First-order phase transitions, where one phase replaces another by virtue of a simple crossing of free energies, are best known between solids, liquids, and vapors, but they also occur in a wide range of other contexts, including even elemental magnets. The key challenges are to establish whether a phase transition is indeed first order, and then to determine how the new phase emerges because this will determine thermodynamic and electronic properties. Here it is shown that both challenges are met for the spin reorientation transition in the topological metallic ferromagnet Fe$_3$Sn$_2$. The magnetometry and variable temperature magnetic force microscopy experiments reveal that, analogous to the liquid–gas transition in the temperature–pressure plane, this transition is centered on a first-order line terminating in a critical end point in the field-temperature plane. The nucleation and growth associated with the transition is directly imaged, indicating that the new phase emerges at the most convoluted magnetic domain walls for the high temperature phase and then moves to self-organize at the domain centers of the high temperature phase. The dense domain patterns and phase coexistence imply a complex inhomogenous electronic structure, which can yield anomalous contributions to the electrical conductivity.

1. Introduction

Ferromagnetic and antiferromagnetic materials often display a preferential orientation of the magnetic moments along magnetic “easy” axes, which in single crystals coincide with high symmetry crystallographic directions. This magnetic anisotropy arises from spin–orbit coupling, which is a microscopic, electronic property, as well as from long-range dipolar interactions. While in most magnets the easy axes do not change within the magnetically ordered state, some systems,

[1,2] including even elemental chromium,[3] undergo spin-reorientation, where the preferred axes change as the temperature is varied since the magnetic anisotropy is temperature-dependent. Such spin-reorientation transitions can be classified as first or second order depending on whether the magnetic easy axis changes abruptly during the spin reorientation, with domains of the new phase nucleating in the presence of the initial phase, or continuously with the whole system undergoing a homogenous transition. Understanding such transitions is important not only from the viewpoint of fundamental statistical physics, but also because the static domain patterns characteristic of first-order transitions can have very substantial effects on electrical properties which one might wish to exploit for spintronics.

While spin-reorientation transitions have been studied extensively,[4] their order is open to debate, as demonstrated for non-stoichiometric DyFe$_7$Ti bulk crystals[5] where the sensitivity of the spin-reorientation temperature to sample composition leads to an averaging of the transition temperature in bulk crystals that make the transition observed in magnetometry appear to be continuous and second order. Images of nucleation, domain growth, and phase coexistence are required to provide the most convincing evidence of a first-order transition. Such a study has been performed for antiferromagnetic chromium,[3] but not for ferromagnets, even though changing domain structures obtained via spin reorientation have been noted for various ferromagnets.[1,4]

Fe$_3$Sn$_2$ is a metallic ferromagnet with a lattice consisting of iron kagome bilayers separated by tin layers.[7] The Curie temperature is $T_c = 640$ K and spin reorientation occurs upon cooling, where the spins rotate from close to the $c$-axis toward the $ab$-plane.[8] Even though it is agreed that the angle that the
moments make with respect to the ab-plane is temperature-dependent, there is no report on the precise direction of the magnetic moment as a function of temperature. In this paper, we assume that the angle that the moments make with respect to the ab-plane is 90° in the high-temperature phase and 0° in the low-temperature phase.

Initial work on the spin-reorientation transition in Fe₃Sn₂ was undertaken using Mössbauer spectroscopy on powder samples, where a transition was observed at 114 K.[9] Subsequent measurements showed that the spectra above 220 K consisted of one peak related to the population of spins in the high-temperature phase whereas below 200 K two additional peaks characterizing the low-temperature phase emerged, with the three peaks co-existing over a wide (80 K < T < 220 K) range of temperatures.[8b] The population of the low-temperature (in-plane polarized) state was shown to grow as the temperature was lowered while that of the high-temperature phase decreased. The spin rotation was suggested to be abrupt based on the constancy of the location of the peaks.[8b]

Subsequent measurements, again performed with powder samples, were associated with the proposal that the magnetic reorientation transition involves a continuous rotation of the spins from the c-axis toward the kagome plane.[8a-c] Neutron powder diffraction data, where Bragg intensities were analyzed, could be interpreted as following from either a continuous or abrupt spin rotation.[8a] As a result, the nature of the spin reorientation, whether it is first or second order, has been open to debate.

