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Magnetic compensation in math

$$\frac{M_n}{M_x} = \frac{C_x}{C_u} \frac{N}{C_x}$$

films on
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$$\text{SrTiO}_3(001)$$
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Phys. Rev. Materials **8**, L091403 — Published 25 September 2024

DOI: [10.1103/PhysRevMaterials.8.L091403](https://doi.org/10.1103/PhysRevMaterials.8.L091403)

Magnetic compensation in $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ films on $\text{SrTiO}_3(001)$ with noncollinear magnetic structures

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We present that $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ films grown by molecular beam epitaxy on $\text{SrTiO}_3(001)$ have a magnetic compensation (MC) composition with noncollinear magnetic components at room temperature. Due to the high crystalline quality and perpendicular magnetic anisotropy, the remanent magnetization ratio was almost 100% for $x \leq 0.6$. At $0.10 \leq x \leq 0.15$, the saturation magnetization was the smallest, while the coercivity was the largest. The hysteresis curves obtained by both the magneto-optical Kerr effect and the anomalous Hall effect showed sign reversal between $x = 0.1$ and 0.15 . X-ray magnetic circular dichroism (XMCD) spectra at the Cu $L_{2,3}$ edges also showed sign reversal over the entire energy range. These results provide evidence that the MC composition is in the vicinity of $x \sim 0.1$. However, the XMCD spectra at the Mn $L_{2,3}$ edges showed a different magnetic structure change from that of Ni-doped Mn_4N , which also exhibits MC. A magnetic structure model for $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ is discussed in comparison with the experimental results.

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Data availability statements

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ferrimagnets have attracted attention as materials for low-power consumption spintronics devices [1]. In some ferrimagnets, total magnetization and angular momentum can be reduced to zero by controlling temperature or composition. These phenomena are called magnetic compensation (MC) and angular momentum compensation (AC), respectively. Near the MC and AC points, attractive properties such as highly efficient current-induced magnetization switching [2], fast current-driven magnetic domain wall motion [3-6], suppression of the skyrmion Hall effect [7], terahertz oscillation [8,9], and anomalous Nernst effect [10-12] have been observed. Such compensations are achieved by controlling the composition ratio of the constituent elements and adjusting the temperature. We have focused on achieving compensations, especially at room temperature (RT) in Mn_4N -based ferrimagnets [13-20].

Mn_4N has an anti-perovskite structure (Fig. 1(a)) with a lattice constant of 0.384–0.388 nm in both bulk and thin-film crystals [21-30]. Bulk polycrystalline Mn_4N has a cubic anti-perovskite structure with the space group of $Pm\bar{3}m$. This material exhibits ferrimagnetism with a frustrated and noncollinear magnetic component, which originates from the coexistence of antiferromagnetic and ferromagnetic coupling due to exchange interactions between Mn atoms and N-mediated super-exchange interactions, respectively [29,31,32]. The easy axis of magnetization is in the [111] direction, its Curie temperature, T_c , is as high as 730–780 K [23,33], and no MC temperature exists. On the other hand, Mn_4N epitaxial films have a tetragonal structure with an out-of-plane lattice constant (c) to in-plane lattice constant (a) ratio, c/a , ~ 0.99 (space group: $P4/mmm$) due to in-plane tensile strain, causing the easy axis of magnetization in the [001] direction [26-28]. Although several magnetic structures including type A and type B (Fig. 1(b)) have been proposed for tetragonal Mn_4N [29,30], no model exists to explain all the magnetic and transport properties. Therefore, experimentally prepared Mn_4N thin films may contain multiple structures. Mn_4N films exhibit a saturation magnetization of $M_s \sim 80 \text{ kA m}^{-1}$ and perpendicular magnetic anisotropy (PMA) of a magnetic anisotropy energy $K_u \sim 10^5 \text{ J m}^{-3}$ [26-28]. Thanks to these properties, fast domain wall motion of 900 m s^{-1} has been achieved at RT using spin transfer torques (STTs) alone [34]. Furthermore, the MC composition, x_{MC} , of the $\text{Mn}_{4-x}\text{A}_x\text{N}$ films ($\text{A} = \text{Co}$ or Ni) was confirmed by the sign reversal of the anomalous Hall effect (AHE) loops and x-ray magnetic circular dichroism (XMCD) spectra across the x_{MC} [13,14]. Using $\text{Mn}_{4-x}\text{Ni}_x\text{N}$ films around $x_{\text{MC}} \sim 0.20$, STT-driven ultrafast domain wall motion reaching $3,000 \text{ m s}^{-1}$ was demonstrated at RT [5].

