



Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/105197/>

Version: Accepted Version

---

**Article:**

Iurchuk, V., Schick, D., Bran, J. et al. (2016) Optical Writing of Magnetic Properties by Remanent Photostriction. *Physical Review Letters*, 117 (10). p. 107403. ISSN: 0031-900

<https://doi.org/10.1103/PhysRevLett.117.107403>

---

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

## Optical Writing of Magnetic Properties by Remanent Photostriction

V. Iurchuk,<sup>1</sup> D. Schick,<sup>2</sup> J. Bran,<sup>1</sup> D. Colson,<sup>3</sup> A. Forget,<sup>3</sup> D. Halley,<sup>1</sup> A. Koc,<sup>2,4</sup> M. Reinhardt,<sup>2,4</sup> C. Kwamen,<sup>2,4</sup>  
 N. A. Morley,<sup>5</sup> M. Bargheer,<sup>2,4</sup> M. Viret,<sup>3</sup> R. Gumenuik,<sup>6</sup> G. Schmerber,<sup>1</sup> B. Doudin,<sup>1</sup> and B. Kundys<sup>1</sup>

<sup>1</sup>*Institut de Physique et Chimie des Matériaux de Strasbourg (IPCMS), UMR 7504 CNRS-UdS 23 rue du Loess, 67034 Cedex 2, Strasbourg, France*

<sup>2</sup>*Institute for Methods and Instrumentation for Synchrotron Radiation Research, Helmholtz-Zentrum Berlin, Albert-Einstein-Str. 15, 12489 Berlin, Germany*

<sup>3</sup>*Service de Physique de l'Etat Condense, DSM/IRAMIS/SPEC, CEA Saclay URA CNRS 2464, 91191 Gif-Sur-Yvette Cedex, France*

<sup>4</sup>*Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam/Golm, Germany*

<sup>5</sup>*University of Sheffield, Department of Materials Science and Engineering, Mappin Street, Sheffield S1 3JD, United Kingdom*

<sup>6</sup>*Institut für Experimentelle Physik, TU Bergakademie Freiberg, Leipziger Str. 23, 09596 Freiberg, Germany*

(Received 12 June 2016)

**1** We present an optically induced remanent photostriction in BiFeO<sub>3</sub>, resulting from the photovoltaic effect, which is used to modify the ferromagnetism of Ni film in a hybrid BiFeO<sub>3</sub>/Ni structure. The 75% change in coercivity in the Ni film is achieved via optical and nonvolatile control. This photoferromagnetic effect can be reversed by static or ac electric depolarization of BiFeO<sub>3</sub>. Hence, the strain dependent changes in magnetic properties are written optically, and erased electrically. Light-mediated straintronics is therefore a possible approach for low-power multistate control of magnetic elements relevant for memory and spintronic applications.

DOI:

Multiferroic phenomena are often summarized in a Venn diagram showing the intersection of ferromagnetic, ferroelectric, and ferroelastic orders [1], each with its own control field. Numerous electric methods of magnetization control use elastic strain to leverage magnetoelectric (ME) properties in solids [2–34] and in magnetostrictive-electrostrictive or ferroelectric structures [5–8]. The expected technological benefit is the possibility of low-power [9–11] operation down to the nanoscale [12–15]. Indeed, strain-mediated electric control of magnetic performance of tunnel junctions has been reported [16]. Furthermore, by using the ferroelastic effect of remanent strain, multiple nonvolatile states can be written on piezoelectric substrates [17,18]. Here we present the optical analog of this memory imprint approach, based on photostriction in BiFeO<sub>3</sub> (BFO) [19], a well-studied benchmark multiferroic material [20] exhibiting cross-linked ferroic orders. Light brings a new layer of functionality to multiferroics [21–24]. In particular, photoferroelectric [25] effects associated with above-band gap photovoltaic (PV) properties, [26–28] can mediate light-induced changes of the ferroelastic order. While it is increasingly well established that BFO exhibits strain under illumination [29–31], the possibility of remanent strain states suggests a new approach [32]. The optical control of strain is particularly important for BFO, which possesses both high photostrictive efficiency [32] and large optoelastic coupling [33]. Furthermore, the magnetoelastic coupling in BFO has been shown to dominate its ME properties [34] that can provide a bridge for ME coupling between magnetic and electric orders [35]. These effects, together with the strain-tunable magnonic response in BFO thin

