

# Vol.45 No.5 2021

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世界初\*、高温超電導マグネットをVSMに採用することで 測定速度 当社従来機1/20を実現。 0.5mm cube磁石のBr, HcJ高精度測定が可能と なりました。 \*2014年7月東英工業調べ

### 測定結果例



### 高温超電導VSMによるNdFeB(sint.) 1mm cube BHカーブ







### 高速測定を実現

高温超電導マグネット採用により、高速測定を 実現しました。Hmax=5Tesla, Full Loop 測定が 2分で可能です。

(当社従来機:Full Loop測定 40分)

### 小試料のBr,HcJ高精度測定

0.5mm cube 磁石の Br, HcJ 高精度測定ができ、 表面改質領域を切り出し Br,HcJ の強度分布等、 微小変化量の比較測定が可能です。 また、試料の加工劣化の比較測定が可能です。

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# Journal of the Magnetics Society of Japan Vol. 45, No. 5

Electronic Journal URL: https://www.jstage.jst.go.jp/browse/msjmag

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# Crystal Structure and Magnetic and Magneto-optical Properties of CoPt, MnPt<sub>3</sub>, CrPt<sub>3</sub>, MnAl and MnGa Films with Ordered Phase and Their Bit-patterned Media

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This paper reviews the crystal structure and magnetic and magneto-optical properties of CoPt, MnPt<sub>3</sub>, CrPt<sub>3</sub>, MnAl and MnGa films with an ordered phase as well as dot patterns fabricated on these films. CoPt film grown on a MgO (111) substrate at 300°C had an L1<sub>1</sub> phase and exhibited a large perpendicular anisotropy. CrPt<sub>3</sub> films, which had a (111) orientation and L1<sub>2</sub> phase, showed a large perpendicular anisotropy due to the magneto-elastic effect. By utilizing the change from L1<sub>2</sub> to a disordered phase caused by low-dose Kr<sup>+</sup> ion irradiation, dot patterns were prepared on CrPt<sub>3</sub> film with a flat surface. It was found that a CoGa buffer layer was effective at growing thinner L1<sub>0</sub> MnAl and MnGa films on a MgO (001) substrate while keeping a (001) orientation. In the case of fabricating MnGa on SiO<sub>2</sub>/Si substrates, a buffer layer of CoGa/Cr/MgO/Cr/NiTa was necessary to grow L1<sub>0</sub> MnGa with a (001) orientation.

Key words: ordered alloy film, perpendicular anisotropy, magneto-elastic effect, magneto-optical effect, ion irradiation, bit-patterned media

### 1. Introduction

The study on crystal structure, magnetic properties and bit pattern fabrication of various ordered alloy films are introduced in this review paper, which is a research subject related to MSJ Achievement Award 2020. Multilayers and ordered alloy films of 3d-transition metals and noble metals were intensely studied from late 1980s as potential materials for magneto-optical and perpendicular magnetic recording because of their large perpendicular magnetic anisotropy and magneto-optical effect. After commercialization of magneto-optical recording in late 1980s using TbFeCo amorphous alloy films, Co/Pt and Co/Pd multilayers were received much attention as next generation materials for high density magneto-optical recording using a blue laser due to their large magneto-optical Kerr rotation around 300 nm<sup>1)·3)</sup>. Ordered CoPt and FePt alloy films with L10 structure were successively investigated because they exhibit larger perpendicular anisotropy and magneto-optical effect than multilayers<sup>4)-6)</sup>.

In addition, perpendicular anisotropy was reported in CoPt film with non-equilibrium L1<sub>1</sub> phase<sup>7)-9)</sup> and CrPt<sub>3</sub> film with L1<sub>2</sub> phase<sup>10), 11)</sup>. Magnetic properties of CrPt<sub>3</sub> films can be controlled from ferrimagnetic to non-magnetic by ion irradiation since ion-implantation destroys ordered L1<sub>2</sub> phase and alters magnetism to non-magnetic phase. Utilizing resist patterning and ion irradiation, bit patterns of perpendicular magnetized CrPt<sub>3</sub> films can be fabricated without etching process of the film<sup>12)-14)</sup>. After 2010s, perpendicular magnetized MnAl and MnGa films with L1<sub>0</sub> phase were received a lot

of attention as spintronic materials because of their high spin polarization and low Gilbert damping<sup>15)-18</sup>. They are also useful materials for bit pattern processing by ion irradiation<sup>19</sup>, <sup>20</sup>.

### 2. L11 CoPt films grown on MgO (111)

Two ordered phases of L10 CoPt and L12 CoPt3 can be seen in phase diagram of Co-Pt binary alloy. L10 CoPt with tetragonal lattice has the structure that atomic mono-layers of Co and Pt stacked in [001] direction and (001) oriented CoPt film exhibits a large perpendicular anisotropy of  $5 \times 10^7$  erg/cc<sup>21</sup>. On the other hand, L1<sub>2</sub> CoPt<sub>3</sub> film does not show uniaxial anisotropy due to its cubic lattice. In case of film fabrication by vapor or sputtering deposition, non-equilibrium structure which is not seen in phase diagram was sporadically appeared under specific growth conditions. Authors reported that Co<sub>50</sub>Pt<sub>50</sub> films MBE-grown on a single crystal MgO(111) substrate show very large perpendicular anisotropy7). Since the  $L1_0$  CoPt film with (111) orientation does definitely not show perpendicular anisotropy, formation of an unknown phase was presumed. Figure 1 shows Xdiffraction patterns of rav Pt(2 nm)/Co50Pt50(100 nm)/Pt(10 nm)/Ag(40 nm)/MgO (001) and Pt(2 nm)/Co<sub>50</sub>Pt<sub>50</sub>(100 nm)/MgO(111) films<sup>7</sup>). In case of the CoPt film grown on MgO(001) at 300°C, superlattice line due to  $L1_0$  phase is observed in  $2\theta=24^\circ$ . In case of the film on MgO(111) grown at 200°C and  $300^{\circ}$ C, a strong peaks around  $2\theta = 20^{\circ}$  and  $65^{\circ}$  are seen. This implies that a superlattice in the film normal direction is formed. In order to identify crystal structure of this film, the reciprocal space map was measured along the  $Q_z$  and  $Q_x$  axes as shown in Fig. 2 (a), where  $Q_z$  is perpendicular component of the momentum transfer vector and  $Q_x$  the in-plane component of [11-2] direction.

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Fig. 1 X-ray diffraction patterns of  $Pt_{50}Co_{50}$  (100 nm) films grown on (111) and (001) MgO substrates with various growth temperatures.



**Fig. 2** Reciprocal space maps for (a)  $Pt_{50}Co_{50}$  film grown on MgO (111) at 300°C and (b) twinned rhombohedral system, where closed and open circles indicate diffraction spots from ABC and ACB stacking, respectively. Lattice image of rhombohedral system (c).