Besides being magnetically interesting, Fe₃Sn₂ displays an exceptional anomalous Hall effect and an intrinsic mechanism was proposed that was due to the nontrivial magnetic spin texture experienced by the conduction electrons.[10] The material began attracting attention[11] as a candidate host for flat, topological 2D bands analogous to the Landau levels in 2D electron gases, and various anomalous electronic characteristics,[12] including those associated with a Weyl semimetal state,[13] have been reported. Research on single crystals where magnetic microscopy (Lorentz force) measurements were performed led to the claim that near room temperature there are magnetic textures and magnetotransport anomalies which could be related to skyrmionic bubbles.[14]

The present work focuses on the spin reorientation in Fe₃Sn₂ single crystals using a combination of bulk magnetometry and local direct space imaging by variable temperature magnetic force microscopy (MFM).[15] We show direct images of spin reorientation where nucleation and growth of the new phase as well as phase coexistence are clearly observed. Due to the coupling between the magnetic and electronic degrees of freedom, the spin reorientation in Fe₃Sn₂ has direct implications for its electronic properties: the complex magnetic domain pattern imprints an electronic domain structure on the system.

2. Results

2.1. Squid Magnetometry Measurements

Figure 1a shows the structure; the equilateral triangles in the kagome planes have sides of length 2.732 and 2.582 Å.[8a] The kagome planes exist in bilayers with a stacking period of 6.69 Å. Despite being metallic, there is a localized moment of 1.7 μ₀ (300 K) to 1.9 μ₀ (4 K) per iron atom. The crystals grow in a shape that is large (of the order of 1 mm) along the kagome plane but very thin (100 μm or less) along the c-axis. The magnetometry data in Figure 1c,d show the change in magnetization within the ab-plane as a function of temperature and magnetic field for crystal A. The data in Figure 1d were collected both on cooling and warming with a measuring field between 50 and 10 000 Oe in the ab-plane. The increase in magnetization on cooling indicates that the moments rotate from the c-axis toward the ab-plane, consistent with previous reports.[8b,16] In addition, we observe large discrete jumps on cooling (but not on warming) at temperatures which appear to be randomly distributed near 130 K. Furthermore, we observe thermal hysteresis, i.e., the magnetization in the ab-plane is larger on warming than on cooling. In contrast, the field sweeps in Figure 1c show no evidence of field hysteresis for both the high-temperature (300 K) and low-temperature phases (4 K), indicating that Fe₃Sn₂ is a soft magnet with negligible coercive field and no memory of field history. The variation in the field-saturated magnetization is very small between 4 and 300 K, indicating that the main effect of the temperature in the range of 4–350 K is to cause the reorientation of the moments.

We notice that at 300 K (Figure 1c), where the easy axis is essentially perpendicular to the planes, ~2000 Oe are required to rotate the moment into the plane. Therefore, when the applied magnetic field in the ab-plane is 2000 Oe, the moments are already rotated into the ab-plane and thus there is negligible spin reorientation upon cooling, as shown in Figure 1d. The point (T = 130 K, H = 1500 G) in the temperature-field plane is analogous to the classic liquid–vapor critical point where the phase boundary between liquid and vapor disappears when the pressure P is above the critical pressure. Concomitantly, the critical end point which we have discovered defines an external field beyond which single domain physics will determine the electron transport. Figure 1b is the corresponding phase diagram where we draw the magnetic states as a function of temperature and field along the ab-plane based on the magnetometry data. The pink region is defined by the points where the thermal hysteresis loops close at various magnetic field values and is where the high- and low-temperature phases coexist.