films [36] provide an attractive strain-engineering prospective [37]. Photostriction control can also be extended to miniaturized structures using light-polarization-dependent functionality in ferroelectric domain walls in BaTiO<sub>3</sub> [38] offering an optical degree of control in spin-based devices [39,40]. Here we will first show that light can impact the internal electric field of BFO through the PV effect to produce optically induced ferroelastic remanent states, and then demonstrate the use of this ferroelastic deformation to stress a superposed ferromagnetic film, thereby achieving strain-mediated optical control of the magnetic anisotropy.

Illuminating a material which is ferroelectric (FE) and PV results in above-band gap voltage generation that changes the internal electric field in the sample [41]. The former process can be compared to the action of "subcoercive" electric fields insufficient to saturate the polarization, resulting in minor (nonswitching) FE loops [42]. Figure 1(a) illustrates how light excitation can be an alternative to the electric field, and generate a minor remanent polarization state via the PV effect [Fig. 1(b)]. A continuous wave (cw) 404 nm laser with a 3 ns rise time was used as the illumination source through an optical fiber. The sample was illuminated through a thin (20 nm) Au film, used as contact transparent electrode for depolarizing the substrate. Under constant illumination, a steady-state photocurrent results in an increase of polarization saturating after ~70 sec (not shown). The light induced change in electric polarization partly persists in ~5.5% after the light is switched off [Fig. 1(a)]. One can conclude from Fig. 1(a) that different remanent polarization levels can result from different illumination times. The electric polarization of the

