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# Magnetic and magneto-transport properties of $\text{Mn}_4\text{N}$ thin films by Ni substitution and their possibility of magnetic compensation

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## ABSTRACT

Ferrimagnets are of interest in spintronics owing to the enhancement of spin transfer and spin-orbit torque in the vicinity of the magnetic compensation point. Here, we study the possibility of achieving compensation at room temperature in  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  films grown on  $\text{SrTiO}_3(001)$  substrates by molecular beam epitaxy. The magnetic and magneto-transport properties of 30-nm-thick epitaxial  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  films ( $x = 0, 0.1, 0.25,$  and  $0.5$ ) were investigated. Ni introduction in  $\text{Mn}_4\text{N}$  causes the spontaneous magnetization ( $M_S$ ) to decrease by 45% at  $x = 0.1$  and by 75% at  $x = 0.25$ . All samples exhibited the perpendicular magnetic anisotropy required for spintronic applications as well as displaying a sharp magnetization reversal. Remarkably, the sign of the anomalous Hall resistivity changed in the samples between  $x = 0.1$  and  $0.25$ . Further, the magnetization increased for  $x = 0$  and  $0.1$  and decreased for  $x = 0.25$  when the temperature was decreased. Based on these results, we propose that there is a magnetic compensation composition between  $x = 0.1$  and  $0.25$ , where the magnetization of  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  becomes zero at room temperature. The small  $M_S$  and perpendicular magnetic anisotropy of the  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  thin films, thus, make them suitable candidates for use in spin transfer torque-based devices.

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## I. INTRODUCTION

The physics of spin torque is based on a transfer of angular momentum to the magnetization to induce its precession or to switch it. The flow of angular momentum is caused by spin-polarized current in the case of spin transfer torques<sup>1,2</sup> or arises from spin-orbit interactions, such as the spin Hall effect or the Edelstein-Rashba effect<sup>3,4</sup> in the case of spin-orbit torques. Magnetization switching is easier if the spontaneous magnetization of the magnetic element is small. This recently triggered a renewal of interest in ferrimagnets to develop fast, high-density, and nonvolatile memory devices, such as racetrack memory,<sup>5,6</sup> domain wall (DW) motion magnetoresistive random access memory,<sup>7</sup> or spin-orbit torques magnetoresistive random access memory.

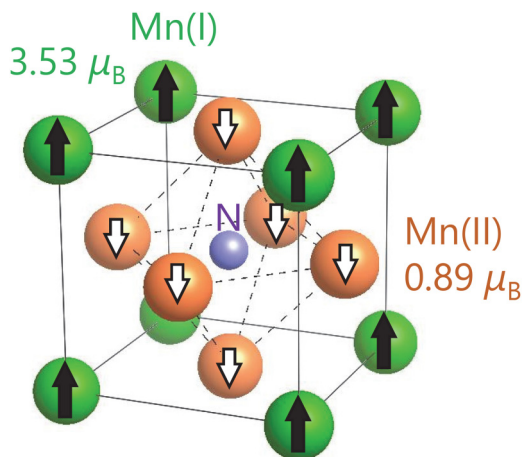
In particular, current-induced DW motion (CIDWM) is faster in antiferromagnetic<sup>8,9</sup> and ferrimagnetic<sup>10,11</sup> materials than in ferromagnetic materials.

To enhance the spin torques in ferrimagnetic materials, it is, thus, necessary to get close to the angular momentum compensation temperature ( $T_A$ ), which can differ from the magnetic compensation temperature ( $T_M$ ).<sup>11,12</sup> In rare-earth-based ferrimagnets, the idea is, thus, to perform the experiments at the compensation temperature  $T_A$ .<sup>13</sup> For instance, the DW velocity ( $v_{DW}$ ) in a  $\text{Gd}_{44}\text{Co}_{56}$  ferrimagnetic nanowire has been reported to reach a record value of 1.3 km/s close to  $T_A$  (260 K).<sup>14</sup> Moreover, many experiments and discussions have also been conducted on the operation of ferrimagnetic materials at  $T_A$  regarding other aspects such

as spin-wave emission,<sup>15</sup> Dzyaloshinskii–Moriya interaction,<sup>16</sup> and maximized exchange coupling torque.<sup>17</sup> In this context, we have paid special attention to ferrimagnetic  $\text{Mn}_4\text{N}$ , which is composed of abundant and inexpensive elements. Recent experiments have shown that epitaxial  $\text{Mn}_4\text{N}$  thin films exhibit a perpendicular magnetization, remarkable magnetic properties within particular millimetric and smooth DWs,<sup>18</sup> and record DW velocities owing to spin transfer torque.<sup>19</sup> As such, we have focused on ferrimagnetic  $\text{Mn}_4\text{N}$  doped with Ni to obtain a material close to magnetic compensation at room temperature (RT). Using neutron diffraction, the magnetic moment of the Mn atoms in bulk cubic  $\text{Mn}_4\text{N}$  was measured and it was found to be  $3.53\mu_B$  at the corner sites (I sites) and  $-0.89\mu_B$  at the face-centered sites (II sites),<sup>20</sup> as shown in Fig. 1, where  $\mu_B$  is the Bohr magneton; the Mn atoms are denoted as Mn(I) and Mn(II), respectively. The easy magnetization axis of bulk  $\text{Mn}_4\text{N}$  is in the [111] direction.<sup>21</sup> In contrast, for thin films, the ratios of the perpendicular lattice constant  $c$  to the in-plane lattice constant  $a$ ,  $c/a$ , were found to be  $\sim 0.99$ , regardless of the lattice mismatch to various substrates,<sup>22–24</sup> and the samples exhibited perpendicular magnetic anisotropy (PMA) large enough to obtain an easy magnetization axis along the [001] direction. The uniaxial magnetic anisotropy constant ( $K_u$ ) of  $\text{Mn}_4\text{N}$  thin films has been reported to be  $\sim 10^5 \text{ J/m}^3$ .<sup>25–28</sup> Materials with PMA generally have Bloch DWs, which contribute to faster DW motion with small current.<sup>28</sup> The width of the DW ( $\Delta$ ) in the nanowire is given by Eq. (1),<sup>29</sup>

$$\Delta = \sqrt{\frac{A}{K_u}}, \quad (1)$$

where  $A$  is the exchange stiffness. As  $K_u$  increases,  $\Delta$  decreases, leading to the reduction in the threshold current density ( $j_{th}$ ) necessary to move the DWs. This behavior occurs because the energy required to cause a precession of magnetic moments in the DW is determined by the difference in energy between the Bloch and the Neel DWs, which is proportional to  $\Delta$ .<sup>28,30</sup> In this respect, materials