In this study, we focus on $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ as another potential candidate to have x_{MC} at RT. Mn_3CuN has a tetragonal structure (space group: $P4/mmm$) with $c/a < 1$ at low temperatures

(<143 K) and shows ferromagnetism with non-collinear magnetic moments (Fig. 1(c)) [35]. Negative thermal expansion, magnetostriction, and magnetocaloric effect have been reported for $\text{Mn}_3\text{Cu}_{1-x}\text{Al}_x\text{N}$ [34-37]. Magnetic and magneto-transport properties of Mn_3CuN epitaxial films prepared by pulsed laser deposition [38], sputtering [39-41], and molecular beam epitaxy (MBE) [42], have also been reported. In addition, R. Zhang *et al.* reported a suggested MC composition of $x_{\text{MC}} \sim 0.22$ at $T = 4$ K for bulk $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ [33]. Furthermore, at $x = 0.26$, the T_c without MC temperature is as high as 650 K, implying stability against temperature fluctuations. However, there have been few reports on $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ thin films for $x < 1.0$, and the MC composition is unknown. This is the motivation to investigate the magnetic properties of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ epitaxial films.

$\text{Mn}_{4-x}\text{Cu}_x\text{N}$ (10–25 nm) films were formed on $\text{SrTiO}_3(001)$ substrates with a lattice mismatch of -0.1 – -0.4 % by MBE. After $\text{SrTiO}_3(001)$ substrates were washed with organic solvents and etched with buffered HF (NH_4F : 36 wt%, HF: 5 wt%) for 30–50 s to expose atomically flat and TiO_2 -terminated (001) surfaces [43], Mn and Cu sources (manufactured by Furuuchi chemical corporation, Japan) of 99.99% purity were deposited from conventional Knudsen cells (K-cells). N_2 was simultaneously supplied from a radio-frequency plasma gun. The N_2 flow rate was 1.0 sccm, and the power was 132 W. The substrate temperature was set at 450 °C and the chamber pressure was about 4.8×10^{-3} Pa. The composition x in $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ was controlled by the crucible temperature of each K-cell. $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ layers were capped with SiO_2 by sputtering to prevent oxidation. The film thicknesses were checked by x-ray reflectometry using SmartLab and GlobalFit software (Rigaku Corporation, Japan), exhibited in Tables S1 and S2 in the Supplemental Material [44]. Crystalline properties were characterized by reflection high-energy electron diffraction (RHEED) using a 20 keV electron beam and x-ray diffraction (XRD) using Cu $K\alpha$ radiation. Magnetic properties were measured using a vibrating sample magnetometer (VSM, TM-VSM2106-HGC, Tamakawa Co. Ltd., Japan) with a maximum field of 1.2 T at RT. Since the magnetizations of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ films were small, 1,500–2,000 plots were integrated at each field. Magneto-optical Kerr effect (MOKE) curves were measured using a polar MOKE microscope (BH-786IP-NM, NEOARK Corporation, Japan). The AHE loops were acquired with a physical properties measurement system (PPMS, Quantum Design, Inc., US). The electrodes were arranged in a Van der Pauw geometry. X-ray absorption spectroscopy (XAS) and x-ray magnetic circular dichroism (XMCD) measurements were performed at beamline BL-16A of KEK-PF, Japan [58]. During the measurements, a magnetic field of 5 T and circularly polarized soft x-rays were incident at an angle of 55° with respect to the sample normal [59]. XMCD spectra were obtained by a

single scan with two undulators, switching between left and right polarizations at 10 Hz. The spectra at the Mn $L_{2,3}$ absorption edges were measured in circular polarization mode by the total electron yield method. The measurements were repeated four times by changing the direction of the magnetic field generated by each undulator and the sign of the circular polarization, and the results were integrated to cancel out the background. On the other hand, the spectra at the Cu $L_{2,3}$ absorption edges were acquired in the elliptical polarization mode by the fluorescence yield method to increase the intensity of signals. The results of the eight repeated measurements were integrated in the same manner as for the Mn- $L_{2,3}$ measurement. The degree of the polarization for circular and elliptical modes were estimated to be 90% and 80%, respectively.