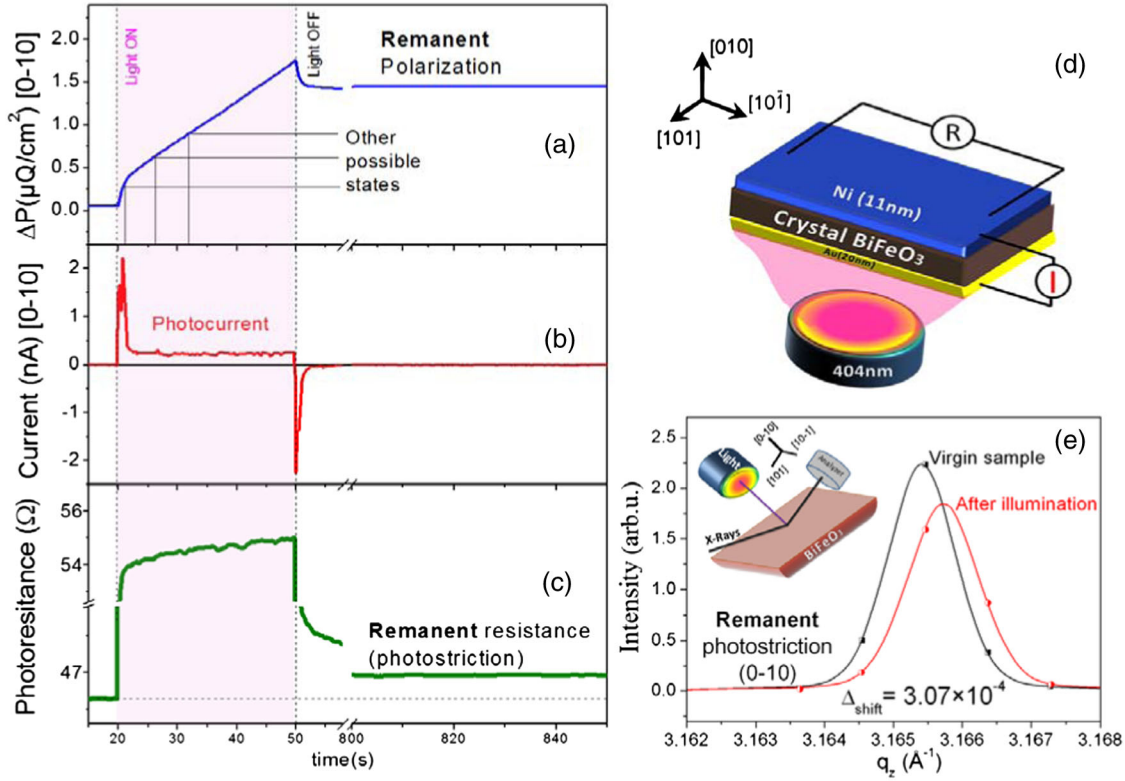


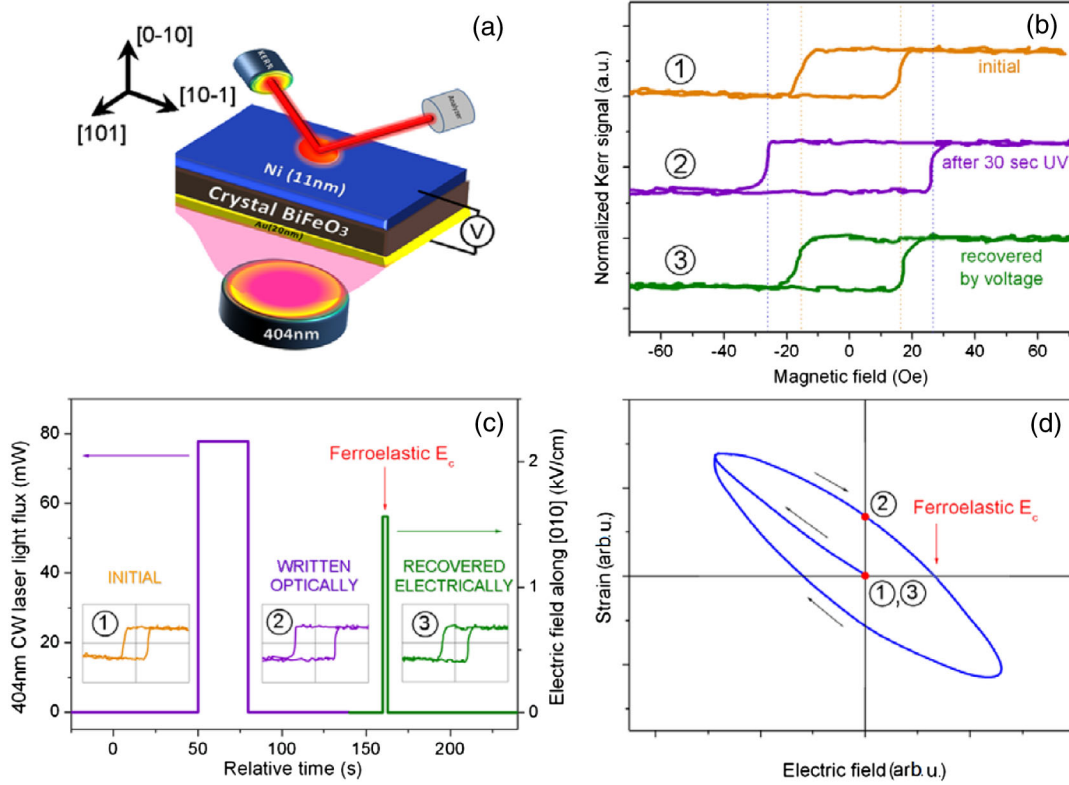
FIG. 1. (a) The remanent polarization state (a) created by 30 sec UV light. (b) Corresponding photocurrent. (c) Remanent photostriction detected by measuring the resistance of the Ni film (d) and by static x-ray diffraction of BFO (e).

