Review

Spin–polarized scanning electron microscopy

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Abstract
Spin-polarized scanning electron microscopy (spin-SEM) is a magnetic domain observation method. In spin-SEM, polarization of secondary electrons emitted from a sample in a scanning electron microscope is detected by a spin detector and used as a signal for forming an image. The characteristics of spin-SEM are detection of all three magnetization vector components, which leads to the detection of the magnetization vector direction, high spatial resolution of around 3 nm and applicability to samples with rough or even 3D surfaces. Spin-SEM combined with other imaging methods using an electron probe beam such as scanning Auger electron microscopy for imaging element distribution and electron backscattering diffraction microscopy for imaging crystal direction distribution provides additional information that is important to study the magnetism. Spin-SEM with these excellent characteristics has a broad range of applications from basic research to applied research and developments in various industries.

Keywords
magnetic domain, magnetization, polarization, SEM, spin-SEM, spin

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Introduction
Magnetic domain observation with high spatial resolution is important in a wide range of research and development fields. One such field is nanomagnetism, which deals with nanoparticles [1], nanoparticle arrays [2], nanowires [3] and thin films in the nanometer range [4]. Other fields include the study of magnetic interactions between magnetic materials [5,6], those between magnetic materials and magnetic fields [7], spin polarized electric currents [8] and even electric fields [9]. It can also be used for magnetic materials such as permanent magnets [10] and strongly correlated materials [11]. Almost, all these fields are related to such technologic applications as magnetic recording, magnetic sensors and spintronics. Magnetic recording is also an important application in which recording media [12], write and read heads [13,14] of a hard disk drive and magnetic random access memory [15] need domain observation.

Many methods are used for high resolution magnetic domain observation, including Lorenz transmission electron microscopy [16], electron holography [17], magnetic force microscopy [18], Spin-polarized scanning electron microscopy (spin-SEM ) (I use this terminology for both the method and the apparatus) [19], spin-polarized low energy electron microscopy [20], spin-polarized photoelectron microscopy [21], transmission type magnetic circular dichroism X-ray microscopy [22] and spin-polarized scanning tunneling microscopy [23]. Each method has its own advantages and disadvantages, so users should select the method appropriate to their purpose.

Among the methods described above, spin-SEM was developed by Koike and Hayakawa [19] and is the subject of this paper. In spin-SEM, polarization of secondary electrons emitted from a sample is detected by a spin detector and is used to form a magnetic domain image. Spin-SEM has several characteristics superior to other methods, as described...
below. In this paper, I review this method starting from the ‘Polarization of secondary electrons’ and ending with ‘Applications.’

Polarization of secondary electrons
The polarization vector \( P \) of an ensemble with \( n \) electrons is given by the average of the expectation value of each electron spin angular momentum \( s \) divided by \( h/2 \);

\[
P = \frac{2}{h} \sum_{i=1}^{n} \langle \varphi^{(i)} | s | \varphi^{(i)} \rangle,
\]

where, \( \varphi^{(i)} \) is a wave function of \( i \)-th electron and is normalized to \( \langle \varphi^{(i)} | \varphi^{(i)} \rangle = 1 \), and \( h = h/2\pi \), where \( h \) is the Planck constant. The relationship between \( s \) and magnetic moment \( \mu \) of the electron is given by

\[
\mu = \frac{e}{m} s,
\]

where \( e \) and \( m \) are the charge and mass of the electron, respectively. Because \( e \) is negative, \( s \) and \( \mu \) are antiparallel and so are the \( P \) and magnetization \( M \), which is defined by the sum of \( \mu \) in a unit volume.