Figure 2 (b) illustrates the predicted map for the rhombohedral lattice shown in Fig. 2 (c), where close packed (111) planes of Co and Pt mono-layers alternately stack and a twinned structure composed of ABC and ACB stacking is formed. The experimental map of the CoPt

film well coincides with the predicted map of the rhombohedral lattice. Although the rhombohedral phase called as L1<sub>1</sub> does not appear in the Co-Pt phase diagram, it is seen in Cu-Pt diagram. Figure 3 shows the dependence of perpendicular anisotropy on the growth temperature. The L1<sub>1</sub> CoPt film grown at 300°C exhibits large anisotropy of  $1.7 \times 10^7$  erg/cc, which is approximately same value with L1<sub>0</sub> CoPt film with (001) orientation. The CoPt film on MgO(111) at 500°C does not show perpendicular anisotropy because of formation of L1<sub>0</sub> phase instead of L1<sub>1</sub>. The preparation of perpendicular magnetized L1<sub>1</sub> CoPt films by sputtering was also reported by H. Sato *et al.*<sup>22)</sup>

Figure 4 shows the spectra of magneto-optical Kerr rotation  $\theta_k$  for the L1<sub>1</sub> film at 300°C, the L1<sub>0</sub> film at 300°C and other magneto-optical materials<sup>7), 10), 23)-26). The difference in  $\theta_k$  spectra between L1<sub>1</sub> and L1<sub>0</sub> CoPt films may reflect the difference in coordination number of Co and Pt atoms.</sup>

### 3. L12 MnPt3 and CrPt3 films grown on fused quartz



**Fig. 3** Growth temperature  $T_{\rm g}$  dependence of perpendicular anisotropy  $K_{\rm u}$  for Pt<sub>50</sub>Co<sub>50</sub> (100 nm) films.



Fig. 4 Spectra of Kerr rotation  $\theta_K$  for various magneto-optical materials.

Alloys containing Mn such as MnBi and PtMnSb are known as materials that exhibit large magneto-optical effect<sup>23), 25)</sup>. It was found that MnPt<sub>3</sub> and CrPt<sub>3</sub> films with L1<sub>2</sub> phase also show a large Kerr rotation as shown in Fig.  $4^{10), 26), 27)$ . MnPt<sub>3</sub> and CrPt<sub>3</sub> films were prepared by sputtering on a fused quartz substrate and post-annealed at 800°C. Their phase was confirmed to be L1<sub>2</sub> by X-ray diffraction. MnPt<sub>3</sub> film shows a large Kerr rotation of 1.2° at 1.2 eV, which is larger than those for CoPt and FePt films. While the Kerr rotation of CrPt<sub>3</sub> film is smaller than that of MnPt<sub>3</sub> in energy range from 0.8 eV to 2.3 eV, the shape of Kerr spectrum of CrPt<sub>3</sub> is similar to that for MnPt<sub>3</sub>. Figure 5 shows the hysteresis loops for the MnPt<sub>3</sub> and CrPt<sub>3</sub> films<sup>28), 29)</sup>. The MnPt<sub>3</sub> film is in-plane magnetized but the CrPt<sub>3</sub> perpendicular magnetized. Since the crystal structure of L1<sub>2</sub> CrPt<sub>3</sub> is a cubic lattice, the perpendicular anisotropy could not be induced from crystal anisotropy. In order to identify the origin of the anisotropy of the CrPt<sub>3</sub> film, the relationship between the perpendicular anisotropy  $K_{\rm u}$  and the lattice distortion was measured as shown in Fig. 611). The distortion was defined as  $2(a_i-a_p)/(2a_i+a_p)$ , where  $a_i$  and  $a_p$  were in-plane and normal lattice constants, respectively. The CrPt<sub>3</sub> film on a fused quartz, which shows a large anisotropy, is distorted by 0.7 %. This is because that the film is expanded in in-plane direction due to the difference of thermal expansion coefficient between the film and the quartz substrate during a cooling process after annealing. On the other hand, the  $CrPt_3$  film on a MgO(111)



**Fig. 5** M-H loops of MnPt<sub>3</sub> (150 nm) and CrPt<sub>3</sub> (150 nm) films with L1<sub>2</sub> phase.



**Fig. 6** Dependence of uniaxial anisotropy  $K_u$  on lattice distortion for CrPt<sub>3</sub> (60 nm) and MnPt<sub>3</sub> (60 nm) alloy films grown on fused quartz, MgO (111) and Al<sub>2</sub>O<sub>3</sub> (001c).

Table 1	Magneto-striction constants $\lambda_{100}$ and $\lambda_{111}$ of
MBE-gro	own CrPt <sub>3</sub> and MnPt <sub>3</sub> films on fused quartz.

	$\lambda_{100}$	$\lambda_{111}$
MnPt <sub>3</sub>	5×10 <sup>-5</sup>	3×10 <sup>-5</sup>
CrPt <sub>3</sub>	$-16 \times 10^{-5}$	$-4 \times 10^{-5}$

substrate, which does not show perpendicular anisotropy, is not distorted because the thermal expansion coefficient of MgO is almost same as that for the CrPt<sub>3</sub> film. This difference between the films on fused quartz and MgO implies that the anisotropy of CrPt<sub>3</sub> films is affected from magneto-elastic effect. The magneto-striction constants shown in Table 1 were estimated from the variation of anisotropy by bending the film on fused quartz of 0.1 mm thickness<sup>11)</sup>. The magneto-striction constants  $\lambda_{100}$  and  $\lambda_{111}$  of CrPt<sub>3</sub> are both negative while those of MnPt<sub>3</sub> are positive. Using the value of lattice distortion and the magneto-striction constants,  $_{\mathrm{the}}$ magneto-elastic contribution to perpendicular anisotropy were estimated as  $1.4 \times 10^6$  erg/cc for CrPt<sub>3</sub> film and  $-0.9 \times 10^6$  erg/cc for MnPt<sub>3</sub> film on fused quartz, which are comparable to the measured anisotropy shown in Fig. 6. This means that the origin of the perpendicular anisotropy of  $CrPt_3$  on fused quartz is magneto-elastic effect.

Since the CrPt<sub>3</sub> films is ferrimagnetic and perpendicular magnetized in L1<sub>2</sub> phase and nonmagnetic in disordered phase, the fabrication of patterned media was made by phase transition using ion irradiation on L1<sub>2</sub> CrPt<sub>3</sub> films<sup>30</sup>. Figure 7 shows the reduction of anisotropy  $K_u$  and magnetization  $M_s$  by Kr<sup>+</sup> ion irradiation of 30 kV to L1<sub>2</sub> CrPt<sub>3</sub> film with 20 nm thickness<sup>12), 13</sup>. The  $K_u$  and  $M_s$  monotonically decrease with ion dose and are reduced to almost zero at  $2 \times 10^{14}$ ions/cm<sup>2</sup>, which implies that the crystal structure is transformed to disordered phase. Figure 8 shows MFM image of bit patterned CrPt<sub>3</sub> film, which was fabricated by the formation of resist patterns on CrPt<sub>3</sub>(20 nm) film and the iron irradiation of  $2 \times 10^{14}$  ions/cm<sup>2</sup>. The MFM



**Fig. 7** Dependence of normalized saturation magnetization  $M_{\rm s}$  and coercivity  $H_{\rm c}$  of CrPt<sub>3</sub> (20 nm) on 30 kV Kr<sup>+</sup> ion dose.