84 BFO is the primary order parameter and it results in a  
 85 change in strain (which is the secondary order parameter)  
 86 that is linearly related to the polarization in the subcoercive  
 87 region through the piezoelectric response of the oxide [43].  
 88 Figure 1(c) shows the remanent photostriction detected  
 89 using a resistive measurement of a Ni thin film adlayer in  
 90 the setup illustrated in Fig. 1(d). The overall remanent  
 91 strain of the sample in Fig. 1(d) is tensile in the (010) plane  
 92 and results in an in-plane expansion of the Ni film. In order  
 93 to verify the remanent deformation of the BFO substrate,  
 94 we carried out static x-ray diffraction experiments  
 95 [Fig. 1(e)] at the XPP/KMC3 beam line in the synchrotron  
 96 facility BESSY II (Berlin, Germany) [44]. A similar BFO  
 97 crystal with the same orientation (but without adlayer) was  
 98 used to determine the lattice spacing along the [010]  
 99 direction in the as-grown [45] state and after 3 sec of light  
 100 illumination. In this case, a femtosecond pulsed laser was  
 101 used yielding a similar integral number of photons to that  
 102 used for the switching in Figs. 1(a)–1(c) with the cw laser.

103 The pulsed laser consists of a multistage oscillator and  
 104 amplifier system (Impulse, Clark-MXR) and delivers 250 fs  
 105 long pulses of 10  $\mu\text{J}$  pulse energy at a central wavelength of  
 106 1030 nm and a repetition rate of 208.3 kHz. They are then  
 107 passed through a third harmonic setup at the beam line to  
 108 generate the laser pump pulses of 350 nm with a final  
 109 average power of 80 mW incident on the sample in a spot  
 110 size of  $277 \times 176 \mu\text{m}^2$  (FWHM) under an incidence angle

of  $20^\circ$  between laser beam and sample surface. The x-ray  
 111 photon energy was set to 9 keV with a relative bandwidth of  
 112  $\Delta E/E = 10^{-3}$ . The x-ray spot size on the sample was  
 113 approximately  $100 \mu\text{m}^2$  and the experiment was conducted  
 114 on a 4-axis goniometer in  $\theta/2\theta$  geometry, with the  
 115 diffracted photons detected by a DECTRIS Pilatus 100k  
 116 hybrid-pixel 2D detector.  
 117

118 After illumination, the x-ray scan reveals a remanent  
 119 shift of  $\Delta q = 3.07 \times 10^{-4} \text{\AA}^{-1}$ , which corresponds to a  
 120 relative lattice contraction of  $1 \times 10^{-4}$  along [010] direc-  
 121 tion. It is accompanied by a peak broadening in the out- and  
 122 in-plane directions, which may be attributed to increase of  
 123 intrinsic nanoscale inhomogeneities, possibly related to  
 124 ferroelastic domains. No significant sample heating is  
 125 expected during the x-ray scan as this would yield lattice  
 126 expansion, contrary to our findings. The observed contrac-  
 127 tion along the [010] direction leads to an overall lattice  
 128 expansion in the (010) plane due to Poisson's ratio and  
 129 agrees well with Fig. 1(c) showing tensile remanent photo-  
 130 striction. The light is therefore able to induce anisotropic  
 131 deformation in BFO that can be used to stress the  
 132 magnetostrictive overlayer, as in piezoelectric-magneto-  
 133 strictive structures. This possibility is demonstrated by  
 134 the experiment in Fig. 2(a), where the 11 nm thick Ni  
 135 film was deposited on the flat side of the BFO crystal in an  
 136  $e$ -beam evaporator at a rate of 0.1 nm/s for  $M(H)$  loop  
 137 measurements [Fig. 2(a)]. The remanent photostriction



F2:1 FIG. 2. (a) Schematics of the experiment. (b) Room-temperature ferromagnetic loops of an 11 nm thick Ni film on top of a BFO single  
 F2:2 crystal before (1) and after (2) excitation by 404 nm light (fluence  $250 \text{ J cm}^{-2}$ ). The initial  $M(H)$  loop (1) can be recovered (3) by an  
 F2:3 electric pulse (c) that corresponds to the ferroelastic coercive force  $E_c$  as represented by an example sketch (d) [46].