**FIG. 1.** Crystal structure of antiperovskite-type  $\text{Mn}_4\text{N}$ . The magnetic moment of corner-site Mn atoms, Mn(I), is antiparallel to that of face-centered Mn atoms, Mn(II).

with PMA are advantageous for CIDWM devices. Furthermore,  $\text{Mn}_4\text{N}$  thin films have been reported to have a relatively small  $M_S$  of  $\sim 100 \text{ kA/m}$ .<sup>20,25,26</sup> The drift velocity  $u$  of DWs submitted to spin polarized currents is given by<sup>31</sup>

$$u = \frac{Pg\mu_B}{2eM_S} J, \quad (2)$$

where  $P$  is the spin polarization of the electrical conductivity,  $g$  is the  $g$  factor,  $e$  is the elemental charge, and  $J$  is the current density. When  $|J|$  is large, we can approximate  $v_{DW}$  to be close to  $|u|$ . Because  $|u|$  is inversely proportional to  $M_S$ , a smaller  $M_S$  should produce faster DW motion and a lower threshold current.<sup>10</sup> Small values of  $M_S$  have been reported for  $\text{Mn}_4\text{N}$  thin films grown on glass,<sup>32</sup> Si(001),<sup>33</sup> MgO(001),<sup>22,24,26,34,35</sup> and SrTiO<sub>3</sub> (STO)(001)<sup>22,23</sup> substrates. Indeed, we achieved a  $v_{DW}$  of  $900 \text{ m/s}$  at  $j = 1.2 \times 10^{12} \text{ A/m}^2$  for a  $\text{Mn}_4\text{N}$  nanowire grown on STO(001) without applying an external magnetic field.<sup>19</sup>

Substituting other transition metal atoms for Mn atoms in  $\text{Mn}_4\text{N}$  is an effective way of modifying the material's magnetic properties. In previous studies, we grew  $\text{Co}_x\text{Mn}_{4-x}\text{N}$ <sup>23</sup> and  $\text{Fe}_{4-x}\text{Mn}_x\text{N}$ <sup>26</sup> epitaxial thin films by molecular beam epitaxy (MBE) and investigated their crystalline qualities and magnetic properties. The  $M_S$  of these materials changed depending on their composition.<sup>23,26,36</sup> In contrast to what we predicted, however, the  $M_S$  and PMA were drastically decreased in the  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  epitaxial thin films on MgO(001), even when only a small amount of Ni was introduced.<sup>27</sup> The  $M_S$  decreased remarkably from  $86.3 \text{ kA/m}$  ( $\text{Mn}_4\text{N}$ ,  $x=0$ ) to  $24.2 \text{ kA/m}$  ( $x=0.1$ ) and then to  $19.0 \text{ kA/m}$  ( $x=0.25$ ) at RT. At  $x > 0.25$ , the PMA vanished. Therefore, much faster  $v_{DW}$  can be expected in  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  at RT when it is close to the magnetic compensation point.

In the current study, we grew  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  ( $x=0, 0.1, 0.25,$  and  $0.5$ ) epitaxial thin films on STO(001), which has a far smaller lattice mismatch to  $\text{Mn}_4\text{N}$  ( $-0.4\%$ ) than to MgO(001) ( $-7.6\%$ ), and investigated their crystalline qualities and magnetic and magneto-transport properties, which we compared with those of the samples deposited on MgO(001). We also discuss the possibility of magnetic compensation in  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  at RT to assess the use of  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  thin films in spintronic devices.

## II. METHODS

### A. Preparation of $\text{Mn}_{4-x}\text{Ni}_x\text{N}$ thin films

$\text{Mn}_{4-x}\text{Ni}_x\text{N}$  ( $x=0, 0.1, 0.25,$  and  $0.5$ ) thin films were grown on STO(001) substrates in an MBE setup equipped with conventional Knudsen cells for solid sources of Mn and Ni and radio-frequency nitrogen plasma. We chose STO(001) because of its excellent lattice match to  $\text{Mn}_4\text{N}$ , the higher degree of crystal orientation of  $\text{Mn}_4\text{N}$  epitaxial films on STO(001) along the  $c$ -axis compared with on MgO(001), and its extraordinarily large magnetic domains (over  $1 \text{ mm}$  in size).<sup>18</sup> To prepare the STO(001) substrates, we washed them with organic solvents and water and then cleaned them with buffered hydrofluoric acid. This process greatly reduced the surface roughness (the resultant root-mean-squared roughness was  $0.2 - 0.8 \text{ nm}$ ) and formed a stepped surface for epitaxial growth.<sup>37</sup> The deposition rates of Mn and Ni were independently measured and controlled by

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**TABLE I.** Thicknesses of Mn<sub>4-x</sub>Ni<sub>x</sub>N and SiO<sub>2</sub> capping layers.

X	t <sub>sample</sub> (nm)	t <sub>cap</sub> (nm)
0	23.80	3.28
0.1	24.46	3.41
0.25	25.12	3.55
0.5	34.3	2.2

changing the crucible temperature of each Knudsen cell. The calculation was performed by assuming that these rates would not change even if the materials were deposited simultaneously. We set the substrate temperature ( $T_S$ ) during growth at 450 °C.<sup>27</sup> Because the vapor pressures of Mn and Ni are sufficiently low at  $T_S = 450$  °C, re-evaporation of these elements from the substrate was negligible. The radio-frequency plasma power was set at 108 W, and the flow rate of N<sub>2</sub> was set at ~1.0 sccm so that the emission intensity at a wavelength of 336 nm would be around 2900 counts at the spectrometer (QE Pro, Ocean Optics Inc., USA). An approximately 3-nm-thick SiO<sub>2</sub> capping layer was sputtered onto each sample. Table I summarizes the sample preparation details. The thicknesses of the grown layers were measured by X-ray reflectivity.