Fig. 8 MFM image of ion-beam-patterned CrPt<sub>3</sub> (20 nm) film with square bit size of  $90 \times 90$  nm<sup>2</sup> separated by spacing of 90 nm fabricated with 30 keV Kr<sup>+</sup> irradiation of  $2 \times 10^{14}$  ions/cm<sup>2</sup> through ZEP resist mask made by EB lithography.

image shows that the square bit patterns of  $90 \times 90$  nm<sup>2</sup> are formed and are randomly magnetized. It is considered to be effective to obtain bit patterned media with very flat surface by utilizing the transition from magnetic to non-magnetic states in ordered alloy films.

### 4. L1<sub>0</sub> MnAl and MnGa films grown on MgO (001)

In previous section, it is presented that bit patterned media can be fabricated utilizing phase change of perpendicular magnetized L1<sub>2</sub> CrPt<sub>3</sub> films. However, the practical application of CrPt<sub>3</sub> to magnetic recording media is not easy because of the high preparation temperature around 800°C. In the next step, L1<sub>0</sub> MnAl and MnGa films were investigated because these films exhibit larger perpendicular anisotropy than CrPt<sub>3</sub> film and can be fabricated at a relatively low process temperature around 400°C<sup>31), 32)</sup>. In addition, these materials are promising candidates for a ferromagnetic electrode of spintronic devices due to their low Gilbert damping.

In the first place, using single crystal MgO(001) substrates, Cr(2 nm)/(MnAl or MnGa)(15 nm)/Cr(20 nm) /MgO(001) films were fabricated by sputtering, where the Cr buffer layer was annealed at 600°C after deposition at room temperature, the MnAl layer was grown at 600°C and the MnGa layer was annealed 30 minutes at 400°C after deposition at less than 100°C. While the both MnAl and MnGa films show large perpendicular anisotropy as shown in Fig. 9, the squareness of the MnGa film is better



**Fig. 9** M-H loops of (a) MnAl (15 nm) and (b) MnGa (15nm) films with L1<sub>0</sub> phase grown on MgO (001) substrates.



**Fig. 10** 30 keV Kr<sup>+</sup> ion dose dependence of normalized  $M_{\rm s}$ ,  $H_{\rm c}$ , and  $K_{\rm u}$  of (a) MnAl (15 nm) and (b) MnGa (15 nm) films.

than that of the MnAl film<sup>20), 33)</sup>. In addition, the saturation magnetization and squareness of MnAl films decline with decreasing growth temperature to 500°C.

Figure 10 shows the dependence of magnetization  $M_{\rm s}$ , perpendicular anisotropy  $K_{\rm u}$  and coercivity  $H_{\rm c}$  on ion dose of 30 keV Kr<sup>+</sup>, where these values are normalized as the values before ion irradiation<sup>20), 33)</sup>. The  $M_{\rm s}$ ,  $K_{\rm u}$  and  $H_{\rm c}$  are reduced to nearly zero at  $1 \times 10^{14}$  ions/cm<sup>2</sup>, which is almost same as that for CrPt<sub>3</sub> film shown in Fig. 7. The  $K_{\rm u}$  of MnGa film proportionally decreases with  $M_{\rm s}$ , whereas the  $K_{\rm u}$  of MnAl decreases faster than the  $M_{\rm s}$ . In case of MnGa film, the  $H_c$  temporarily increases by 10 % and then steeply decreases with the ion dose. This increase of  $H_c$  is considered due to the creation of pinning sites by ion irradiation. The reason of these difference between MnGa and MnAl films is considered to be island growth of MnAl films grown at 600°C and smaller average mass of MnAl, which causes straightforward penetration of ions compared to MnGa.

Figure 11 shows MFM images of bit patterns of MnGa film fabricated by ion dose of  $1 \times 10^{14}$  ions/cm<sup>2</sup> <sup>19), 20)</sup>. The clear magnetic contrast due to randomly magnetized bits is observed in both pitch sizes of 100 and 80 nm. In order to fabricate smaller bit patterns than 80 nm, it is necessary to decrease the thickness of MnGa layer, because sharper transition interface between magnetic and non-magnetic areas will be realized by shortening the penetration depth of ion irradiation and suppressing ion scattering in MnGa layer. However, the  $M_{\rm s}$  and the squareness of both MnAl and MnGa decrease with decreasing layer thickness from 15 nm to 5 nm<sup>34</sup>). Since it had been reported that the insertion of CoGa buffer



**Fig. 11** MFM images of ion-beam patterned MnGa (15 nm) film with pitch sizes of (a) 100 nm and (b) 80 nm.

layer was effective to improve the degradation of  $M_{\rm s}$  and squareness<sup>35), 36)</sup>, Cr(2 nm)/MnAl(5 nm)/CoGa(0 or 30 nm) /Cr(20 nm)/MgO(001) films were fabricated by sputtering, where the CoGa/Cr layers were annealed at 600°C after deposition at 400°C and the MnAl layer was deposited at 200°C. Figure 12 shows XRD profiles of 5nm thick MnAl films on Cr or CoGa buffer layer, where one of MnAl film on CoGa layer was post-annealed at  $T_a$ =500°C and another was not annealed<sup>34)</sup>. The 001 and 002 peaks from L10 MnAl were clearly observed in all films and both the insertion of the CoGa buffer layer and the post-annealing of the MnAl layer are effective to enhance 001 peak due to the ordered phase. The peak positions of 001 and 002 are shifted to high angle side from the angles for bulk L10 MnAl, which are indicated by dotted lines in Fig. 12. This is because the lattice constant of MnAl layer is enlarged in in-plane direction due to lattice mismatch between MnAl and the buffer CoGa or Cr layers. Figure 13 shows the hysteresis loops of these films<sup>34</sup>). The  $M_s$  of the MnAl (5 nm) on Cr layer significantly decreases compared to the MnAl (15 nm) film shown in Fig. 9, whereas the  $M_{\rm s}$  and squareness of the MnAl (5 nm) on CoGa are considerably improved.

### 5. L10 MnGa films grown on Si

In order to utilized MnAl or MnGa films as magnetic



**Fig. 12** XRD profiles of MnAl (5 nm) films grown on Cr and CoGa layers at  $T_s = 200^{\circ}$ C, where profiles are shown in linear scale. One sample on CoGa was post-annealed at 500°C and another was not annealed. Dotted lines indicate peak positions of bulk L1<sub>0</sub>-MnAl.