138 largely modifies the magnetic properties of the Ni thin film  
 139 [Fig. 2(b)], as revealed by the longitudinal magneto-optic  
 140 Kerr effect (MOKE) magnetometry. The shape of the initial  
 141  $M(H)$  loop is modified after light exposure, with a change  
 142 in coercivity of 75%, which remains stable over a long  
 143 period. For this particular sample, we waited 5 days before  
 144 electrical recovery tests, but other samples showed that the  
 145 effect persisted for more than a month. The scenario  
 146 explaining how light can impact magnetic properties is  
 147 clearly seen from Fig. 1(a). When the light is turned on, the  
 148 concentration of free carriers (electrons and holes) starts to  
 149 increase due to the above-band gap PV effect, and the  
 150 photocurrent across the BFO crystal stabilizes. This creates  
 151 an electric field in the bulk of the crystal that tends to  
 152 influence the net polarization [Fig. 1(a)]. Since the magni-  
 153 tude of this light-induced electric field is small compared to  
 154 the ferroelectric coercive field, there is no polarization  
 155 reversal but only slight displacements of the ferroelastic  
 156 domains in BFO which contribute to its net deformation.  
 157 After the light is turned off, the generation of free carriers  
 158 ceases and the ferroelastic domains gradually relax to a new  
 159 equilibrium configuration that determines the remanent  
 160 photostriction. This optically induced strain is imprinted in  
 161 the magnetostrictive Ni adlayer.

162 Successful electrical erasing, namely, recovery of the  
 163 initial ferroelastic configuration of BFO, can be achieved in

164 two ways. If the coercive ferroelastic force is known, it can  
 165 be done by applying the voltage corresponding to the  
 166 ferroelastic coercive force [Fig. 2(d)]. The electric field  
 167 amplitude of  $5\text{V}/32 \mu\text{m}$  was enough to recover a close to  
 168 initial “virgin”  $M(H)$  loop in the sample (Fig. 2).  
 169 Alternatively, an oscillating damped voltage procedure  
 170 analogous to ac demagnetization can be used, as in the  
 171 case of electrically written states [17,18]. When the initial  
 172 spontaneous ferroelastic state is not characterized, the ac  
 173 electrical erasure may be more convenient.

174 The possibility of direct ME coupling at the interface  
 175 [47] can be discarded because the optical writing [Fig. 2(a)]  
 176 was also demonstrated for samples where a 5 nm Au film is  
 177 inserted between the BFO substrate and the Ni film to  
 178 screen any electric charges at the interface. The Au film  
 179 also excludes the possibility of direct magnetic coupling  
 180 between the BFO and the Ni.

181 All MOKE loop measurements were performed at room  
 182 temperature after excitation and are therefore free of Joule  
 183 heating artifacts. The data shown in Fig. 1(a) obtained  
 184 during excitation suggest a negligible heating effect of the  
 185 laser light, because the polarization of BFO should  
 186 decrease when warming to its ferroelectric Curie temper-  
 187 ature of  $\sim 1143 \text{ K}$  [48]. A temperature increase of 12.3 K,  
 188 detected with a thermal camera during the 30 s illumination  
 189 had no influence on the  $M(H)$  loops of the Ni film. Even

190 after heating to 325 K (13 K more than detected by the  
 191 thermal camera), the  $M(H)$  loops remained unchanged. We  
 192 can therefore safely infer that the optical modification of  
 193 the magnetic properties has a photovoltaic-photostrictive  
 194 origin, as confirmed by the electrical erasure test we  
 195 performed. Our data indicate that the magnetostriction of  
 196 the Ni adlayer explains the modification of its magnetic  
 197 properties, originating from the remanent strain state  
 198 imprinted by light on the BFO substrate.

