Atomic Layer Epitaxy of Kagome Magnet Fe₃Sn₂ and Sn-modulated Heterostructures

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Magnetic materials with kagome crystal structure exhibit rich physics such as frustrated magnetism, skyrmion formation, topological flat bands, and Dirac/Weyl points. Until recently, most studies on kagome magnets have been performed on bulk crystals or polycrystalline films. Here we report the atomic layer molecular beam epitaxy synthesis of high-quality thin films of topological kagome magnet Fe₃Sn₂. Structural and magnetic characterization of Fe₃Sn₂ on epitaxial Pt(111) identifies highly ordered films with c-plane orientation and an in-plane magnetic easy axis. Studies of the local magnetic structure by anomalous Nernst effect imaging reveals in-plane oriented micrometer size domains. Superlattice structures consisting of Fe₃Sn₂ and FeSn are also synthesized by atomic layer molecular beam epitaxy, demonstrating the ability to modulate the sample structure at the atomic level. The realization of high-quality films by atomic layer molecular beam epitaxy opens the door to explore the rich physics of this system and investigate novel spintronic phenomena by interfacing Fe₃Sn₂ with other materials.

In recent years, studies on magnetic topological materials with kagome lattices have become one of the hottest frontiers of condensed matter research, due to their exotic physical properties in both real space and momentum space [1, 2]. In momentum space, angle-resolved photoemission spectroscopy (ARPES) experiments on Mn₃Sn, Fe₃Sn₂, FeSn, and CoSn [3, 4] show that kagome lattices give rise to Dirac cones and flat bands which are topologically protected and are of particular interest. In addition, scanning tunneling microscopy finds evidence for topological flat bands as a sharp peak in the local density of states [7]. These topologically nontrivial features result in signatures of anomalous transport (e.g. chiral anomaly) in magnetotransport experiments [3, 8]. Furthermore, it is theoretically predicted that the band structures of the kagome topological magnets can be controlled by tuning of their magnetic structures [1, 8]. In real space, the kagome topological magnets have layered structures with spins occupying corner-sharing triangular lattices, which leads to geometrical spin frustration [9, 10]. A surprisingly large anomalous Hall effect (AHE) and magneto-optic Kerr effect (MOKE) have been reported in noncollinear antiferromagnet Mn₃Sn, even with vanishingly small net magnetization [10, 11]. Skyrmion spin textures have been observed in ferromagnetic Fe₃Sn₂ resulting from the competition of exchange, dipolar, and Zeeman energies [12, 13]. However, most of the studies on the kagome magnets have been done on bulk materials [1, 5, 9, 15] with a few papers reporting the growth and characterization of epitaxial films [16–20]. Looking forward, the heterostructures consisting of kagome magnets will be interesting for both fundamental research and applications, due to the possibility of tuning the magnetic and topological properties via interface interactions, epitaxial strain, and quantum confinement. However, all the reported studies on epitaxial Fe₃Sn₂ thin films have been focusing on high temperature growth so far, which may not allow for the formation of well-defined heterostructures due to interdiffusion at elevated temperatures. Therefore, lower temperature growth of Fe₃Sn₂ is desired for the future development of heterostructures and superlattices based on kagome magnets.

In this paper, we report the atomic layer molecular beam epitaxy (AL-MBE) growth of high-quality Fe₃Sn₂ thin films on Pt(111)/Al₂O₃(0001) substrates at lower temperatures. By sequentially depositing Fe₃Sn kagome layers and Sn₂ layers (see Figure 1a), we are able to control the sample structure at the atomic level. The crystalline structure of our Fe₃Sn₂ sample is confirmed by a combination of in situ reflection high energy electron diffraction (RHEED), X-ray diffraction (XRD) and transmission electron microscopy (TEM). Energy-dispersive X-ray spectroscopy (EDX) shows sharp interfaces for low temperature growth. The magnetic properties of Fe₃Sn₂ are investigated using MOKE, superconducting quantum interference device (SQUID) and anomalous Nernst effect (ANE). Using a microscopy technique based on ANE, we successfully image the in-plane oriented domain structure of the epitaxial Fe₃Sn₂ films and investigate the magnetization reversal as a function of applied field. We further utilize AL-MBE to precisely control the stacking sequences of Fe₃Sn and Sn₂ atomic layers, making superlattices with modulation of Sn₂ layers and confirm their structures by TEM and EDX. This demonstrates the potential of using AL-MBE to generate designer materials consisting of kagome layers (Mn₃Sn, Fe₃Sn, Co₃Sn, etc.) and Sn₂ spacer layers with precision control of sample structures at the atomic level.