### B. Evaluation of Mn<sub>4-x</sub>Ni<sub>x</sub>N thin films

The crystalline qualities of the samples were evaluated by reflection high-energy electron diffraction (RHEED), out-of-plane ( $\omega-2\theta$ ) X-ray diffraction (XRD), and in-plane ( $\phi-2\theta_\chi$ ) XRD (Smart Lab, Rigaku Inc, Japan). A Cu-K $\alpha$  radiation source was used for XRD, and Ge(220) single crystals were set to monochromatize the X-ray beam. The magnetization vs magnetic field ( $M-H$ ) loops were measured at RT by a vibrating sample magnetometer (VSM) using  $6 \times 6$  mm<sup>2</sup> samples.  $K_u$  and the effective magnetic anisotropy constant ( $K_u^{\text{eff}}$ ) were calculated from the following equations:

$$K_u = K_u^{\text{eff}} + \frac{\mu_0}{2} M_S^2, \quad (3)$$

$$K_u^{\text{eff}} = \left( \mu_0 \int_0^{M_S} H dm \right)_{\text{hard}} - \left( \mu_0 \int_0^{M_S} H dm \right)_{\text{easy}}, \quad (4)$$

where easy (hard) refers to the easy (hard) magnetization axis. The  $\mu_0 M_S^2/2$  term in Eq. (3) is the demagnetization component.<sup>38</sup> Because the magnetization could not be saturated when the field was applied in the VSM along the hard axis, it was impossible to correctly calculate these constants from the measured  $M-H$  loops. Thus, we used the fact that the loops acquired from the anomalous Hall effect (AHE) measurements (mentioned later) correspond to the  $M-H$  loops measured by VSM. We calculated the subtractions of the loops from the AHE using Eqs. (3) and (4).<sup>39</sup> Additionally, since the Hall voltage is known to be proportional to  $M_\perp/M_S$ , we calculated  $M_\parallel$  using Eq. (5), assuming that the layer is well squared.

$$M_\parallel = M_S \sqrt{1 - \left( \frac{M_\perp}{M_S} \right)^2}. \quad (5)$$

Here,  $M_\parallel$  ( $M_\perp$ ) is the in-plane (vertical) component of the

magnetization. The temperature dependence of the magnetization was measured using a VSM-superconducting quantum interference device (Quantum Design). The field was set to 0.1 T perpendicular to the plane, and the temperature was modulated from 5 to 350 K under field cooling.

AHE measurements were performed with a physical properties measurement system (Quantum Design). To clarify the effect of the substrate, we also characterized Mn<sub>4-x</sub>Ni<sub>x</sub>N ( $x = 0, 0.1, 0.25, \text{ and } 0.5$ ) epitaxial thin films grown on MgO(001). The growth of Mn<sub>4-x</sub>Ni<sub>x</sub>N epitaxial films on MgO(001) and their magnetic properties has been reported in Ref. 27. We used the Van der Pauw method for the AHE measurements, as shown in the inset of Fig. 4(a). The magnetic field was applied from -3 to 3 T perpendicular to the plane and from -9 to 9 T in the in-plane direction.