199 In conclusion, we have demonstrated that ferroelastic  
 200 deformation states can be written optically in BFO, and that  
 201 it is possible to erase them electrically. The remanent  
 202 photostriction naturally depends on the remanent ferro-  
 203 electric state of the sample. The possibility to recover the  
 204 initial state of the functional materials is of key importance,  
 205 as we observed that the ferroic electric or elastic orders  
 206 results in remanent states values that depend on the  
 207 sample's history (spontaneous polarization). This observa-  
 208 tion requires a special care when performing repetitive  
 209 experiments (e.g., pump and probe procedures) with  
 210 unsaturated FE samples in order to guarantee proper reset  
 211 of the initial polarization. The observed photopolarization  
 212 induces a deformation that can be coupled to a ferromag-  
 213 netic adlayer, resulting in optically controlled magnetic  
 214 anisotropy. This optically induced effect manifests itself in  
 215 a 75% change in the ferromagnetic coercivity, exceeding by  
 216 55% the well-known electric control in the BaTiO<sub>3</sub>/Fe  
 217 structures [49] with the nonvolatile and wireless advantage,  
 218 thus opening the technologically interesting possibility of  
 219 multistate magnetic operation [Fig. 1(a)]. The ultrafast  
 220 photostriction in BFO films [50–52] and ceramics [53]  
 221 combined with the possibility of ultrafast gating [54],  
 222 provides a perspective for light-controlled magnetic switch-  
 223 ing devices and magnetoresistive memories on sub-ns time  
 224 scales. Furthermore, the fact that photostriction can exist in  
 225 a number of different materials [32,55] expands the horizon  
 226 of photo-magneto-elastic interactions beyond inorganic  
 227 compounds [56].

228 **2** This work was partially supported by French National  
 229 Research Agency via hvSTRICTSPIN ANR-13-JS 04-  
 230 0008-01, Labex NIE 11-LABX-0058-NIE within the  
 231 ANR-10-IDEX-0002-02 research grants. D. S. acknowl-  
 232 edges the Helmholtz Association for funding via the  
 233 Helmholtz Postdoc Programme PD-142. The technical  
 234 support of the STnano cleanroom (IPCMS) facility is  
 235 acknowledged. B.K. is grateful to J.M.D. Coey for  
 236 comments on the manuscript.

239  
 240 **3** [1] W. Eerenstein, N.D. Mathur, and J.F. Scott, *Nature*  
 241 **442**, 759 (2006).  
 242 **4** [2] A. Kumar, R. S. Katiyar, R. N. Premnath, C. Rinaldi, and  
 243 J. F. Scott, *J. Mater. Sci.* **44**, 5113 (2009).  
 244 [3] D. A. Sanchez, N. Ortega, A. Kumar, G. Sreenivasulu,  
 245 Ram S. Katiyar, J. F. Scott, D. M. Evans, M. Arredondo-

