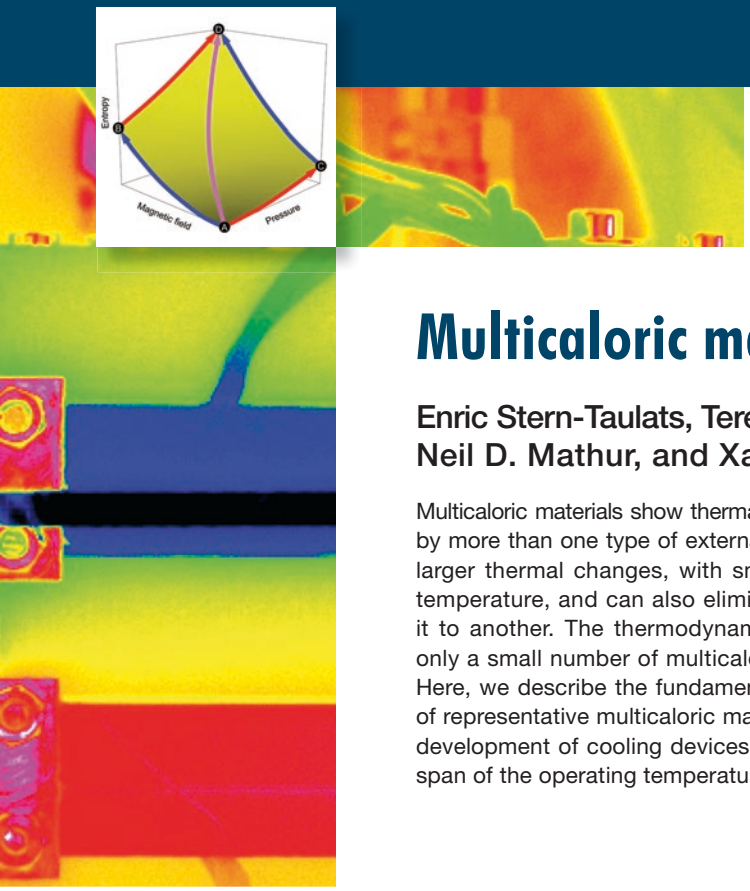


Multicaloric materials and effects

Enric Stern-Taulats, Teresa Castán, Lluís Mañosa, Antoni Planes, Neil D. Mathur, and Xavier Moya

Multicaloric materials show thermal changes that can be driven simultaneously or sequentially by more than one type of external field. The use of more than one driving field can induce larger thermal changes, with smaller field magnitudes, over wider ranges of operating temperature, and can also eliminate hysteresis in one control parameter by transferring it to another. The thermodynamics behind multicaloric effects is well established, but only a small number of multicaloric materials have been experimentally studied to date. Here, we describe the fundamentals of multicaloric effects and discuss the performance of representative multicaloric materials. Exploiting multicaloric effects could aid the future development of cooling devices, where key challenges include energy efficiency and the span of the operating temperature.

Introduction

Caloric materials show reversible thermal changes in response to field-induced changes of a ferroic order parameter. Specifically, one may achieve magnetocaloric,[1] electrocaloric,[2] and mechanocaloric[3,4] (barocaloric and elastocaloric) effects using magnetic fields, electric fields, and stress fields, respectively. In practice, caloric responses are quantified in two thermal extremes, as either isothermal entropy change or adiabatic temperature change.[5–7] In recent years, interest has focused on the development of materials that display large caloric effects near room temperature, specifically for application in solid-state refrigeration devices.[8]

Giant caloric responses are expected to occur in the vicinity of phase transitions, where the properties of the materials are strongly temperature dependent.[5,6,9] Materials that display ferromagnetic, ferroelectric, or ferroelastic phase transitions of the first order [6,7] can show particularly large caloric effects because the driving field can access a large latent heat.

