Magnetoresistance of epitaxial and polycrystalline Fe_3O_4 films near Verwey transition

Xiang Liu, Wenbo Mi, Qiang Zhang, and Xixiang Zhang

Citation: *Appl. Phys. Lett.* **113**, 012401 (2018); doi: 10.1063/1.5035403

View online: <https://doi.org/10.1063/1.5035403>

View Table of Contents: <http://aip.scitation.org/toc/apl/113/1>

Published by the [American Institute of Physics](#)

Articles you may be interested in

[Unraveling thickness-dependent spin relaxation in colossal magnetoresistance manganite films](#)

Applied Physics Letters **113**, 012402 (2018); 10.1063/1.5013258

[Control of misfit strain in ferroelectric \$\text{BaTiO}_3\$ thin-film capacitors with \$\text{SrRuO}_3\$ -based electrodes on \(Ba, Sr\) \$\text{TiO}_3\$ -buffered \$\text{SrTiO}_3\$ substrates](#)

Applied Physics Letters **113**, 012903 (2018); 10.1063/1.5031156

[Engineering magnetic heterostructures to obtain large spin Hall efficiency for spin-orbit torque devices](#)

Applied Physics Letters **113**, 022402 (2018); 10.1063/1.5036836

[Magnetic field dependence of antiferromagnetic resonance in \$\text{NiO}\$](#)

Applied Physics Letters **112**, 252404 (2018); 10.1063/1.5031213

[Artificial electronic synapse characteristics of a \$\text{Ta}/\text{Ta}_2\text{O}_5\text{-x}/\text{Al}_2\text{O}_3/\text{InGaZnO}_4\$ memristor device on flexible stainless steel substrate](#)

Applied Physics Letters **113**, 013503 (2018); 10.1063/1.5027776

[A non-collinear double \$\text{MgO}\$ based perpendicular magnetic tunnel junction](#)

Applied Physics Letters **113**, 022403 (2018); 10.1063/1.5038060

**THE WORLD'S RESOURCE FOR
VARIABLE TEMPERATURE
SOLID STATE CHARACTERIZATION**

OPTICAL STUDIES SYSTEMS

SEEBECK STUDIES SYSTEMS

MICROPROBE STATIONS

HALL EFFECT STUDY SYSTEMS AND MAGNETS

WWW.MMR-TECH.COM

Magnetoresistance of epitaxial and polycrystalline Fe₃O₄ films near Verwey transition

Xiang Liu,¹ Wenbo Mi,^{1,a)} Qiang Zhang,² and Xixiang Zhang²

¹Tianjin Key Laboratory of Low Dimensional Materials Physics and Preparation Technology, School of Science, Tianjin University, Tianjin 300354, China

²PSE Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia

(Received 15 April 2018; accepted 18 June 2018; published online 5 July 2018)

We report investigations of magnetoresistance (MR) in epitaxial and polycrystalline Fe₃O₄ films. MR in epitaxial Fe₃O₄ films exhibits a local maximum at T_V and a large value of -20% at 60 K. Based on a 1D half infinite spin chain model, the fitting parameter, which depends on the volume fraction of electronic scattering boundaries, sharply increases below T_V with the decreased temperature. We suppose that the twin boundaries formed below T_V facilitate the increase in MR and can act as antiphase boundaries (APBs) where the magnetic moments across twin boundaries are coupled antiferromagnetically. Similar MR behavior in Fe₃O₄(100) and (111) epitaxial films manifests the independence of MR on the spatial distribution of APBs. The outline of normalized MR in the epitaxial films shows a distinct temperature dependence. The temperature dependence may result from the different electronic transport mechanisms in Fe₃O₄ films. In a polycrystalline Fe₃O₄ film, MR comes from the disordered distribution of magnetic moments at grain boundaries. The effects of APBs, twin boundaries, and grain boundaries on MR are discussed in detail.