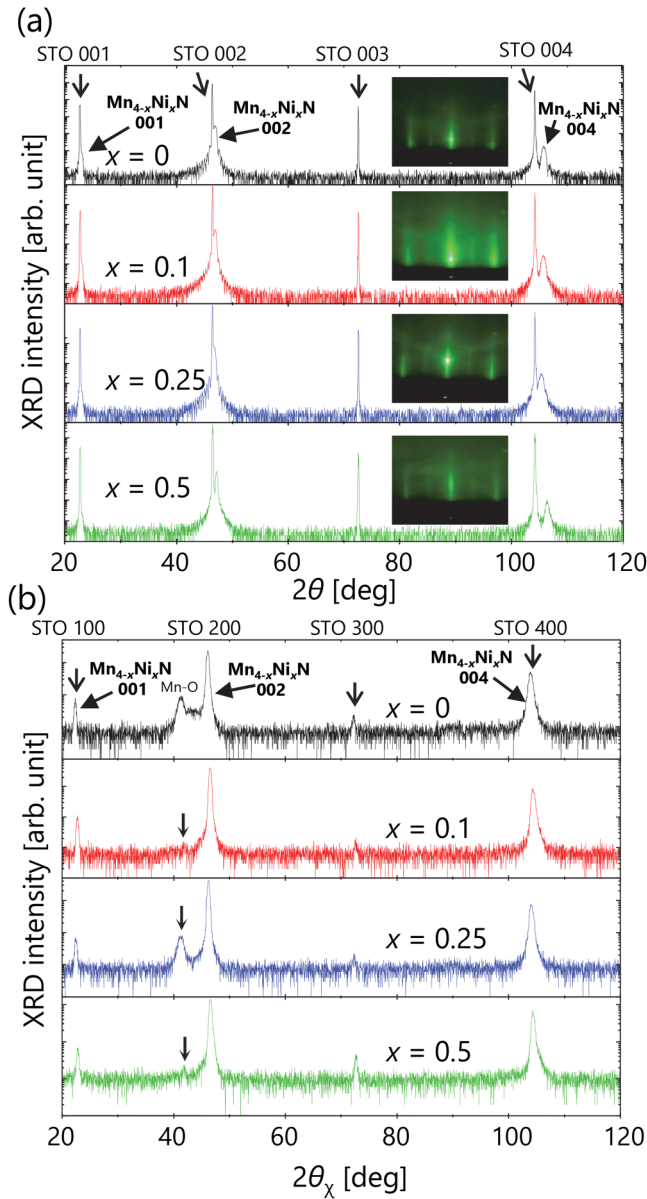
## III. RESULTS AND DISCUSSION

### A. Crystalline qualities and magnetic properties

Figure 2(a) shows the out-of-plane XRD and RHEED patterns of the Mn<sub>4-x</sub>Ni<sub>x</sub>N ( $x = 0, 0.1, 0.25, \text{ and } 0.5$ ) thin films along the STO[100] azimuth, and Fig. 2(b) shows their in-plane XRD patterns. Diffraction peaks of the grown layers appear at small  $2\theta$  angles in Fig. 2(a) and overlap with the intense diffraction peaks of the STO substrate because of the excellent lattice match between the Mn<sub>4-x</sub>Ni<sub>x</sub>N films and the STO(001) substrate. Judging by the presence of diffraction peaks such as 002 and 004 from Mn<sub>4-x</sub>Ni<sub>x</sub>N, we achieved epitaxial growth of Mn<sub>4-x</sub>Ni<sub>x</sub>N thin films on STO(001) substrates. Very sharp, streaky lines appeared in the RHEED patterns, and Kikuchi lines also verified the highly oriented epitaxial growth of the Mn<sub>4-x</sub>Ni<sub>x</sub>N films. From these sharp peaks and streaks, we conclude that the  $c$ -axis of the Mn<sub>4-x</sub>Ni<sub>x</sub>N film is more highly oriented on STO(001) than on MgO(001) owing to better lattice matching. Notably, the diffraction peaks of Mn<sub>4-x</sub>Ni<sub>x</sub>N appear at slightly higher angles than those of cubic STO(001) in Fig. 2(a), showing  $c/a < 1$ , which indicates the presence of in-plane tensile strain in the grown films. This result agrees with the results obtained for Mn<sub>4-x</sub>Ni<sub>x</sub>N epitaxial thin films on MgO(001).<sup>27</sup> The 002 and 004 diffraction peaks of Mn<sub>4-x</sub>Ni<sub>x</sub>N shift toward a higher angle in Fig. 2(a), which is reasonable, because Ni<sub>4</sub>N has a much smaller lattice constant than Mn<sub>4</sub>N. However, diffraction peaks other than those belonging to Mn<sub>4-x</sub>Ni<sub>x</sub>N appear at a  $2\theta$  value of around 41.3° at  $x = 0$  and 0.25 in Fig. 2(b). Tiny but distinct peaks, denoted by arrows, are also observed at  $x = 0.1$  and 0.5. We ascribe these peaks to the 200 reflection of MnO formed by interactions with the SiO<sub>2</sub> capping layer.

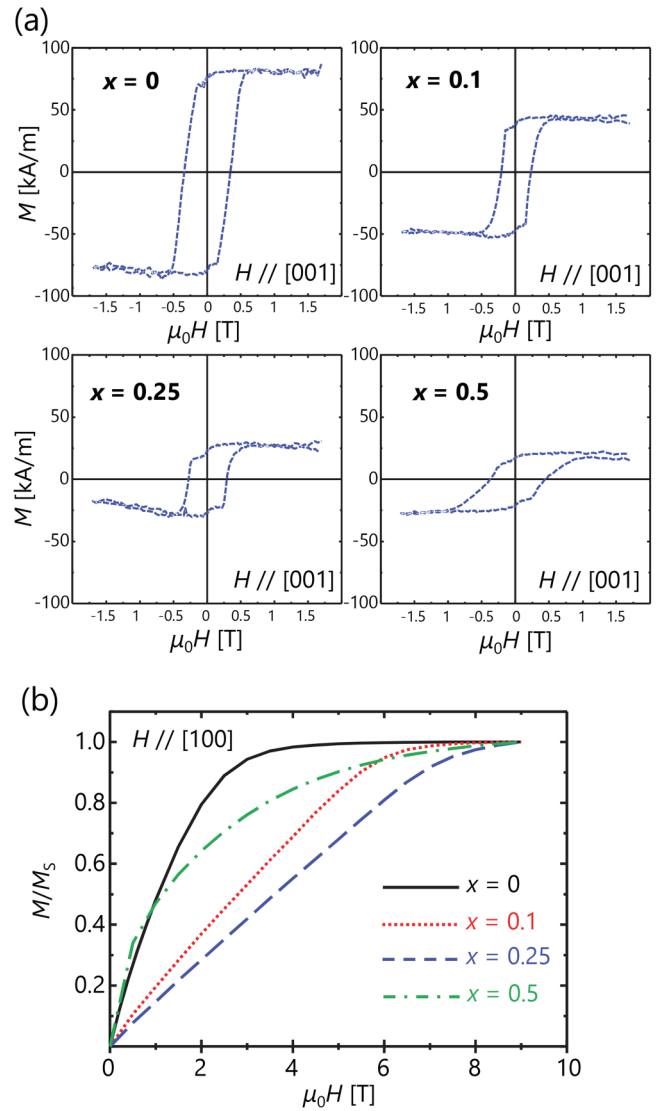
Figure 3(a) shows the  $M-H$  loops of Mn<sub>4-x</sub>Ni<sub>x</sub>N ( $x = 0, .0.1, 0.25, \text{ and } 0.5$ ) measured by VSM at RT with a magnetic field applied perpendicular to the plane. Table II shows the values of  $M_S$  and  $K_u$  obtained for Mn<sub>4-x</sub>Ni<sub>x</sub>N films on both STO(001) and MgO(001).<sup>24</sup> The Mn<sub>4-x</sub>Ni<sub>x</sub>N films tend to show a larger  $M_S$  on STO(001) than on MgO(001). For example, the  $M_S$  of Mn<sub>3.9</sub>Ni<sub>0.1</sub>N/MgO(001) is 24.2 kA/m, while that of Mn<sub>3.9</sub>Ni<sub>0.1</sub>N/STO(001) is 47.4 kA/m.

Ni introduction into Mn<sub>4</sub>N caused  $M_S$  to decrease by 45% at  $x = 0.1$  and by 75% at  $x = 0.25$ . This can be explained using a simple calculation, which is described later. PMA appeared in the Mn<sub>3.5</sub>Ni<sub>0.5</sub>N film on STO(001); however, it was absent in the



**FIG. 2.** (a) Out-of-plane XRD (line spectra) and RHEED (inset images) patterns of  $Mn_{4-x}Ni_xN$  along the STO[001] azimuth. The arrows indicate the positions of the superlattice diffraction lines. (b) In-plane XRD patterns of  $Mn_{4-x}Ni_xN$ . The scattering vector was set along the STO[100] azimuth.