**Fig. 13** *M*·*H* curves of MnAl (5 nm) films grown on (a) Cr and (b), (c) CoGa layers at  $T_s = 200^{\circ}$ C. Sample (c) was post-annealed at  $T_a = 500^{\circ}$ C.

recording media, (001) oriented films with  $L1_0$  phase must be grown on inexpensive substrates instead of single crystal MgO substrates. Successively, (001) oriented MnGa film was made an attempt to be grown on Si substrate with SiO<sub>2</sub> oxidized layer. Since it had been reported that the insertion of CrB/NiTa buffer layer improved (001) orientation of  $L1_0$  FePt films<sup>37)</sup>, Cr(5 nm)/MnGa(15 nm)/Cr(20 nm)/MgO(5 nm)/CrB(5 nm)/NiTa(25 nm)/SiO2/Si substrate films were fabricated, where CrB/NiTa and Cr/MgO layers were grown by sputtering and e-beam evaporation at room temperature, respectively and then annealed at 800°C<sup>38)</sup>. The MnGa layer was annealed at 400°C for 60 minutes after sputter deposition at temperature  $T_{\rm s}$ . Figure 14 shows XRD profiles of MnGa films on Si substrate grown at various  $T_{\rm s}$ . The 002 peaks of MgO and Cr layers are clearly observed in all films, which means that the buffer layers are grown with (001) orientation. In addition, the 001 peak from L10 MnGa phase was observed for the films of  $T_s=200$  and  $300^{\circ}$ C, whose 001 peak position coincides with the bulk position indicated by a dotted line. Both  $M_{\rm s}$  and squareness of out-of-plane M-H loops are improved by raising the growth temperature at  $T_{\rm s}=200^{\circ}{\rm C}$ as shown in Fig. 15. Figure 16 shows the MFM images of the dot-patterned MnGa film with 300, 150 and 100 nm pitch sizes fabricated by the 30 keV Kr<sup>+</sup> ion dose of  $1 \times$  $10^{14}$  ions/cm<sup>2</sup>. Although the magnetic dot images are observed in all the samples, the outlines of circular dots is not sharp and some of dots do not show clear magnetic contrast. This implies that the improvement of



**Fig. 14** X-ray profiles of MnGa (15 nm) films on Si substrate grown at various temperatures  $T_{\rm s}$ .



**Fig. 15** M-H loops of MnGa (15 nm) films on Si substrate grown at various temperatures  $T_{\rm s}$ .



Fig. 16 MFM images of dot-patterned MnGa (15 nm) film fabricated by 30 keV Kr<sup>+</sup> ion dose of  $1 \times 10^{14}$  ions/cm<sup>2</sup>.

homogeneity of the MnGa films on Si substrates is necessary for practical application.

In order to fabricate smaller dot patterns of MnGa film on Si substrate, the MnGa layer thickness was reduced to 5nm, whereas the  $M_{\rm s}$  substantially decreased. Therefore, the insertion of CoGa buffer layer was employed since it was confirmed to be effective for reduction of the thickness of MnAl films. Figure 17 shows the XRD profiles of Cr(2 nm)/MnGa(5 nm)/CoGa(30 nm)/Cr(20 nm)/MgO(20 nm)/CrB(5 nm)/NiTa(25 nm)/ SiO<sub>2</sub>/Si substrate films, where Cr/MgO/CrB/NiTa layers were annealed at 800°C and then CoGa buffer layer was annealed at  $T_{\rm a}^{\rm CoGa}$  for 30 minutes after deposition at 400°C<sup>39)</sup>. After the preparation of the buffer layers, the MnGa layer was grown at 200°C and annealed



**Fig. 17** X-ray profiles of MnGa (5 nm) films on Si substrate for samples with various annealing temperatures  $T_a^{CoGa}$  for CoGa buffer layer.



**Fig. 18** Dependence of  $M_{\rm s}$  and average surface roughness  $R_{\rm a}$  of MnGa (5 nm) films on Si substrate on annealing temperature  $T_{\rm a}^{\rm CoGa}$  of CoGa buffer layer.



**Fig. 19** *M*-*H* loops (a) and AFM image (b) of MnGa (5 nm) film with  $T_a^{CoGa} = 700^{\circ}$ C.

CoGa layer was clearly seen in the XRD profiles while the peaks from L1<sub>0</sub> phase of MnGa layer were very weak due to its reduced thickness. Figure 18 shows the  $T_{\rm a}^{\rm CoGa}$  dependence of  $M_{\rm s}$  and average surface roughness  $R_{\rm a}$  of the MnGa films on Si substrates. The  $M_{\rm s}$  increases with increasing  $T_{\rm a}^{\rm CoGa}$  and takes a peak value at 700°C while the roughness is degrading with  $T_{\rm a}^{\rm CoGa}$ . Figure 19 shows M·H loops and AFM image of the MnGa film of  $T_{\rm a}^{\rm CoGa}$ =700°C. This film shows large  $M_{\rm s}$ , large perpendicular anisotropy and good squareness, which are similar to the film on MgO substrate shown in Fig. 9 (b). However, improvement of the large surface roughness is necessary for the application to recording media.

### 6. Summary

In this paper, the crystal structure, magnetic and magneto-optical properties of CoPt, MnPt<sub>3</sub>, CrPt<sub>3</sub>, MnAl and MnGa films with ordered phase and the dot patterning by ion irradiation are reviewed. The CoPt films grown on a heated MgO(111) substrate have  $L1_1$ phase, which does not appear in Co-Pt phase diagram, and exhibit large perpendicular anisotropy. The CrPt<sub>3</sub> films with L12 phase show large perpendicular anisotropy due to magneto-elastic effect. By utilizing the change from L12 to disordered phase caused by the low dose Kr<sup>+</sup> ion irradiation, dot patterns of CrPt<sub>3</sub> film with flat surface were successfully prepared. It is found that the CoGa buffer layer is effective to grow thinner L10 MnAl and MnGa films on MgO(001) substrate with keeping (001) orientation. In the case of fabrication of MnGa on SiO<sub>2</sub>/Si substrates, the buffer layer of CoGa/Cr/MgO/Cr/NiTa is necessary to grow L10 MnGa with (001) orientation. The ordered alloy films described in this review are considered to be useful materials for magnetic recording and spintronics technology.

**Acknowledgment** The authors would like to thanks to the students who performed a lot of experiments in our laboratory and to M. Kumazawa for his dedicated assistance in experiments.

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Received May 01, 2021; Accepted July 19, 2021

# Reluctance Network Model of Interior Permanent Magnet Motor with Polar Anisotropic Magnet

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To establish a practical method for analyzing interior permanent magnet (IPM) motors that have complicated flux distribution, this paper presents a method for deriving an analytical model for the IPM motor with polar anisotropic magnets, based on a reluctance network analysis (RNA). The proposed model can calculate the basic characteristics of the IPM motor with high accuracy and high speed by comparing the calculation results with the FEM and experiment.

Key words: interior permanent magnet (IPM) motor, reluctance network analysis (RNA), polar anisotropic magnet

### 1. Introduction

In recent years, electrification has been promoted in various fields such as industry, transportation, and people's livelihood so that the demand for motors has been expanding. Among various types of motors, utilization of a permanent magnet (PM) motor has been extremely increasing due to the rapid development of power electronics technology and the significant performance improvement of permanent magnets. PM motors can be divided into a surface permanent magnet (SPM) motor and an interior permanent magnet (IPM) motor. Among them, an IPM motor generally has high output and efficiency characteristics because it can utilize the reluctance torque generated from the magnetic saliency, in addition to the magnet torque. To further improve the performances of IPM motors, it is necessary to design not only the motor structure but also the control system. However, in the design and analysis based on a finite element method (FEM), it is not necessarily practical to perform the coupled analysis of the electromagnetic and control systems, which generally requires a long calculation time and a large computer memory.