Published by AIP Publishing. <https://doi.org/10.1063/1.5035403>

In ferromagnets, magnetoresistance (MR) is one of the most important transport properties, which have extensive applications from magnetic random access memory devices to microensors and biodetection devices.^{1–4} Most of the ferrites are kinds of specific materials which combine insulating behavior and ferrimagnetism.⁵ However, magnetite (Fe₃O₄) is an outstanding magnetic material with conductivity which applies in particular to MR. Fe₃O₄ has attracted much attention because of its unique properties including high Curie temperature ($T_C \approx 858$ K),⁶ full spin polarization at the Fermi level,⁷ and a large net magnetic moment of about 4 μ_B /f.u.⁸ In epitaxial Fe₃O₄ films grown on MgO, Al₂O₃, and SrTiO₃ substrates, the mis-stacking of the Fe₃O₄ lattice on a substrate at the first stage of nucleation could form antiphase boundaries (APBs) which preserve the electronic and magnetic properties of Fe₃O₄ films away from its bulk one.^{9–15} Across APBs, magnetic moments are coupled antiferromagnetically.^{16,17} The spin interaction under the magnetic field across APB is considered to illustrate the MR in Fe₃O₄.^{9,10} The magnetic field dependent MR can be expressed as

$$MR \approx -C \left[\frac{M_S}{W_{AF}} \mu_0 H - \left(\frac{M_S}{W_{AF}} \mu_0 H \right)^{3/2} \right], \quad (1)$$

where the parameter C only depends on the density of APBs and has no correlation with the spatial distribution of APBs. The spatial distribution of APBs is related to the crystal orientation. M_S is the saturation magnetization. $W_{AF} = A_{AF}^2 / A_F d^2$, where A_F is the bulk ferromagnetic exchange stiffness, A_{AF} is

the antiferromagnetic exchange stiffness across APBs, and d is the distance between the two spin chains across APBs.¹⁰

As temperature decreases to about 120 K (T_V), a first-order phase transition, which is known as Verwey transition, has been observed through the ρ - T measurement in Fe₃O₄.¹⁸ Below T_V , the magnetic easy axis changes from $\langle 111 \rangle_c$ to $[001]_m$.^{19–22} The cubic lattice structure of Fe₃O₄ distorts to a monoclinic one. The lattice distortion introduces a twin crystal structure with 24 unique possible Cc orientations, which is separated by twin boundaries.^{23–25} However, as far as we know, the studies on the magnetic coupling and electronic transport across twin boundaries in Fe₃O₄ below T_V are rare.²⁴ In this work, high quality epitaxial (EP) and polycrystalline (PC) Fe₃O₄ films are fabricated. In Fe₃O₄ (EP) films, the formation of twin boundaries facilitates the increase in MR below T_V . We suppose that magnetic moments across the twin boundaries are antiferromagnetically coupled. Above T_V , the mechanism of MR may depend on temperature. In the Fe₃O₄ (PC) film, the MR is dominated by the distribution of magnetic moments at grain boundaries (GBs).

Epitaxial Fe₃O₄ on MgO(100) and Al₂O₃(0001) substrates and polycrystalline Fe₃O₄ films on quartz and SiO₂/Si substrates were deposited by a DC magnetron sputtering apparatus. The details of fabrication have been published elsewhere.²⁶ The film thickness of about 200 nm was determined using a Dektak 6M surface profiler and by transition electron microscopy (TEM). Stoichiometry of Fe_{3(1- δ)}O₄ thin films with δ less than 3.5×10^{-4} was determined by Rutherford backscattering spectroscopy with the precision of 10^{-3} – 10^{-2} at. %.²⁶ Electronic transport properties of Fe₃O₄ films were measured using the standard four-probe method using a Quantum Design physical property measurement system. The Verwey temperatures of Fe₃O₄(100), Fe₃O₄(111),

^{a)} Author to whom correspondence should be addressed: miwenbo@tju.edu.cn

and $\text{Fe}_3\text{O}_4/\text{quartz}$ samples are 117.7, 122.8, and 122.4 K, respectively, which are decided by the maximum slope of $\log\rho$ [see Fig. 1(o)]. Magnetic properties were measured by Quantum Design SQUID. Three configurations between applied field and current are considered during the measurements, including magnetic field $\mathbf{H}$ parallel to current density $\mathbf{J}$ ($\mathbf{H} \parallel \mathbf{J}$), $\mathbf{H}$ perpendicular to $\mathbf{J}$ but parallel to the sample ($\mathbf{H} \perp \mathbf{J}$), and $\mathbf{H}$ perpendicular to the film surface ($\mathbf{H} \perp \mathbf{J}$).