We note here some subtleties concerning phase boundaries terminating in critical points, especially when we move from clean liquids without a background medium to solids with their inevitable disorder. In particular, there are three possibilities to consider. i) Without fixed nucleation sites and in the long-time limit, the liquid–vapor phase boundary in the P–T plane is a line of first-order transitions terminating at a critical point, and coexistence of liquid and vapor is found only on that line. ii) If we operate at finite times and/or there is a random (nucleating) medium, the line is broadened, and there will be coexistence of liquid and gas phases as well as thermal hysteresis in the density, and for a small enough sample there will be density jumps randomly distributed near the critical line which would have characterized the clean thermodynamic limit. On the other hand, when we look at iii) a clean system for variable volume V at fixed temperature, there will be condensation and two-phase coexistence even at equilibrium (for which there will also be no hysteresis in thermodynamic quantities), and the broad two-phase region will narrow to a point at a critical temperature and volume. The density will be a continuous function of
V and P, even though of course its derivatives will be discontinuous. What we see experimentally is closest to the case (ii) of an out-of-equilibrium/random nucleation critical point in the P–T plane in that the magnetization data reveal steps clustered around a critical line, and there is substantial thermal hysteresis. Magnetic field is conjugate to the magnetization density in a manner analogous to how pressure is conjugate to particle density in the liquid/gas problem, and temperature of course carries the same meaning in both problems. The control parameters in our experiments are magnetic field and temperature, so it is most natural to view our experiments as analogs of the liquid–vapor transition in the P–T plane. A solid medium such as the binary intermetallic compound of interest here has ample disorder in the form of stacking faults, other grain boundaries, and chemical defects to serve for random nucleation.

The magnetometry data from the aligned single-crystal sample show discrete jumps that were not previously observed in powder samples as there they would be masked by powder averaging. For powders, where there is a uniform distribution of crystal orientations, the increase in the magnetization along the applied field observed by magnetometry upon cooling could be accounted for by the higher probability that the ab-plane rather than the c-axis of a crystallite is nearly parallel to the external field. Because there is no statistical sampling over crystallite orientations, the single-crystal data highlight the thermal hysteresis and abrupt jumps in the magnetization on cooling as the moments rotate toward the ab-plane. We observe a variation in the size of the jumps between samples with most samples showing very small jumps. We conducted heat capacity measurements but could not see any singular behavior due to the large phonon background. Of course, magnetization is a thermodynamic quantity, related via Maxwell relations to the magnetic contribution to the specific heat, and is therefore a reliable indicator of the nature of phase transitions.

2.2. Magnetic Domain Structure at Room Temperature

To avoid the averaging of bulk magnetometry over domains, we investigated the underlying physics of the phase transition.
using MFM as a direct space local probe. All the images presented in this paper were collected at zero field, which is the ideal condition for studying ferromagnetic transitions that are thermally driven since an external magnetic field induces the order parameter. The plane in all the images is parallel to the kagome plane. The first task was to investigate the magnetic domain structure at room temperature which corresponds to the high-temperature phase with the easy axis along $c$.

**Figure 2.** a–c) Magnetic domain pattern of three different crystals B, C, and D imaged at room temperature with the out-of-plane direction parallel to the $c$-axis. They all display meandering domains with branches, which are characteristic of ferromagnets with uniaxial anisotropy. The dark and bright regions correspond to the oppositely polarized magnetic domains in the $c$-direction. The domain width or periodicity depends on the sample thickness. d,e) Images of magnetic domains of the crystals cleaved from that in (c). As the crystal thickness is reduced due to the cleaving, the domain periodicity is reduced compared to that of the original crystal in (c).

Figure 2a–c displays the magnetic domain structure of Fe$_3$Sn$_2$ for three different crystals B, C, and D. They all show a meandering domain pattern characteristic of ferromagnets with uniaxial magnetic anisotropy perpendicular to the plane of the image. The sharp contrast between the magnetic domains with magnetization pointing up or down indicates that the direction of the magnetic moment changes abruptly between the two domains, i.e., parallel or antiparallel to the $c$-axis. Such branched domain patterns are typical of highly anisotropic materials where the moments align perpendicular to the surface, and occur to minimize the stray field.$^{[17,18]}$ The width or periodicity of the magnetic domains differs from sample to sample, and it...
is determined by the thickness of the crystal. This can be shown directly by cleaving crystal D and seeing that the length scale of the magnetic domain structure of each half (Figure 2d,e) is smaller than that of the original crystal (Figure 2c).