Figures 2 show the results of the crystalline characterization for 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ ($x = 0.0, 0.5$, and 1.0). In the RHEED images of Fig. 2(a), sharp RHEED streaks taken along the $[100]$ and $[110]$ azimuths and the Kikuchi lines suggest well-ordered atoms of the $\text{Mn}_{4-x}\text{Cu}_x\text{N}$. The ω - 2θ XRD profiles (Fig. 2(b)) show $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ 002 and 004 reflections as well as Laue oscillations due to the smooth surface and interface. The full width at the half maximum (FWHM) values of the ω -rocking curve XRD for these peaks were less than 0.05° (See Figs. S1, S2, and Table S3 in Supplemental Material [44] for detailed characterizations of the grown films). These FWHM values indicate that the degradation of crystal quality with increasing Cu content is negligible, and the films are homogeneous and of high quality. Figure 2(c) shows the x -dependent out-of-plane lattice constant c with error bars. The lattice constant of Mn_3CuN ($x = 1.0$) on $\text{STO}(001)$ was slightly larger than that on $\text{MgO}(001)$ ($c \sim 0.388$ nm) and smaller than that of bulk Mn_3CuN ($a \sim 0.391$ nm). The c/a was smaller than 1, assuming that in-plane lattice constant, a was fixed as 0.3905 nm by the substrate.

Figures 3 show the magnetic properties of 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ measured with VSM. At $x = 0.1$, the M_s was the smallest (Fig. 3(a)) and the coercivity H_c was the largest (Fig. 3(b)). These are the general characteristics found near the MC point. The measured results are generally consistent with the results of linear function fitting (blue broken line) for M_s up to $x = 0.15$, suggesting that the MC composition x_{MC} is in the range $0.10 \leq x_{\text{MC}} \leq 0.15$ at RT. Assuming that K_u is constant around x_{MC} and governs the coercivity so that $H_c \propto H_k$ (H_k : anisotropic magnetic field), the following equation holds,

$$K_u = \frac{\mu_0}{2} M_s(x) H_k = k(x - x_{\text{MC}}) H_c = \text{const.} \quad (1)$$

$$H_c = \frac{k}{x - x_{\text{MC}}}. \quad (2)$$

Here, μ_0 is the vacuum magnetic permeability, and k is a constant. The fitting of the H_c - x plots

(red broken line) using Eq. (2) is also in good agreement. At $x \geq 0.2$, the reason for the gradual deviation in fitting results was suggested to be the decrease in M_s , K_u , and T_c due to the change of the magnetic structure. The remanence ratio in Fig 3(c) is calculated as M_r/M_s . The remanence magnetization M_r is the absolute value of the magnetization at a field of 0 T. This ratio shows a decrease at x near the MC composition, originating from the canting magnetic moments. For other samples up to $x = 0.6$, the remanence ratio remained almost 1.0 as a result of high crystallinity and PMA. On the other hand, at $x \sim 0.8$, it became almost zero as a result of T_c being below RT (see Fig. S4 in Supplemental Material [44] for magnetization curves of the other samples).

Figures 4 show the magnetization, MOKE, and AHE loops measured for 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ films ($x = 0.00, 0.10$, and 0.15). The magnetization curves of the samples with the composition close to x_{MC} showed kinks around zero fields. They are indicative of canting magnetic moments in the films. A sign reversal was observed between $x = 0.10$ and 0.15 in the MOKE and AHE magnetization curves. Such sign reversals are also observed near the MC point in other ferrimagnetic materials, suggesting the presence of x_{MC} . For coercivity, the sample with $x = 0.15$ shows the maximum value. Thus, x_{MC} is in this neighborhood. In addition, the remanence of the AHE curve was almost 1, suggesting that there was no degradation of magnetic properties near x_{MC} .

Figures 5(a)–5(e) show the XAS and XMCD spectra of 24-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ measured at the Mn and Cu $L_{2,3}$ absorption edges. These samples show similar properties of 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ discussed thus far. (See sections S6 and S7 for 24-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ layers in Supplemental Material [44]). The XAS spectra at the Mn $L_{2,3}$ edges shown in the upper panels of Figs. 5(a) and 5(b) are almost the same, revealing that the electronic states of Mn atoms remained almost unchanged. This is consistent with those in previous studies [18-20]. The satellite peaks at 642.4 eV and 644.7 eV and the split peaks at the L_2 edges are theoretically predicted in spherically symmetric $O(3)$ Mn with a crystal field splitting of $10Dq = 0$ eV rather than octahedrally symmetric O_h with $10Dq = 1$ eV [60]. Similar peaks were observed in metallic Mn on Cu(001) [61]. It has also been reported that the satellite peaks are due to Mn $3d$ -N $2p$ hybridization and oxidation of Mn [15]. The XMCD spectra of the Mn edges shown in the lower panels of Figs. 5(a) and 5(b) show a large variation with composition x , indicating a change in magnetic structure due to Cu addition. The change is not similar to that in $\text{Mn}_{4-x}\text{A}_x\text{N}$ ($\text{A} = \text{Ni}$ and Co) [13,14], which has MC compositions at RT, but is similar to that in $\text{Mn}_{4-x}\text{Z}_x\text{N}$ ($\text{Z} = \text{In}$, Au , and Ga) [16,19,20]. This means that the magnetic moments of Mn projected onto the quantization axis are ferromagnetically aligned in 5 T fields by the Cu addition. Figure 5(c)