Figure 1 shows the TEM results of Fe_3O_4 EP and PC samples. In Figs. 1(a) and 1(g), clear interfaces can be observed in Fe_3O_4 (EP) samples. Figures 1(b) and 1(h) are the magnifying images of the blue square region in Figs. 1(a) and 1(g) acquired through fast Fourier transformation using Gatan's Digital MicrographTM software. Figure 1(c) shows the characterized spinel structure with the tetrahedral and octahedral sites after further magnifying the upper green region in Fig. 1(b). Figure 1(i) shows the magnification of the corresponding green region in Fig. 1(h) of the Fe_3O_4 (111) sample. Figures 1(d) and 1(j) show the microstructure of MgO and Al_2O_3 . Figures 1(e) and 1(k) show the SAED patterns focused on the interfaces of Fe_3O_4 (100) and Fe_3O_4 (111) samples at room temperature. The superposition of diffraction patterns from MgO and Fe_3O_4 manifests the nearly exact lattice match between the MgO substrate and the Fe_3O_4 film. However, in Fig. 1(k), two groups of diffraction patterns appear because of the larger c -axis lattice constant of Al_2O_3 . Figures 1(f) and 1(l) show the SAED patterns

focused on Fe_3O_4 (100) and Fe_3O_4 (111) films at 95 K. In Figs. 1(f) and 1(l), no additional patterns related to the twin boundaries, which deriving from the 24 unique Cc orientations have been observed by TEM and scan tunneling microscopy,^{23,24} can be observed due to the small tilt angle of 0.236° in the monoclinic structure.²⁷ A group of additional low order diffraction patterns, which may come from the charge ordering,²⁸ appear below T_V [Figs. 1(f) and 1(l)]. Because of the Verwey transition, the $\langle 110 \rangle_c$ direction transforms to the $[100]_m$ or $[010]_m$ direction below T_V , and the diffraction order below T_V is larger than that above T_V . Figures 1(m) and 1(n) show the TEM results of the $\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{Si}$ sample. Because of the formation of amorphous SiO_2 on the Si substrate, the growth of the Fe_3O_4 thin film is polycrystalline. One can see GB in Fig. 1(m). In Fig. 1(n), the diffraction pattern of the $\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{Si}$ sample shows polycrystalline characteristics with diffraction rings.

Figure 2 shows the MR as a function of applied field and temperature in the Fe_3O_4 (100) sample. The MR is defined as $\text{MR} = (R_H - R_0)/R_0 \times 100\%$. The dependence of MR on the magnetic field is shown in the left column of Fig. 2. Above T_V , MR slowly increases with the increasing magnetic field. In the vicinity of T_V , MR with the in-plane field [Figs. 2(a) and 2(b)] shows a sharp increase at a low field but a slow growth under high field compared with other temperature ranges. With $\mathbf{H} \perp \mathbf{J}$ [Fig. 2(c)], the sharp increase in MR at T_V is absent. In the right column of Fig. 2, the temperature

FIG. 1. TEM results of Fe_3O_4 films on (a)–(f) MgO (100), (g)–(l) Al_2O_3 (0001), and (m)–(n) SiO_2/Si substrates. (o) Temperature dependence of resistivity in Fe_3O_4 (100), (111), and PC films. Crystal orientations in (k) are marked with yellow for Al_2O_3 and cyan for Fe_3O_4 . Here, AO and FO indicate Al_2O_3 and Fe_3O_4 , respectively.