2.3. Evolution of the Magnetic Domain Structure on Cooling

Crystal E was selected for MFM imaging due to its large size. The MFM data in Figure 3a–f show the evolution of the domain structure on cooling from 200 to 4 K. Over this temperature range, the evolution of the spin alignment from largely along the c-axis toward the ab-plane changes the images drastically. As the contrast in the MFM images is due to stray fields perpendicular to the sample surface, the range of signals observed by MFM from the magnetic images decreases as the moments rotate toward the ab-plane. Consequently, the magnetic domain images at low temperatures show contributions from topography as well as magnetism, implying that steps (corresponding to the straight lines) in the surface structure are visible.

The domain structure at 200 K is similar to that observed at room temperature and consists of a highly branched

![Figure 3. MFM images for crystal E showing the moments rotating from the out-of-plane direction to in-plane. The fine dendrites on the branched structure are lost on cooling: a) 200, b) 160, c) 120, d) 100, e) 80, f) 4 K. The black boxes in panels (a) and (b) correspond to the same region of the sample.](image-url)
structure with fine dendritic fingers. On cooling from 200 to 4.2 K, the spin structure changes from being primarily due to out-of-plane moments to consisting predominantly of in-plane domains. Correspondingly, the branching of the domain walls reduces, giving way to looping curves which become ever straighter. On further cooling, the loops are not visible and domain walls associated with the low-temperature phase appear.

Our data show that the initial cooling from high temperature leads to the development of a fragmented fine structure within the interior of the branched domains. The domain evolution is shown from 200 to 4 K in Figure 3a–f and in greater detail from 160 to 140 K in Figure 4a–c, with the areas in the boxes corresponding to the same sample area. The image sequence shows that between 160 and 140 K there is a growth of disjointed fine structures at the interior of the branches that have opposite contrast to the branch within which they reside. Initially, these fine filaments emanate from the tips of the nearly periodic dendritic protrusions on the walls between the bright and dark regions, i.e., they are nucleated at points of maximum field gradient. Further cooling leads to growth and extension of the fine structure throughout the branches and by 140 K the thin filaments are also largely parallel to rather than emanating from the major walls. The image at 120 K in Figure 3c clearly shows that the inner filaments have become broader, continuous inner cores within both up and down branches.

Throughout the cooling process, there is a smoothing not only of the inner filaments but also of the principal walls between up and down domains, with the fine dendritic features that are easily seen at 160 K (Figure 3b) being completely lost at 120 K (Figure 3c). The smoothing and broadening follows from a temperature-dependent reduction of the anisotropy energy which confines the spins to the z-direction perpendicular to the kagome planes.

The inner core regions of the branches continue to expand on cooling; in the 100 K image (Figure 3d), the outer edges of the branches separate due to the expansion of the inner core. The 4 K image (Figure 3f) shows large domains with predominantly in-plane magnetic moments and a number of low contrast magnetic domain walls.

The variation of subtle fine structure in Figure 4d observed at 130 K suggests that there is a variation in the completion of the transition, with the scan across the sample showing regions with different degrees of structure within the branches. These correspond to different stages of nucleation and growth through the spin-reorientation transition. Domains in the top right of Figure 4d have a fine structure, while in the bottom left far thicker core-like structures are present. The images in Figure 4e,f correspond to separate scans of smaller regions. The radial average of their 2D fast Fourier transform (FFT), shown in Figure 6b, can be used to characterize the contrasting length scales in the images, and shows a larger high-frequency component above 0.002 nm⁻¹ for the top right quadrant of Figure 4d.
compared to the bottom left quadrant. Plots of the same quantity, shown for 160 and 120 K in the inset of Figure 6b, confirm that the high-frequency component is associated with fine structure as seen for higher temperature (160 K) domains.