$Mn_{3.5}Ni_{0.5}N$  film on  $MgO(001)$ .<sup>27</sup>  $Mn_{4-x}Ni_xN$  films on STO(001) showed a larger  $K_u$  than on  $MgO(001)$  for all  $x$  values. In particular, the  $K_u$  of  $Mn_{3.9}Ni_{0.1}N$  and  $Mn_{3.75}Ni_{0.25}N$  films on STO(001) reached values as large as those of  $Mn_4N$  films on STO(001). Kinks appeared in the  $M-H$  loops of  $Mn_{4-x}Ni_xN$  films on STO(001). We attribute this result to mixed phases with hard ( $Mn_{4-x}Ni_xN$ ) and soft magnetism.



**FIG. 3.** (a) Magnetization vs magnetic field ( $M-H$ ) curves of  $Mn_{4-x}Ni_xN$  on STO(001) measured at RT by VSM with a magnetic field,  $H$ , applied perpendicular to the plane, along the STO[001] azimuth. (b)  $M/M_S$  vs magnetic field curves of  $Mn_{4-x}Ni_xN$  on STO(001) measured at RT by AHE with  $H$  in parallel to the plane, along the STO[100] azimuth.

**TABLE II.**  $M_S^{STO}$  ( $M_S^{MgO}$ ) and  $K_u^{STO}$  ( $K_u^{MgO}$ ) values of  $Mn_{4-x}Ni_xN/STO$  ( $MgO$ )(001).

$x$	$M_S^{STO}$ (kA/m)	$M_S^{MgO}$ (kA/m)	$K_u^{STO}$ (J/m <sup>3</sup> )	$K_u^{MgO}$ (J/m <sup>3</sup> )
0	86.6	86.3	$1.1 \times 10^5$	$6.3 \times 10^4$
0.1	47.4	24.2	$1.4 \times 10^5$	$2.7 \times 10^4$
0.25	30.4	19.0	$1.1 \times 10^5$	$1.0 \times 10^4$
0.5	24.4	27.7	$4.2 \times 10^4$	No anisotropy

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Figure 3(b) shows the AHE curves of  $Mn_{4-x}Ni_xN$  on STO (001) with a magnetic field applied parallel to the plane along the STO[100] azimuth. A comparison of the  $M$ - $H$  curves reveals that a much larger magnetic field was necessary for the magnetization to saturate compared with when the magnetic field was applied normal to the plane, as shown in Fig. 3(a). Based on these results, we can state that  $Mn_{4-x}Ni_xN$  films on STO(001) show PMA at  $x = 0, 0.1, 0.25, \text{ and } 0.5$ .

### B. Magneto-transport properties

In Fig. 4, panels (a) and (b) show the AHE loops of  $Mn_{4-x}Ni_xN$  thin films on STO(001) and MgO(001), respectively, with a magnetic field applied perpendicular to the plane. The transverse voltage ( $V_y$ ) was calculated using Eq. (6),

$$V_y = \left( R_H \frac{B_z}{t} + \frac{\rho_{AH} M_{\perp}}{t M_S} \right) I_x = \frac{\rho_{xy}}{t} I_x, \quad (6)$$

where  $R_H$ ,  $B_z$ ,  $\rho_{AH}$ ,  $t$ ,  $\rho_{xy}$ , and  $I_x$  are the ordinary Hall coefficient, the magnetic flux density perpendicular to the sample surface, the anomalous Hall resistivity, the film thickness, the Hall resistivity, and the current, respectively. We did not consider the planar Hall effect because the anomalous magnetoresistance of the  $Mn_4N$  thin film is negligibly small at RT.<sup>25</sup> The slope in the high- $H$  region, where  $M$  is saturated, corresponds to the first term in Eq. (5). Thus, we can subtract the contribution of this term from the measured value. Remarkably, the ratio of the remnant magnetization ( $M_r$ ) to  $M_S$ ,  $M_r/M_S$ , was almost 1 for  $x = 0, 0.1, \text{ and } 0.25$  on STO (001). In contrast,  $Mn_{4-x}Ni_xN$  thin films on MgO(001) showed an  $M_r/M_S < 1$  and their PMA vanished at  $x = 0.5$ . Thus, one can speculate that  $Mn_{4-x}Ni_xN$  films on STO(001) are preferable for CIDWM applications, because of their sharp magnetization reversal at  $x = 0, 0.1, \text{ and } 0.25$ . Conversely,  $Mn_{3.5}Ni_{0.5}N$  films on STO(001) and  $Mn_{4-x}Ni_xN$  films on MgO(001) showed a slow magnetization reversal, and reversing their magnetization required a large magnetic field. This behavior is caused by the degradation of the crystalline quality of  $Mn_{4-x}Ni_xN$  on MgO(001) and  $Mn_{3.5}Ni_{0.5}N$  on STO(001), as proven by the fact that the full width at half maximum value obtained from an X-ray  $\omega$ -scan rocking curve was one order of magnitude larger for the  $Mn_4N$  films on MgO(001) than for those on STO(001).<sup>18</sup> In addition, the formation of  $Mn_{4-x}Ni_xN$  films becomes more difficult with increasing Ni content  $x$ , because the films are significantly decomposed into  $Ni_8N$  or Mn-Ni alloys.<sup>27</sup>