Fe₃Sn₂ is a ferromagnet with a high Curie temperature,
FIG. 1. Material structure and growth. (a) Left: Top view of an individual Fe$_3$Sn$_2$ layer with kagome structure (top) and Sn$_2$ layer with honeycomb structure (bottom), respectively. Right: Side view of the crystal structure of Fe$_3$Sn$_2$ consisting of alternating stacking of two Fe$_3$Sn kagome layers and one Sn$_2$ layer. (b) RHEED patterns for the Al$_2$O$_3$(0001) substrate (top row), 5 nm Pt buffer layer (middle row), and the Fe$_3$Sn$_2$ layer after 20 nm of growth (bottom row). The left and right columns show patterns taken for the beam along the [1100] and [1120] directions of the substrate, respectively. Oscillations in the normalized RHEED intensity as a function of time. The RHEED intensity is measured within the red box and normalized by the intensity of the whole image as background.

The streaky patterns observed during Fe$_3$Sn$_2$ growth signify diffraction from a two-dimensional surface. In ad-
dition, we observe oscillations (Fig. 1c) in the normalized RHEED intensity where the maxima occurs for the Fe$_3$Sn$_2$ termination and the minima occurs for the Sn$_2$ termination. The normalization is performed by dividing the intensity of the background and is helpful for canceling variations in the incident beam intensity and background lighting. Except for the change in RHEED intensity, we did not observe any other significant differences in the RHEED pattern between Sn$_2$ and Fe$_3$Sn$_2$ terminations. Nevertheless, the presence of RHEED oscillations in atomic layer MBE confirms the modulation of the surface termination during growth.

Films grown by this method were studied with XRD using Cu K-$\alpha$ line (wavelength 1.5406 Å) to analyze their crystal structure. A representative $\omega$-2$\theta$ scan of a 20 nm film grown at 100 °C is shown in Figure 2a and includes the Fe$_3$Sn$_2$ (0009) peak with several Laue oscillations, indicating a smooth film. The out-of-plane lattice parameter extracted from analysis of this scan is 19.85 Å which agrees well with previous reports of 19.789 Å [21]. A peak from the 5 nm Pt(111) buffer also shows Laue oscillations with larger angular period due to smaller thickness of the Pt layer in comparison with Fe$_3$Sn$_2$ layer (Pt Laue peaks at $\sim$34.5°, $\sim$36.7°, and $\sim$43.5°) demonstrating high quality of the buffer layer. At larger 2$\theta$ angles we observe Fe$_3$Sn$_2$ (00018) and Pt(222) peaks, with no additional peaks that could be attributed to impurity phases (see Supplementary Material (SM) sections 2 for full range scans).

To characterize the surface topography of the sample, we performed atomic force microscope (AFM) measurements on uncapped 20 nm Fe$_3$Sn$_2$ films. Figure 2b shows a typical 10 µm × 10 µm scan of a 20 nm Fe$_3$Sn$_2$ sample grown at 100 °C. The AFM image indicates that the sample has flat surface, with root-mean-square (rms) roughness of 0.362 nm.

An important factor for material synthesis is the growth temperature. To optimize the growth temperature, we performed AFM and XRD measurements on a series of samples grown at different temperatures ranging from room temperature to 200 °C. The AFM and XRD results are shown in SM sections 1 and 2, respectively. We conclude that 100 °C is the optimized growth temperature as it gives the best AFM roughness and sharp XRD peaks.