shows a magnified view of the L_3 edges of XAS and XMCD spectra at $x = 0.0, 0.09$, and 0.15 . The peaks seen in the XMCD spectra for the $x = 0.0$ sample consist mainly of two peaks. The negative sharp peak α on the lower energy side is a peak originating from the localized electrons of Mn(i) located at the corners with magnetic moments parallel to the magnetization. The positive broad peak β on the higher energy side is a peak originating from itinerant electrons of face-centered Mn(ii) with magnetic moments antiparallel to the magnetization [15]. At $x = 0.09$ and 0.15 , the XMCD intensities decay sharply compared to $x = 0.0$, suggesting that the overall magnetic moments cancel each other out. The negative peak is also shifted to the higher energy side. For $x = 0.15$, the position of the negative peak was almost the same as that of Mn_3CuN consisting only of face-centered Mn(ii) [62,63]. Therefore, the peak shift of the negative peak indicates that the contribution of the magnetic moment of Mn(i) sublattice to the XMCD spectrum was weakened by Cu doping, possibly because Cu displaces Mn(i) and the magnetic moment of Mn(i) was changed antiparallel to each other.

Figures 5(d) and 5(e) show XAS and XMCD spectra at the Cu $L_{2,3}$ edge. The step backgrounds were determined using the calculations in the previous report [63]. The XAS spectra in the upper panels did not change with composition x . The satellite peaks shown in the green regions are also observed in the metallic Cu [64]. The XMCD spectra in the lower panels show peaks, although the profiles were noisy due to their low concentration; their sign reversal observed between $x = 0.09$ and 0.15 is similar to those observed in XMCD spectra for both Co and Ni added to Mn_4N films [13,14]. However, the magnitude of the magnetic moment of Cu is small and therefore contributes little to the overall magnetization, according to the results of the sum rule calculation (See section S8 in Supplemental Material [44]). It is noted that the sign of Cu L_3 peak in the XMCD spectrum at the $x = 0.09$ ($< x_{\text{MC}}$) sample in Fig. 5(d) is different from that of peak α for Mn_4N , but is the same as that at $x = 0.15$ (Fig. 5(c)). This means that the magnetic moment of Cu(i) at $x = 0.09$ ($x = 0.15$) is antiparallel (parallel) to the magnetization. Based on these results, we consider the magnetic structure of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ as shown in Figs. 5(f) and 5(g). In $\text{Mn}_{4-x}\text{Cu}_x\text{N}$, the corner-site Cu(i) induces ferromagnetic coupling with neighboring Mn(i) atoms. This is the same as in Mn_3CuN [31]. For $x < x_{\text{MC}}$, the contribution of the Mn(i) sublattice to magnetization decreases as x increases toward x_{MC} . Therefore, Mn(ii), not Mn(i), becomes the dominant contribution to magnetization although the magnetic moment of the Mn(ii) sublattice is small due to the canting magnetic moment. At $x = 0.15$, which is a little greater than x_{MC} , the magnetic moment of Mn(i) almost cancels out, and the magnetic moment of Cu(i) becomes parallel to the magnetization. Since the sign of the XMCD spectrum at the L_3 edge for the $x = 0.15$ sample is the same as that of peak α in Fig. 5(c), the magnetic moment of

the Mn(ii) sublattice is considered parallel to the magnetization. The above consideration can explain the presence of MC and the change in the XMCD spectra in the experiment. This model suggests that MC compositions may also exist in $\text{Mn}_{4-x}\text{Z}_x\text{N}$ ($\text{Z} = \text{In, Au, and Ga}$) [16,19,20], whose XMCD spectra suggested that the magnetic moments of Mn(i) and Mn(ii) are parallel. However, quantitative details such as the magnitude of each moment and the degree of canting require further experiments and calculations.