FIG. 2. MR of the $\text{Fe}_3\text{O}_4(001)$ epitaxial film. (a)–(c) and (d)–(f) depict MR as a function of magnetic field and temperature. The left inset shows the normalized MR. The right insets show the temperature dependence of C and M_S/W_{AF} .

dependence of MR with different magnitudes of the magnetic field is extracted. At the in-plane magnetic field [Figs. 2(d) and 2(e)], one can find that MR shows a local maximum at T_V . In Fig. 2(f), MR with $H \perp J$ monotonically increases with the decreased temperature and shows no extreme value. Figure 3 shows the MR behavior in the $\text{Fe}_3\text{O}_4(111)$ film at an in-plane magnetic field. Similarly, in Figs. 3(a) and 3(b), the MR curves at T_V show a rapid increase at a low field. In Figs. 3(c) and 3(d), similar temperature dependence of MR can be observed. However, the spatial distribution of APBs

FIG. 3. MR of the $\text{Fe}_3\text{O}_4(111)$ epitaxial film. (a)–(d) show the dependence of MR on the magnetic field and temperature. The left inset shows the normalized MR. The right insets show the temperature dependence of C and M_S/W_{AF} .

is different in $\text{Fe}_3\text{O}_4(100)$ and (111) films. The similar MR behavior in $\text{Fe}_3\text{O}_4(100)$ and (111) films manifests the independence of MR on the spatial distribution of APBs although the MR is derived from APBs.¹⁷

The MR results in Fe_3O_4 (EP) films with an in-plane field are fitted using the expressions given in Refs. 9, 10, 13, and 14. The linear dependence of MR on the magnetic field^{9,13,14} does not reproduce our experimental MR data. The fittings based on Eq. (1) can reduce the discrepancy. However, the fittings are only effective at $T < T_V - 10$ K. The fitting curves show a discrepancy under a high-field at $T > T_V - 10$ K. The fitting parameters C and M_S/W_{AF} are plotted in the inset of Figs. 2(d), 2(e), 3(c), and 3(d). The different agreement between theory and experiment in Fe_3O_4 (EP) films at different temperatures is nontrivial. Previous results deemed that the mechanism of MR in the Fe_3O_4 film is independent of temperature.^{9,10} The normalized MR at different temperatures shows a similar outline¹⁰ which, however, is contradictory to our results [see insets of Figs. 2(a) and 3(a)]. The previous works focused on the effects of APBs on MR. So, thinner films were fabricated at a lower substrate temperature to introduce dense APBs.^{9,10,14} However, in this work, thicker films were fabricated at a higher substrate temperature to reduce the density of APBs and realize a sharp Verwey transition. We suppose that the high density APBs impact the electronic transport mechanism above T_V and obscure the dependence of the mechanism of MR on temperature. Different electronic transport mechanisms in Fe_3O_4 may respond for the temperature-dependent mechanism of MR.^{26,29}

Electronic microscopic studies have manifested the existence of twin boundaries below T_V .^{23–25} However, Eq. (1), which is derived assuming the strong antiferromagnetic coupling of Fe ions across APBs, can effectively reproduce the MR curves in this temperature range where parameter C shows a striking increase. As far as we know, APB in Fe_3O_4 is a structure defect which forms during the growth and cannot move or reproduce after fabrication. Thus, the fitting results at $T < T_V$ indicate a strong interaction across the twin boundaries. As shown in Fig. 4(c), the magnetic moments across twin boundaries may be antiferromagnetically coupled then act like APBs, which can be confirmed by the decreased saturation magnetization with the decreased temperature below T_V [Fig. 4(d)]. At temperatures far below T_V , in the upper panel of Fig. 4, the twin boundaries are frozen and the monoclinic c -axis cannot be aligned by magnetic field.²⁴ The dense twin boundaries increase the MR below T_V . As temperature warms up to the vicinity of T_V , the lattice distortion collapses.²⁶ In the middle panel of Fig. 4, the aligned easy axis by a strong magnetic field reduces the scattering of electronic transport and maintains at a low field with higher temperature.²⁴ The decrease in twin boundaries is in line with the reduction of C below T_V . At T_V , Fe_3O_4 is in a metastable state which results in a disordered distribution of monoclinic crystal axes and magnetic moments at zero-field [see the lower panel of Fig. 4(c)], which results in the related change of remanence (M_R) as shown in Fig. 4(e). On the one hand, the disordering enhances the number of twin boundaries extensively with no field. On the other hand, the easy axis, i.e., the monoclinic c -axis, can be tuned by the