The epitaxial quality of the 20 nm Fe$_3$Sn$_2$ sample grown at 100 °C was examined using a probe-corrected Themis Z S/TEM at 200 kV. Figures 2c and 2d show the energy-dispersive x-ray (EDX) chemical map and cross-sectional scanning transmission electron microscopy (STEM) image, revealing a clear interface between the Pt buffer and Fe$_3$Sn$_2$ thin film. The stoichiometry of Fe$_3$Sn$_2$ thin films was confirmed by electron energy loss spectroscopy (EELS), which gives an atomic ratio of Fe:Sn $\approx$ 1.5 (see SM sections 3 for details). To identify the crystalline quality of the Fe$_3$Sn$_2$ thin films, atomic resolution high-angle annular dark-field (HAADF) STEM images of the Fe$_3$Sn$_2$/Pt interface were acquired along the Fe$_3$Sn$_2$ [1120] direction (see Figure 2a). Since the contrast in HAADF STEM is approximately proportional to the square of the atomic number, the Sn atoms in the Sn$_2$ atomic layers appear as the brightest spots, while the atoms in Fe$_3$Sn$_2$ kagome layers are dimmer (the atomic numbers of Sn and Fe are 50 and 26, respectively). The alternating sequence of one Sn$_2$ monolayer and two Fe$_3$Sn$_2$ kagome layers shows a highly crystalline film with the expected Fe$_3$Sn$_2$ phase, although some stacking faults are observed.

To investigate the in-plane and out-of-plane magnetic properties of the Fe$_3$Sn$_2$ films, we measured longitudinal and polar MOKE hysteresis loops. The samples were probed using a linearly-polarized He-Ne laser (633 nm wavelength, $\sim$ 100 µW power) and a polarizing beamsplitter, photodiode bridge, and lock-in amplifier (463 Hz intensity modulation) to detect the Kerr rotation. The laser beam had a $\sim$45° angle of incidence for longitudinal MOKE and normal incidence for polar MOKE. Figure 3a shows a representative longitudinal hysteresis loop (red curve) measured on a 20 nm thick Fe$_3$Sn$_2$ sample. The square hysteresis loop with a coercivity of 2.4 mT indicates ferromagnetic order with in-plane magnetization. In contrast, the polar hysteresis loop (blue curve) shows a small Kerr rotation with slight variation with out-of-plane magnetic field. We repeated the longitudinal MOKE measurements on additional samples with thicknesses varying from 5 nm to 20 nm. The coercive fields of the samples are between 3.0 mT and 4.2 mT (SM section 4). Together, the longitudinal and polar MOKE loops show that the Fe$_3$Sn$_2$ samples have easy-plane magnetic anisotropy. This agrees with previous studies of Fe$_3$Sn$_2$ films grown by sputter deposition [19] and in bulk crystals thinned to below $\sim$100 nm [22].

We also performed SQUID magnetometry measurements on our Fe$_3$Sn$_2$ films. Figure 3b shows hysteresis loops of a 20 nm thick Fe$_3$Sn$_2$ sample measured with in-plane (red curve) and out-of-plane (blue curve) magnetic fields. The in-plane hysteresis loop exhibits a sharp switching behavior while the out-of-plane hysteresis loop exhibits almost linear behavior within $\pm$1 Tesla and saturates at $\sim$1 Tesla, suggesting that our Fe$_3$Sn$_2$ samples have easy-plane anisotropy. Furthermore, our SQUID results give a saturation magnetization $M_s = 630$ kA/m, which is consistent with previous studies [19, 24].

The magnetic domain structures of Fe$_3$Sn$_2$ films are of interest due to the observation of skyrmions in bulk Fe$_3$Sn$_2$, but has not yet been studied in thin films. Longitudinal MOKE microscopy with oblique angle incidence can detect the in-plane magnetization and therefore determine in-plane domain structure of our Fe$_3$Sn$_2$ films. However, in this manuscript, we choose to use thermal gradient microscopy (TGM) [24, 26] over longitudinal MOKE to image domain structure because we found that it has a better signal-to-noise ratio in our experimental setup.