The fact that the polarization of secondary electrons emitted from a ferromagnetic sample is antiparallel to the sample magnetization was found for the first time by Chrobok and Hofmann in 1976 [24]. The possibility of magnetic domain observation using this phenomenon was proposed by DiStefano in 1978 [25], without knowing the experimental results of Chrobok and Hofmann The relationships among the polarization, primary energy and secondary electron energy, however, are not so simple because the secondary electrons suffer spin-dependent inelastic scattering during the process of emission [26–28]. Figure 1 shows secondary electron energy dependency of secondary intensity and polarization for an Fe (110) sample, for primary energies from 50 to 2000 eV [29]. As it is well known, the secondary intensity decreases exponentially with the secondary energy. The polarization also decreases with the secondary energy, but reaches an almost constant value at around 20 eV. This characteristic is advantageous for spin-SEM because the polarization is larger around the energy, where the intensity is higher, which gives a high signal-to-noise ratio \( S_p/N_s \) for spin-SEM images. This is very important because the signal is very small as described below. Figure 2 shows the primary energy

![Fig. 1. Secondary electron energy dependency of secondary intensity and polarization for an Fe (110) sample, for primary energies from 50 to 2000 eV. The higher the intensity of secondary electrons, the larger the polarization. This is advantageous to use polarized electrons for spin-SEM because the signal-to-noise ratio becomes large.](image-url)

![Fig. 2. Primary energy dependency of secondary polarization and intensity of Fe (110) samples. The black squares and circles show experimental data. Solid lines are calculated results taking into account the spin-dependent inelastic mean free path. The polarization increased with the primary energy and reached a constant value at around 1 keV.](image-url)
dependency of secondary polarization and intensity for Fe (110) samples [30]. Here, the black squares and circles show experimental data. Solid lines are calculated results taking into account the spin-dependent inelastic mean free path. The general tendency is that when the primary energy increases, polarization also increases and reaches a constant value at around 1 keV. This characteristic is again advantageous for the same reason as above because the primary energy is usually higher than 1 keV in SEM. When high spatial resolution is required, however, the primary energy should be increased. In this case, secondary electron yield decreases, and the advantage described above no longer holds. The characteristics mentioned above are common for all the 3d magnetic materials investigated so far [31]. If we sacrifice the spatial resolution, the best $S_p/N_s$ can be obtained at the primary energy around 1 keV.

The information depth of magnetization of the polarized secondary electrons is important to analyze the spin-SEM image. The best way to obtain the information depth by an experiment is to measure the polarization of secondary electrons as a function of film thickness of a magnetic material on a non-magnetic substrate. The open circles in Fig. 3 show the results for Fe on paramagnetic FeO, where the polarization was measured during Fe evaporation at room temperature [32]. The solid line in Fig. 3 is obtained by least squares curve fitting.

We assume the curve is given by $A[1-\exp(-t/d)]$, where $A$ and $d$ are fitting parameters and $t$ is film thickness. From the obtained value of $d = 0.63$ nm, we determine that the information depth of magnetization is about 0.6 nm for Fe. Almost the same value of 0.4–0.5 nm was also obtained for Ni, although the experimental method was different [33]. From these results, we can safely say that the information depth of magnetization obtained by spin-SEM is about 0.5 nm.

Information depth of about $d = 0.5$ nm is advantageous to observe ultrathin film [4] or surface magnetism. In addition, samples with contamination or destroyed crystalinity layers with a thickness of less than $d$ are observable. The samples exposed to air, however, usually have oxidized or contaminated layers thicker than $d$. In this case, these layers should be removed by iron spattering or by chemically reactive gas [34] depending on the sample. If the magnetism is very sensitive to the crystalinity [35], the ion spattering should be done carefully by reducing the spattering energy.

**Principle of spin-SEM**

Figure 4 shows the principle of the spin-SEM for magnetic domain observation. When a ferromagnetic sample is irradiated by a probe electron beam, electrons inside the sample, the spins of which are...
the origin of the magnetization, are emitted as secondary electrons while keeping their spin directions. Therefore, if we scan the sample surface with a fine probe electron beam and detect the polarization vector of secondary electrons via a spin detector and use it as an image signal, we can obtain the magnetic domain image. Because the polarization vector is antiparallel to the magnetization vector, the spin-SEM can detect the magnitude and orientation of the magnetization vector.