Regarding the sign of  $\rho_{xy}$  in Figs. 4(a) and 4(b),  $\rho_{xy}$  became negative in the  $+H$  region for  $Mn_{4-x}Ni_xN$  films at  $x = 0 \text{ and } 0.1$ . However, the sign of  $\rho_{xy}$  was reversed for  $Mn_{4-x}Ni_xN$  films between  $x = 0.1 \text{ and } 0.25$ , regardless of the substrate. Figure 4(c) shows the dependence of the anomalous Hall angle given by  $\theta_{AHE} = \rho_{AH}/\rho_{xx}$ , where  $\rho_{xx}$  is the longitudinal resistivity of the grown layers with Ni content  $x$ . The sign of  $\theta_{AHE}$  switched from negative to positive between  $x = 0.1 \text{ and } 0.25$ , which also indicates magnetic compensation. Such a sudden reversal of  $\theta_{AHE}$  is probably linked to ferrimagnetic compensation: at the compensation point, the direction of the magnetic moment at each sublattice is reversed with respect to the external magnetic field. Below the compensation point ( $x = 0 \text{ and } 0.1$ ), the magnetic moment at the Mn(I) sites

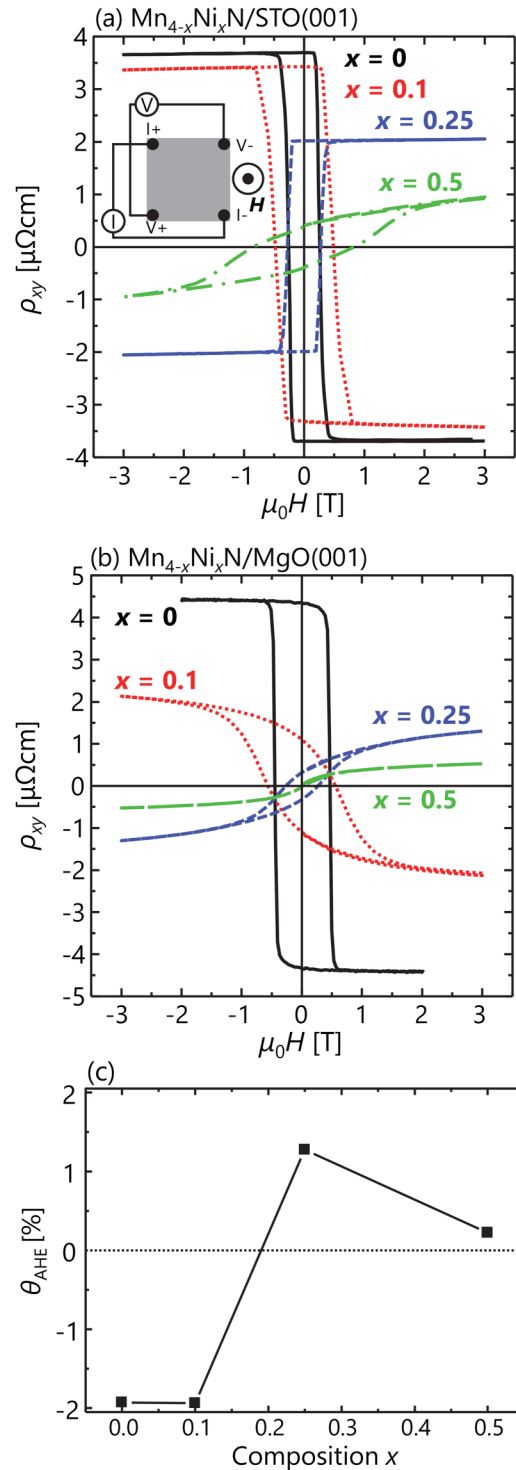


FIG. 4. Anomalous Hall effect measured at RT for  $Mn_{4-x}Ni_xN$  thin films on (a) STO(001) and (b) MgO(001) substrates. A magnetic field,  $H$ , was applied perpendicular to the plane. (c) Ni content  $x$  dependence of  $\theta_{AHE}$  measured at RT.

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determines the direction of the magnetization, while above the compensation point ( $x = 0.25$ ), the direction of the magnetization is determined by the magnetic moment at the Mn(II) sites. Therefore, this sign reversal is commonly used to confirm the compensation point in rare-earth ferrimagnets.<sup>11,40</sup> It should be noted that a reversal of the sign of  $\rho_{\text{AH}}$  is common in alloys with various compositions, for example, in Mn<sub>4</sub>N-based materials. Isogami *et al.* recently investigated the magneto-transport properties of Mn<sub>4-x</sub>Fe<sub>x</sub>N thin films<sup>41</sup> and found that the sign of  $\rho_{\text{AH}}$  reversed at around  $x = 1$ . However, the  $\rho_{\text{AH}}$  changed gradually with  $x$  at 300 K because of the shift of the Fermi level  $E_{\text{F}}$  and because of the change in the exchange coupling splitting energy<sup>42</sup> caused by Fe doping. Meng *et al.* also reported a reversal of the sign of  $\rho_{\text{AH}}$  in Mn<sub>4-x</sub>Dy<sub>x</sub>N thin films for  $x = 0.08$  and  $0.2$ <sup>43</sup> and concluded that this was caused by changes to the band structure and position of the  $E_{\text{F}}$ . In the Mn<sub>4-x</sub>Ni<sub>x</sub>N system, the sign reversal was caused by substitution with a small amount of Ni, and the change in the sign of  $\rho_{\text{AH}}$  was quite sharp when the Ni content was varied, which differs from the smooth change observed for Mn<sub>4-x</sub>Fe<sub>x</sub>N thin films. Therefore, we expect that this reversal is caused by the compensation point being crossed by the change in the composition.