TGM is based on moving a laser spot over the sam-
ple surface, and recording a voltage induced by the local laser heating. The thermal gradient generated in the out-of-plane direction $Z$ and a component of magnetization in the $X$ direction give rise to the anomalous Nernst effect, which is detected as a voltage along the $Y$ direction, $V_{ANE} \sim [\nabla T \times \mathbf{M}]$ (see Fig. 4a).

For the ANE imaging, we fabricated 10 $\mu$m wide Hall bar devices by a combination of photolithography and argon ion milling (Fig. 4b). The laser excitation for the thermal gradient was produced by a frequency-doubled (BaB$_2$O$_4$ crystal) mode-locked Ti:Sapphire laser for a wavelength of 400 nm. The laser beam with 0.7 mW power was focused by a 50× objective lens (NA of 0.6) to a spot size of 0.9 $\mu$m, and a fast steering mirror in the 4f alignment scheme was used for scanning the laser spot over the sample surface. The intensity of the beam was modulated at a frequency of 120 kHz and the generated ANE voltage was detected using a lock-in amplifier.
FIG. 3. Magnetic properties of Fe₃Sn₂ films. (a). Longitudinal (red) and polar (blue) MOKE hysteresis loops of a 20 nm Fe₃Sn₂ film. (b). Magnetic hysteresis loops of a 20 nm Fe₃Sn₂ film measured using SQUID magnetometry with in-plane (red) and out-of-plane (blue) geometries.

FIG. 4. Anomalous Nerst effect imaging. (a) Schematics of thermal gradient microscopy. The laser beam is scanned over the sample surface, the induced local ANE voltage reflects the local magnetic properties. (b) Microscope image of a typical device, (the dashed rectangle corresponds to the area imaged in (d)) (c) ANE hysteresis loop of a 20 nm Fe₃Sn₂ film. (d) Magnetization reversal of a 20 nm film through multidomain state imaged by ANE at a series of magnetic fields $\mu_0H_x$. 
We first utilized the ANE microscope to measure a detailed hysteresis loop at a fixed position. As shown in Fig. 4c for magnetic field along the X direction, the hysteresis loop shows a gradual reversal followed by magnetization switching with coercivity of 2.3 mT. This has a similar coercivity but more gradual initial reversal than the in-plane hysteresis loops obtained by MOKE (Fig. 3a). The origin of the different hysteresis properties is revealed by imaging the magnetic domain structure of Fe$_3$Sn$_2$ films at a series of magnetic fields. A representative sequence during the magnetization reversal is shown in Fig. 4d. Starting at -10.0 mT, the magnetization is in a saturated state along $-X$ (blue). The reversal initiates with the nucleation of white regions with $M_a$ saturated state along $+X$. The reversal initiates magnetization reversal which results in a more rounded hysteresis loop compared to the uniform films. With increasing magnetic field, domains of opposite polarity grow inward and coalesce across the channel. At about +1.5 mT, the magnetic structure is in a multidomain state with characteristic features (e.g. blue and red regions) ranging from 1 to 10 microns in size. By +2.5 mT, most of the magnetic moments have switched to $+X$. Finally, at +10.0 mT the magnetization reversal is complete and the films is fully saturated along $+X$.

Finally, to demonstrate the ability to control the sample structure at the atomic level, we synthesized a [Fe$_3$Sn$_2$ (2 nm)/Fe$_3$Sn (2 nm)]$_5$ superlattice using the AL-MBE technique. The [Fe$_3$Sn$_2$/Fe$_3$Sn]$_5$ superlattice samples were grown under the same conditions as Fe$_3$Sn$_2$ samples but with different atomic layer deposition sequences. For a 2 nm Fe$_3$Sn layer, we deposit nine atomic layers of Fe$_3$Sn without any Sn$_2$ spacers. For a 2 nm Fe$_3$Sn$_2$ layer, we deposit two atomic layers of Fe$_3$Sn, and one atomic layer of Sn$_2$ and repeat a total of three times. The RHEED pattern of a [Fe$_3$Sn$_2$/Fe$_3$Sn]$_5$ superlattice along the [110] direction of c-sapphire is shown in Figure 5a.