**Principle of spin detector**

In spin-SEM, the scattering of the electrons by heavy atoms, where spin–orbit interaction is large, is used to detect \( \mathbf{P} \). If we define \( H \) as a Hamiltonian of the interaction, \( \xi \) as a constant determined by scattering potential, \( l \) and \( s \) as the orbital and spin angular momenta of the scattering electron, respectively, the \( H \) of the spin–orbit interaction is given by

\[
H = \xi l \cdot s
\]  

Figure 5 shows the principle of the spin detector using the spin–orbit interaction. When a polarized electron beam with polarization vector \( \mathbf{P} \) is scattered by gold foil, the numbers of the backscattered electrons detected by four electron detectors A, B, C and D located at 4-fold symmetrical positions about the incident beam are not equal as can be seen from Eqs. (1) and (3). If we define these electron numbers as \( N_A, N_B, N_C, \) and \( N_D \), in the case of Fig. 2a, the polarization vector components \( P_x \) and \( P_y \) of \( \mathbf{P} \) defined by Eq. (1) are given by [36]

\[
P_x = \frac{1}{SN_A + N_B} \left( N_A - N_B \right), \quad P_y = \frac{1}{SN_C + N_D} \left( N_C - N_D \right)
\]  

Here, \( S \) is a constant determined by the scattering condition and is typically between 0.1 and 0.3.

The \( z \) component \( P_z \), however, cannot be detected with the geometry in Fig. 2a because the \( P_z \) direction is perpendicular to the \( l \), and there is no contribution of \( P_z \) to the spin–orbit interaction, as can be seen from Eqs. (1) and (3). For detecting the \( z \) component, we use a spin rotator [37] at the position shown in Fig. 2b. In this case, after passing through the spin rotator, the polarization vector \( \mathbf{P} \) of electrons rotates by 90°about the \( y \)-axis. Then, we can detect \( \mathbf{P} \) in the same way as we detect \( P_x \).

\[
P_z = \frac{1}{SN_A + N_B} \left( N_A - N_B \right)
\]

In the spin-SEM application, we switch the spin rotator on and off within a pixel time. Thus, we can detect the all \( \mathbf{P} \) components \( P_x, P_y \) and \( P_z \) substantially and simultaneously [38].

Generally, the number of electrons detected in the spin detector is less than 1% of that of electrons entering into the spin detector. Thus, the detection error due to the statistical fluctuation becomes prominent. If we define the errors \( \delta P_x \) of \( P_x \), due to the fluctuation of \( N = N_A + N_B \), \( \delta P_z \) is given by [36]

\[
\delta P_x = \frac{1}{\sqrt{S^2 \eta N_0}},
\]

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**Fig. 5.** Principle of the spin detector. Polarization is detected by scattering the electron beam with gold foil, where spin–orbit interaction causes asymmetry of the backscattered electron number. (a) Configuration for detecting polarization components \( P_x \) and \( P_y \). (b) Configuration with a spin rotator for detecting \( P_y \) and \( P_z \).
where $\eta = N/N_0$, and $N_0$ is the number of electrons entering into the spin detector. From Eq. (6), we can see that, if $N_0$ is constant, the larger the $S^2\eta$, the smaller the $\delta P_x$. From this consideration, we define

$$F = S^2\eta,$$  \hspace{1cm} (7)

as the efficiency of the spin detector. The value of $F$ used in spin-SEM is around $10^{-4}$.

Here, we compare the efficiency of the spin detector with that of the electron detector used in conventional SEM. The signal $S_g$ to noise $N_s$ ratio of the image signal obtained in spin-SEM is roughly

$$\frac{S_g}{N_s} \sim \frac{P_x}{\delta P_x} \sim \frac{1}{\delta P_x} = \sqrt{FN_0},$$  \hspace{1cm} (8)

whereas that in conventional SEM is roughly

$$\frac{S_g}{N_s} \sim \frac{N_0}{\sqrt{N_0}} = \sqrt{N_0}.$$  \hspace{1cm} (9)

From Eqs. (8) and (9), we can see that for obtaining the same $S_g/N_s$ signal with a spin detector as with an electron detector, we need $1/F$, i.e. around 10 000 times more electrons for the spin detector than for the electron detector.