Multiferroic materials necessarily display two or more of the aforementioned ferroic orders, and these may be strongly coupled[10] such that each ferroic order parameter can respond to more than one type of applied field. Consequently, different ferroic properties can emerge at nearby temperatures, or even simultaneously. Large caloric effects can thus be driven by the simultaneous or sequential application of more than one type of external field, in what are known as multicaloric materials.[7]

The main limitation of materials displaying caloric effects near first-order phase transitions is thermal and field hysteresis.[11] While hysteresis typically arises as a consequence of nucleation, in caloric materials it occurs primarily due to domain-wall pinning, which is the net result of long-range elastic strain associated with phase transitions of interest. It was recently shown that hysteresis can be bypassed by exploiting the response of multicaloric materials to more than one type of driving field,[12] but work must then be done to vary the secondary field.

Most giant magnetocaloric and electrocaloric materials (undergoing first-order phase transitions) are expected to also show mechanocaloric effects, as the ferroic order parameter is likely to be strongly coupled to the lattice (**Figure 1**).[1–3,13–26] Over the last few years, there has been growing interest in studying caloric effects while varying the stress field along with the magnetic or electric field.[27–29] So far, most of this type of work has employed hydrostatic pressure as the primary control parameter. On the other hand, there has been much less research on multicaloric effects that employ magnetic and electric fields, in spite of the ongoing interest in multiferroic materials and the

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magnetoelectric effects that they display. In this article, we discuss the state of the art in research on multicaloric materials and multicaloric effects, and prospects for future advances.

Thermodynamics of multicaloric effects

Here, we briefly recall the main thermodynamic relations that are required to understand multicaloric responses in materials that display more than one ferroic property. Let's assume the likely scenario of two external fields Y_1 and Y_2, which are associated with their two conjugate ferroic variables X_1 and X_2, respectively. For example, a magnetic field $\mu_0 H$ and an electric field E would be associated with sample magnetization M and polarization P, respectively. We will restrict our discussion to isothermal changes of entropy ΔS, and we will assume equilibrium thermodynamics.

Given that entropy is a state function, it will undergo path-independent changes that do not depend on whether the driving fields are applied simultaneously, or in some sequence. We therefore express the entropy change arising due to a change in both applied fields by following any specific path,[30] e.g.,:

$$\Delta S\left[(0,0)\rightarrow(Y_1,Y_2)\right]=\Delta S\left[(0,0)\rightarrow(Y_1,0)\right]+\Delta S\left[(Y_1,0)\rightarrow(Y_1,Y_2)\right]. \quad (1)$$

The first term on the right is the monocaloric effect due to the application of field Y_1 at $Y_2 = 0$, while the second term on the right is the monocaloric effect due to the application of field Y_2 at constant Y_1. One may then express the two terms via the appropriate Maxwell relations to obtain:

$$\Delta S\left[(0,0)\rightarrow(Y_1,Y_2)\right]=\int_0^{Y_1}\left(\frac{\partial X_1}{\partial T}\right)_{Y_1',Y_2=0}\mathrm{d}Y_1'+\int_0^{Y_2}\left(\frac{\partial X_2}{\partial T}\right)_{Y_1Y_2'}\mathrm{d}Y_2'. \quad (2)$$

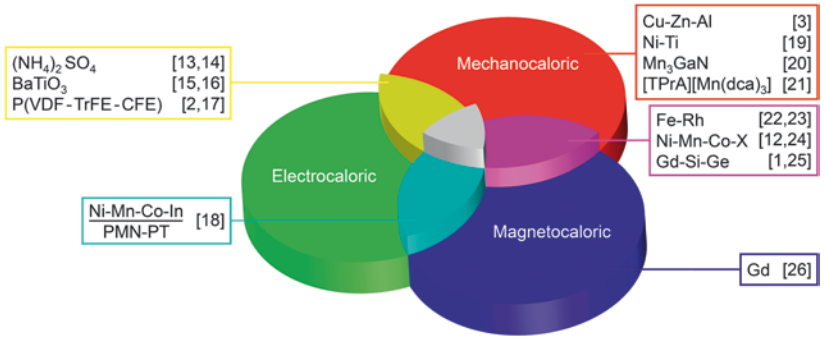


Figure 1. The relationship between magnetocaloric, electrocaloric, and mechanocaloric materials.[1–3,13–26] Materials lying at the intersections are multicaloric. Selected examples are based on existing measurements of large caloric effects near room temperature. It is likely that all magnetocaloric and electrocaloric materials will show mechanocaloric effects that may or may not be large. Note: PMN-PT, $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3$-$xPbTiO_3$; P(VDF-TrFE-CFE), poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene); TPrA, tetrapropylammonium; dca, dicyanamide.