FIG. 4. Summary of the mechanism of MR below T_V in Fe_3O_4 (EP) films. (a) Temperature dependent MR in the $\text{Fe}_3\text{O}_4(100)$ sample with a 50-kOe-field. (b) Monoclinic c -axis and magnetic moment distribution under a high-field. (c) Magnetic moment distribution under a null field. Temperature dependence of (d) M_S and (e) M_R in the $\text{Fe}_3\text{O}_4(100)$ sample.

magnetic field³⁰ and thus reduces the number of twin boundaries. The difference between the two conditions leads to a prominent MR at T_V .

With $\mathbf{H} \perp \mathbf{J}$ as shown in Figs. 2(c) and 2(f), the field and temperature dependence of MR in the $\text{Fe}_3\text{O}_4(100)$ film shows two distinctive features compared to the MR with an in-plane field. First, the low-field MR shows a quadratic outline. Due to the intrinsic shape anisotropy of the film sample, the magnetic moments tend to align with an in-plane direction.^{19,31} The competition between magnetic anisotropic energy and Zeeman energy results in the quadratic MR behavior.⁹ At $H < H_A$, where H_A is the anisotropic field in Fe_3O_4 , the in-plane moments rarely align to the external field. Besides, the out-of-plane magnetization can introduce large demagnetization energy which further disturbs the spin direction and reduces MR at a low field. So, the low-field MR is insignificant. At $H > H_A$, the magnetic moments away from twin boundaries and APBs are aligned perpendicular to the film surface by the external field. The spin-dependent scattering results in a prominent MR. The MR curves can be reproduced by Eq. (1) at $H > H_A$ while cannot be reproduced at $H < H_A$. The value of H_A is estimated by fitting the MR curves with Eq. (1). The magnetic field where the fittings lose validity in the low-field region can be regarded as H_A . In the $\text{Fe}_3\text{O}_4(100)$ sample, H_A is about 9 kOe.¹⁶ Second, the local maximum of MR at T_V is absent. At T_V , the nominal monoclinic c -axis is established by an out-of-plane field. However, the monoclinic a and b axes cannot be aligned by the perpendicular field which leaves the disordered distribution of a and b axes.²⁴ Hence, we suppose that the MR mainly comes from the reduction of c -axis disordering.

Figure 5 presents the MR of the Fe_3O_4 (PC) film. MR around zero-field shows a peak with an in-plane magnetic field [Figs. 5(a) and 5(b)] and a hump at an out-of-plane field [Fig. 5(c)]. In Figs. 5(d)–5(f), the temperature dependence of MR in the PC film is quite different from that in the EP film. At temperature far below T_V , MR is almost independent of

FIG. 5. MR of the Fe_3O_4 (PC) film. (a)–(c) and (d)–(f) exhibit the field-dependent and temperature-dependent MR, respectively.

temperature at a low field. As temperature increases to T_V , MR increases and exhibits a local maximum at T_V . Above T_V , MR with an in-plane magnetic field decreases linearly with the increased temperature and shows no rapid change. However, the MR with $\mathbf{H} \perp \mathbf{J}$ shows a steep increase at 130 K, and it is almost temperature-independent at a 5-kOe-field.

In the Fe_3O_4 (PC) film, the Fe_3O_4 grain surrounded by dispersive GBs can be regarded as a core-shell structure, where the inner part is well structured and the shell part has deficiencies.³² The deficient shell causes uncompensated surface spins with a spin-glass state, which results in a weak magnetic interaction at GBs.^{33–35} Above T_V , the disordered magnetic moments at GBs increase the scattering of carriers. Below T_V , the disordered crystal orientations and GBs inhibit the long range ordering in the PC sample and thus delay the increase in resistivity at GBs and lead to the non-uniformity of Verwey transition.³⁶ The broad Verwey transition through ρ - T measurements as presented in Fig. 1(o) indicates the continuous transition in the Fe_3O_4 (PC) film. Based on preceding discussions, the formation of twin boundaries improves MR, whereas in the Fe_3O_4 (PC) film, the MR is suppressed as temperature decreases below T_V which indicates the lack of twin boundaries in our Fe_3O_4 (PC) film. Therefore, MR below T_V in the Fe_3O_4 (PC) film is dominated by the alignment of magnetic moment at GBs. With decreasing temperature, the increased pinning of magnetic moments at GBs reduces the proportion of the field-dependent part of total resistance. Together with the increase in resistance, MR in the Fe_3O_4 (PC) film shows a reduction as temperature decreases below T_V . Above T_V , the linear temperature dependence of MR is extrapolated to zero at about 430 ± 30 K, which is almost independent of the