**Configuration of the apparatus**

Figure 6 shows the structure of our group’s newest spin-SEM, developed in 2009. This apparatus consists of an electron gun column equipped with a high brightness ZrO/W Schottky emitter and an aberration corrector, a spin detector, a high vacuum sample exchange chamber, ultra-high vacuum preparation chamber and observation chamber. Attached to the

Fig. 6. Structure of the spin-SEM.
preparation chamber are an ion gun, evaporator, film thickness monitor, quadrupole mass analyzer, parking lot for samples, ion pump, pressure gage and transfer rods. Attached to the observation chamber are a sample stage with five motion axes and a control unit for temperatures from 10 to 400 K combining a liquid helium cryostat and an electric heater, a spin detector, an electron backscattering diffraction (EBSD) unit, a scanning Auger electron microscopy (SAM) unit, including an energy analyzer, ion pump, pressure gage and transfer rods.

**Characteristics of spin-SEM**

The spin-SEM described above has the following characteristics.

1. Information obtainable for the same observation area:
   - (1) Magnetization vector
   - (2) Elements
   - (3) Crystal direction
   - (4) Topography

2. Spatial resolution: 3 nm
3. Temperature: 10–400 K

Examples of characteristics 1: (1), (3) and (4) are given in the ‘Applications’ section. The others are given below.

Figure 7 shows (a) Nd distribution, (b) Fe distribution, (c) topography and (d) magnetic domain images for the same area of a NdFeB permanent magnet. Here the element images (a) and (b) were obtained by SAM. By comparing Fig. 7a–c, Nd-rich areas can be seen to coincide with the grain boundary regions as is already known. We can see that the domain walls run mainly inside the grains as shown in Fig. 7d, which is not the case for soft magnetic materials like Fe or magnetic recording media. The domain wall width is narrower for some walls, but wider for other walls, the reason for which is not clear at present.

Figure 8 shows (a) $M_x$, (b) $M_y$, (c) $M_z$, (d) topography and (e) pseudocolor crystal direction images for the same area of an iron polycrystal. The $M_x$, $M_y$ and $M_z$ images (a)–(c) were obtained using magnetization components along the $x$, $y$ and $z$ directions, respectively. The crystal direction image (e) was obtained by EBSD. The relationship between the crystal direction and color is given by the color triangle to the right of (e). The surface index of the blue grain in (d) is (111), which is perpendicular to the hard axis of magnetization of Fe. In this case, the domains are more complicated and finer than the other grain surfaces, which include an easy axis of magnetization of $<001>$, to reduce the magnetostatic energy by making closure domains at the surface. As can be seen in Fig. 8c, the surface of the Fe does not have any surface normal component of magnetization. This is the case for any soft magnetic material like Fe and a permalloy, where even bulk Bloch walls do not have a normal surface component [39–41]. An example of detailed analysis of this kind of domain structure is given in the ‘Applications’ section.

Many magnetic domain observation methods give magnetic images with a mixture of magnetic and topographic information. In these methods, the magnetic information is obtained by subtracting the topographic information from the obtained image. If the surface topography becomes large, however, this procedure does not work. In spin-SEM, the magnetic image and topographic image are
obtained using mutually independent physical quantities: spin polarization and electric current. Thus, both images can be obtained separately [40], even for samples with a 3D surface structure. Fig. 9 shows (a) magnetic, (b) topographic and (c) the sum of magnetic and topographic images of the pole piece of a magnetic recording head for the same area obtained simultaneously by spin-SEM [42]. The magnetic image was obtained using the magnetization component along the arrow above the image (a). Although the sample surface has a 3D structure, we can obtain magnetic domain contrast for the whole area. The left half of the stripe domain structure in Fig. 9a is ideal for the head. However, the right half of the domain structure with the zigzag domain walls is not. In Fig. 9c, we can see that domain walls in the right half run along the black lines seen in topography image (b), which, we speculate, are grooves formed during the manufacturing process and become pinning sites of the domain walls. By optimizing the process, ideal heads will be obtained.

