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Large exchange bias obtainable through zero-field cooling from an unmagnetized state in Ni-Mn-Sn alloys

B. M. Wang,¹ Y. Liu,^{1,a)} B. Xia,² P. Ren,² and L. Wang²¹*School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798*²*Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371*

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We report a large unusual exchange bias effect occurred after zero-field cooling from an unmagnetized state (ZEB) in Ni-Mn-Sn alloys, in which the maximum ZEB field is about twice as large as that observed in Ni-Mn-In alloys at moderate field range (< 40 kOe). The ZEB field can be tuned by tuning the magnitude of the initial magnetization fields and its sign is strongly dependent on the direction of the initial magnetization fields. Furthermore, the ZEB effect only exists in alloys with volume fraction of superparamagnetic domains less than the percolation limitation in three-dimensional system ($\sim 16\%$). The present results confirm the universality of this unusual ZEB effect and suggest that NiMn-based alloys provide a platform to obtain this unusual ZEB effect. Such ZEB effect may also exist in other systems with similar magnetic properties. © 2012 American Institute of Physics. [doi:10.1063/1.3686717]

I. INTRODUCTION

Exchange bias (EB) is usually observed in systems with interface between different magnetic phases after field cooling (FC).^{1–4} The EB effect after FC has also been observed in NiMn-based bulk alloys with coexistence of AFM and FM phases.^{5–9} Very recently, we observed a large EB effect in Ni-Mn-In alloys after zero-field cooling (ZFC) from an unmagnetized state (ZEB),¹⁰ which cannot be expected in the previous EB systems.^{1–4} We proposed a model to explain this unusual ZEB effect to be related to the isothermally formed magnetic unidirectional anisotropy,¹⁰ and it seems to be able to explain many experimental observations in Ni-Mn-In alloys successfully. According to this model, if the initial magnetic state is superparamagnetic (SPM) domains embedded in an antiferromagnetic (AFM) matrix and under external magnetic field the SPM domains can grow in size at the expense of AFM matrix, a superferromagnetic (SFM) unidirectional anisotropy can thus be created resulting in an EB effect.¹⁰ It is well known that NiMn alloy has AFM state below Néel temperature ($T_N \sim 1140$ K).¹¹ However, when the Mn is partially replaced by X ($X = \text{In, Sn, Sb, etc.}$), a partial ferromagnetic (FM) exchange will appear between Mn-Mn with larger distance.^{12,13} Thus, NiMn-based alloys are expected to be good candidates for obtaining this new ZEB effect. Based on such consideration, in the present work, we have developed a series of $\text{Ni}_{50}\text{Mn}_{50-x}\text{Sn}_x$ (NiMnSn $_x$) alloys and investigated their magnetic properties in detail. We observed a large ZEB effect in NiMnSn $_x$ alloys with Sn content less than 11%, which confirms the above approach of alloy design for searching more alloys with such unusual ZEB effect. Moreover, it is observed that the maximum EB field (H_{EB}) in Ni-Mn-Sn alloys (at 10 K) is about twice as large as that in Ni-Mn-In alloys under moderate field (< 40 kOe).¹⁰

II. EXPERIMENT

The polycrystalline NiMnSn $_x$ ($x = 8, 9, 10, 11$ and 12) alloys were fabricated with Ni, Mn and Sn of 99.9% purity using arc melting technique under argon atmosphere. The samples were remelted several times and subsequently annealed at 1000°C under high vacuum for 24 h and slowly cooled to room temperature to ensure homogeneity. The phase purity and crystal structure were determined by X-ray diffraction and the compositions were determined by energy dispersive X-ray analysis. The martensitic transformation temperatures were determined by differential scanning calorimetry. The dc magnetic properties were measured using a physical properties measurement system (PPMS, Quantum Design) with a vibrating sample magnetometer (VSM) module. Two measurement procedures were used to obtain a closed magnetic hysteresis loop $[M(H)]$ after ZFC (only consider $|+H| = |-H|$):

$$\text{P type, } 0 \rightarrow (+H) \rightarrow 0 \rightarrow (-H) \rightarrow 0 \rightarrow (+H), \quad (1)$$

$$\text{N type, } 0 \rightarrow (-H) \rightarrow 0 \rightarrow (+H) \rightarrow 0 \rightarrow (-H). \quad (2)$$

The first $0 \rightarrow (+H)/(-H)$ curve is the initial magnetization curve. Before each ZFC, the superconductor magnet was demagnetized by oscillating fields at 300 K to remove the pinned magnetic flux.