Expanding the second term on the right of Equation 2,[30,31] the expression becomes:

$$\Delta S\left[(0,0)\rightarrow(Y_1,Y_2)\right]=\int_0^{Y_1}\left(\frac{\partial X_1}{\partial T}\right)_{Y_1',Y_2=0}\mathrm{d}Y_1'+\int_0^{Y_2}\left(\frac{\partial X_2}{\partial T}\right)_{Y_1=0,Y_2'}\mathrm{d}Y_2'+\int_0^{Y_1}\int_0^{Y_2}\frac{\partial \chi_{12}}{\partial T}\mathrm{d}Y_1'\,\mathrm{d}Y_2'. \quad (3)$$

In contrast to Equation 2, the entropy change is now expressed as the sum of two monocaloric responses that are determined while the inactive field is zero, and a cross-coupling term that is significant if the cross-susceptibility,

$$\chi_{12}=\left(\frac{\partial X_1}{\partial Y_2}\right)_{T,Y_1}=\left(\frac{\partial X_2}{\partial Y_1}\right)_{T,Y_2}, \quad (4)$$

exhibits a notable temperature dependence. (This cross-susceptibility represents the magnetoelectric coupling coefficient[10] when applying magnetic and electric fields.)

Equation 3 shows that the multicaloric response of a material is not given by the sum of each monocaloric response while the inactive field is zero, unless $\partial\chi_{12}/\partial T = 0$. This may be appreciated by considering the diagram in **Figure 2**, where the field variables are magnetic field and pressure. First, it is necessary to observe that path independence implies that one may achieve the same entropy change (A → D) either by applying pressure at zero magnetic field (A → C) and then magnetic field at finite pressure (C → D), or by applying magnetic field at zero pressure (A → B) and then pressure at finite magnetic field (B → D). It then follows that the magnitude of a caloric effect driven by one field variable depends on the magnitude of the other field variable, due to the cross-coupling. For example, the magnetocaloric effects are different in magnitude when driven at zero pressure (A → B) or finite pressure (C → D).

Multicaloric examples

The ability to vary more than one field gives access to a wider range of parameter space, such that a given phase transition may become accessible with lower fields in a broader window of temperatures. This may be appreciated by considering the (anhysteretic) phase diagrams in **Figure 3**a–b where the field variables are again magnetic field and pressure. For example, finite pressure permits the α → β transition in Figure 3a to be isothermally driven using relatively small magnetic fields. More generally, the signs of both field changes should be chosen in order to drive the transition in the same direction. For example, the

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α → β transition in Figure 3b is favored by increasing magnetic field and reducing pressure.

The hysteresis that is, in practice, associated with first-order phase transitions can be manipulated by judiciously using a secondary applied field. This strategy can shift hysteresis from the primary field to the secondary field,[12] or fully undrive caloric effects that cannot be fully undriven by the removal of the primary field alone. An example of the former scenario is explained in **Figure 4**, again using magnetic field and pressure as the field variables. The energy dissipated during the multicaloric cycle shown (red dashed line) is given to a good approximation by $|\Delta p \Delta v|$, where $\Delta p = p_2 - p_1$ and Δv is the difference in specific volumes for the two phases (Figure 4b).[23] Experimentally, these types of multicaloric cycles have been realized using Fe-Rh[23] and La-Fe-Mn-Si.[32]