Spatial resolution

As mentioned above, the efficiency of the spin detector is extremely low. To overcome this difficulty and obtain an image with reasonable quality, we increase the probe current $I_p$ to around 1 nA, which is two orders of magnitude larger than that of the conventional SEM, using a high brightness electron emitter and increase the diameter of the objective lens aperture. In addition, we insert a secondary electron collector between the objective lens and the sample, so that we can collect as many secondary electrons as possible by increasing the working distance (WD) to around 10 mm, which is much larger than that of conventional SEM, where WD is almost 0 mm. The larger aperture diameter and WD prevent reduction of the probe beam diameter, and the spatial resolution becomes lower.

Even in this situation, to obtain higher spatial resolution, we employed an aberration corrector [43]. Because the electron optical system is very different from the conventional SEM, in the sense that the $I_p$ of around 1 nA and WD of 10 mm are much
larger than those of conventional SEM, we newly designed the corrector to correct third-order spherical and first-order chromatic aberrations, exclusively effective for the special conditions mentioned above. The detailed structure will be given elsewhere [M. Hososkawa et al., in preparation]. In brief, it consists of 4 stages with 12-polar lenses, where the outer 2 lenses produce electric fields and the inner 2 lenses produce electric and magnetic fields to correct the chromatic aberration. The calculated beam diameter $d$ without and with the corrector are given in Fig. 10a and b respectively, as the function of the beam angle for $I_p = 0.1, 1$ and 10 nA and an acceleration voltage of 20 kV. In Fig. 10a, $d_S, d_C, d_D$ and $d_G$ are spherical, chromatic and diffraction aberrations and emitter size imaged at the sample, respectively. Using these four variables, $d$ is given by

$$d^2 = d_S^2 + d_C^2 + d_D^2 + d_G^2$$  \hspace{1cm} (10)

In the case of the conventional SEM with a smaller probe current, $d_D$ is more dominant than $d_G$, whereas in the case of the spin-SEM with a larger probe current, $d_G$ is more dominant than $d_D$. The beam diameter of 4.0 nm is obtained for $I_p = 1$ nA without the corrector as shown in Fig. 10a. In Fig. 10b, $d_{S5A}$ and $d_{S5B}$ are fifth-order spherical aberrations appearing because of the combination of the corrector and objective lens and that left being uncorrected by the corrector, respectively. The beam diameter is reduced to 1.5 nm using the corrector as shown in Fig. 10b.

The larger $I_p$ of around 1 nA is not large enough to obtain a reasonable quality image with the same image acquisition time as that of conventional SEM because the number of electrons is still two orders of magnitude smaller than that obtained in the conventional SEM. To compensate for the lack of electrons, we increase the image acquisition time from 10 min to 1 h in the Spin SEM, depending on the polarization of the secondary electrons.

To check the spatial resolution of the spin-SEM used in the SEM mode, we observed gold particles evaporated on a carbon block. Figure 11a shows an SEM image obtained with a probe current of 0.5 nA and acceleration voltage of 20 kV. Figure 11b shows the line profile along the red line in the white circle in Fig. 11a. By applying the ASTM E986-04 standard of 20–80% intensity width to the line profile, we determined the spatial resolution to be 2.1 nm as shown in Fig. 11b.
resolution is lower than the calculated one. The main cause of the difference is mechanical vibration of the apparatus. To check the spatial resolution of the spin-SEM image, we observed a perpendicular recording medium. Figure 12a shows a spin-SEM image obtained with a probe current of 0.5 nA and acceleration voltage of 20 kV. The black and white bands running longitudinally in the left part of the image are recorded tracks with a bit length of 50 nm. Also shown in Fig. 12b is a transmission electron microscope (TEM) image of the medium. From image (b), we can see that the average size of ferromagnetic grains is around 10 nm and the width of the grain boundary that consists of non-magnetic material is around 1 nm.