Arechavala, A. Schilling, and J. M. Gregg, *J. Appl. Phys.* **113**, 074105 (2013). 246  
 247  
 [4] B. Kundys, A. Maignan, C. Martin, N. Nguyen, and Ch. 248  
 Simon, *Appl. Phys. Lett.* **92**, 112905 (2008). 249  
 [5] Y. Wang, J. Hu, Y. Lin, and C.-W. Nan, *NPG Asia Mater.* **2**, 250  
 61 (2010). 251  
 [6] A. Brandlmaier, S. Geprägs, G. Woltersdorf, R. Gross, and 252  
 S. T. B. Goennenwein, *J. Appl. Phys.* **110**, 043913 (2011). 253  
 [7] T. Taniyama, *J. Phys. Condens. Matter* **27**, 504001 (2015). 254  
 [8] Y. Shirahata, *NPG Asia Mater.* **7**, e198 (2015). 255  
 [9] K. Roy, *Appl. Phys. Lett.* **103**, 173110 (2013). 256  
 [10] K. Roy, S. Bandyopadhyay, and J. Atulasimha, *Phys. Rev. B* 257  
**83**, 224412 (2011). 258  
 [11] K. Roy, S. Bandyopadhyay, and J. Atulasimha, *J. Appl.* 259  
*Phys.* **112**, 023914 (2012). 260  
 [12] N. Lei, N. *et al.*, *Nat. Commun.* **4**, 1378 (2013). 261  
 [13] M. Buzzi, *Phys. Rev. Lett.* **111**, 027204 (2013). 262  
 [14] P. Li, A. Chen, D. Li, Y. Zhao, S. Zhang, L. Yang, Y. Liu, M. 263  
 Zhu, H. Zhang, and X. Han, *Adv. Mater.* **26**, 4320 (2014). 264  
 [15] D. Halley, N. Najjari, H. Majjad, L. Joly, P. Ohresser, F. 265  
 Scheurer, C. Ulhaq-Bouillet, S. Berciaud, B. Doudin, and Y. 266  
 Henry, *Nat. Commun.* **5**, 3167 (2014). 267  
 [16] P. Li, A. Chen, D. Li, Y. Zhao, S. Zhang, L. Yang, Y. Liu, M. 268  
 Zhu, H. Zhang, and X. Han, *Adv. Mater.* **26**, 4320 (2014). 269  
 [17] B. Kundys, V. Iurchuk, C. Meny, H. Majjad, and B. Doudin, 270  
*Appl. Phys. Lett.* **104**, 232905 (2014). 271  
 [18] V. Iurchuk, B. Doudin, and B. Kundys, *J. Phys. Condens.* 272  
*Matter* **26**, 292202 (2014). 273  
 [19] B. Kundys, M. Viret, D. Colson, and D. O. Kundys, *Nat.* 274  
*Mater.* **9**, 803 (2010). 275  
 [20] G. Catalan and J. F. Scott, *Adv. Mater.* **21**, 2463 (2009). 276  
 [21] N. Leo, D. Meier, P. Becker, L. Bohatý, and M. Fiebig, *Opt.* 277  
*Express* **23**, 27700 (2015). 278  
 [22] D. Meier, M. Maringer, Th. Lottermoser, P. Becker, L. 279  
 Bohatý, and M. Fiebig, *Phys. Rev. Lett.* **102**, 107202 280  
 (2009). 281  
 [23] B. Mettout, P. Tolédano, A. S. B. Sombra, A. F. G. Furtado 282  
 Filho, J. P. C. do Nascimento, M. A. Santos da Silva, P. 283  
 Gisse, and H. Vasseur, *Phys. Rev. B* **93**, 195123 (2016). 284  
 [24] W. Jin Hu, Z. Wang, W. Yu, and T. Wu, *Nat. Commun.* **7**, 285  
 10808 (2015). 286  
 [25] J. Kreisel, M. Alexe, and P. A. Thomas, *Nat. Mater.* **11**, 260 287  
 (2012). 288  
 [26] T. Choi, S. Lee, Y. J. Choi, V. Kiryukhin, and S.-W. Cheong, 289  
*Science* **324**, 63 (2009). 290  
 [27] S. Y. Yang *et al.* *Nat. Nanotechnol.* **5**, 143 (2010). 291  
 [28] F. Wang, S. M. Young, F. Zheng, I. Grinberg, and A. M. 292  
 Rappe, *Nat. Commun.* **7**, 10419 (2016). 293  
 [29] Y. Li, C. Adamo, P. Chen, P. G. Evans, S. M. Nakhmanson, 294  
 W. Parker, C. E. Rowland, R. D. Schaller, D. G. Schlom, 295  
 D. A. Walko, H. Wen, and Q. Zhang, *Sci. Rep.* **5**, 16650 296  
 (2015). 297  
 [30] H. Wen, M. Sassi, Z. Luo, C. Adamo, D. G. Schlom, K. M. 298  
 Rosso, and X. Zhang, *Sci. Rep.* **5**, 15098 (2015). 299  
 [31] Ch. Paillard, B. Xu, B. Dkhil, G. Geneste, and L. Bellaiche, 300  
*Phys. Rev. Lett.* **116**, 247401 (2016). 301  
 [32] B. Kundys, *Appl. Phys. Rev.* **2**, 011301 (2015). 302  
 [33] D. Sando, Yurong Yang, E. Bousquet, C. Carretero, V. 303  
 Garcia, S. Fusil, D. Dolfi, A. Barthelemy, Ph. Ghosez, L. 304  
 Bellaiche, and M. Bibes, *Nat. Commun.* **7**, 10718 (2016). 305  
 [34] S. Lee, S. *et al.*, *Phys. Rev. B* **88**, 060103 (2013). 306