To solve the above problem, we have proposed a reluctance network analysis (RNA), which expresses an analytical object by one reluctance network. All the reluctances can be determined by the *B-H* curve of the material and dimensions <sup>1)</sup>. The RNA has some advantages such as a simple model, fast calculation, and easy coupling with external electric circuits and motion equation. The RNA has been applied to the calculation of characteristics of various electric machines including motors <sup>2)-7)</sup>. In the previous papers on the RNA, the SPM motors were often used as objects of discussion. In most of these considerations, the RNA models are relatively coarsely divided, and their rotational motions are expressed by only switching the positive and negative of the MMFs generated from the permanent magnets, that

is, the circuit topology does not change.

On the other hand, only the IPM motors with relatively simple structures such as an inset type were examined for the RNA. This fact seems to be due to the model complexity. To express the complicated flux distribution with high accuracy, it is necessary to finely divide the RNA model into a large number of elements in the same manner as the FEM in general. However, in this way, the calculation time and cost increase as the model scale becomes larger, and the model construction becomes too complicated since the MMFs in each divided element should be intricately changed depending on the rotor position angle. In contrast, in a few papers on the RNA, the reluctance connections between the stator and rotor are switched with rotations 8). However, this technique leads to low calculation speed and constraints on the fineness of division due to deterioration of solution convergence. Thus, the original requirements of the RNA cannot be satisfied so far.

Therefore, this paper presents a method for deriving the RNA model which can express the flux distribution with necessary and sufficient calculation accuracy without fine model division. In this way, it is possible to analyze with practical calculation time and cost even when the RNA is applied to IPM motors with complicated structures. Among IPM motors with various structures which have been proposed so far, this paper focuses on the one which has neodymium-bonded magnets magnetized with polar anisotropy. In this paper, the basic characteristics of the IPM motor are calculated by using the proposed RNA model, and its validity is proved by comparing the calculation results with the FEM and experiment.

### 2. Derivation of RNA Model for IPM Motor with Polar Anisotropic Magnets

### 2.1 Basic configuration of IPM motor

Fig. 1(a), (b), and (c) show the IPM motor used in the consideration and its rotor structure. The magnet material is bonded Nd-Fe-B magnet, the recoil permeability is 1.275, and the coercive force is 461 kA/m. Besides, as shown in Fig. 1(c), the rotor magnets are

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magnetized in the arcuate direction, not in the general radial and parallel ones, so that the flux concentrates at the center of the magnetic pole. As a result, the gap flux distribution becomes almost sinusoidal, and the amplitude of the fundamental wave component, which contributes to the torque, increases  $^{9), 10)}$ .

### 2.2 Derivation method of RNA model

Fig. 2 shows the simplified view of the proposed RNA model of one pole of the IPM motor. This model is halved in the z-axis direction in consideration of the magnetic field symmetry. As shown in this figure, each divided element is expressed by a reluctance element, whose parameters can be determined by the B-H curve of the material and dimensions of the divided elements. In the following, the derivation method of the proposed model is described in detail for each part of the IPM motor.

First, the derivation method of the magnetic circuit of the stator is explained <sup>1)</sup>. Each reluctance in the stator core has to be determined in consideration of the nonlinear magnetic properties. Besides, it is preferable to express the *B-H* curve by using an approximate equation rather than a look-up table from the view point



(c) Rotor structure. **Fig. 1** IPM motor used in the consideration.



**Fig. 2** Simplified view of the RNA model of one pole of the IPM motor.

of solution convergence. Here, the magnetic nonlinearity is given by

$$H = \alpha_1 B + \alpha_m B^m \tag{1}$$

where the coefficients are  $\alpha_1 = 51$  and  $\alpha_m = 2.5$ , respectively. The order m = 15 is determined by the strength of the nonlinearity of the *B*-*H* curve. Fig. 3 shows the measured *B*-*H* curve of the core material and its approximated curve. From the equation (1), the relationship between the MMF  $f_m = Hl$  and the magnetic flux  $\phi = BS$  in each reluctance can be expressed by the following equation:

$$f_m = \left(\frac{\alpha_1 l}{S} + \frac{\alpha_m l}{S^m} \phi^{m-1}\right) \phi \tag{2}$$

where the average cross-sectional area and magnetic path length of each element are S and l, respectively. Therefore, the nonlinear reluctance  $R_m$  is given by the following equation:

$$R_m = \frac{\alpha_1 l}{S} + \frac{\alpha_m l}{S^m} \phi^{m-1}$$
(3)

Next, the air region surrounding the stator core is also included in the analytical model so that the leakage flux between the center and tip of the stator pole can be taken into consideration. The reluctance in the air region is simply given by the following equation:

$$R_a = \frac{l}{\mu_0 S} \tag{4}$$

where the vacuum permeability is  $\mu_0$ . Besides, the MMF generated by the winding current is concentrated in which the winding is applied.

On the other hand, the stator pole tips, air gaps, and rotor magnets, where the flux distribution is more complicated, are divided into 360 in increments of 1 degree in the circumferential direction. Here, the reluctances in the rotor core are neglected since they are



**Fig. 3** *B-H* curve of core material and its approximated curve.

extremely smaller than those in the magnets, whereas those in the stator core must be considered due to the relatively high flux density in the poles, which are the main flux paths, and the local saturation at the pole tips. The reluctances in the stator pole tips and air gaps are represented by using the equations (3) and (4), respectively. Further, the reluctances  $R_p$  and MMF  $F_c$  in the magnets are given by the following equations:

$$R_{p}(\theta) = \frac{|l_{p}(\theta)|}{\mu_{0}\mu_{r}S}$$
(5)

$$F_c(\theta) = H_c l_p(\theta) \tag{6}$$

where the recoil permeability is  $\mu_r$  and the coercive force is  $H_c$ , respectively. The effective length  $l_p(\theta)$  in the arc-shaped magnetized direction, changes depending on the rotor position angle  $\theta$  as shown in Fig. 4(a) and (b), and is given by the Fourier series as follows:



(b) Relationship between the rotor position angle  $\theta$  and the effective length  $l_p(\theta)$ .

**Fig. 4** Effective length  $l_p(\theta)$  of the permanent magnet corresponding to the rotor position angle  $\theta$ .

$$l_p(\theta) = \sum_{j=1}^{N} a_j \cos^2(2j-1)\theta \tag{7}$$

where the coefficient is N = 15. In this way, the complicated flux distribution of the rotor with polar anisotropic magnets can be expressed with a simple model, compared to a finely divided FEM model.

Moreover, some flux flows into the laminated surface of the stator core from the protruding rotor magnets and leaks into the air region since this IPM motor has an overhang structure. To strictly consider it, a threedimensional magnetic circuit is generally required. However, it is expected that the calculation time increases as the model becomes larger. Thus, to simply represent the overhang structure, each circumferential element in the protruding parts of the rotor magnets is connected to the laminated surface at the opposing stator pole tips and the leakage reluctances from all other circumferential elements, as shown in Fig. 5.