III. RESULTS

A. Compositions of NiMnSn $_x$ determined by EDX analysis

The actual compositions of the nominal compositions $\text{Ni}_{50}\text{Mn}_{50-x}\text{Sn}_x$ ($x = 8, 9, 10, 11$, and 12) alloys were determined by using energy dispersive X-ray (EDX) analysis (Fig. 1) and are summarized in Table I. The final

^{a)}Author to whom correspondence should be addressed. Electronic mail: mliuy@ntu.edu.sg.

FIG. 1. (Color online) The EDX spectra of NiMnSn_x ($x=8, 9, 10, 11$, and 12) alloys. The insets show the scanning electron microscopic pictures. The small rectangles indicate the positions at which the EDX spectra were taken.

compositions were obtained by averaging data from 5 different areas with similar compositions in each sample. Due to the high vapor pressure of Mn, it is very easy to lose Mn during arc melting. Hence, we added about 4% more Mn in all nominal compositions during alloys production. We use the nominal compositions to represent the samples throughout the whole text.

B. Crystal structures of NiMnSn_x at room temperature

The crystal structures of NiMnSn_x at room temperature were determined by using powder X-ray diffraction (XRD) with a Bruker D8 advanced X-ray diffractometer at accelerating voltage of 40 kV, tube current of 40 mA, Cu-K_α radiation, and normal $\theta/2\theta$ scanning mode (Fig. 2). The scan step was 0.01° , the time per step is 5 s and the scan range was

TABLE I. Compositions of NiMnSn_x ($x=8, 9, 10, 11$, and 12) determined by EDX analysis.

x (nominal)	Ni	Mn	Sn
8	49.3	42.3	8.4
9	49.2	41.5	9.3
10	49.4	40.3	10.3
11	49.4	39.3	11.3
12	49.1	38.5	12.4

from 20° to 80° . Before performing powder XRD, all samples were annealed at 973 K under high vacuum ($\sim 2 \times 10^{-6}$ Torr) for 5 h to remove the residual stress induced during grinding. All the XRD peaks can be indexed for a monoclinic crystal structure, which is similar to the result observed by Krenke *et al.*¹² for the alloy of the same nominal composition ($x=10$). The lattice parameters decrease with increasing the Mn content due to the smaller atomic radius of Mn (Table II).

C. Martensitic transformation temperature of NiMnSn_x

The martensitic transformation peak temperatures (T_m) were measured using differential scanning calorimeter (DSC) (TA Instruments, MDSC 2920). A heating and cooling rate of 10 K/min was used. In NiMnX ($X=\text{In, Sn, Sb, Ga}$ etc.) alloys, the magnetic transition always accompany with the first-order martensitic transformation. The first-order AFM transition has been confirmed by recent neutron polarization analysis in $\text{Ni}_{50}\text{Mn}_{40}\text{Sn}_{10}$ with higher Mn content,¹⁴ Furthermore, first-order FM-AFM transition in $\text{Ni}_{50}\text{Mn}_{37}\text{Sn}_{13}$ with lower Mn content,¹⁴ and paramagnetic-FM transition in $\text{Ni}_{2.19}\text{Mn}_{0.81}\text{Ga}$,¹⁵ have also been observed. Thus, we can use DSC, a technique which is sensitive to the first-order phase transition, to determine the AFM transition of Ni-Mn-Sn alloys with higher Mn content [Fig. 3(a)]. The T_m or AFM transition temperature increases continuously with decreasing Sn content [Fig. 3(b)].

D. Magnetic properties

1. $M(T)$, $RM(T)$, and $M(H)$ at 300 K in NiMnSn_x

Figures 4(a) and 4(b) show the temperature dependence of magnetization [$M(T)$] of NiMnSn_x measured under $H=100$ Oe after ZFC and FC from 300 K. The ZFC curve exhibits a peak and an irreversibility between ZFC and FC curves occurring below 300 K, being similar to that of Ni-Mn-In or Co-doped Ni-Mn-Sn alloys.^{10,16} The magnetic state at low temperatures is the SPM domains embedded in

FIG. 2. Powder X-ray diffraction patterns taken at room temperature for NiMnSn_x ($x=8, 9, 10, 11$, and 12) alloys. The inset highlights the details in the range of $40^\circ \leq 2\theta \leq 46^\circ$.