Such control of the stacking sequence with atomic level precision is confirmed by the HAADF STEM image of the [Fe$_3$Sn$_2$/Fe$_3$Sn] superlattice structure in Figure 5b. From the STEM image, an alternating sequence of 2 nm Fe$_3$Sn$_2$ (false colored in green) and 2 nm Fe$_3$Sn (false colored in red) can be observed with atomic resolution. Within a 2 nm Fe$_3$Sn$_2$ layer, a repetitive stacking of two Fe$_3$Sn atomic layers and one Sn$_2$ atomic layer can be observed. In contrast, we can only see Fe$_3$Sn atomic layers in 2 nm Fe$_3$Sn layer. The STEM-EDX chemical map further reveals the repetition of the [Fe$_3$Sn$_2$/Fe$_3$Sn]$_5$ superlattice structure along the growth direction as shown in Figure 5c where a 2 nm Fe$_3$Sn$_2$ layer has a stronger signal for the Sn element compared to a 2 nm Fe$_3$Sn layer.

In conclusion, we report the atomic layer epitaxy growth of kagome ferromagnet Fe$_3$Sn$_2$ thin films on Pt(111)/Al$_2$O$_3$(0001) at low temperatures. The high quality of epitaxial Fe$_3$Sn$_2$ films is confirmed by in situ RHEED, XRD, AFM and TEM. Low temperature growth helps to generate a sharp interface between Fe$_3$Sn$_2$ and Pt layers, which has been observed by EDX. The magnetic properties are investigated by magneto-optical Kerr effect, SQUID magnetometry, and anomalous Nernst effect, confirming the easy-plane magnetic anisotropy of the thin films. Using ANE microscopy, we successfully resolve the local in-plane oriented micrometer size domains during magnetization reversal. Finally, we demonstrate the ability to control the sample structure at the atomic level by synthesizing [Fe$_3$Sn$_2$/Fe$_3$Sn]$_5$ superlattices and confirming their structure by TEM. These advances enable novel heterostructures for exploring the rich physics of kagome magnets.
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AUTHOR CONTRIBUTIONS

S.C., I.L., and R.K.K. conceived the experiments. S.C. conducted the MBE growth, AFM measurements, MOKE measurements and SQUID measurements. I.L. conducted the ANE measurements. A.J.B. and I.L. conducted the XRD measurements. B.W., N.B., and D.W.M. conducted the TEM measurements. All authors participated in data analysis and preparation of the manuscript.

