Engineering room-temperature multiferroicity in Bi and Fe codoped BaTiO$_3$

Pratap Pal, Tapas Paramanik, Krishna Rudrapal, Supriyo Majumder, Satish Yadav, Sudipta Mahana, Dinesh Topwal, Ram Janay Choudhary, Kiran Singh, Ayan Roy Chaudhuri, and Debraj Choudhury

ARTICLES YOU MAY BE INTERESTED IN

Interfacial charge and strain effects on lanthanum doped barium stannate thin film under ferroelectric gating
Applied Physics Letters 117, 012101 (2020); https://doi.org/10.1063/5.0006999

Barkhausen noise analysis of thin film ferroelectrics
Applied Physics Letters 117, 012902 (2020); https://doi.org/10.1063/5.0012635

BaTiO$_3$-based piezoelectrics: Fundamentals, current status, and perspectives
Applied Physics Reviews 4, 041305 (2017); https://doi.org/10.1063/1.4990046

Your Qubits. Measured.
Meet the next generation of quantum analyzers

- Readout for up to 64 qubits
- Operation at up to 8.5 GHz, mixer-calibration-free
- Signal optimization with minimal latency

Find out more
Zurich Instruments
Engineering room-temperature multiferroicity in Bi and Fe codoped BaTiO$_3$

Cite as: Appl. Phys. Lett. 117, 012901 (2020); doi: 10.1063/5.0004785
Submitted: 14 February 2020 · Accepted: 19 June 2020 · Published Online: 6 July 2020

Pratap Pal, Tapas Paramanik, Krishna Rudrapal, Supriyo Majumder, Satish Yadav, Sudipta Mahana, Dinesh Topwal, Ram Janay Choudhary, Kiran Singh, Ayan Roy Chaudhuri, and Debraj Choudhury

AFFILIATIONS
1Department of Physics, Indian Institute of Technology Kharagpur, West Bengal 721302, India
2Department of Physics, School of Sciences, National Institute of Technology Andhra Pradesh, Tadepalli, 534101, India
3Advanced Technology Development Centre, Indian Institute of Technology Kharagpur, West Bengal 721302, India
4UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore 452001, India
5Rajdhani College, Baramunda square, Bhubaneswar 751003, India
6Institute of Physics, Sachivalaya Marg, Bhubaneswar 751005, India
7Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400085, India
8Dr. B. R. Ambedkar National Institute of Technology, Jalandhar 144011, India
9Materials Science Centre, Indian Institute of Technology Kharagpur, West Bengal 721302, India

a) Author to whom correspondence should be addressed: debraj@phy.iitkgp.ac.in

ABSTRACT

Fe doping into BaTiO$_3$ stabilizes the paraelectric hexagonal phase in place of the ferroelectric tetragonal one. We show that simultaneous doping of Bi along with Fe into BaTiO$_3$ effectively enhances the magnetoelectric (ME) multiferroic response (both ferromagnetism and ferroelectricity) at room temperature, through careful tuning of Fe valency along with the controlled recovery of the ferroelectric-tetragonal phase. We also report a systematic increase in large dielectric constant values as well as reduction in loss tangent values with relatively moderate temperature variation of the dielectric constant around room temperature with increasing Bi doping content in Ba$_{1-x}$Bi$_x$Ti$_{0.90}$Fe$_{0.10}$O$_3$ (0 $\leq x \leq$ 0.10), which makes the higher Bi–Fe codoped sample ($x = 0.08$) promising for use as a room-temperature high-$\kappa$ dielectric material. Interestingly, the $x = 0.08$ (Bi–Fe codoped) sample is not only found to be ferroelectrically (~20 times) and ferromagnetically (~6 times) stronger than $x = 0$ (only Fe-doped) at room temperature, but also observed to be better insulating (larger bandgap) with indirect signatures of larger ME coupling as indicated from anomalous reduction of the magnetic coercive field with decreasing temperature. Thus, room-temperature ME multiferroicity has been engineered in Bi and Fe codoped BTO (BaTiO$_3$) compounds.