### 3. Simulation Results by Using Proposed Method

In this chapter, the basic characteristics of the IPM motor are calculated by using the proposed RNA model. The RNA is performed by using Ansys Twin Builder 2021 R1, which is the general-purpose circuit simulator. In the analysis, the three-phase sinusoidal current is input when the current phase angle is 18 deg., and the rotational speed of the IPM motor is constant at 12600 rpm. The RNA calculation results are validated by comparing with the experimental and FEM calculation ones. In the experiment, characteristics of the IPM motor are obtained by measuring input current and







Fig. 6 Experimental setup.

power when the motor is arbitrarily loaded while driven by a PWM converter at a constant rotational speed of 12600 rpm, using the system as shown in Fig. 6. The FEM is conducted by using JMAG-Designer Ver.20.0, which is the general-purpose electromagnetic field analysis software.

Fig. 7(a) and (b) show the comparisons of the calculated flux density waveforms flowing through the center of the stator pole, between the RNA and FEM. From these figures, it is understood that both results are in good agreement.

Fig. 8 shows the measured and calculated winding current density versus torque characteristics. From this figure, it is clear that the calculation results of the RNA and FEM are in good agreement. On the contrary, the measured and calculated results are almost in good



(b) Winding current density is 7 A/mm<sup>2</sup>.Fig. 7 Flux density waveforms flowing through the stator pole center.



**Fig. 8** Winding current density versus torque characteristics.

agreement though there is a little error, whose cause is that the iron and mechanical losses are neglected in the analysis.

### 4. Calculation Considering Iron Loss

### 4.1 RNA model of IPM motor considering iron loss

In this section, the derivation method of the improved RNA model which can consider the iron loss in a simple way <sup>11)</sup> is described, to further increase the calculation accuracy of the above-proposed RNA model.

Fig. 9 shows the RNA model of the IPM motor considering the iron loss. As shown in this figure, each part in the stator core is expressed by connecting an inductance element representing the iron loss in series with the reluctance given by the equation (3). Here, the relationship between the MMF  $f_m$  and the magnetic flux  $\phi$  in each divided element can be expressed by the following equation:

$$f_{m} = \left(\frac{\alpha_{l}l}{S} + \frac{\alpha_{m}l}{S^{m}}\phi^{m-1}\right)\phi + \frac{\beta_{l}l}{S}\frac{d\phi}{dt}$$
$$= R_{m}\phi + L_{m}\frac{d\phi}{dt}$$
(8)

where the coefficient is  $\beta_1 = 0.0438$ , which can be approximately determined by fitting the core loss curves of the materials by the least squares method based on the following equation:

$$W_i = \frac{2\pi^2 \beta_1}{q} f^2 B_m^2$$
 (9)

where the iron loss per unit weight is  $W_i$ , the mass density is q, the frequency is f, and the maximum flux density is  $B_m$ , respectively. In this way, it is possible to calculate the iron loss without post-processing using the Steinmetz' equation <sup>12</sup> in the RNA.

### 4.2 Iron loss and efficiency calculation results

In this section, the analysis is performed by using the improved RNA model under the same conditions as in Chapter 3. The validity of the RNA calculation results is verified by comparing with the experimental and FEM calculation ones.

Fig. 10 shows the measured and calculated winding current density versus torque characteristics. This figure reveals that the calculated values of the RNA are somewhat closer to the measured ones than those shown in Fig. 8 by considering the iron loss. On the other hand, there are still some errors since the mechanical loss is not taken into account in the analysis.

Fig. 11 shows the measured and calculated iron loss characteristics. In the RNA, the iron loss is calculated by taking the sum of the products of the MMF and the time derivative of the flux in each divided element. On the other hand, in the FEM, FFT is performed on the flux density waveforms in each element obtained from the electromagnetic field analysis, and the iron loss is calculated by applying the Steinmetz' equation to the waveforms of each order <sup>12</sup>. From the figure, it is clear that the calculated values of the RNA and FEM are in



**Fig. 9** Simplified view of the RNA model of one pole of the IPM motor which can consider the iron loss.



**Fig. 10** Winding current density versus torque characteristics considering the iron loss in the RNA.



good agreement. On the contrary, when comparing the RNA calculation results and experimental ones, it can be seen that both are almost in good agreement at high load, while the errors are larger at low load. The cause of the errors is that the additional loss generated by the

carrier harmonics in the measured current waveforms, as shown in Fig. 12(a) and (b), is not taken into consideration in the analysis. It is known that the iron loss cannot be accurately calculated when this RNA model is applied to a complicatedly distorted excitation waveform <sup>13)</sup>. Therefore, a further increase in the calculation accuracy is indispensable by improving the current RNA model.

Fig. 13 shows the measured and calculated efficiency characteristics. In the RNA and FEM, to calculate the efficiency including the mechanical loss, the measured values are substituted. From this figure, it is understood that the calculated and measured results are in good agreement.

Table 1 shows the comparison of the calculation time per one cycle of electric angle between the RNA and



**Table 1**Comparison of calculation time per one cyclebetween RNA and FEM.

Winding current density (A/mm <sup>2</sup> )	RNA calculation time (s)	FEM calculation time (s)
0	15.0	3237.5
1	15.0	3236.5
2	15.0	3285.0
3	15.0	3342.5
4	15.0	3301.5
5	15.0	3222.5
6	15.5	3293.5
7	15.5	3381.0

FEM. Here, the RNA is non-parallel computation, while the FEM is conducted by using two processor cores. The numbers of calculation steps per one cycle in the RNA and FEM are 240 and 180, respectively. As shown in the table, the RNA calculation time is less than 1% of that of the FEM in each case, which indicates that the proposed RNA model is excellent from the view point of not only the calculation accuracy but also the calculation speed.

### 5. Conclusion

This paper presented a method for deriving the RNA model of the IPM motor with the complicated structure, by using the one which has polar anisotropic magnets as a representative. As a result of the consideration, it is clarified that the proposed RNA model can calculate several characteristics of the IPM motor with high accuracy. Besides, in this way, it is possible to construct the relatively simple model without problems such as an increase in model scale and deterioration of solution convergence. In the future, we plan to study the following two things:

 To more accurately calculate the iron loss including the minor loop when the IPM motor is driven by a PWM converter by incorporating the play model <sup>14)</sup> and Cauer circuit <sup>15)</sup>, as suggested in the previous paper <sup>16)</sup>.

(2) To derive a simple RNA model for IPM motors with other various structures, such as when magnets are arranged in a V-shape.

**Acknowledgements** This work was supported by Grant-in-Aid for JSPS Fellows (JP19J20572).

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Received Apr. 16, 2021; Accepted Jul. 18, 2021

<Paper>

## Magnetocardiography Current Source Estimation using Multiple Spatial Filters

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In this study, cardiac current source localization was simulated using the spatial filter method. We estimated current sources using data from two measurement surfaces, i.e., the front and back of the subject, to reduce the large spatial extension in the depth direction. Three methods for creating spatial filters were developed using the exact low-resolution brain electromagnetic tomography method based on different creation procedures. The first method is a general method that has been conventionally used to create a spatial filter (64ch spatial filter) using a 64ch sensor on the front side. The second method is to create a spatial filter (128ch spatial filter) using two 64ch sensors on the front and back sides as a 128ch sensor. The third method is to create two spatial filters separately and use them as one spatial filter ( $2 \times 64ch$  spatial filter). In this case, different Tikhonov regularization parameters can be determined on the front and back sides, and optimum noise immunity can be given to each. The accuracy of the estimated current sources using the three types of spatial filters was examined using simulation and MCG data. The results show that the  $2 \times 64$  spatial filter has the highest estimation accuracy and suppresses the large spatial extension of the estimated current sources.