2.4. Evolution of the Magnetic Domain Structure on Warming

We observe the features characterizing the spin-reorientation transition in more than one sample and on warming as well as cooling. In Figure 5, we show MFM images for a different crystal F taken on warming from 78 to 170 K. The images clearly show how the sample transitions from the low-temperature phase to the high-temperature phase. In the 78 K images, there is a generally featureless in-plane domain structure with very little contrast. On warming to 120 K, the large featureless in-plane domain structure is lost and the whole area consists of a meandering stripe (string) domain structure. What is interesting at 140 K is that the domain structure is built upon the string-dominated structure seen at 120 K but with hair-like side branches appearing. In other words, we are seeing the reverse of the process which we saw on cooling, where the filamentary “hair”

![Figure 5](image-url)

**Figure 5.** Images of the domain structure for crystal F on warming. a) 78, b) 120, c) 140, d) 150, e) 160, and f) 170 K.
disappears. Furthermore, while at 120 K the domain pattern can be described as an alternation of bright and dark regions with a periodicity slightly less than 1 μm (distance from bright to bright region), at 140 K we have another modulation of longer wavelength superimposed on the alternation observed at 120 K. The longer wavelength modulation produces an overall darker or brighter region, which we believe is the precursor of the high-temperature phase, except that it has a smaller wavelength modulation inside. As we raise the temperature to 150 and 160 K, the domain structure remains the same except for more addition of side branches. Between 160 and 170 K, the morphology of the domain structure stays the same with the exception of a clearer distinction between overall bright versus dark regions.

We believe that the strings marked by ovals for the 170 K image, either bright in the middle of a dark region, or dark in the middle of a white region are the same as the continuous inner cores that we observe on cooling. However, the temperature at which they disappear on warming is higher \(T > 170\) K than the temperature at which they form on cooling \(T < 140\) K. The fact that the inner core can be superheated suggests that it belongs to the low-temperature phase. Subsequent measurements on a different sample carried out to higher temperatures show (see Figure 8) that the inner core is gone at 180 K.

### 2.5. Distributions of Magnetic Forces

MFM measures magnetic force along the z-direction, and so when moments are predominantly in-plane, we expect a signal only near domain walls where the spin might rotate through \(z\). This would imply passing from a strongly bimodal distribution for the MFM signal in the high-temperature phase, corresponding to up and down magnetic domains, to a single, narrower peak centered on zero that arises from in-plane magnetic domains. The histograms of the MFM frequency shifts (see Figure 6a) are in agreement with this expectation: there is a distribution which at high temperatures has two peaks, which merge as the low-temperature phase nucleates and increases in area. The merger occurs between 150 and 100 K, the temperature range where large discrete jumps in the bulk magnetization are found to occur (Figure 1d).

### 2.6. Effect of Thermal Cycling on the Magnetic Domain Structure

To understand the microscopic nature of the thermal hysteresis seen in bulk magnetometry, we compare MFM data on crystal E, shown in Figure 7, collected on cooling from 300 K and on warming from 80 K. The domains in Figure 7a–c and Figure 7d–f were imaged at 150 and 80 K, respectively, while cycling the temperature between 150 and 80 K. The domain image Figure 7a at 150 K taken on cooling shows an extensive fine structure due to the formation of the low-temperature phase and the subsequent growth of the in-plane phase. In contrast, the images in Figure 7b,c collected at the same temperature after warming from 80 K show a continuous inner core structure, indicating that the development of the high-temperature phase on warming from 80 K follows a qualitatively different path than that leading to the low-temperature structure upon cooling from 300 K, thus accounting for the long-observed thermal hysteresis of Fe₃Sn₂. The images at 150 K reveal that upon warming, vestiges of the low-temperature phase remain as cores within the branches of the high-temperature phase. Examination of Figure 7, and in particular comparison of (b) and (c) also reveals that multiple warming and cooling cycles yield patterns with identical microstructures, but with numerous features on longer length scales rearranged.