Published under license by AIP Publishing. https://doi.org/10.1063/5.0004785

Room-temperature magnetoelectric (ME) multiferroic materials are extremely promising for future technological applications.\textsuperscript{1,2} In this regard, efforts toward turning BaTiO$_3$ (a strong proper ferroelectric\textsuperscript{3}) into a multiferroic material by Fe\textsuperscript{4,5} (or other transition metals like Mn, Co, etc.) doping has attracted a lot of attention. However, the observed multiferroicity in Fe-doped BTO is seen to be of mixed phase kind where the ferromagnetism arises from the majority paraelectric-hexagonal phase and weak ferroelectricity due to a minority tetragonal phase.\textsuperscript{5} Thus, in such a case, the ME coupling is naturally supposed to be weak due to the independent origin of two ferroic orders at two different structural units. So, the necessity is to stabilize the tetragonal phase, even in this magnetically Fe-doped BTO compound, such that both ferroelectricity and ferromagnetism can emerge from the same tetragonal phase, which may lead to better ME coupling along with pronounced ferroelectricity. It is important to note that for a material to be a potential room-temperature multiferroic, it is desirable to have (a) a strong ferroelectric polarization, (b) a high ferromagnetic remnant moment, and (c) a low leakage-current density (i.e., highly insulating) along with (d) ME coupling between the two ferroic-orders.\textsuperscript{5}

With these goals, we examine polycrystalline Ba$_{1-x}$Bi$_x$Ti$_{0.90}$Fe$_{0.10}$O$_3$ compounds (0 $\leq x \leq$ 0.10) and show that with increasing Bi doping content not only the paraelectric-hexagonal phase of $x = 0$ (only Fe-doped BTO) gets destabilized (with concomitant recovery of the ferroelectric-tetragonal phase), but also there is a surprising and
significant enhancement of room-temperature ferromagnetism. Interestingly, we find that the observed ferroelectricity is strongest around $x = 0.02$ and ferromagnetism around $x = 0.08$, while the intermediate $x = 0.05$ shows an indirect signature of most robust ME-coupling (see Fig. 1).

All phase pure (related to BTO hexagonal and tetragonal phases only) polycrystalline samples which were prepared via solid state reactions (for details refer to Ref. 5) were characterized using XRD and Raman measurements. Dielectric and magnetic measurements were performed using a Keysight E4980A LCR meter and SQUID-VSM, respectively. Electron Paramagnetic Resonance (EPR) measurements were carried out using a Bruker spectrometer. Intrinsic ferroelectric properties have been investigated using ferroelectric PUND (Positive Up Negative Down) and temperature dependent pyroelectric measurements. XANES (X-ray absorption near edge spectroscopy) and XPS (X-ray photoelectron spectroscopy) measurements were carried out using a P-65 beamline in a PETRA-III synchrotron source, DESY, Hamburg, Germany and using an in-house PHI 5000 Versaprobe-II spectrometer, respectively, while the diffused reflectance spectra were acquired using a Cary 5000 UV-Visible near-infrared spectrophotometer.

Figure 2(a) covers the 2θ range in the XRD spectrum which includes the strongest diffraction peaks from the hexagonal [H(110)] and the tetragonal [T(101)] BTO phases (also see Fig. S1 of the supplementary material). While $x = 0$ crystallizes in the hexagonal phase, with increasing $x$, the tetragonal phase gets fully recovered as observed from the systematic increase in tetragonal T(101) peak intensity and concomitant decrease in hexagonal H(110) peak intensity. The XRD observations of tetragonal phase recovery are further validated by Raman spectroscopy as shown in Fig. 2(b), where clear evolution of tetragonal Raman modes from the majority hexagonal phase with increasing Bi concentration has been observed.10,11 The amount of hexagonal [shown in Fig. 2(c)] and tetragonal phase [shown in Fig. 3(b)] fractions present in each of these samples is determined from Rietveld refinement of their room-temperature XRD spectra incorporating both hexagonal (P63/mmc) and tetragonal (P4mm) phases [an example is shown in the inset of Fig. 2(c) for $x = 0.02$, see also Fig. S2 of the supplementary material]. It is interesting to note that there is strong shifting of the tetragonal T(101) XRD peak to higher angles with Bi doping; however, such is not the case for the hexagonal H(110) as shown in Fig. 2(a). Similarly, no significant change in $d_{h(110)}$ [spacing between H(110) planes] is observed beyond $x = 0.02$, whereas $d_{T(101)}$ systematically gets reduced with increasing Bi doping concentration, as shown in the inset to Fig. 2(d). The reduction of $d_{T(101)}$ is driven by the substitution of BaTiO$_3$ ions by relatively smaller Bi$^{3+}$ ions. Furthermore, we note the monotonic shifting of the tetragonal Raman $A_{1g}$ mode toward higher energy with Bi doping, which is, however, not quite prominent in the case of the hexagonal Raman $A_{1g}$ mode as shown in Fig. 2(d). Thus, both XRD and Raman analyses suggest a maximum doping percentage of Bi at the Ba site of the hexagonal BTO.