magnetic field. The spin-glass state at GBs gradually melts as temperature increases close to the melting temperature of the spin-glass state, so the moments cannot be aligned by the external magnetic field.^{32,35,37} With $\mathbf{H} \perp \mathbf{J}$ [Fig. 5(c)], the low-field MR of the Fe_3O_4 (PC) film shows a similar quadratic outline owing to the magnetocrystalline anisotropy. However, because of the shrink of long-range ordering, the reduction of magnetocrystalline anisotropy leads to a smaller H_A in the Fe_3O_4 (PC) film. In Fig. 5(f), the temperature dependent MR with $\mathbf{H} \perp \mathbf{J}$ is similar to the MR with an in-plane field because of the isotropic structure in the Fe_3O_4 (PC) film.

In conclusion, the investigations of MR in Fe_3O_4 (100) and (111) films below T_V manifest the antiferromagnetic coupling across twin boundaries, which is confirmed by the decrease in M_S with the decreased temperature. Owing to the reduction of the density of APBs in our Fe_3O_4 (EP) films fabricated at a relatively high temperature, we find that the mechanism of MR in Fe_3O_4 (EP) samples is temperature dependent. In the Fe_3O_4 (PC) film, MR comes from the disordered distribution of magnetic moments at GBs and it is extrapolated to zero at about 430 K because of the melting of the spin-glass state at GBs.

This work was supported by the National Natural Science Foundation of China (Nos. U1632152 and 51671142) and Key Project of Natural Science Foundation of Tianjin (No. 16JCZDJC37300).

¹B. Dieny, V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri, *Phys. Rev. B* **43**, 1297 (1991).

²F. Montaigne, A. Schuhl, F. N. Van Dau, and A. Encinas, *Sens. Actuators, A* **81**, 324 (2000).

³D. L. Graham, H. A. Ferreira, and P. P. Freitas, *Trends Biotechnol.* **22**, 455 (2004).

⁴H. C. Wu, R. Ramos, R. G. S. Sofin, Z. M. Liao, M. Abid, and I. V. Shvets, *Appl. Phys. Lett.* **101**, 052402 (2012).

⁵K. P. Belov, *Phys.-Usp.* **37**, 563 (1994).

⁶P. A. Miles, W. B. Westphal, and A. Von Hippel, *Rev. Mod. Phys.* **29**, 279 (1957).

⁷A. Yanase and K. Siratori, *J. Phys. Soc. Jpn.* **53**, 312 (1984).

⁸J. P. Attfield, *J. Jpn. Soc. Powder Powder Metall.* **61**, S43 (2014).

⁹W. Eerenstein, T. T. M. Palstra, S. S. Saxena, and T. Hibma, *Phys. Rev. Lett.* **88**, 247204 (2002).

¹⁰A. V. Ramos, J. B. Moussy, M. J. Guittet, A. M. Bataille, M. Gautier-Soyer, M. Viret, C. Gatel, P. Bayle-Guillemaud, and E. Snoeck, *J. Appl. Phys.* **100**, 103902 (2006).

¹¹X. H. Liu, W. Liu, and Z. Z. Dong, *Phys. Rev. B* **96**, 094405 (2017).

¹²S. K. Arora, R. G. S. Sofin, I. V. Shvets, R. Jumar, M. W. Khan, and J. P. Srivastava, *J. Appl. Phys.* **97**, 10C310 (2005).

¹³P. Li, L. T. Zhang, W. B. Mi, E. Y. Jiang, and H. L. Bai, *J. Appl. Phys.* **106**, 033908 (2009).