TABLE II. Lattice parameters of NiMnSn_x ($x = 8, 9, 10, 11$, and 12) at room temperature.

x	a (Å)	b (Å)	c (Å)	β (°)
8	4.322	5.532	30.404	94.11
9	4.333	5.583	30.057	94.09
10	4.339	5.611	29.864	93.51
11	4.341	5.620	29.888	93.32
12	4.348	5.619	29.863	92.98

FIG. 3. (Color online) (a) DSC curves of NiMnSn_x ($x = 8, 9, 10, 11$, and 12) alloys. The horizontal arrows indicate the heating and cooling directions. The vertical arrows indicate the T_m s of NiMnSn_x alloys. (b) T_m as a function of Sn content.

AFM matrix. The SPM domains are collectively frozen forming a superspin glass state at lower temperatures. The remanent magnetization (RM) as a function of temperature in NiMnSn_x was measured under zero field on heating after the samples were field-cooled under 10 kOe from 300 to 10 K [Fig. 4(c)]. The RMs decrease with increasing temperature and become zero before reaching 300 K in all NiMnSn_x samples. The $M(H)$ at 300 K in all NiMnSn_x alloys are straight lines without any SPM/FM feature, indicating that their T_c s are at lower temperatures [Fig. 4(d)]. These results ensure that unmagnetized initial states can be obtained in these samples at lower temperatures after ZFC from 300 K.

2. $M(H)$ loop measured after FC

We measured the $M(H)$ loops of NiMnSn10 at 10 K after FC from 300 K under different cooling fields [Fig. 5(a)]. The maximum measurement field $|H_m^{\max}|$ ($=|+H| = |-H|$) is equal to the cooling field for each curve. For example, for cooling field is +60 kOe, the sample was cooled under +60 kOe from 300 K to 10 K, thereafter a closed $M(H)$ loop was measured following $+60 \text{ kOe} \rightarrow 0 \rightarrow -60 \text{ kOe} \rightarrow 0 \rightarrow +60 \text{ kOe}$. The $M(H)$ loops measured after FC shift along the magnetic field axis [Fig. 5(b)], indicating that EB effect can be produced in Ni-Mn-Sn alloys after FC. This is consistent with the previous reports attributing this effect to the coexistence of AFM and FM phases and the interaction at the interface below blocking temperature (T_B).^{5,9}

3. P and N types $M(H)$ loops measured after ZFC

We measured the P type $M(H)$ loops of NiMnSn_x with various magnitudes of the initial magnetization field (different $|H_m^{\max}|$ s) at 10 K after ZFC from 300 K. Figure 6 shows the result for NiMnSn10 as an example. It is worth noting that the ZFC $M(H)$ loops shift along the magnetic field axis. Moreover, both the shape of $M(H)$ loop and its shift (H_{EB}) are strongly dependent on the magnitude of the initial

FIG. 4. (Color online) $M(T)$ curves measured in $H = 100$ Oe under ZFC and FC in NiMnSn_x (a) $x = 12$, 11. (b) $x = 10, 9, 8$. (c) RM as a function of temperature for NiMnSn_x. (d) $M(H)$ curves for NiMnSn_x at 300 K.

FIG. 5. (Color online) (a) $M(H)$ loops of NiMnSn10 measured at 10 K after FC from 300 K under different cooling fields. The $|H_m^{\max}|$ is equal to the cooling field for each curve. (b) A larger scale at low field.

magnetization field at $H < 40$ kOe. The magnetization at the starting point of the initial magnetization curve ($H = 0$) is zero and the magnetization values at the highest positive and negative magnetic fields are equal (Fig. 7). Figure 8(a) shows H_{EB} and coercivity (H_c) as a function of $|H_m^{\max}|$. The H_{EB} and H_c are defined as $H_{EB} = -(H_L + H_R)/2$ and $H_c = -(H_L - H_R)/2$, respectively, where H_L and H_R are the left and right coercive fields. There is a critical $|H_m^{\max}|$ (H^{crit}) = 35 kOe, at which H_{EB} reaches the maximum value and H_R remains almost constant at higher $|H_m^{\max}|$ [Fig. 8(b)]. The maximum H_{EB} is ~ 2230 Oe at 10 K, which is about 2 times larger than that observed in Ni-Mn-In alloys (~ 1300 Oe).¹⁰ The decrease of the H_{EB} at higher $|H_m^{\max}|$ is only due to the decrease of the H_L , which may originate from the change of bulk AFM spin structure under large applied magnetic field.^{10,17} The N type $M(H)$ loops measured at 10 K after ZFC with opposite direction of the initial magnetization field have shifted to the positive side of the magnetic field axis [Fig. 9(b)], showing a centrally symmetric image of the P type $M(H)$ loops [Fig. 9(a)]. This result cannot be expected from the effect of remanent field of superconductor magnet-remnant magnetization of the samples, in which the shift direction of $M(H)$ loop is independent of the direction of the initial magnetization field.