Next, to study the intrinsic ferroelectric properties, we have employed the PUND technique (for details see Ref. 5). In Fig. 3(a), we see that from $x = 0$ there is a sudden increase in the ferroelectric polarization value for $x = 0.02$ and then it continues to decrease up to $x = 0.10$ (also see Fig. S3 of the supplementary material). However, such a nonmonotonic trend of polarization-change cannot be
understood from the monotonic evolution of the tetragonal phase fraction (%) as seen in Fig. 3(b). To investigate such a behavior, we have calculated the sample tetragonality (c/a), which is shown in Fig. 3(c). Here, we note that the tetragonality, which is found to be maximum for x = 0.02, exhibits the same trend as observed for polarization change in Fig. 3(a). Therefore, the tetragonality, measure of the amount of Ti-off centric distortion in the corresponding TiO₆ cage (see Fig. S7 of the supplementary material), overrides the amount of tetragonal phase percentage present in regard to the observed ferroelectricity in these systems. Such observations were further validated from temperature dependent pyrocurrent measurements (see Fig. S4 of the supplementary material).

Now, to have a holistic view, we have plotted the remanent polarization value (dPr) vs sample tolerance factor (which can strongly influence structural instabilities of such perovskite oxides) as shown in Fig. 3(d), using Fe and Ti valencies determined from the Fe-K edge XANES and XPS spectroscopic studies (for details see Secs. V–VII of the supplementary material). Interestingly, there is a window of tolerance factor around which ferroelectric response is optimum in these systems, useful for achieving an optimized multiferroic response.

Interestingly, we find a systematic increase in large dielectric constant values as well as reduction in loss tangent values with increasing Bi doping content [see Fig. 3(e)], which makes the higher Bi–Fe codoped system (x = 0.08) promising for use as a room-temperature high-κ dielectric material since it exhibits a unique combination of often contradictory physical properties, i.e., very large dielectric constant, extremely low dielectric loss, and moderate temperature dependence of dielectric constant values around room temperature [TC = (1/κ) × (∂ε/∂ T)] (see Table I). While undoped BaTiO₃ also exhibits a very high dielectric constant and low loss values, but the corresponding [TC] value changes a lot within the 50 K temperature window around room temperature rendering it unsuitable as a high-κ dielectric material. Interestingly, the dielectric response of x = 0.08 (i.e., higher dielectric constant value, comparable loss, and [TC] values) seems better compared to SrTiO₃, very well-known as a high-κ dielectric material.¹⁷

| Sample     | Dielectric constant (εr) | Loss (D) | Avg. TC (ppm/K) at (300 ± 25) K |
|------------|--------------------------|----------|-------------------------------|
| SiO₂       | 3.7                      | 0.0015   | …                             |
| SrTiO₃     | 285                      | 0.006    | −2400                         |
| BaTiO₃     | 1626                     | 0.015    | −799 ± 408%                   |
| x = 0      | 37                       | 0.027    | −541 ± 8%                     |
| x = 0.05   | 177                      | 0.019    | 2358 ± 17%                    |
| x = 0.08   | 785                      | 0.008    | 2262 ± 14%                    |

TABLE I. Dielectric constant (εr), dielectric loss (D), and the temperature coefficient of dielectric constant TC (which is averaged from 275 K to 325 K temperature window) measured at a frequency of ~100 kHz. Here, only values of SiO₂ and SrTiO₃ are taken from previous reports. Reproduced with permission from Choudhury et al. Appl. Phys. Lett. 96, 162903 (2010). Copyright 2010 AIP Publishing.

FIG. 3. (a) Variation of remanent-ferroelectric polarization at room temperature, obtained from PUND measurements, (b) and (c) show the variation of tetragonal phase fraction (%) and sample tetragonality (c/a), respectively. (d) Variation of remanent polarization with the sample tolerance factor, and (e) variation of the dielectric constant and loss tangent values at room temperature with Bi doping amount.