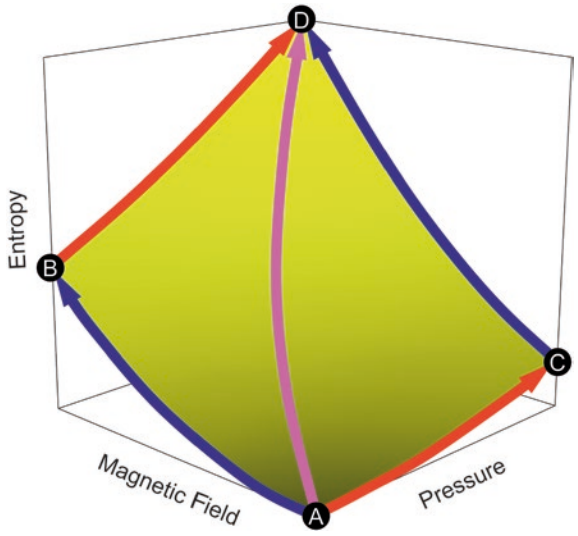


Figure 2. Schematic variation of isothermal entropy with pressure and magnetic field ($\chi_{12} \neq 0$). Multicaloric entropy changes can be achieved by applying pressure and magnetic field either simultaneously or sequentially. For example, the entropy change associated with pathway A → D can be achieved in either one step, two steps (by applying first pressure [A → C] and then field [C → D], or by applying first field [A → B] and then pressure [B → D]), or multiple steps.

The pressure and magnetic field variables were chosen in Figures 2–4 because most multicaloric studies focus on magnetocaloric effects that are modified by hydrostatic pressure.[33–37] For example, the peak magnetocaloric effects in Mn-Ni-Si-based compounds[36] and Mn-rich Ni-Mn-Ga Heusler alloys[37] are increased by hydrostatic pressure, whereas there is a decrease in the peak magnetocaloric effects in Gd-Si-Ge[34] and Ni-Mn-Co-Sb Heusler alloys.[38] There are also reports on elastocaloric effects that are modified by either magnetic or electric fields.[24,39] In Heusler alloys, the elastocaloric refrigerant capacity can be increased by ~20% using magnetic fields of $\mu_0 H = 1$ T.[24] By contrast, the elastocaloric properties of single-crystal ferroelectric oxides are hardly affected by an electric field.[39]

There are still few reports on caloric effects driven by both magnetic and electric fields. However, it should be possible to electrically control the magnetocaloric effect in multiferroic heterostructures via strain.[18,40–42] For, example a small multicaloric response has been demonstrated using ribbons of the Heusler material Ni-Co-Mn-In on a ferroelectric substrate of $(1–x)Pb(Mg_{1/3}Nb_{2/3})$-$xPbTi_{0.28}O_3$,[18] where an electric field modified the peak temperature of the inverse magnetocaloric effects. Similar results were also obtained[42] in FeRh-films on $BaTiO_3$ substrates.

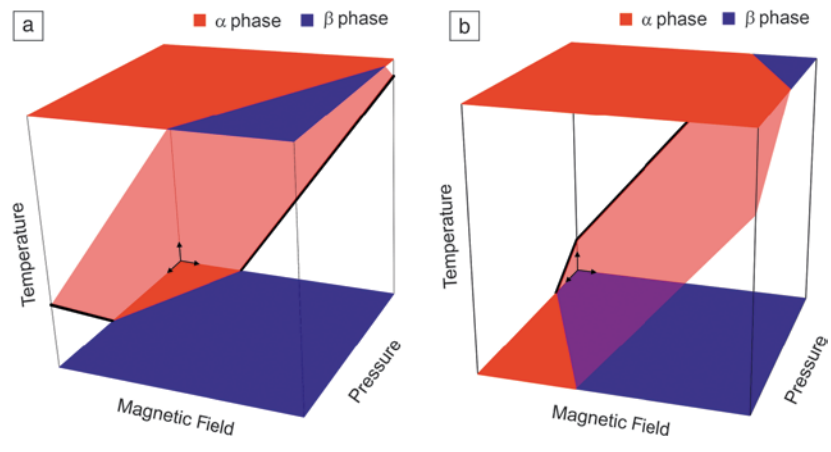


Figure 3. Schematic phase diagrams for materials at finite temperatures, in which transitions between a high-temperature α phase and a low-temperature β phase are associated with (a) conventional magnetocaloric effects ($dT/dH > 0$) and conventional barocaloric effects ($dT/dp > 0$), and (b) conventional magnetocaloric effects ($dT/dH > 0$) and inverse barocaloric effects ($dT/dp < 0$). The sloping pink planes denote the (anhysteretic) phase boundary.