The line profile of magnetization, averaged along the horizontal direction over the area surrounded by the red rectangle in Fig. 12a, is shown in Fig. 13 as black dots connected by a dashed line. The spatial resolution of the spin-SEM cannot be determined by the ASTM E986-04 standard because the scatter of the data in the line profile is rather large. Therefore, we conducted least squares curve fitting by convolution of the real magnetization distribution and probe beam intensity distribution. Here, we assume that the magnetization distribution is given by the inset of Fig. 13, which includes a 1-nm-wide non-magnetic grain boundary as seen in the TEM image of Fig. 12b, the boundary runs horizontally and the probe
beam profile is Gaussian. The result is given by the solid line in Fig. 13. From the full width at half maximum of the obtained Gaussian distribution, we determined the spatial resolution of the spin-SEM to be 2.7 nm. This value is about half of the best resolution reported so far for spin-SEM [44], but lower than the SEM image in Fig. 11a and calculated value. The cause is again mechanical vibration, which is more serious than for the SEM image because of the longer image-acquisition time.

Applications

Fe78B13Si9 amorphous ribbon [45]

Figure 14 shows magnetic domain images of an as-quenched Fe78B13Si9 amorphous ribbon. The magnification increases from Fig. 14a–d. In Fig. 14a, we can see large domains whose size is a few hundred micrometers and neighboring fine domains. From the magnified image of Fig. 14b, we can see that these fine domains have a stripe structure. In Fig. 14c, we can see that the stripe domain walls wave with a constant period, and there is also periodical fluctuation of magnetization inside the stripe domains. In Fig. 14d, arrows showing magnetization directions are superimposed. This sample has positive magnetostriction. Thus, the large and fine domains in Fig. 14a are formed by uniaxial anisotropy parallel to the surface due to tensile residual stress, and by perpendicular anisotropy due to compressive residual stress, respectively. As seen in Fig. 14d, the magnetization direction is perpendicular on average to the domain wall, and heads or tails of the magnetization vectors meet together at the domain walls. This structure suggests that the stripe domains are the well-known closure domains that appear at the surface to close the magnetic flux of the underlying domains. To explain the wavy domain walls and the periodic magnetization fluctuation inside the stripe, a 3D domain structure model is proposed as shown in Fig. 15. In this
figure, some of the domains are broken out to reveal the structural details. The domains are classified into bulk domains $B$ with perpendicular magnetization and closure domains $C$ at the surface. The closure domains are further classified into domains $C_1$ and $C_2$. The magnetization in the $C_2$ domains fluctuates up and down, as shown by the dashed arrows, to reduce anisotropic energy due to perpendicular anisotropy. The $C_1$ domains appear to prevent magnetic poles from appearing on the sample surface. To eliminate magnetic poles in the wall between the $C_1$ and $C_2$ domains, the wall normal component of the magnetization vector should be conserved across the wall. As a result, in-sample surface fluctuation occurs. Thus, the $C_1$ domains are types of closure domains. The wavy walls are formed by this fluctuation. As a whole, this domain structure is a double closure structure.

The domain structure is determined to minimize the total magnetic energy, i.e. the sum of the wall energy, anisotropic energy and magnetostatic energy. In the tensile stress region with in-surface plane anisotropy, the magnetizations are parallel to the surface and no magnetic poles appear on the surface. In this case, the anisotropic energy and magnetostatic energy are negligible, and the domain size is determined to minimize wall energy, which results in larger domains as seen in Fig. 14a. On the other hand, in the tensile stress region with perpendicular anisotropy, the magnetizations tend to be parallel to the surface normal to minimize anisotropic energy. However, if this situation is maintained even at the surface, magnetic poles that increase the magnetostatic energy would appear. The minimum energy structure for this sample is to form closure domains at the surface at the cost of anisotropic energy and eliminate the magnetostatic energy.
energy. The size of the closure domain is determined by the tradeoff of wall and anisotropic energies; the larger (smaller) the stripe domain width, the larger (smaller) the anisotropic energy and the smaller (larger) the wall energy. The fine domains seen in Fig. 14a are formed in this way. In general, it is true that domain size is finer when easy axes of magnetization tilt from the surface, whether magnetic poles appear or not at the surface, to reduce magnetostatic energy.