FIG. 4. (a) Room temperature MH plots. (b) Variation of remanent magnetization (M₀). The inset to it shows the corresponding change in coercive field (Hc). (c) Temperature dependent magnetization behavior for applied field of 0.5 T, where bottom and top insets, respectively, show the dM/dT vs T plot and the change in ferromagnetic TC with Bi doping concentration. (d) and its top inset show variation of resonance magnetic field and HPP (peak to peak linewidth) as determined from EPR spectra, while its bottom inset shows the corresponding change in the Lande g-factor.

Applied Phys. Lett. 117, 012901 (2020); doi: 10.1063/5.0004785

Published under license by AIP Publishing
To investigate the magnetic properties, first we discuss the room-
temperature MH data as shown in Fig. 4(a), which exhibit finite ferro-
magnetic loops; however, they do not saturate, indicating the presence of
some paramagnetic contributions. Thus, we consider the intrinsic
ferromagnetic remanent moment (M_r) which is seen to monotontically
increase from x = 0 up to x = 0.08 (having ~6 times enhanced mag-
netization) and then decreases for x = 0.10 as shown in Fig. 4(b). Such
a non-monotonic trend is also reflected even in the case of coercive field
[see the inset to Fig. 4(b)]. Temperature dependent magnetization
measurements display clear ferromagnetic to paramagnetic phase
transition and the Curie temperature (T_c) [as estimated from dM/dT
vs T plot, shown in the bottom inset to Fig. 4(c)] is found to increase
systematically with Bi doping concentration as shown in Fig. 4(c)
and its top inset. To further investigate the above trend of magnetization
in the microscopic scale, we employ EPR spectroscopy, which is shown
in Fig. S10 of the supplementary material, where we see marked
changes in line shape with Bi doping. First, we have determined the
peak-to-peak linewidth (ΔHpp) [see the top inset of Fig. 4(d)], which
increases monotonically with Bi doping, indicating increasing Fe–Fe
echange interaction. Subsequently, we see that the resonance
magnetic field monotonically decreases up to x = 0.08 and then
slightly increases for x = 0.10. Such observations strongly indicate that
the strength of ferromagnetic interaction gets enhanced up to x = 0.08,
followed by a reduction for x = 0.10, possibly due to some antiferro-
magnetic interaction. Even, the Lande g-factor for all these com-
ounds, as shown in the bottom inset of Fig. 4(d), shows a similar
trend to the remanent magnetization value. Such enhancement of ferro-
magnetism, however, cannot be understood from the framework of
increasing oxygen vacancy content or increasing hexagonal phase
fractions, as both are simultaneously and monotonically reduced with
increasing Bi doping concentration. Such trends of magnetic response
cannot be understood from the possible presence of any extrinsic con-
tributions, like from BiFeO_3, Fe_2O_3, or Fe_3O_4 related impurity phases,
which, however, could not be detected through detailed XRD analyses,
as discussed in the last section of the supplementary material (also,
note Refs. 22–25). These results suggest an alternative source of ferro-
magnetism for higher x members beyond the hexagonal BTO phase
that can likely be the tetragonal BTO phase (Fe^{3+}–O–Fe^{3+}, FM super-
exchange interaction), as beyond some doping limit both Bi and Fe
tend to go into the tetragonal phase (for schematic visualization, see
Sec. IX of the supplementary material).

The x = 0.08 compound, in addition to possessing ~20 times
enhanced ferroelectric remanent polarization value compared to that
of x = 0 (also, evident from their room-temperature PE loops, shown
in Fig. S11 of the supplementary material), is also more insulating
than x = 0 (the optical bandgap of x = 0.08 is greater than that of
x = 0 as determined from diffused reflectance spectroscopy measure-
ments) as shown in Fig. 5(a). Therefore, x = 0.08 (Bi–Fe codoped
BTO), which is found to have much enhanced ferroelectric, ferromag-
netic, and insulating properties at room-temperature compared to
x = 0 (only Fe-doped BTO), is more suitable as a better multiferroic.
Figure 5(b) and its inset show isothermal MH plots of x = 0.08 and
x = 0, respectively. The difference in 300 K and 10 K MH curves is
more prominent in the former than the latter. Variations of their
extracted coercive fields (H_c) and remanent magnetizations (M_r) are
shown in Fig. 5(c) and its inset. Here, we note that though M_r
increases on decreasing temperature like an usual ferromagnet,