[1] L. Šmejkal, Y. Mokrousov, B. Yan, and A. H. MacDonald, Topological antiferromagnetic spintronics, Nature Physics 14, 242 (2018).
[2] H. Yang, Y. Sun, Y. Zhang, W.-J. Shi, S. S. Parkin, and B. Yan, Topological weyl semimetals in the chiral antiferromagnetic materials Mn₃Ge and Mn₃Sn, New Journal of Physics 19, 015008 (2017).
[3] K. Kuroda, T. Tomita, M.-T. Suzuki, C. Bareille, A. A. Nugroho, P. Goswami, M. Ochi, M. Ikhlas, M. Nakayama, S. Akebi, R. Noguchi, R. Ishii, N. Inami, K. Ono, H. Kumigashira, A. Varykhalov, T. Muro, T. Koretsune, R. Arita, S. Shin, T. Kondo, and S. Nakatsuji, Evidence for magnetic Weyl fermions in a correlated metal, Nature Materials 16, 1090 (2017).
[4] L. Ye, M. Kang, J. Liu, F. von Cube, C. R. Wicker, T. Suzuki, C. Jozwiak, A. Bostwick, E. Rotenberg, D. C. Bell, L. Fu, R. Comin, and J. G. Checkelsky, Massive Dirac fermions in a ferromagnetic kagome metal, Nature 555, 638 (2018).
[5] M. Kang, L. Ye, S. Fang, J.-S. You, A. Levitan, M. Han, J. I. Facio, C. Jozwiak, A. Bostwick, E. Rotenberg, M. K. Chan, R. D. McDonald, D. Graf, K. Kaznatcheev, E. Vescovo, D. C. Bell, E. Kaxiras, J. van den Brink, M. Richter, M. Prasad Ghimire, J. G. Checkelsky, and R. Comin, Dirac fermions and flat bands in the ideal kagome metal Fe₃Sn, Nature Materials 19, 163 (2020).
[6] M. Kang, S. Fang, L. Ye, H. C. Po, J. Denlinger, C. Jozwiak, A. Bostwick, E. Rotenberg, E. Kaxiras, J. G. Checkelsky, and R. Comin, Topological flat bands in frustrated kagome lattice CoSn, Nature Communications 11, 4004 (2020).
[7] J.-X. Yin, S. S. Zhang, G. Chang, Q. Wang, S. S. Tsirkin, Z. Guguchia, B. Lian, H. Zhou, K. Jiang, I. Belopoliski, N. Shumiya, D. Multer, M. Litskevich, T. A. Cochran, H. Lin, Z. Wang, T. Neupert, S. Jia, H. Lei, and M. Z. Hasan, Negative flat band magnetism in a spin-orbit-coupled correlated kagome lattice, Nature Physics 15, 443 (2019).
[8] T. Chen, T. Tomita, S. Minami, M. Fu, T. Koretsune, M. Kitatani, I. Muhammad, D. Nishio-Hamane, R. Ishii, F. Ishii, R. Arita, and S. Nakatsuji, Anomalous transport due to Weyl fermions in the chiral antiferromagnets Mn₃X, X = Sn, Ge, Nature Communications 12, 572 (2021).
[9] L. Fenner, A. Dee, and A. Wills, Non-collinearity and spin frustration in the itinerant kagome ferromagnet Fe₃Sn₂, Journal of Physics: Condensed Matter 21, 452202 (2009).
[10] S. Nakatsuji, N. Kiyohara, and T. Higo, Large anomalous Hall effect in a non-collinear antiferromagnet at room temperature, Nature 527, 212 (2015).
[11] T. Higo, H. Man, D. B. Gopman, L. Wu, T. Koretsune, O. M. van ’t Erve, Y. P. Kabanov, D. Rees, Y. Li, M.-T. Suzuki, S. Patankar, M. Ikhlas, C. L. Chien, R. Arita, R. D. Shull, J. Orenstein, and S. Nakatsuji, Large magneto-optical Kerr effect and imaging of magnetic octupole domains in an antiferromagnetic metal, Nature Photonics 12, 73 (2018).
[12] 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, and Z. Zhang, Observation of Various and Spontaneous Magnetic Skyrmionic Bubbles at Room Temperature in a Frustrated Kagome Magnet with Uniaxial Magnetic Anisotropy, Advanced Materials 29, 1701144 (2017).
[13] Z. Hou, Q. Zhang, G. Xu, S. Zhang, C. Gong, B. Ding, H. Li, F. Xu, Y. Yao, E. Liu, G. Wu, X.-x. Zhang, and W. Wang, Manipulating the Topology of Nanoscale Skyrmion Bubbles by Spatially Geometric Confinement, ACS Nano 13, 922 (2019).
[14] T. Kida, L. A. Fenner, A. A. Dee, I. Terasaki, M. Hagiwara, and A. S. Wills, The giant anomalous Hall effect in the ferromagnet Fe₃Sn—a frustrated kagome metal, J. Phys.: Condens. Matter 23, 112205 (2011).
[15] A. K. Nayak, J. E. Fischer, Y. Sun, B. Yan, J. Karel, A. C. Komarek, C. Shekhar, N. Kumar, W. Schnelle, J. Kübler, C. Felser, and S. S. P. Parkin, Large anomalous Hall effect driven by a nonvanishing Berry curvature in the noncolinear antiferromagnet Mn₃Ge, Science Advances 2, e1501870 (2016).
[16] A. Markou, J. M. Taylor, A. Kalache, P. Werner, S. S. P. Parkin, and C. Felser, Noncollinear antiferromagnetic Mn₃Sn films, Phys. Rev. Materials 2, 051001 (2018).
[17] H. Inoue, M. Han, L. Ye, T. Suzuki, and J. G. Checkelsky, Molecular beam epitaxy growth of antiferromagnetic Kagome metal FeSn, Appl. Phys. Lett. 115, 072403 (2019).
[18] J. M. Taylor, A. Markou, E. Lesne, P. K. Sivakumar, C. Luo, F. Radu, P. Werner, C. Felser, and S. S. P.
Parkin, Anomalous and topological Hall effects in epitaxial thin films of the noncollinear antiferromagnet Mn$_3$Sn, Phys. Rev. B 101, 094404 (2020).