La$_{1.4}$Sr$_{1.6}$Mn$_2$O$_7$ [46]

Figure 16 shows crystal and magnetic structures of La$_{1.4}$Sr$_{1.6}$Mn$_2$O$_7$ in the ground state, where the latter is determined by neutron diffraction. It has a multilayered perovskite structure, where a metallic ferromagnetic MnO$_2$ bilayer in plane $ab$ and a non-magnetic insulating (La,Sr)$_2$O$_2$ layer are stacked alternately along direction $c$. It has a layered antiferromagnetic structure with perpendicular anisotropy.

We set a La$_{1.4}$Sr$_{1.6}$Mn$_2$O$_7$ single crystal on the sample stage of the spin-SEM, cooled it down to 40 K, cleaved it and obtained an $ab$ plane with steps and terraces. The observation by spin-SEM shows that the sample has a layered antiferromagnetic structure as expected, except for small areas of a ferromagnetic structure. Among these, we investigated the temperature dependence of the magnetic structure for the former area. The results are shown in Fig. 17. The temperature range is from 50 to 90 K. $M_x$, $M_y$, and $M_z$ are spin-SEM images obtained using magnetization components along the $x$, $y$ and $z$ directions, respectively. The black dashed lines in the $M_z$ image at 50 K are the domain wall because its position shifts at 60 K. The white dashed lines in the same image are steps because their positions do not change with the temperature, and the
contrast appearing between both sides of the areas in the images of $M_x$ and $M_y$ from 50 to 80 K confirms that the sample has a layered antiferromagnetic structure. At 70 K, the contrast in $M_z$ disappears, whereas that in $M_x$ and $M_y$ survives until 80 K. This means that magnetization lies in the surface plane at 70 K. Because all the contrasts of $M_x$, $M_y$ and $M_z$ disappear at 90 K, this temperature is the Neel temperature. From the polarization data in Fig. 17, the angle $\theta$ between the magnetization and the surface parallel is calculated as a function of temperature and shown in Fig. 18. Kimura et al. found that the lattice constant in the $ab$ plane ($c$ axis) increases (decreases) with the temperature until 80 K and decreases (increases) above that [49]. When the lattice constant in the $ab$ plane increases and that of the $c$ axis decreases, the $3z^2-r^2$ orbital of $e_g$ orbitals has lower energy than $x^2-y^2$ and the electron occupies the $3z^2-r^2$ orbital. In this case, the magnetization lies in plane $ab$ because of spin-orbit interaction. This behavior of the lattice constant, however, has not been resolved yet.

Summary

Spin-SEM can obtain magnetic domain images using the phenomenon that the polarization vector of secondary electrons emitted from the magnetic sample is antiparallel to the magnetization vector at their originating point on the sample. It has excellent characteristics such as high spatial resolution of around 3 nm that can be obtained using a high brightness emitter and aberration corrector, and all three magnetization vector components, or magnetization detection, can be obtained using a spin detector combined with a spin rotator. Pure magnetic images can be obtained even for samples with 3D surfaces because of the independence of polarization and current, and elements and crystal direction distribution images can be obtained for the same area as the magnetic image using Auger electrons and backscattered diffraction electrons, respectively. Some spin-SEM results obtained by application of an Fe$_{78}$B$_{13}$Si$_9$ amorphous ribbon and strongly correlated La$_{1.4}$Sr$_{1.6}$Mn$_2$O$_7$ have been presented. Further applications of spin-SEM in basic and applied research in both academic and research and development fields in industry are expected.

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