### C. Discussion on compensation

Figure 5 shows the temperature dependence of  $M_{\text{S}}$ ,  $M_{\text{S}}(T)$ , for Mn<sub>4-x</sub>Ni<sub>x</sub>N films at  $x = 0, 0.1$ , and  $0.25$  normalized using the  $M_{\text{S}}$  at RT,  $M_{\text{S, RT}}$ . For comparison, the temperature dependences of  $M_{\text{S}}$  for Gd<sub>21</sub>(FeCo)<sub>79</sub> and Gd<sub>23</sub>(FeCo)<sub>77</sub> are inserted in Fig. 5.<sup>44</sup> The curve for Gd<sub>21</sub>(FeCo)<sub>79</sub> shows that the behavior of FeCo is dominant at all temperatures, whereas a transition from FeCo- to Gd-dominant is observed for Gd<sub>23</sub>(FeCo)<sub>77</sub>, i.e., with decreasing temperature, Gd dominates owing to its larger magnetic moment. In contrast, as the temperature increases for Gd<sub>23</sub>(FeCo)<sub>77</sub>, the net magnetization,  $m_{\text{net}}$ , decreases and eventually vanishes at  $T_{\text{M}} = 75$  K, because the demagnetization process is faster in Gd. As the temperature decreases for Mn<sub>4-x</sub>Ni<sub>x</sub>N films,  $M_{\text{S}}$  increased for  $x = 0$  and  $0.1$  and decreased for  $x = 0.25$ . Mekata confirmed similar temperature dependences of the magnetization in Sn- and In-doped Mn<sub>4</sub>N when magnetic compensation occurred.<sup>45</sup> Thus, we propose that in Mn<sub>4-x</sub>Ni<sub>x</sub>N, different sublattices have different temperature dependences of the magnetization owing to 3d metals at the I sites being farther away from the N atoms at the body-centered site than those at the II sites. Thus, 3d metal atoms at I sites tend to be localized. In contrast, 3d metals located at II sites are closer to N atoms and thus tend to be itinerant.<sup>46</sup>

Because of the sharp decrease in  $M_{\text{S}}$  with increasing  $x$  [cf. Fig. 3(a)], the sign reversal of  $\rho_{xy}$  and  $\theta_{\text{AHE}}$  in Figs. 4(a)–4(c), and the difference in the temperature dependence of the magnetization depending on the Ni content  $x$  (cf. Fig. 5), we believe that the magnetization of Mn<sub>4-x</sub>Ni<sub>x</sub>N might be compensated by a small amount of Ni. Let us discuss this possibility, assuming the following two hypotheses. Firstly, Ni atoms are positioned at I sites. This hypothesis is based on the fact that Ni atoms in Fe<sub>4-x</sub>Ni<sub>x</sub>N preferentially occupy I sites according to X-ray magnetic circular dichroism data.<sup>47</sup> As mentioned above, the  $M_{\text{S}}$  of Mn<sub>4</sub>N drastically decreased with a small amount of Ni substitution, and the magnetic moment of Mn atoms is larger at I sites than at II sites. Thus, Ni atoms

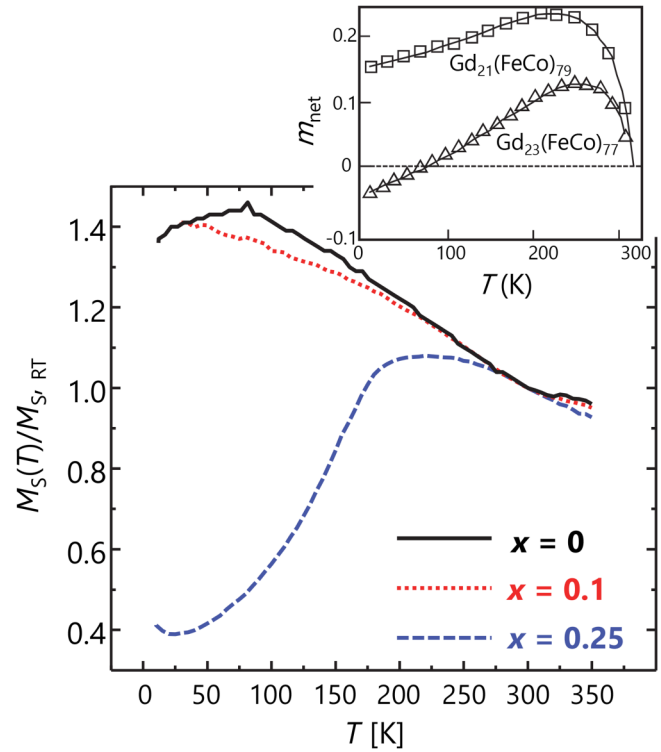


FIG. 5. Temperature dependence of the magnetization of Mn<sub>4-x</sub>Ni<sub>x</sub>N films ( $x = 0, 0.1$ , and  $0.25$ ). Samples were measured under field cooling, and the magnetic field,  $H$ , was applied perpendicular to the plane. The inset is reprinted with permission from Zhu *et al.*, J. Appl. Phys. **124**, 193901 (2018). Copyright 2018 AIP Publishing LLC.

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preferentially occupying I sites is necessary to explain the magnetization compensation in Mn<sub>4-x</sub>Ni<sub>x</sub>N. Secondly, the magnetic moment of a Ni atom is assumed to be  $0.6 \mu_{\text{B}}$  based on a report on the calculation of magnetic moments of Ni atoms in Ni<sub>4</sub>N<sup>35</sup> and on the Slater–Pauling curve.<sup>48</sup> Concerning the direction of the magnetic moment of the Ni atoms at the I sites, Ni(I), there are two options: the magnetic moment can be parallel to that of Mn(I) or Mn(II). When we assume the direction of the magnetic moment of Mn(I) to be positive, the parallel and antiparallel magnetic moments ( $\mu_{\uparrow}$  and  $\mu_{\downarrow}$ ) in a unit cell are given by Eqs. (7) and (8), respectively, when the magnetic moment of Ni is parallel to that of Mn(I),

$$\mu_{\uparrow} = (1 - x)\mu_{\text{Mn(I)}}^{\uparrow} + x\mu_{\text{Ni(I)}}^{\uparrow}, \quad (7)$$

$$\mu_{\downarrow} = 3\mu_{\text{Mn(II)}}^{\downarrow}. \quad (8)$$

Here,  $\mu_{\text{Mn(I)}}^{\uparrow}$ ,  $\mu_{\text{Mn(II)}}^{\downarrow}$ , and  $\mu_{\text{Ni(I)}}^{\uparrow}$  are the magnetic moments of Mn(I), Mn(II), and Ni(I) atoms, respectively. Thus, the net magnetic moment ( $\mu_{\text{net}}$ ) per unit cell can be described by

$$\mu_{\text{net}} = (1 - x)\mu_{\text{Mn(I)}}^{\uparrow} + x\mu_{\text{Ni(I)}}^{\uparrow} + 3\mu_{\text{Mn(II)}}^{\downarrow}. \quad (9)$$

TABLE III. Calculated contributions of Mn(I), Mn(II), and Ni(I) atoms to the magnetic moment and measured magnetizations.