Outlook

The use of more than one field variable opens up what may be considered to be a new field of research, just as the use of both magnetic and electric fields has opened up the field of magnetoelectrics following the large separate bodies of work on ferromagnetic and ferroelectric materials. The study of multicaloric materials and effects is now particularly timely given the confluence of research in magnetocaloric, electrocaloric, and mechanocaloric effects. This confluence is manifested in both review articles[5–7,43] and international conferences. In addition to a cross-fertilization of expertise, one can anticipate a blossoming of multicaloric research itself, yielding both novel science and possible applications. Consequently, we can say with confidence that the field of multicalorics will continue to be greater than the sum of the parts.

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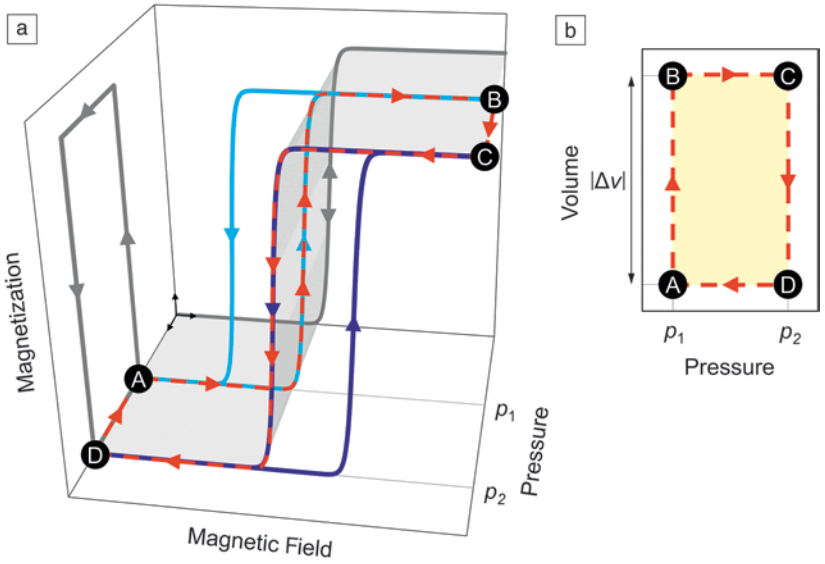


Figure 4. Multicaloric trajectories. (a) The red dashed line (A → B → C → D → A) includes isobaric magnetization-field legs at pressures p_1 (light blue dashed and solid lines) and p_2 (dark blue dashed and solid lines). Projections of this trajectory along the pressure and field axes (gray solid lines, located for convenience at the plot edge) help understand the hysteresis. The projection along the pressure axis shows that magnetic hysteresis can be traded for pressure hysteresis by increasing the pressure before removing the magnetic field. The resulting dissipation is seen by plotting (b) the corresponding changes of volume versus pressure. For simplicity, we assume that the magnetization and volume do not change when the pressure is varied (B → C and D → A).