In contrast, the images in Figure 7d–f at 80 K show essentially the same domain structure. Based on magnetotransport studies,[16] the spin reorientation to the low-temperature phase is complete around 70 K. Therefore, around 80 K or below, we believe that the system is in its ground state, resulting in a stable magnetic domain configuration. On the other hand, based on our phase diagram of Figure 1b, 150 K is around the center of the regime where there is thermal hysteresis and phase coexistence. Therefore, depending on the thermal history, the system can be in a different state. During the initial cool down from room temperature to 150 K, i.e., in Figure 7a, the low-temperature phase is hardly present. However, upon cooling to 80 K, where the low-temperature phase is the ground state, and warming up to 150 K, i.e., in Figure 7b, the...
The low-temperature phase coexists with the high-temperature phase, giving rise to the string structure at the core of the \( c \) domains. The same is true for Figure 7c. The different domain structures in Figure 7a–c indicate the presence of the low-temperature phase inside the \( c \) domains due to thermal hysteresis, and can be attributed to that phase's reduced stability at higher temperature due to larger thermal fluctuations. The magnetic domains are more stable at low temperature due to reduced thermal fluctuations resulting in a reproducible magnetic domain pattern at 80 K even after thermal cycling.

The presence of a continuous inner core structure persisting to higher temperature on warming is also observed on a different crystal (G), which we studied in detail both on cooling and warming. The domain pattern of this sample...
is significantly more complex than that of any other sample (Figure 8). Even the high-temperature phase (Figure 8a), consists of more than alternating bright and dark domains.

The images (a)–(i) in Figure 8 were obtained during cooling, whereas the images (j)–(r) were obtained upon warming after the sample was cooled down to 4 K. At first
instance, we clearly notice that the images on cooling are different from those on warming, implying that the domain pattern on warming is different from that on cooling. On cooling we observe a substantial change of the domain pattern around 140 K becoming more obvious at 130 K. After careful examination of the images, what is thermally hysteric besides the domains and domain walls having moved is in essence the presence of the continuous inner core structure characteristic of the low-temperature phase up to higher temperatures during warming. As indicated by the blue ovals, this inner core structure persists up to 160 K, but is not visible at 180 K.

3. Discussion and Conclusion

Our single-crystal MFM and magnetometry data show that the much-studied kagome ferromagnet Fe₃Sn₂ undergoes a first-order spin reorientation transition which in the magnetic field-temperature plane is analogous to a liquid–gas transition in the pressure–temperature plane. The images reveal that ferromagnetic domain walls, as well as nucleation and growth of the minority phase on both cooling and warming are responsible for the hysteretic effects. The fact that hysteresis is present when cycling the temperature and not the magnetic field indicates that the thermal hysteresis arises from the first-order nature of the spin-reorientation transition and not because of spin glass behavior.

A key aspect of a first-order phase transition is that the order parameter, in this case the magnetic easy axis, changes abruptly through the phase transition. Our experiments have resulted in the discovery of such jumps in certain small samples of Fe₃Sn₂, while also explaining the more gradual evolution of the magnetization in others on account of nucleation and growth of small domains.

The MFM images reveal the development of a fine magnetic structure on cooling that corresponds to the nucleation and growth of the low-temperature phase from the domain walls of the high-temperature phase. This is reminiscent of the growth of the longitudinal spin density wave state from the domain walls separating regions with different orientations of the spin density wavevector for the transverse phase in chromium. Although the order parameter in chromium is more complex than for ferromagnetic Fe₃Sn₂, the reason for nucleation at high-temperature phase domain walls is the same—at the domain walls, the magnetic moments can rotate into the direction favored in the low-temperature phase.

At zero magnetic field, the thermal hysteresis spans a large temperature window, from temperatures below 50 K to temperatures close to or above 200 K. In this temperature window, phase coexistence of magnetization along the c-axis and along the ab-plane occurs. We have shown that at temperatures around the midpoint of the thermal hysteresis temperature window, i.e., around 130 K, the two magnetic phases that coexist in a nonequilibrium system self-organize with the low-temperature phase running through the core of the high-temperature phase domains. This is a realization of self-organization of the spin degrees of freedom in a homogenous system and can be contrasted to other examples of self-organization where external factors such as substrate bending or polymer mixing lead to self-organization.

