagantsev, Effect of mechanical boundary conditions on phase diagrams of epitaxial ferroelectric thin films, Phys. Rev. Lett. 80 (1998) 1988. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.80.1988.
[26] Z.H. Ren, et al., Electrostatic force-driven oxide heteroepitaxy for interface control, Adv. Mater. 30 (2018), 1707017, https://doi.org/10.1002/adma.201707017.
[27] I. Lazic, E.G.T. Bosch, S. Lazar, Phase contrast STEM for thin samples: integrated differential phase contrast, Ultramicroscopy 160 (2016) 265–280, https://doi.org/10.1016/j.ultramic.2015.10.011.
[28] G. Catalan, et al., Flexoelectric rotation of polarization in ferroelectric thin films, Nat. Mater. 10 (2011) 963–967, https://doi.org/10.1038/nmat3141.
[29] P. Yudin, J. Duchon, O. Pacherova, M. Klementova, T. Kocourek, A. Dejneka, M. Tyunina, Ferroelectric phase transitions induced by a strain gradient, Phys. Rev. Research 3 (2021), 033213. https://journals.aps.org/prresearch/pdf/10.1103/PhysRevResearch.3.033213.
[30] B. Noheda, D.E. Cox, G. Shirane, S.-E. Park, L.E. Cross, Z. Zhong, Polarization rotation via a monoclinic phase in the piezoelectric 92% $Pb(Zn_{1/3}Nb_{2/3})O_3$-8% $PbTiO_3$, Phys. Rev. Lett. 86 (2001) 3891–3894, https://doi.org/10.1103/physrevlett.86.3891.
[31] R. Zhang, B. Jiang, W. Cao, Orientation dependence of piezoelectric properties of single domain $0.67Pb(Mn_{1/3}Nb_{2/3})O_3$–$0.33PbTiO_3$ crystals, Appl. Phys. Lett. 82 (2003) 3737–3739, https://doi.org/10.1063/1.1576510.
[32] M. Davis, M. Budimir, D. Damjanovic, N. Setter, Rotator and extender ferroelectrics: importance of the shear coefficient to the piezoelectric properties of domain-engineered crystals and ceramics, J. Appl. Phys. 101 (2007), 054112, https://doi.org/10.1063/1.2653925.