In conclusion, we have determined the MC composition of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ films at room temperature: $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ ($x \leq 1.0$) films grown by MBE were epitaxially grown on $\text{SrTiO}_3(001)$ substrates and were confirmed by RHEED and XRD profiles. Magnetic characterization revealed a minimum value of magnetization and a maximum value of coercivity in the range of $0.1 \leq x \leq 0.15$. The sign reversal of the MOKE, AHE, and XMCD spectra at the Cu $L_{2,3}$ edges indicates that MC occurs. Furthermore, XMCD at the Mn $L_{2,3}$ edge suggests a change in magnetic structure, which is different from previous reports on MC in collinear ferrimagnetism such as $\text{Mn}_{4-x}\text{A}_x\text{N}$ ($\text{A} = \text{Ni and Co}$). We found that the change in XMCD at the Mn $L_{2,3}$ edge can be qualitatively explained by a change in the local magnetic moment around Cu(i) located at the corner. The $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ thin films obtained in this study, which exhibit MC composition $x_{\text{MC}} \sim 0.1$, are very useful materials for spintronics applications such as high-efficiency current-driven magnetic wall motion, terahertz spin-torque oscillations, and magnetocaloric effects with stable small magnetization.

Acknowledgments

This work was financially supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI (Grant Nos. JP19KK0104 and JP21H04548). T.Y. acknowledges support from Support for Pioneering Initiated by the Next Generation (SPRING) program by the Japan Science and Technology Agency (JST) (JPMJSP2124). The XAS and XMCD measurements were performed at BL-16A of KEK-PF with the approval of the Photon Factory Program Advisory Committee (Proposal No. 2022G036). The magnetic properties obtained by using a VSM and the AHE measurements using a physical properties measurement system were measured with the help of Professor H. Yanagihara and Mr. T. Takahashi of the University of Tsukuba. The measurements using a polar MOKE microscopy were performed with the help of Dr. S. Mitani of the National Institute for Materials Science, Tsukuba, Japan. This work was supported by “Advanced Research Infrastructure for Materials and Nanotechnology in Japan (ARIM)” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) (JPMXP1224BA0012).

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[44] See Supplemental Material at ****, for more information on the thickness of the grown layers; film properties from RHEED and XRD patterns, magnetization curves at RT for 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$, MOKE curves at RT, AHE loops at various temperatures, and results of XAS and XMCD analysis for 24-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$. The Supplemental Material also contains Refs. [45-57].

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Figure captions

Figures 1.

(a) Crystal structure of anti-perovskite nitride. (b) Ferrimagnetic structure of tetragonal Mn_4N film. (c) Noncollinear ferromagnetic structure of tetragonal Mn_3CuN [35]. Brown and blue arrows are magnetic moments of each atom. The lower views in (b) and (c) are the top views of the structures shown above.

Figures 2.

(a) RHEED images along the $[100]$ and $[110]$ azimuths for 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ with $x = 0.0, 0.5$ and 1.0 . (b) Out-of-plane XRD profiles measured with Cu $K\alpha$ radiation around STO 002 and 004 reflection peaks. Blue triangles show the position of the $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ reflection peaks. (c) Out-of-plane lattice constants of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ calculated from the peak position of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ 004 reflection peaks in ω - 2θ XRD profiles. Error bars exhibit variation derived from the resolution of the X-ray. Dotted line is the result of the linear fitting.

Figures 3.

Magnetic properties of 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ measured with VSM at RT. Cu composition dependences of (a) saturation magnetization M_s , (b) coercivity H_c , and (c) remanence ratio M_r/M_s . Red and blue broken lines are the fitting results for $x \leq 0.15$.

Figures 4.

(a) Magnetization, (b) MOKE, and (c) AHE loops of 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ at RT for $x = 0.00, 0.10$ and 0.15 . Brown and black symbols and lines are the data for the increasing and decreasing fields, respectively.

Figures 5.

XAS and XMCD spectra at the Mn $L_{2,3}$ edges for samples of (a) $x = 0.09$ and (b) 0.15 . (c) Magnified spectra for the Mn L_3 edge for samples of $x = 0.00$ (black), 0.09 (red), and 0.15 (blue). XAS and XMCD spectra at the Cu $L_{2,3}$ edges for samples of (a) $x = 0.09$ and (b) 0.15 . Dotted lines with XAS spectra are step backgrounds. Magnetic structure model of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ for (f) $x \leq x_{\text{MC}}$ and (g) $x \geq x_{\text{MC}}$. Blue and brown arrows represent the magnetic moment of each atom.