The microscopic origin of the change in the preferred spin direction is also likely to be the same for Fe₃Sn₂ and Cr, namely, a cooling-induced change in the band structure when spin–orbit effects are included. More specifically, there are different band structures for the possible spin orientations and as the chemical potential is changed with temperature, the free energy for one orientation crosses that for the other, resulting in a simple first-order transition. For ferromagnetic Fe₃Sn₂ and not for antiferromagnetic Cr, the magnetic dipolar interaction also enters, resulting in a much broader transition, and especially when moments are perpendicular to the sample plane, much more complex, and ramified domain walls.

Our results are significant not only in showing that we are dealing with different band structures that yield different free energies for different magnetization directions in Fe₃Sn₂, but also in revealing complex domain wall phenomena which are strongly temperature-dependent. This implies that over a large temperature range, low field magnetotransport occurs in an electronically highly inhomogenous ferromagnetic Weyl semimetal characterized by more than ordinary domain walls and skyrmions. We therefore need to consider electrons moving across boundaries between thermal history-dependent regions which have different band structures near the Fermi level even though they are hosted by the same crystal.

4. Experimental Section

Materials and Methods: Fe₃Sn₂ powder was prepared from stoichiometric quantities of Fe and Sn that were ground together and pressed into a pellet. This was placed into a silica ampoule and evacuated to 10⁻³ mbar before being back filled to 3.5 mbar with argon to reduce Sn evaporation. The ampoule was heated to 800 °C at a ramp rate of 1 °C min⁻¹ and left for 7 days. The reaction was then quenched by submersion in cold water. Single crystals were prepared by chemical vapor transport from 500 mg of the prepared Fe₃Sn₂ powder loaded into a 16 cm long silica ampoule with 40 mg of iodine. The ampoule was evacuated to a pressure of 10⁻⁶ mbar and sealed. After heating at a rate of 1 °C min⁻¹ in a two-zone furnace to 650 and 720 °C, the reaction was left over 8 days. It led to crystals up to 6 mm in diameter.

A Quantum design MPMS dc-SQUID magnetometer measured the bulk properties of the single crystals, which were aligned with their c-axes both perpendicular and parallel to the applied magnetic field using a purpose-built sample holder where Apiezon-N grease was used for adhesion. The influence of the magnetic history of the crystals on the magnetometry was minimized by warming to 350 K in zero-field before measuring.

Direct space images of the magnetic domains were collected using an Attocube variable temperature MFM with the sample cleaved along the ab-plane prior to imaging. The samples and MFM system were held under an inert helium atmosphere at 1 mbar in a cryostat. Sample temperature was controlled by local counter-heating. A region of the sample with a few topographical features was selected for study, allowing the signal from the magnetic domains to be easily isolated from the topographical features while the latter was allowed for tracking the same regions with changing temperature. A Veeco MESP-LM MFM tip with a moment of 0.3 emu was employed, with the moment of the tip oriented along the c-axis of the sample, using a lift height of 50 nm. The magnetic images were a 2D map of the shift in the resonance frequency of the cantilever with a magnetic tip, driven near resonance.
A large number of Fe₃Sn₂ single-crystal samples were measured in the current study. Among those, seven are reported in this article and labeled A to G in the order in which they appear in the article.

Acknowledgements
The authors acknowledge David Boldrin’s assistance in preparing Figure 1.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
first-order phase transition, magnetic domains, magnetic force microscopy, magnetometry, spin reorientation

Received: October 31, 2019
Revised: April 29, 2020
Published online: July 12, 2020