However, the coercive field shows opposite trend. Even, such surprising
behavior is stronger in x = 0.08 than x = 0. It is important to note that
such an unusual trend of coercive field with temperature has been
used as an indicative (indirect) measure of the ME coupling strength
in many related ME multiferroic systems. The presence of ME coupling in
these compounds also becomes evident from the correlation of the ferroelectric polarisation and the spontaneous
magnetisation at various temperatures, as shown in Fig. S12 of the
supplementary material, similar to that observed in the ME multiferroic
0.9BiFeO_3-0.1BiTiO_3 system. Thus, such anomalous temperature
dependent variations of magnetic coercivity in our Bi–Fe codoped
compounds are likely governed by the competition between magneto-
crystalline anisotropy and ME coupling. The ratio of H_c at 300 K
to H_c at 10 K (the factor of reduction of coercive field) can, thus,
be used as an indicative marker for the strength of ME coupling [which is plotted in Fig. 5(d)], which, for this series, becomes the strongest for
x = 0.05 composition, possibly driven by the right appropriate mix of
simultaneously large ferroelectric polarization and ferromagnetic
moment value, likely within the same tetragonal phase.

In summary, we have investigated room-temperature multiferro-
ic properties of Ba_{1-x}Bi_xTi_{0.9}Fe_{0.1}O_3 (0 ≤ x ≤ 0.10) compounds.
By codoping Bi and Fe into BaTiO_3, we completely recover the ferro-
electric tetragonal phase in the magnetically doped BTO compounds.
However, the role of sample tetragonality in the recovered ferroelec-
tricity is found to be stronger. Both macro- and microscopic measure-
ments reveal that the intrinsic ferromagnetic property gets enhanced
up to x = 0.08 with Bi doping, which is followed up by a reduction for
x = 0.10 due to increased antiferromagnetic interaction. Interestingly,
in this series of compounds, though x = 0.02 shows the highest
ferroelectric polarization and $x = 0.08$ shows the largest magnetic moment, however, the signature of ME coupling, as indicated from the anomalous change of magnetic coercive field with temperature, seems to be strongest in the intermediate $x = 0.05$ due to the simultaneous presence of both ferroelectricity and ferromagnetism in significant amounts and likely within the same tetragonal phase. However, it would be interesting to further probe such ME coupling present in these compounds by some direct measurement techniques. Thus, simultaneous Bi–Fe codoped BTO compounds around the composition $x = 0.05$ to $x = 0.08$ are found to exhibit better room-temperature ME multiferroic properties compared to only Fe doped BTO as shown in Fig. 1.

See the supplementary material for additional supporting data like XRD refinements, XANES, XPS, EPR, and related discussions.

We acknowledge the use of XPS under the DST-FIST (India) facility in the Department of Physics, IIT Kharagpur for this work. P.P. would like to acknowledge the financial support from MHRD, India. D.C. would like to acknowledge SERB, DST, India (Project file no. ECR/2016/000019) and BRNS, DAE (Sanction No. 37(3)/20/23/2016-BRNS) for financial support. D.T. would like to acknowledge financial support by DST under the India@DESY collaboration.

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material file.