[19] D. Khadka, T. R. Thapaliya, S. Hurtado Parra, J. Wen, R. Need, J. M. Kikkawa, and S. X. Huang, Anomalous Hall and Nernst effects in epitaxial films of topological kagome magnet Fe$_3$Sn$_2$, Phys. Rev. Materials 4, 084203 (2020).

[20] D. Hong, C. Liu, H.-W. Hsiao, D. Jin, J. E. Pearson, J.-M. Zuo, and A. Bhattacharya, Molecular beam epitaxy of the magnetic kagome metal FeSn on LaAlO$_3$(111), AIP Advances 10, 105017 (2020).

[21] H. Giefers and M. Nicol, High pressure X-ray diffraction study of all Fe–Sn intermetallic compounds and one Fe–Sn solid solution, Journal of Alloys and Compounds 422, 132 (2006).

[22] B. Wang, P.-k. Wu, N. Bagués Salguero, Q. Zheng, J. Yan, M. Randeria, and D. W. McComb, Stimulated nucleation of skyrmions in a centrosymmetric magnet, ACS nano 15, 13495 (2021).

[23] T. Kida, L. Fenner, A. Dee, I. Terasaki, M. Hagiwara, and A. Wills, The giant anomalous hall effect in the ferromagnet Fe$_3$Sn$_2$—a frustrated kagome metal, Journal of Physics: Condensed Matter 23, 112205 (2011).

[24] M. Weiler, M. Althammer, F. D. Czeschka, H. Huebl, M. S. Wagner, M. Opel, I.-M. Imort, G. Reiss, A. Thomas, R. Gross, and S. T. B. Goennenwein, Local Charge and Spin Currents in Magnetothermal Landscapes, Phys. Rev. Lett. 108, 106602 (2012).

[25] I. Gray, T. Moriyama, N. Sivadas, G. M. Stiehl, J. T. Heron, R. Need, B. J. Kirby, D. H. Low, K. C. Nowack, D. G. Schlom, D. C. Ralph, T. Ono, and G. D. Fuchs, Spin Seebeck Imaging of Spin-Torque Switching in Antiferromagnetic Pt/ NiO Heterostructures, Phys. Rev. X 9, 041016 (2019).

[26] H. Reichlova, T. Janda, J. Godinho, A. Markou, D. Kriegner, R. Schlitz, J. Zelezny, Z. Soban, M. Bejarano, H. Schultheiss, P. Nemec, T. Jungwirth, C. Felser, J. Wunderlich, and S. T. B. Goennenwein, Imaging and writing magnetic domains in the non-collinear antiferromagnet Mn$_3$Sn, Nature Communications 10, 5459 (2019).