- 307 [35] T. Zhao, T. *et al.*, *Nat. Mater.* **5**, 823 (2006). 332
- 308 [36] D. Sando *et al.*, *Nat. Mater.* **12**, 641 (2013). 333
- 309 [37] Y. Yang, I. C. Infante, B. Dkhil, and L. Bellaiche, *C.R. Phys.* 334
- 310 **16**, 193 (2015). 335
- 311 [38] F. Rubio-Marcos, A. D. Campo, P. Marchet, and J. F. 336
- 312 Fernández, *Nat. Commun.* **6**, 6594 (2015). 337
- 313 [39] A. Hirohata and K. J. Takanashi, *J. Phys. D* **47**, 193001 338
- 314 (2014). 339
- 315 [40] S. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, 340
- 316 S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova, and D. 341
- 317 M. Treger, *Science* **294**, 1488 (2001). 342
- 318 [41] V. M. Fridkin, *Photoferroelectrics* (Springer, New York, 343
- 319 1979). 344
- 320 [42] D. Damjanovic, *Sci. Hysteresis* **3**, 337 (2006). 345
- 321 [43] K. M. Rabe, Ch. H. Ahn, and J.-M. Triscone, *Physics of* 346
- 322 *Ferroelectrics: A Modern Perspective* (Springer, New York, 347
- 323 2010). 348
- 324 [44] H. Navirian, R. Shayduk, W. Leitenberger, J. Goldshteyn, P. 349
- 325 Gaal, and M. Bargheer, *Rev. Sci. Instrum.* **83**, 063303 350
- 326 (2012). 351
- 327 [45] The sample preparation is described in D. Lebeugle, D. 352
- 328 Colson, A. Forget, M. Viret, P. Bonville, J. F. Marucco, and 353
- 329 S. Fusil, *Phys. Rev. B* **76**, 024116 (2007). The observation 354
- 330 in polarized light in the reflection mode along [010] revealed 355
- 331 a monodomain FE state. 356
- [46] W.-C. Lin, C.-W. Huang, Y.-C. Ting, F.-Y. Lo, and M.-Y. 357
- Chern, *J. Magn. Magn. Mater.* **381**, 446 (2015). 358
- [47] C.-G. Duan, J. P. Velev, R. F. Sabirianov, Z. Zhu, J. Chu, 359
- S. S. Jaswal, and E. Y. Tsymbal, *Phys. Rev. Lett.* **101**, 360
- 137201 (2008). 361
- [48] I. Sosnovska, T. Peterlin-Neumaier, and E. Steichele, *J.* 362
- Phys. C* **15**, 4835 (1982). 363
- [49] S. Sahoo, S. Polisetty, C.-G. Duan, S. S. Jaswal, E. Y. 364
- Tsymbal, and C. Binek, *Phys. Rev. B* **76**, 092108 (2007). 365
- [50] D. Schick, M. Herzog, H. Wen, P. Chen, C. Adamo, P. Gaal, 366
- D. G. Schlom, P. G. Evans, Y. Li, and M. Bargheer, *Phys.* 367
- Rev. Lett.* **112**, 097602 (2014). 368
- [51] L. Y. Chen, J. C. Yang, C. W. Luo, C. W. Laing, K. H. Wu, 369
- J.-Y. Lin, T. M. Uen, J. Y. Juang, Y. H. Chu, and T. 370
- Kobayashi, *Appl. Phys. Lett.* **101**, 041902 (2012). 371
- [52] Z. Jin, Y. Xu, Z. Zhang, X. Lin, G. Ma, Z. Cheng, and X. 372
- Wang, *Appl. Phys. Lett.* **101**, 242902 (2012). 373
- [53] M. Lejman, G. Vaudel, I. C. Infante, P. Gemeiner, V. E. 374
- Gusev, B. Dkhil, and P. Ruello, *Nat. Commun.* **5**, 4301 375
- (2014). 376
- [54] F. Chen *et al.* *Adv. Mater.* **27**, 6371 (2015). 377
- [55] Y. Zhou, L. You, S. Wang, Z. Ku, H. Fan, D. Schmidt, A. 378
- Rusydi, L. Chang, L. Wang, P. Ren, L. Chen, G. Yuan, L. 379
- Chen, and J. Wang, *Nat. Commun.* **7**, 11193 (2016). 380
- [56] E. Orgiu and P. Samori, *Adv. Mater.* **26**, 1827 (2014). 381