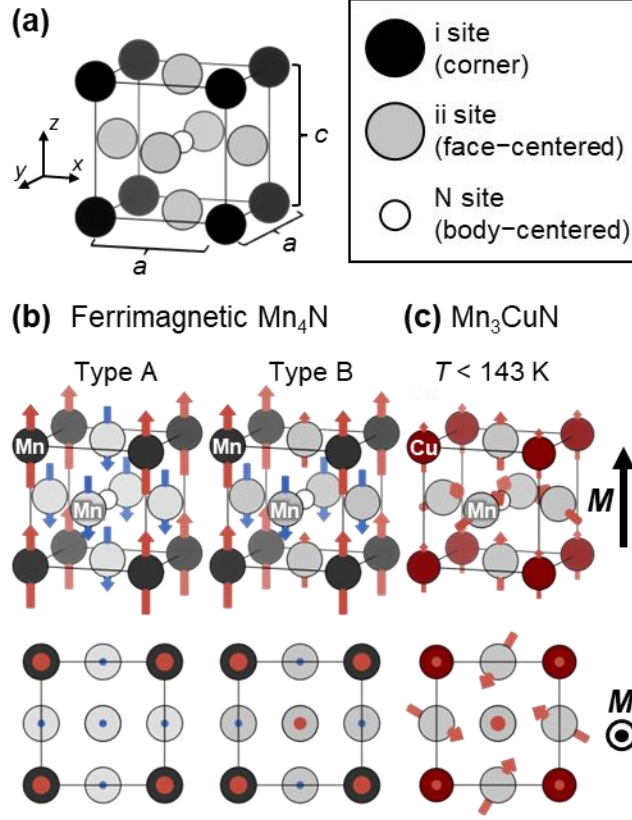


FIG. 1. (a) Crystal structure of anti-perovskite nitride. (b) Ferrimagnetic structure of tetragonal Mn_4N film. (c) Noncollinear ferromagnetic structure of tetragonal Mn_3CuN .³² Red and blue arrows are magnetic moments of each atom. The lower views in (b) and (c) are the top views of the structures shown above.

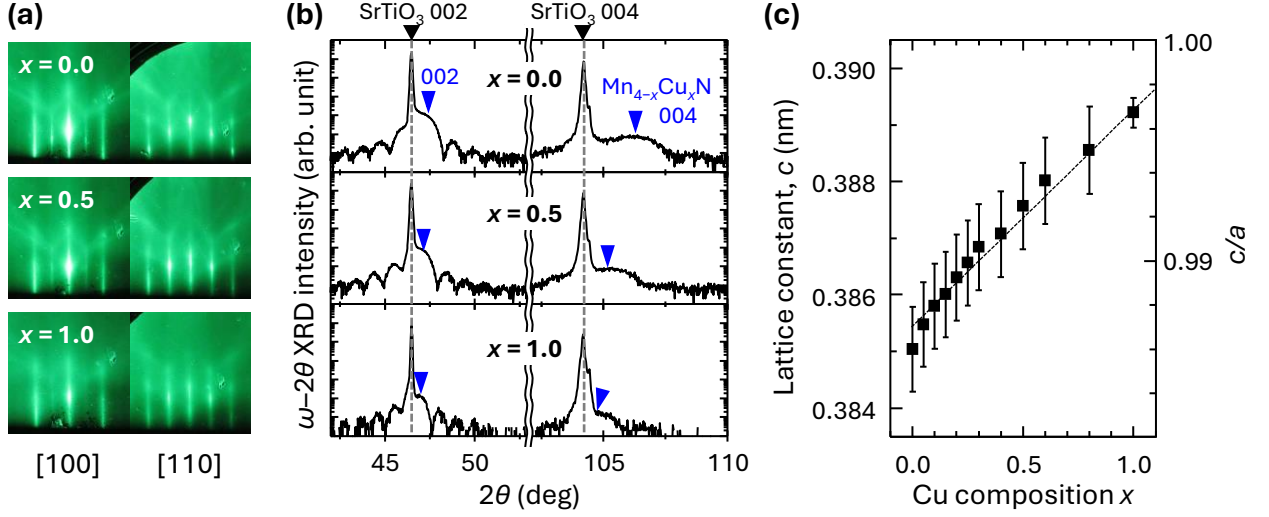


FIG. 2. (a) RHEED images along the [100] and [110] azimuths for $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ with $x = 0.0, 0.5$ and 1.0 . (b) Out-of-plane XRD profiles measured with Cu $K\alpha$ radiation around STO 002 and 004 reflection peaks. Blue triangles show the position of the $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ reflection peaks. (c) Out-of-plane lattice constants of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ calculated from the peak position of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ 004 reflection peaks in $\omega-2\theta$ XRD profiles. Error bars exhibit variation derived from the resolution of the X-ray. Dotted line is the result of the linear fitting.