Key words: magnetocardiography, current source estimation, spatial filter, eLORETA

### 1. Introduction

Magnetocardiography (MCG) is a noninvasive technique used for detecting the magnetic field generated by electrical activities in the heart. Recently, its efficacy in the early detection of heart diseases has been evaluated <sup>1)</sup>, and its multichannel measurements, which are unaffected by the shape of the lungs and torso, have been used in clinical applications <sup>2)</sup>. MCG aims to obtain functional mapping, starting from the visualization of signal sources. Because the MCG inverse problem is illposed and does not have a unique solution, the estimation of MCG signal sources is the biggest challenge for its application <sup>3)</sup>. In the past decades, the equivalent current dipole model has been used for MCG source localization; however, single or several dipoles cannot efficiently explain measured data. Recently, the spatial filter method has been used to visualize cardiac activities. This method was developed for MCG source localization and can be used to obtain a reliable three-dimensional outline of the heart <sup>4), 5)</sup>. MCG current sources are modeled by many current dipoles of a fixed location, orientation, and variable strength. As the unknowns are more than the knowns, the inverse problem is ill-posed. Generally, the ill-posed problem can be approached by minimum-norm least squares estimation (MNLE). However, it always favors sources that are close to the magnetic field sensors and leads to the reconstruction of blurred source imaging for deep sources. A weighting matrix was used to remove the depth bias for the weighted MNLE method <sup>6)</sup>. Lead field normalization was performed to compensate for the varying sensitivities of the sensors to the current sources at different depths <sup>7</sup>). These methods could be suppressed the spread of deep sources. However, when the data in only one measurement plane is used, a sufficient suppressing effect is not obtained. Therefore, we proposed the method using two planes data<sup>8)</sup>. First, the current source is estimated using one plane (MCG data). Next, the magnetic field distribution in the opposite plane is calculated using the estimated current source. This method is the current source estimation based on two planes data using the measurement MCG data and calculated magnetic field distribution in the opposite direction. However, in current source estimation using these measurement surfaces, the estimated current sources cannot be obtained at the correct position.

In this study, we attempted to estimate the current sources using data from the two measurement surfaces, i.e., the front (chest) and the back of the subject, to reduce the large spatial extension for deep sources. In reference 8, a standardized low-resolution brain electromagnetic tomography (sLORETA) 9) was used, but in this study, an exact low-resolution brain electromagnetic tomography (eLORETA)<sup>10</sup>, which can further suppress the spread of the estimated current source, was used for MCG current source estimation. eLORETA is a non-adaptive spatial filter that can effectively localize the source with a proper Tikhonov regularization parameter <sup>11)</sup>. In addition, we aim to reduce the large spatial extension for the depth direction of the estimated current sources and proposed the spatial filter creation method using two measurement planes. The accuracy of the estimated current sources was examined using simulation and MCG data.

### 2. Methods

### 2.1 eLORETA

eLORETA is a spatial filter method used to solve illposed problems. It can obtain a blurred source image

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using a linear inverse operator  $^{10)}$ .

$$\boldsymbol{\Phi} = \boldsymbol{K}\boldsymbol{J} + \boldsymbol{n} \tag{1}$$

where  $\boldsymbol{\Phi}$  is the detected signal,  $\boldsymbol{K}$  is the lead-field matrix,  $\boldsymbol{J}$  is the original current source within the heart, and  $\boldsymbol{n}$  is the noise at each sensor. The eLORETA solution can be obtained as follows, and the estimated current sources  $\hat{\boldsymbol{J}}$  can be written as

$$\hat{J} = T\Phi \tag{2}$$

$$\boldsymbol{T} = \boldsymbol{W}^{-1}\boldsymbol{K}^{T}(\boldsymbol{K}\boldsymbol{W}^{-1}\boldsymbol{K}^{T} + \lambda\boldsymbol{I})^{-1}$$
(3)

$$W = \{K^{T}(KW^{-1}K^{T} + \lambda I)^{-1}K\}^{1/2}$$
(4)

where T is a spatial filter matrix, T denotes the matrix transpose,  $\lambda$  is the Tikhonov regularization parameter, I represents an identity matrix, and W denotes a symmetric weight matrix. The particular case of interest here is the structured block-diagonal weight matrix W. W be obtained as follows,

- Initialize the weight matrix W as an identity matrix I.
- 2. Calculate a matrix A,

 $\boldsymbol{A} = (\boldsymbol{K}\boldsymbol{W}^{-1}\boldsymbol{K}^T + \lambda\boldsymbol{I})^{-1}$ (5)

3. Calculate the new weight W,

$$\boldsymbol{W} = (\boldsymbol{K}^T \boldsymbol{A} \boldsymbol{K})^{1/2} \tag{6}$$

4. Using the new weight, go to step 2 until convergence (i.e. stop when the change in the weight matrix is sufficiently small).

In this paper, the convergence condition is that the inner product before and after the update of W is 1 (within  $10^{-12}$ ).

### 2.2 MCG measurements

The MCG data were measured using a 64-channel (8 × 8) SQUID magnetometer (MC-6400, Hitachi Ltd.) in a magnetically shielded room <sup>12)</sup>. The MCG measurements were performed on two measurement surfaces, i.e., on the back and the front (chest) side, which is the conventional measurement surface. MCGs of the two subjects were measured. Approximately 30 trials were averaged to reduce the noise. This study was approved by the Ethics Committee of Iwate University (No. 202002).

### 2.3 Proposed methods to create spatial filters

We examined three types of spatial filter fabrication methods using the two measurement surfaces. The first method is a general method that has been conventionally used to create a spatial filter (64ch spatial filter) using a 64ch sensor on the front side. The second method is to create a spatial filter (128ch spatial filter) using two 64ch sensors on the front and back sides as a 128ch sensor.



Fig. 1 Coordinate system and analysis conditions.

In this case, the Tikhonov regularization parameter  $\lambda$ has the same value on the front and back sides. The third method is to create two spatial filters separately and use them as one spatial filter  $(2 \times 64ch \text{ spatial filter})$ . In this case, different  $\lambda$  can be determined on the front and back sides, and the optimum noise immunity can be given to each. In this study, a spatial filter was created by setting  $\lambda$  to 1% of the maximum eigenvalue ( $KW^{-1}K^{T}$ ) in the second method, 1% of the maximum eigenvalue on the front side, and 5% on the back side in the third method. Here, 1% and 5% were determined by the signalto-noise ratio of the MCG on the two measurement sides. At this time, a high estimation accuracy was obtained using these values. These values affect the estimation accuracy and need to be changed depending on the measurement conditions.