Acknowledgments

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References

1. V.K. Pecharsky, K.A. Gschneidner Jr., *Phys. Rev. Lett.* **78**, 4494 (1997).
2. B. Neese, B. Chu, S.G. Lu, Y. Wang, E. Furman, Q.M. Zhang, *Science* **321**, 821 (2008).
3. E. Bonnot, R. Romero, L. Mañosa, E. Vives, A. Planes, *Phys. Rev. Lett.* **100**, 125901 (2008).
4. L. Mañosa, D. González-Alonso, A. Planes, E. Bonnot, M. Barrio, J.-L. Tamarit, S. Aksoy, M. Acet, *Nat. Mater.* **9**, 478 (2010).
5. S. Fähler, U.K. Rößler, O. Kastner, J. Eckert, G. Eggeler, H. Emmerich, P. Entel, S. Müller, E. Quandt, K. Albe, *Adv. Eng. Mater.* **14**, 10 (2012).
6. L. Mañosa, A. Planes, M. Acet, *J. Mater. Chem. A* **1**, 4925 (2013).
7. X. Moya, S. Kar-Narayan, N.D. Mathur, *Nat. Mater.* **13**, 439 (2014).
8. A. Kitanovski, U. Plaznic, U. Tomc, A. Poredoš, *Int. J. Refrig.* **57**, 288 (2015).
9. A. Planes, L. Mañosa, M. Acet, *J. Phys. Condens. Matter* **21**, 233201 (2009).
10. W. Eerenstein, N.D. Mathur, J.F. Scott, *Nature* **442**, 759 (2006).
11. O. Gutfleisch, T. Gottschall, M. Fries, D. Benke, I. Radulov, K.P. Skokov, H. Wende, M. Gruner, M. Acet, P. Entel, M. Farle, *Phil. Trans. R. Soc. A* **374**, 20150308 (2016).
12. J. Liu, T. Gottschall, K.P. Skokov, J.D. Moore, O. Gutfleisch, *Nat. Mater.* **11**, 620 (2012).
13. P. Lloveras, E. Stern-Taulats, M. Barrio, J.-L. Tamarit, S. Crossley, W. Li, V. Pomjakushin, A. Planes, L. Mañosa, N.D. Mathur, X. Moya, *Nat. Commun.* **6**, 8801 (2015).
14. S. Crossley, W. Li, X. Moya, N. Mathur, *Phil. Trans. R. Soc. Lond. A* **374**, 20150313 (2016).
15. X. Moya, E. Stern-Taulats, S. Crossley, D. González-Alonso, S. Kar-Narayan, A. Planes, L. Mañosa, N.D. Mathur, *Adv. Mater.* **25**, 1360 (2013).
16. E. Stern-Taulats, P. Lloveras, M. Barrio, E. Defay, M. Egilmez, A. Planes, J.-Ll. Tamarit, L. Mañosa, N.D. Mathur, X. Moya, *APL Mater.* **4**, 091102 (2016).
17. Y. Yoshida, K. Yuse, D. Guyomar, J.F. Capsal, G. Sebald, *Appl. Phys. Lett.* **108**, 242904 (2016).
18. Y.Y. Cong, D.-H. Wang, Q.-Q. Cao, E.-K. Liu, J. Liu, Y.-W. Du, *Adv. Mater.* **27**, 801 (2015).
19. J. Tušek, K. Engelbrecht, L.P. Mikkelsen, N. Pryds, *J. Appl. Phys.* **117**, 124901 (2015).
20. D. Matsunami, A. Fujita, K. Takenaka, M. Kano, *Nat. Mater.* **14**, 73 (2015).
21. J.M. Bermúdez, M. Sánchez-Andújar, S. Castro-García, J. López-Beceiro, R. Artiaga, M.A. Señarís-Rodríguez, *Nat. Commun.* **8**, 15715 (2017).
22. E. Stern-Taulats, A. Planes, P. Lloveras, M. Barrio, J.-L. Tamarit, S. Pramanick, S. Majumdar, C. Frontera, L. Mañosa, *Phys. Rev. B Condens. Matter* **89**, 214105 (2014).
23. E. Stern-Taulats, T. Castán, A. Planes, L.H. Lewis, R. Barua, S. Pramanick, S. Majumdar, L. Mañosa, *Phys. Rev. B Condens. Matter* **95**, 104424 (2017).