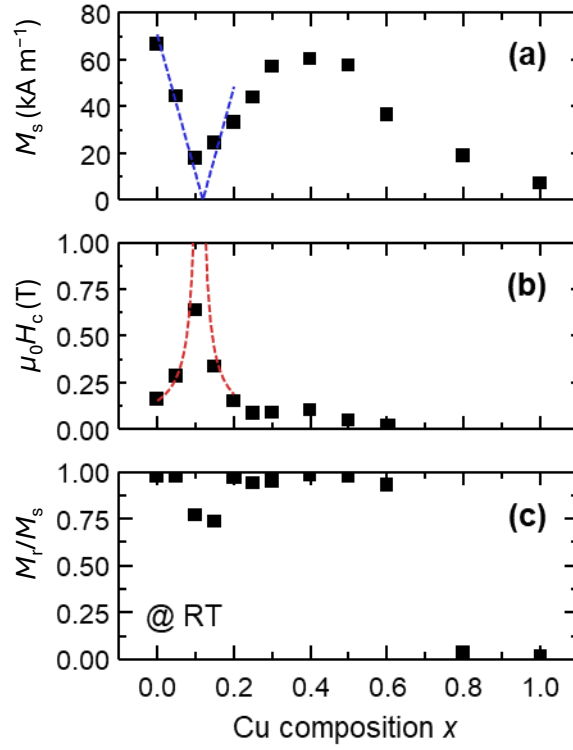


FIG. 3. Magnetic properties of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ measured with VSM at RT. Cu composition dependences of (a) saturation magnetization M_s , (b) coercivity H_c , and (c) remanence ratio M_r/M_s . Red and blue broken line are the fitting results for $x \leq 0.15$.

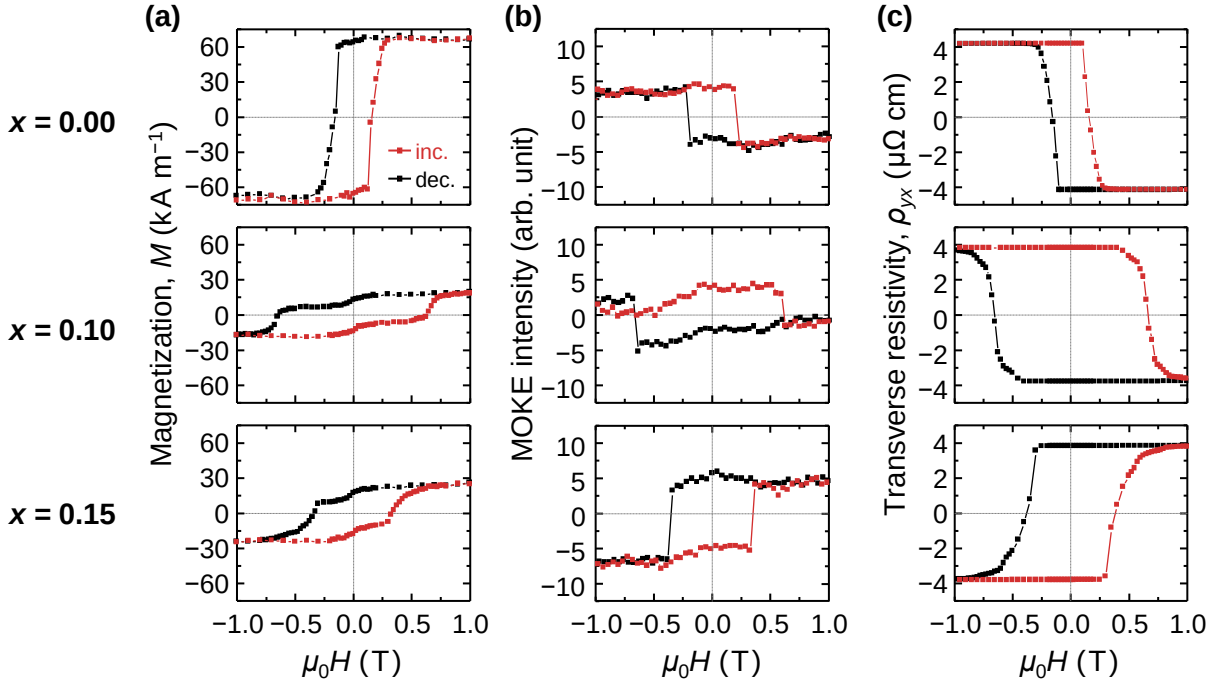


FIG. 4. (a) Magnetization, (b) MOKE, and (c) AHE loops of 10-nm-thick $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ at RT for $x = 0.00, 0.10$ and 0.15 . Brown and black symbols and lines are the data for increasing and decreasing fields, respectively.