### 2.4 Coordinate system and analysis conditions

Fig. 1 shows the coordinate system and analysis conditions. The origin of the coordinates is the center of the bottom of the dewar of the SQUID magnetometer. The 64-channel sensor plane is at Z = 28 mm on the front side and Z = -218 mm on the back side. In this sensor arrangement, the front is located near the analysis space (48 mm) and the back is located far away (98 mm), assuming measurement by actual MCGs. The top voxel in the analysis space was Z = -20 mm. We estimated the MCG current sources within a 180 mm  $\times$  180 mm  $\times$  100 mm volume. A total of 3,240 voxels were divided, with the size of each voxel being 10 mm × 10 mm × 10 mm. For the forward problem, we calculated the lead-field matrix K using the Biot-Savart law. For each current source location, K includes two columns that represent the X and Y components.

### 3. Results and Discussions

### 3.1 Simulation results

To examine the effectiveness of the proposed methods, the current sources were estimated by a simulation. One signal source was set at coordinates (0, 0, -65) with a



(a) Z = 28 mm (270 pT/step) (b) Z = -218 (85 pT/step)

Fig. 2 Calculated isofield contour maps.



Fig. 3 Three types of estimation results: (a) 64ch spatial filter, (b) 128 spatial filter, and (c)  $2 \times 64$  spatial filter.

signal strength of 1  $\mu$ Am in the X direction. Uniform random noise of 5% of the maximum intensity was added to the calculated magnetic field. In the case of 5% uniform random noise, there was almost no effect of outliers. Fig. 2 shows the calculated isofield contour maps obtained by the simulation. The solid line indicates the positive direction of the z-axis, and the dotted line indicates the negative direction. Fig. 3 shows the estimation results of the three types of filters. Fig. 3(a) shows the estimation result of the 64ch spatial filter using one conventional measurement surface, Fig. 3(b) is the estimation result of the 128 spatial filter with two measurement surfaces as 128-channel sensors, and Fig. 3(c) is the estimation result of the  $2 \times 64$  spatial filter in which spatial filters are individually created on the two measurement surfaces. In these figures, more than 90% of the maximum value of each estimated current source is shown as the estimated voxels. The top squares of Fig. 3(a), (b), and (c) and the bottom squares of Fig. 3(b) and (c) indicate the sensor surface, and the rectangular parallelepiped indicates the analysis space.

The estimated number of voxels was 47 for Fig. 3(a), 55 for Fig. 3(b), and 27 for Fig. 3(c). In addition, in Fig. 3(a), the estimated current sources were the large spatial extension in the deep direction; in Fig. 3(b), the estimated current sources were divided into a shallow part and a deep part and were not estimated correctly; and in Fig. 3(c), the estimated current sources were suppressed at the center and were estimated correctly. Therefore, the 2  $\times$  64 spatial filter in Fig. 3(c) suppresses the spread of the estimated current sources in the depth direction.

### 3.2 MCG results

Fig. 4 shows the overlaid waveform of the 64-channel MCG of subject A on the front and back sides and the isofield contour maps of the R peak. Fig. 5 shows the estimated current sources of the R wave peak of subject A. Fig. 5 (a), (b), and (c) represent the estimated current sources of the three spatial filters, which are similar to the simulation study. The upper side is a view of the chest surface, and the lower side is the view of the heart from below. The square frame represents the analysis space. More than 90% of the maximum value of each estimated current sources (black areas) are shown as an estimated voxel on a cardiac model positioned from the current arrows map. The estimated current sources of 3D data are shown projected in 2D. The cardiac model was created from three-dimensional data of the heart, which was made by simulating the shape of a general heart by authors. In subject A, the estimated number of voxels was 64 for Fig. 5(a), 34 for Fig. 5(b), and 21 for Fig. 5(c).



(c) Front side (2.3pT/step) (d) Back side (0.37pT/step) Fig. 4 MCG waveforms and isofield contour maps of subject A.



Fig. 5 Estimated current sources of the R wave peak of subject A: (a) 64ch spatial filter, (b) 128 spatial filter, and (c)  $2 \times 64$  spatial filter.

The estimated current sources of Fig. 5 (a) and (b) were divided into two, one was estimated near the atrium, and the estimation was not performed correctly. By contrast, in Fig. 5 (c), the estimated current sources existed in the lower part of the ventricle (called the apex of the heart), suggesting that it could be estimated the medically correct location.

Fig. 6 shows the overlaid waveform of the 64-channel MCG of subject B on the front and back sides and the isofield contour maps of the R peak. Fig. 7 shows the estimated current sources of the R-wave peak for subject B. In subject B, the estimated number of voxels was 62 for Fig. 7(a), 33 for Fig. 7(b), and 18 for Fig. 7(c). The estimated current sources of Fig. 7 (b) were near the atrium and could not be estimated correctly. The estimated current sources of Fig. 7 (a) and (c) were divided into two parts, which appeared in the atrium and ventricle. However, in Fig. 7 (c), the large spatial extension of the estimated current sources was suppressed compared to that in Fig. 7 (a), and a strong estimated current source was obtained in the lower part of the ventricle. Therefore, the  $2 \times 64$  spatial filter of Fig. 7 (c) has the highest estimation accuracy and suppresses the large spatial extension of the estimated current sources.

These MCG results showed the following. In the 64ch spatial filter, since the measurement is one measurement plane, the estimated current source is spread. In the 128 spatial filter, the spread of the estimated current source can be suppressed. However, since the signal-to-noise ratio is different on the front and back sides, it cannot be estimated at the correct position. In the  $2 \times 64$  spatial filter, the spread of the estimated current source can be suppressed. Furthermore, since the filter can be created according to the signal-to-noise ratio on the front and back side, the estimated current source can be suppressed.

### 4. Conclusions

We aim to reduce the large spatial extension of the estimated current sources by investigating the spatial filter creation method using two measurement planes.



Fig. 6 MCG waveforms and isofield contour maps of subject B.



Fig. 7 Estimated current sources of the R wave peak of subject B: (a) 64ch spatial filter, (b) 128 spatial filter, and (c)  $2 \times 64$  spatial filter.

We propose three types of spatial filter methods of eLORETA using two-side measurements of the front and back of the body. The large spatial extension of the estimated current sources can be further suppressed using the back and front sides. Among them, the signal source can be estimated at the correct position using a 2 × 64ch spatial filter that can determine the regularization parameter  $\lambda$  on the front and back sides, respectively. Visualization of the electrical heart activity is useful for diagnosis using MCG. In the future, the value of the Tikhonov regularization parameter is an important factor, we will consider how to determine the optimum value.

Acknowledgment This work was supported by Japan Society for the Promotion of Science KAKENHI (Grantsin-Aid for Scientific Research (C)) Grant Number JP19K12837 and the Soft-Path Science and Engineering Research Center,

Iwate University.

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Received May 03, 2021; Revised May 28, 2021; Accepted Jul. 06, 2021

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### Journal of the Magnetics Society of Japan

Vol. 45 No. 5 (通巻第317号) 2021年9月1日発行

Vol. 45 No. 5 Published Sep. 1, 2021 by the Magnetics Society of Japan Tokyo YWCA building Rm207, 1–8–11 Kanda surugadai, Chiyoda-ku, Tokyo 101–0062 Tel. +81–3–5281–0106 Fax. +81–3–5281–0107

Printed by JP Corporation Co., Ltd. Sports Plaza building 401, 2–4–3, Shinkamata Ota-ku, Tokyo 144–0054 Advertising agency: Kagaku Gijutsu-sha

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