[1] O. Isnard, G. J. Long, D. Hautot, K. H. J. Buschow, F. Grandjean, J. Phys.: Condens. Matter 2002, 14, 12391.
[2] a) F. Yen, B. Lorenz, Y. Y. Sun, C. W. Chu, L. N. Bezmaternykh, A. N. Vasiliev, Phys. Rev. B 2006, 73, 054435; b) S. Mizusaki, Acta Mater. 2006, 54, 1350.
[3] P. G. Evans, E. D. Isaacs, G. Aeppli, Z. Cai, B. Lai, Science 2002, 295, 1042.
[4] K. Binder, Rep. Prog. Phys. 1987, 50, 783.
[5] M. D. Kuz’m’in, J. Appl. Phys. 2000, 88, 7217.
[6] a) J. Huang, C. Hyun, T. M. Chuang, J. Kim, J. B. Goodenough, J. S. Zhou, J. F. Mitchell, A. de Lozanne, Phys. Rev B 2008, 77, 024405; b) M. Seifert, L. Schultz, R. Schafer, V. Neu, S. Hankemeier, S. Rossler, R. Fromter, H. P. Oepen, New J. Phys. 2013, 15, 013019;
[7] b) F. Fayazi, K. P. Skokov, T. Faske, I. Opale, M. Duerrsschnabel, T. Helbig, I. Soldatov, U. Rohrmann, L. Molina-Luna, K. Guth, H. Zhang, W. Donner, R. Schäfer, O. Gutfleisch, Acta Mater. 2019, 180, 126.
[8] a) L. A. Fenner, A. A. Dee, A. S. Wills, J. Phys.: Condens. Matter 2009, 21, 452202; b) G. Lecaer, B. Malaman, B. Roques, J. Phys. F: Met. Phys. 1978, 8, 323; c) G. Le Caer, B. Malaman, L. Haggsrom, T. Ericsson, J. Phys. F: Met. Phys. 1979, 9, 1905; d) B. Malaman, G. Lecaer, D. Fruchart, J. Phys. F: Met. Phys. 1978, 8, 2389.
[9] G. Trumpy, E. Both, C. Djega-Mariadassou, P. Lecocq, Phys. Rev. B 1970, 2, 3477.
[10] T. Kida, L. A. Fenner, A. A. Dee, I. Terasaki, M. Hagiwara, A. S. Wills, J. Phys.: Condens. Matter 2011, 23, 112205.
[11] E. Tang, J. W. Mei, X. G. Wen, Phys. Rev. Lett. 2011, 106, 236802.
[12] a) J. X. Yin, S. S. Zhang, H. Li, K. Jiang, G. Chang, B. Zhang, B. Lian, C. Xiang, I. Belopolksi, H. Zheng, T. A. Cochran, S. Y. Xu, G. Bian, K. Liu, T. R. Chang, H. Lin, Z. Y. Lu, Z. Wang, S. Jia, W. Wang, M. Z. Hasan, Nature 2018, 562, 91; b) Q. Wang, S. Sun, X. Zhang, F. Pang, H. Lei, Phys. Rev. B 2016, 94, 075135.
[13] M. Yao, H. Lee, N. Xu, Y. Wang, J. Ma, O. V. Yazyev, Y. Xiong, M. Shi, G. Aeppli, Y. Soh, ArXiv e-prints, 2018, arXiv:1810.01514.
[14] Z. Hou, W. Ren, B. Ding, G. Xu, Y. Wang, B. Yang, Q. Zhang, Y. Zhang, E. Liu, F. Xu, W. Wang, G. Wu, X. Zhang, B. Shen, Z. Zhang, Adv. Mater. 2017, 29, 1701144.
[15] a) Y. A. Soh, G. Aeppli, N. D. Mathur, M. G. Blamire, J. Magn. Magn. Mater. 2001, 226–230, 857; b) Y. A. Soh, G. Aeppli, N. D. Mathur, M. G. Blamire, Phys. Rev. B 2001, 63, 020402.
[16] N. Kumar, Y. Soh, Y. H. Wang, Y. Xiong, Phys. Rev. B 2019, 100, 7.
[17] a) Y. A. Soh, G. Aeppli, J. Appl. Phys. 1999, 85, 4607; b) U. Welp, A. Berger, V. K. Vlasko-Vlasov, Q. A. Li, K. E. Gray, J. F. Mitchell, Phys. Rev. B 2000, 62, 8615.
[18] A. Hubert, R. Schafer, Magnetic Domains: The Analysis of Magnetic Microstructures, Springer, Berlin 1998.
[19] J. Q. Wu, Q. Gu, B. S. Guitton, N. P. de Leon, O. Y. Lian, H. Park, Nano Lett. 2006, 6, 2313.
[20] F. S. Bates, Science 1991, 251, 898.
[21] K. Kobayashi, Y. Ominato, K. Nomura, J. Phys. Soc. Jpn. 2018, 87, 5.