$x$	$(1-x)\mu_I^{\text{MnI}} (\mu_B)$	$x\mu_I^{\text{NiI}} (\mu_B)$	$x\mu_I^{\text{NiI}} (\mu_B)$	$3\mu_{\text{II}}^{\text{MnI}} (\mu_B)$	$\mu_{\uparrow} (\mu_B)$	$\mu_{\downarrow} (\mu_B)$	$\mu_{\text{net}} (\mu_B)$	$M_S^{\text{cal}} (\text{kA/m})$	$M_S^{\text{exp}} (\text{kA/m})$
0	3.53	...	...	-2.67	3.53	-2.67	0.86	136.9	86.6
0.1	3.18	0.06	...	...	3.24	-2.67	0.57	90.3	47.4
		...	-0.06	...	3.18	-2.73	0.45	71.2	
0.25	2.65	0.15	...	...	2.80	-2.67	0.13	20.3	30.4
		...	-0.15	...	2.65	-2.82	-0.17	-27.5	
0.5	1.77	0.30	...	...	2.07	-2.67	-0.60	-96.4	24.4
		...	-0.30	...	1.77	-2.97	-1.20	-191.8	

Similarly, when the magnetic moment of Ni(I) is parallel to that of Mn(II), the net magnetic moment per unit cell can be described as Eq. (10) using the magnetic moment of Ni atoms  $\mu_{\text{Ni(I)}}^{\downarrow}$ ,

$$\mu_{\text{net}} = (1-x)\mu_{\text{Mn(I)}}^{\uparrow} + x\mu_{\text{Ni(I)}}^{\downarrow} + 3\mu_{\text{Mn(II)}}^{\downarrow}. \quad (10)$$

Table III shows the contribution to the magnetic moment per unit cell from Mn(I), Mn(II), and Ni(I) atoms and the calculated  $M_S$ . For comparison, the measured  $M_S (M_S^{\text{exp}})$  and calculated ( $M_S^{\text{cal}}$ ) values are also shown.

Our simple model explains the experimental results quite well. Most importantly, it shows that the magnetization of  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  becomes zero at small  $x$  regardless of the direction of the magnetic moment of Ni(I). The calculated compensation composition of Ni atoms is  $x = 0.29$  for  $\mu_{\text{Ni(I)}}^{\uparrow} / \mu_{\text{Mn(II)}}^{\downarrow}$  and  $x = 0.21$  for  $\mu_{\text{Ni(I)}}^{\downarrow} / \mu_{\text{Mn(II)}}^{\downarrow}$ . There is, however, a large difference in  $M_S$  between the calculation and the experiment at  $x = 0.5$ , as shown in Fig. 6. We cannot exclude the possibility that Ni atoms would begin to occupy II sites as  $x$  increases. In this regard, X-ray magnetic circular dichroism could be a powerful tool to determine the site of Ni atoms in  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$ . Additionally, we must correctly evaluate the composition, i.e., the value of  $x$ , in  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  films at which magnetic

compensation occurs. Rutherford back-scattering spectrometry, energy-dispersive X-ray spectrometry, or inductively-coupled plasma mass spectrometry could be used for this purpose.

#### IV. CONCLUSION

We grew highly  $c$ -axis-oriented epitaxial  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  ( $x = 0, 0.1, 0.25, \text{ and } 0.5$ ) thin films by MBE on STO(001) substrates and measured their magnetic and magneto-transport properties, which we compared with those of  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  films on MgO(001) substrates. The  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  thin films on STO(001) showed a squareness ratio of  $M_r/M_S = 1$ , fast magnetization reversal, and a perpendicular magnetization when  $x \leq 0.25$ , which are desirable features for CIDWM devices. In contrast, the  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  thin films on MgO(001) substrates did not show such features. We ascribed this difference to the superior crystalline qualities of  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  thin films on STO(001) owing to the smaller lattice mismatch compared with  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  thin films on MgO(001). Three factors point toward magnetic compensation in  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  occurring between  $x = 0.1$  and  $0.25$ : the sharp decrease in  $M_S$  when increasing the Ni content, the sign reversal of the anomalous Hall effect, and the anomalous temperature dependence of  $M_S$ . We discussed the validity of this assumption by taking into account that the Ni atoms preferentially occupy I sites and that the magnetic moment of Ni atoms is  $0.6\mu_B$ . We conclude that magnetic compensation is likely to occur regardless of the direction of the magnetic moment of the Ni atoms at the I sites. We thus believe that, in view of its magnetic properties,  $\text{Mn}_{4-x}\text{Ni}_x\text{N}$  close to the compensation composition is a very attractive candidate for applications based on spin transfer torques or spin-orbit torques, particularly for CIDWM.

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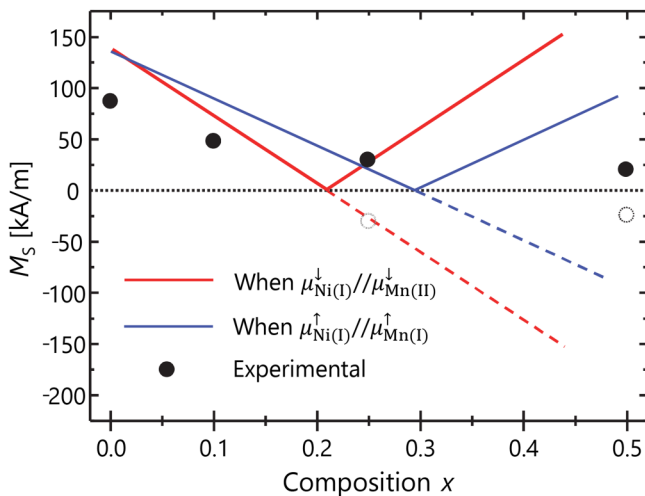


FIG. 6. Calculated and measured Ni content  $x$  dependence of  $M_S$ .

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