24. P.O. Castillo, D.E. Soto-Parra, J.A. Matutes-Aquino, R.A. Ochoa-Gamboa, A. Planes, L. Mañosa, D. González-Alonso, M. Stipcich, R. Romero, D. Ríos-Jara, H. Flores-Zúñiga, *Phys. Rev. B Condens. Matter* **83**, 174109 (2011).
25. S. Yüce, M. Barrio, B. Emre, E. Stern-Taulats, A. Planes, J.-L. Tamarit, Y. Mudryk, K.A. Gschneidner Jr., V.K. Pecharsky, L. Mañosa, *Appl. Phys. Lett.* **101**, 071906 (2012).
26. S.Y. Dan'kov, A.M. Tishin, V.K. Pecharsky, K.A. Gschneidner, *Phys. Rev. B Condens. Matter* **57**, 3478 (1998).
27. A. Planes, T. Castán, A. Saxena, *Phil. Trans. R. Soc. A* **374**, 20150304 (2016).
28. L. Mañosa, A. Planes, *Adv. Mater.* **29**, 1603607 (2017).
29. Y. Liu, J.F. Scott, B. Dkhil, *APL Mater.* **4**, 064109 (2016).
30. A. Planes, T. Castán, A. Saxena, *Philos. Mag.* **94**, 1893 (2014).
31. E. Stern-Taulats, "Giant Caloric Effects in the Vicinity of First-Order Phase Transitions," PhD thesis, University of Barcelona (2017).
32. E. Lovell, H.N. Bez, D.C. Boldrin, K.K. Nielsen, A. Smith, C.R.H. Bahl, L.F. Cohen, *Phys. Status Solidi RRL* **11**, 1700143 (2017).
33. S. Gama, A.A. Coelho, A. de Campos, A.M.G. Carvalho, F.C.G. Gandra, P.J. von Ranke, N.A. de Oliveira, *Phys. Rev. Lett.* **93**, 237202 (2004).
34. A.M.G. Carvalho, E.S. Alves, A. de Campos, A.A. Coelho, S. Gama, F.C.G. Gandra, P.J. von Ranke, N.A. Oliveira, *J. Appl. Phys.* **97**, 10M320 (2005).
35. J. Lyubina, K. Nenkov, L. Schultz, O. Gutfleisch, *Phys. Rev. Lett.* **101**, 177203 (2008).
36. T. Samanta, D.L. Lepkowski, A.U. Saleheen, A. Shankar, J. Prestigiacomo, I. Dubenko, A. Quetz, I.W.H. Oswald, G.T. McCandless, J.Y. Chan, P.W. Adams, D.P. Young, N. Ali, S. Stadler, *Phys. Rev. B Condens. Matter* **91**, 020401(R) (2015).
37. F. Albertini, J. Kamarád, Z. Arnold, L. Pareti, E. Villa, L. Righi, *J. Magn. Magn. Mater.* **316**, 364 (2007).
38. A.K. Nayak, K.G. Suresh, A.K. Nigam, A.A. Coelho, S. Gama, *J. Appl. Phys.* **106**, 053901 (2009).
39. A. Chauhan, S. Patel, R. Vaish, *Acta Mater.* **89**, 384 (2015).
40. X. Moya, L.E. Hueso, F. Maccherozzi, A.I. Tovstolytkin, D.I. Podyalovskii, C. Ducati, L.C. Phillips, M. Ghidini, O. Hovorka, A. Berger, M.E. Vickers, E. Defay, S.S. Dhesi, N.D. Mathur, *Nat. Mater.* **12**, 52 (2013).
41. R.O. Cherifi, V. Ivanovskaya, L.C. Phillips, A. Zobelli, I.C. Infante, E. Jacquet, V. Garcia, S. Fusil, P.R. Briddon, N. Guiblin, A. Mougin, A.A. Ünal, F. Kronast, S. Valencia, B. Dkhil, A. Barthélémy, M. Bibes, *Nat. Mater.* **13**, 345 (2014).
42. Y. Liu, L.C. Phillips, R. Mattana, M. Bibes, A. Barthélémy, B. Dkhil, *Nat. Commun.* **7**, 11614 (2016).
43. S. Crossley, N.D. Mathur, X. Moya, *AIP Adv.* **5**, 067153 (2015). □



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