4. Temperature dependence of ZEB

To further confirm this unusual phenomenon occurred after ZFC, we measured the temperature dependence of H_{EB}

FIG. 6. P type $M(H)$ loops of NiMnSn10 measured under different $|H_m^{\max}|$ s at 10 K after ZFC from 300 K. The initial magnetization curves [$0 \rightarrow (+H)$] are shown in Fig. 7.

FIG. 7. (Color online) (a) Initial magnetization curves $[0 \rightarrow (+H)]$ for different $|H_m^{\max}|$ s at 10 K after ZFC from 300 K in NiMnSn10. (b) Magnetization values under the highest positive (M^P) and negative ($|M^N|$) magnetic fields for different $|H_m^{\max}|$ s.

and H_c for $|H_m^{\max}| = 40$ kOe in NiMnSn10 as shown in Fig. 10(a). The H_{EB} approximately linearly decreases with increasing temperature at low temperatures and gradually disappears around the T_B , at which the H_c reaches its maximum value [Fig. 10(c)]. These relationships are similar to those reported in the EB systems after FC.¹⁸ It was explained as follows. The AFM anisotropy decreases with the increase of temperature. Thus, the FM rotation can drag more AFM

FIG. 8. (Color online) (a) H_{EB} (left) and H_c (right) as a function of $|H_m^{\max}|$ in NiMnSn10 at 10 K after ZFC. (b) The left (H_L) and right (H_R) coercive fields as a function of $|H_m^{\max}|$. The dotted line shows the position of $H^{\text{crit}} = 35$ kOe. (c) H_{EB} and (d) H_c as a function of $|H_m^{\max}|$ after ZFC (P and N types) and FC.

FIG. 9. (Color online) (a) Low field portion of P type $M(H)$ loops $[0 \rightarrow (+H) \rightarrow 0 \rightarrow (-H) \rightarrow 0 \rightarrow (+H)]$ for different $|H_m^{\max}|$ s at 10 K after ZFC from 300 K shown in Fig. 6. (b) Low field portion of N type $M(H)$ loops $[0 \rightarrow (-H) \rightarrow 0 \rightarrow (+H) \rightarrow 0 \rightarrow (-H)]$ for different $|H_m^{\max}|$ s at 10 K after ZFC from 300 K. The initial magnetization curves $[0 \rightarrow (+H/-H)]$ are not shown.

spins, giving rise to the increase in H_c ; whereas the AFM can no longer hinder the FM rotation above T_B . As a result, the H_c reaches its maximum value and H_{EB} reduces to zero at higher temperatures. The key difference in the present case is that this relationship is observed after ZFC. That is, magnetic unidirectional anisotropy, usually realized by FC from

FIG. 10. (Color online) (a) P type $M(H)$ loops with $|H_m^{\max}| = 40$ kOe at different temperatures after ZFC from 300 K. (b) Low field portion of $M(H)$ loops. (c) Temperature dependence of H_{EB} and H_c after ZFC for $|H_m^{\max}| = 40$ kOe.

higher temperature in contact with AFM, can be induced isothermally during the initial magnetizing process in NiMnSn10 alloy.

5. ZEB effect at different Sn contents

Figure 11(a) shows the field dependence of magnetization of NiMnSn x at 10 K. The saturation magnetization of NiMnSn x increases with increasing Sn content [Fig. 11(b)], which is in agreement with the previous results.¹² The saturation magnetization of stoichiometric compound Ni₅₀Mn₂₅Sn₂₅ is about 73 emu/g (pure FM state at low temperatures).¹² The decrease of saturation magnetization in the off-stoichiometric alloys is due to the excess of Mn atoms occupying a number of Sn sites, which produces AFM coupling.¹² So the SFM (may include some SPM or FM domains) volume fraction in off-stoichiometric alloys can be estimated from the ratio of their saturation magnetizations to the stoichiometric compound, which increases from ~0.1% in NiMnSn8 to ~33% in NiMnSn12 at 10 K [Fig. 11(b)]. The $|H_m^{\max}|$ dependence of H_{EB} and H_c obtained after ZFC from an unmagnetized state in NiMnSn x alloys shows three features [Figs. 11(c) and 11(d)]: (1) The $H^{\text{crit}} = 25$ kOe in NiMnSn11 is smaller than that of NiMnSn10; (2) The $M(H)$ loops in $x=12$ alloy after ZFC shows double-shifted behavior with no EB effect (not shown), which is in agreement with the previous results of Ni-Mn-Sn alloys with higher content of Sn¹²; (3) For $x=8$ and 9, the H_{EB} increases with $|H_m^{\max}|$ up to 80 kOe and the H_c of NiMnSn9 shows the maximum value at higher $|H_m^{\max}|$ s prior to reaching the maximum of its H_{EB} .