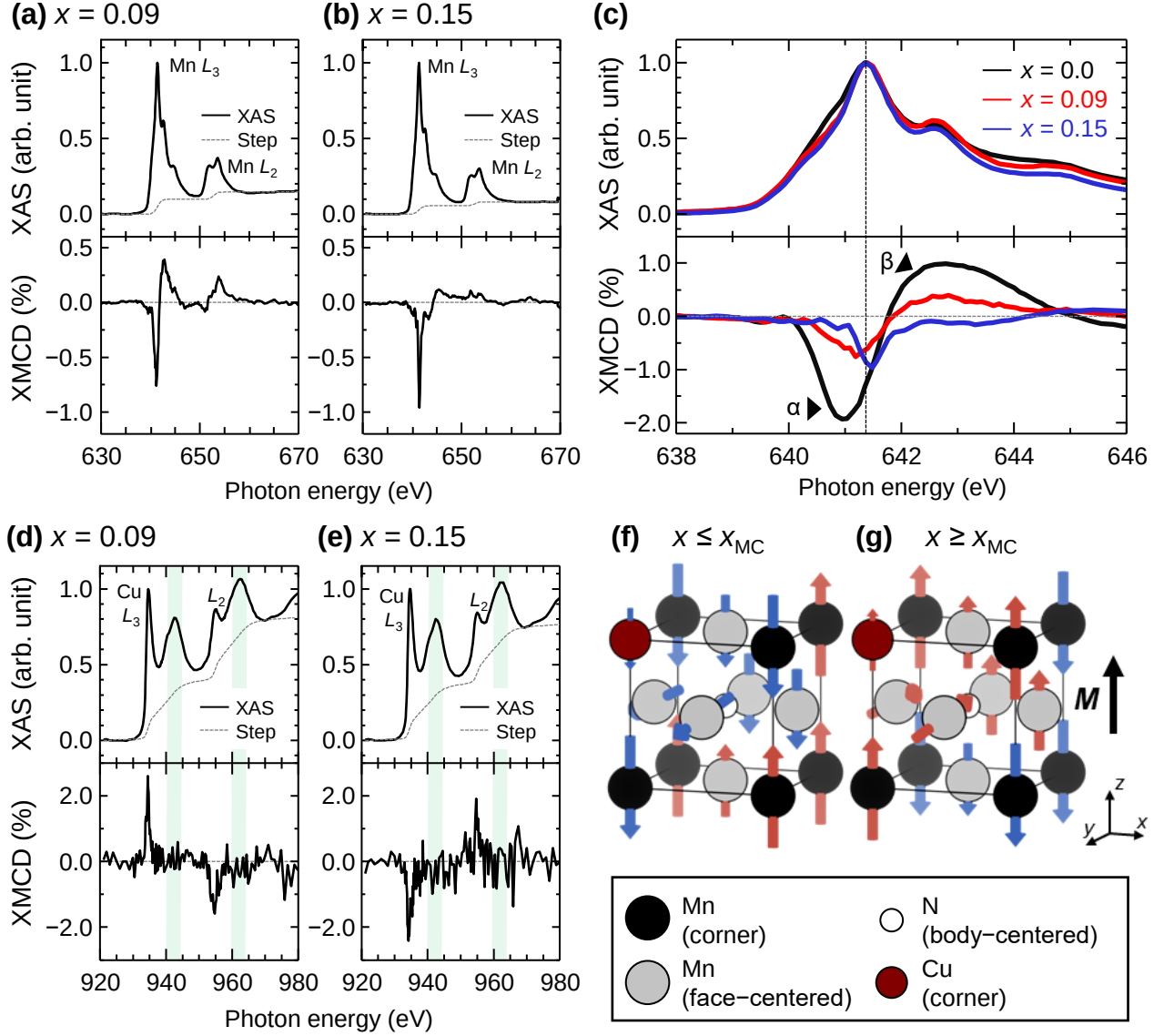


FIG. 5. XAS and XMCD spectra at the Mn $L_{2,3}$ edges for samples of (a) $x = 0.09$ and (b) 0.15. (c) Magnified spectra for the Mn L_3 edge for samples of $x = 0.00$ (black), 0.09 (red), and 0.15 (blue). XAS and XMCD spectra at the Cu $L_{2,3}$ edges for samples of (a) $x = 0.09$ and (b) 0.15. Dotted lines with XAS spectra are step backgrounds. Magnetic structure model of $\text{Mn}_{4-x}\text{Cu}_x\text{N}$ for (f) $x \leq x_{\text{MC}}$ and (g) $x \geq x_{\text{MC}}$. Blue and brown arrows represent the magnetic moment of each atom.