REFERENCES

1N. A. Hill, J. Phys. Chem. B 104, 6694 (2000).
2D. Khomskii, Physica C 2, 20 (2009).
3R. E. Cohen, Nature 358, 136 (1992).
4B. Xu, K. B. Yin, J. Lin, Y. D. Xia, X. G. Wan, J. Yin, X. J. Bai, J. Du, and Z. G. Liu, Phys. Rev. B 79, 134109 (2009).
5P. Pal, K. Rudrapal, S. Mahana, S. Yadav, T. Paramanik, S. Mishra, K. Singh, G. Sheet, D. Topwal, A. R. Chaudhuri, and D. Choudhury, Phys. Rev. B 101, 064409 (2020).
6Y. H. Lin, J. Yuan, S. Zhang, Y. Zhang, J. Liu, Y. Wang, and C. W. Nan, Appl. Phys. Lett. 95, 033105 (2009).
7L. B. Luo, Y. G. Zhao, H. F. Tian, J. J. Yang, J. Q. Li, J. J. Ding, B. He, S. Q. Wei, and C. Gao, Phys. Rev. B 79, 115210 (2009).
8N. A. Spaldin and R. Ramesh, Nat. Mater. 18, 203 (2019).
9D. H. Kim and B. W. Lee, J. Korean Phys. Soc. 68, 574 (2016).
10C. H. Perry and D. B. Hall, Phys. Rev. Lett. 15, 700 (1965).
11H. M. Tejeyen, N. V. Dang, P. Y. Chuang, T. D. Huang, C. W. Hu, T. Y. Chen, V. D. Lam, C. H. Lee, and L. V. Hong, Appl. Phys. Lett. 99, 205201 (2011).
12B. Rajeswaran, D. I. Khomskii, A. K. Zvezdin, C. N. R. Rao, and A. Sundaresan, Phys. Rev. B 86, 214409 (2012).
13A. R. Chaudhuri and S. B. Krupanidhi, Solid State Commun. 150, 660 (2010).
14V. Choudhury, A. Venimadhav, C. Kakkarla, K. T. Delaney, P. S. Devi, P. Mondal, R. Nirmala, J. Gopalakrishnan, N. A. Spaldin, L. V. Waghmare, and D. D. Sarma, Appl. Phys. Lett. 96, 162903 (2010).
15Z. Li, M. Yang, J. S. Park, S. H. Wei, J. J. Berry, and K. Zhu, Chem. Mater. 28, 284 (2016).
16A. I. Kingon, J. P. Maria, and S. K. Streiffer, Nature 406, 1032 (2000).
17K. Eisenbeiser, J. M. Finder, Z. Yu, J. Ramdani, J. A. Curless, J. A. Hallmark, R. Droopad, W. J. Ooms, I. Salem, S. Bradshaw, and C. D. Overgaard, Appl. Phys. Lett. 76, 1324 (2000).
18D. Karmakar, S. K. Mandal, R. M. Kadam, P. L. Paulose, A. K. Rajarajan, T. K. Nath, A. K. Das, I. Dasgupta, and G. P. Das, Phys. Rev. B 75, 144404 (2007).
19T. Chakraborty, S. Ray, and M. Itoh, Phys. Rev. B 83, 144407 (2011).
20S. D. Bhave, V. I. I. Joly, and P. A. Joy, Phys. Rev. B 72, 054426 (2005).
21J. Gutiérrez, A. Peña, J. M. Barandiarán, J. L. Pizarro, T. Hernández, L. Lezama, M. Insauti, and T. Rojo, Phys. Rev. B 61, 9028 (2000).
22J. Lu, A. Günther, F. Schrettle, F. Mayr, S. Krohns, P. Lunkemeier, A. Pimenov, V. D. Trushkin, A. A. Mukhin, and A. Loudi, Eur. Phys. J. B 75, 451 (2010).
23A. S. Teja and P. Y. Koh, Prog. Cryst. Growth Charact. Mater. 55, 22 (2009).
24Y. Ishikawa and S. I. Akimoto, J. Phys. Soc. Jpn. 13, 1298 (1958).
25S. Akimoto, T. Katsura, and M. J. Yoshida, J. Geomagn. Geoelectr. 9, 165 (1957).
26X. H. Huang, J. F. Ding, G. Q. Zhang, Y. Hou, Y. P. Yao, and X. G. Li, Phys. Rev. B 78, 224408 (2008).
27V. Markovich, I. Fita, A. Wismierski, D. Mogilyansky, R. Puzniak, L. Titelman, C. Martin, and G. Gorodetsky, Phys. Rev. B 81, 094428 (2010).
28S. Patankar, S. K. Pandey, V. R. Reddy, A. Gupta, A. Banerjee, and P. Chaddah, Europhys. Lett. 90, 50070 (2010).
29B. Ahmmad, M. Z. Islam, A. Billah, and M. A. Basith, J. Phys. D: Appl. Phys. 49, 095901 (2016).
30T. J. Park, G. C. Papaefthymiou, A. J. Viescas, Y. Lee, H. Zhou, and S. S. Wong, Phys. Rev. B 82, 024431 (2010).
31N. Wang, J. Cheng, A. Pyatakov, A. K. Zvezdin, J. F. Li, D. Viehland, and T. Wu, Phys. Rev. B 72, 104434 (2005).
32R. E. Fayling, J. Appl. Phys. 49, 1823 (1978).
33R. Ruette, S. Zyugin, A. P. Pyatakov, A. Bush, J. F. Li, V. I. Belotelov, A. K. Zvezdin, and D. Viehland, Phys. Rev. B 69, 064414 (2004).
34A. Singh, V. Pandey, R. K. Kotnala, and D. Pandey, Phys. Rev. Lett. 101, 247602 (2008).