IV. DISCUSSION

An unmagnetized state at 10 K can be obtained after ZFC (the remanent field of the magnet is zero) from an unmagnetized state (ZFC starts from an unmagnetized state of the samples). Before each ZFC $M(H)$ loop measurement in the present case, two steps have been taken: (1) The superconductor magnet was demagnetized by oscillating field at

300 K to remove the pinned magnetic flux; (2) The samples were zero-field cooled from 300 K. Since the T_c s of all samples are below 300 K, the ZFC thus starts from an unmagnetized state. The magnetization at the starting point of the initial magnetization curve is zero, indicating that the initial state at 10 K is an unmagnetized state. The equal magnetization values in the highest positive and negative magnetic fields indicate that the shifted loop is not a nonsymmetrical minor hysteresis loop. That is, the shifted $M(H)$ loops (EB effect) are obtained isothermally from an unmagnetized initial state. The shift direction of $M(H)$ loop is strongly dependent on the direction of the initial magnetizing field [Figs. 8(c) and 9], further indicating the isothermal formation of magnetic unidirectional anisotropy (the origin of EB effect) during the initial magnetization process. Furthermore, both the H_{EB} and H_c after ZFC can be larger than those after FC [Figs. 8(c) and 8(d)], which indicates that the ZEB in the present case is not a spontaneous EB.¹⁹ This suggests that an intrinsic ZEB effect is observed in NiMnSn x alloys.

In NiMnSn x Heusler alloys, the modulated/unmodulated martensitic crystal structure has been reported.¹² However, the EB effect originates from an FM unidirectional anisotropy formed at the interface between FM and AFM.¹⁸ The process of field cooling from higher temperature is usually used to obtain FM unidirectional anisotropy in different EB systems. The different crystal structures of magnetic phases may affect the amplitude of FM/AFM coupling; while it cannot be the origin of EB effect. Furthermore, the sign of H_{EB} is strongly dependent on the direction of the initial magnetization field in the present case (Fig. 9). All of these results indicate that the ZEB effect does not originate from the modulated/unmodulated martensitic crystal structure.

In a previous report, we proposed a model to explain the first observation of ZEB effect in Ni-Mn-In alloys.¹⁰ The SPM domains can grow in size under external magnetic field, which induces a transition from a superspin glass to a SFM state. This process results in a SFM unidirectional anisotropy when it is in contact with an AFM phase below T_B and therefore produces EB effect.¹⁰ The meaning of H^{crit} is that at which superspin glass completely transforms to SFM state, producing maximum SFM unidirectional anisotropy. The smaller $H^{\text{crit}} = 25$ kOe in NiMnSn11 is due to the larger average domain size and smaller inter-domain distance in this alloy at the initial state. Note that the SFM volume fraction in $x=11$ alloy is about 20% (the volume fraction of SPM in the initial state is less than this value), which is close to the threshold concentration for percolation in three dimensional system (~16%).²⁰ Here, we would like to highlight that the limitation for ZEB effect is $y=14$ in NiMnIn y alloys with the similar SFM volume fraction (22%).¹⁰ This result suggests that the ZEB effect only exists in the alloys with volume fraction of SPM domains less than the percolation limitation in three dimensional system. For $x=12$ alloy, the SFM domains no longer separate from each other in AFM matrix resulting in the formation of FM domains. As a result, there is no SPM domain at the initial state. For $x=8$ and 9, the continuous increase of H_{EB} with $|H_m^{\max}|$ up to 80 kOe is due to the smaller size of SPM domain and larger inter-domain distance, which agrees with the results of NiMnSn10 for $|H_m^{\max}| < H^{\text{crit}}$.