¹⁴R. G. S. Sofin, S. K. Arora, and I. V. Shvets, *Phys. Rev. B* **83**, 134436 (2011).

¹⁵M. Ziese and H. J. Blythe, *J. Phys.: Condens. Matter* **12**, 13 (2000).

¹⁶D. T. Margulies, F. T. Parker, M. L. Rudee, F. E. Spada, J. N. Chapman, P. R. Aitchison, and A. E. Berkowitz, *Phys. Rev. Lett.* **79**, 5162 (1997).

¹⁷S. Celotto, W. Eerenstein, and T. Hibma, *Eur. Phys. J. B* **36**, 271 (2003).

¹⁸E. J. Verwey, *Nature* **144**, 327 (1939).

¹⁹L. R. Bickford, Jr., *Phys. Rev.* **78**, 449 (1950).

²⁰J. P. Wright, J. P. Attfield, and P. G. Radaelli, *Phys. Rev. Lett.* **87**, 266401 (2001).

²¹J. P. Wright, J. P. Attfield, and P. G. Radaelli, *Phys. Rev. B* **66**, 214422 (2002).

²²H. T. Jeng, G. Y. Guo, and D. J. Huang, *Phys. Rev. B* **74**, 195115 (2006).

²³T. Kasama, N. S. Church, J. M. Feinberg, R. E. Dunin-Borkowski, and R. J. Harrison, *Earth Planet. Sci. Lett.* **297**, 10 (2010).

²⁴T. Kasama, R. J. Harrison, N. S. Church, M. Nagao, J. M. Feinberg, and R. E. Dunin-Borkowski, *Phase Transitions* **86**, 67 (2013).

²⁵J. da la Figuera, Z. Novotny, M. Setvin, T. J. Liu, Z. Q. Mao, G. Chen, A. T. N'Diaye, M. Schmid, U. Diebold, A. K. Schmid, and G. S. Parkinson, *Phys. Rev. B* **88**, 161410(R) (2013).

²⁶X. Liu, W. B. Mi, Q. Zhang, and X. X. Zhang, *Phys. Rev. B* **96**, 214434 (2017).

²⁷M. S. Senn, J. P. Wright, and J. P. Attfield, *Nature* **481**, 173 (2012).

²⁸W. B. Mi, Z. B. Guo, Q. X. Wang, Y. Yang, and H. L. Bai, *Scr. Mater.* **68**, 972 (2013).

²⁹R. Ramos, S. K. Arora, and I. V. Shvets, *Phys. Rev. B* **78**, 214402 (2008).

³⁰B. A. Calhoun, *Phys. Rev.* **94**, 1577 (1954).

³¹P. Li, E. Y. Jiang, and H. L. Bai, *Appl. Phys. Lett.* **96**, 092502 (2010).

³²P. V. M. Shameem, L. Mekala, and M. S. Kumar, *IEEE Trans. Magn.* **53**(11), 4800205 (2017).

³³J. M. D. Coey, A. E. Berkowitz, L. Balcells, F. F. Putris, and F. T. Parker, *Appl. Phys. Lett.* **72**, 734 (1998).

³⁴M. Ziese, R. Höhne, H. C. Semmelhack, H. Reckentin, N. H. Hong, and P. Esquinazi, *Eur. Phys. J. B* **28**, 415 (2002).

³⁵P. Li, E. Y. Jiang, and H. L. Bai, *J. Phys. D: Appl. Phys.* **43**, 265002 (2010).

³⁶S. I. Rybchenko, Y. Fujishiro, H. Takagi, and M. Awano, *Phys. Rev. B* **72**, 054424 (2005).

³⁷H. Y. Huang, Z. Y. Chen, R. P. Wang, F. M. F. de Groot, W. B. Wu, J. Okamoto, A. Chainani, A. Singh, Z. Y. Li, J. S. Zhou, H. T. Jeng, G. Y. Guo, J.-G. Park, L. H. Tjeng, C. T. Chen, and D. J. Huang, *Nat. Commun.* **8**, 15929 (2017).