FIG. 11. (Color online) (a) Field dependence of magnetization of NiMnSn x at 10 K. (b) Saturation magnetization (M^{sat}) and SFM volume fraction as a function of Sn content at 10 K. (c) and (d) $|H_m^{\max}|$ dependence of H_{EB} and H_c at 10 K for $x=8, 9$ (right), and 11, 12 (left).

V. CONCLUSION

In conclusion, a large ZEB effect was observed in NiMnSn x alloys with Sn content no more than 11%. The maximum H_{EB} in NiMnSn x alloys (at 10 K) is about twice as large as that observed in Ni-Mn-In alloys at moderate field range. The ZEB effect only exists in alloys with volume fraction of SPM domains less than about 16% (the percolation limitation in three dimensional system), regardless of the type of element X in NiMn X ($X = \text{In}, \text{Sn}$) alloys. The results obtained from NiMnSn x alloys further validate the assumptions made in our recent model¹⁰ such as, isothermal field-induced transition from a superspin glass to a SFM state, field-induced local AFM to FM transition at the interface. Furthermore, the present findings suggest a possibility of finding such unusual ZEB effect in other NiMn-based alloys, such as Ni-Mn-Sb, Ni-Mn-Ga, Ni-Mn-Al, etc.

¹W. H. Meiklejohn and C. P. Bean, *Phys. Rev.* **102**, 1413 (1956).

²M. Ali, P. Adie, C. H. Marrows, D. Greig, B. J. Hickey, and R. L. Stamps, *Nat. Mater.* **6**, 70 (2007).

³G. Salazar-Alvarez, J. Sort, S. Suriñach, M. D. Baró, and J. Nogués, *J. Am. Chem. Soc.* **129**, 9102 (2007).

⁴W. C. Cain and M. H. Kryder, *J. Appl. Phys.* **67**, 5722 (1990).

⁵Z. Li, C. Jing, J. P. Chen, S. J. Yuan, S. X. Cao, and J. C. Zhang, *Appl. Phys. Lett.* **91**, 112505 (2007).

⁶M. Khan, I. Dubenko, S. Stadler, and N. Ali, *J. Appl. Phys.* **102**, 113914 (2007).

⁷H. C. Xuan, Q. Q. Cao, C. L. Zhang, S. C. Ma, S. Y. Chen, D. H. Wang, and Y. W. Du, *Appl. Phys. Lett.* **96**, 202502 (2010).

⁸B. M. Wang, Y. Liu, L. Wang, S. L. Huang, Y. Zhao, Y. Yang, and H. Zhang, *J. Appl. Phys.* **104**, 043916 (2008).

⁹M. Khan, I. Dubenko, S. Stadler, and N. Ali, *Appl. Phys. Lett.* **91**, 072510 (2007).

¹⁰B. M. Wang, Y. Liu, P. Ren, B. Xia, K. B. Ruan, J. B. Yi, J. Ding, X. G. Li, and L. Wang, *Phys. Rev. Lett.* **106**, 077203 (2011).

¹¹J. S. Kasper and J. S. Kouvel, *J. Phys. Chem. Solids* **11**, 231 (1959).

¹²T. Krenke, M. Acet, E. F. Wassermann, X. Moya, L. Mañosa, and A. Planes, *Phys. Rev. B* **72**, 014412 (2005).

¹³T. Krenke, M. Acet, E. F. Wassermann, X. Moya, L. Mañosa, and A. Planes, *Phys. Rev. B* **73**, 174413 (2006).

¹⁴S. Aksoy, M. Acet, P. P. Deen, L. Mañosa, and A. Planes, *Phys. Rev. B* **79**, 212401 (2009).

¹⁵L. Pareti, M. Solzi, F. Albertini, and A. Paoluzi, *Eur. Phys. J. B* **32**, 303 (2003).

¹⁶D. Y. Cong, S. Roth, J. Liu, Q. Luo, M. Pötschke, C. Hürrieh, and L. Schultz, *Appl. Phys. Lett.* **96**, 112504 (2010).

¹⁷R. Morales, Z. P. Li, J. Olamit, K. Liu, J. M. Alameda, and I. K. Schuller, *Phys. Rev. Lett.* **102**, 097201 (2009).

¹⁸J. Nogués and I. K. Schuller, *J. Magn. Magn. Mater.* **192**, 203 (1999).

¹⁹J. Saha and R. H. Victora, *Phys. Rev. B* **76**, 100405 (2007).

²⁰H. Scher and R. Zallen, *J. Chem. Phys.* **53**, 3759 (1970).