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Visualization of Magnetic Domain Structures on $L1_0$-type Ferromagnetic Alloys by Scanning Electron Microscopy

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Abstract
Direct observation of magnetic microstructures is vital for advancing spintronics and other technologies. Here we report a method for imaging surface domain structures on bulk samples by scanning electron microscopy (SEM). Complex magnetic domains, referred to as the maze state in $L1_0$-type CoPt/FePt ferromagnetic alloys, were observed at a spatial resolution of 100 nm or less by using an in-lens annular detector. The method allows for imaging almost all the domain walls in the mazy structure, whereas the visualization of the domain walls with the classical SEM method was limited. Our method provides a simple way to analyze surface domain structures in the bulk state that can be used in combination with SEM functions such as orientation or composition analysis. Thus, the method extends applications of SEM-based magnetic imaging, and is promising for resolving various problems at the forefront of fields including physics, magnetics, materials science, engineering, and chemistry.

1. Introduction

Understanding magnetic domain structures, sometimes referred to as spin textures, is vital for developing magnetic materials[1,2]. Magnetic domain structures have been imaged by magnetic force microscopy (MFM)[3], scanning electron microscopy polarization analysis[4], magneto-optical Kerr microscopy[5], and techniques using a transmission electron microscope (TEM), *i.e.*, Lorentz microscopy[6,7] and electron holography[8,9]. Here we report a SEM-based technique with an annular in-lens detector (ILD), which is placed inside the column of SEM as schematically shown in Fig. 1. Although conventional SEM has also provided a method of magnetic imaging, referred to as type-I and type-II imaging[5,10,11], the asymmetric geometry of the classical detector can only visualize limited orientations of magnetic domains. As discussed below, the ILD-based method provides an easy way to visualize a surface domain structure in any orientation over a wide region. We emphasize that this method can be combined with other SEM functions, such as composition[12] and crystal orientation analyses[13]. The method thus allows in-depth study of microstructures including magnetic domains, and is widely applicable to problems in materials and engineering sciences, for which understanding the interplay between magnetism and crystallographic microstructure is essential.

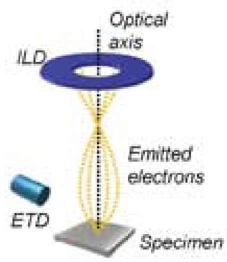

Figure 1. Schematic illustration of ILD, ETD, and the specimen.

2. Experimental

Ingots of Co-50 at% Pt and Fe-40 at% Pt alloys were prepared by arc melting, with single crystals grown using the floating zone method. Samples were homogenized for 168 h in an evacuated quartz tube at 1273 and 1423 K, respectively, followed by quenching in ice-water. After determining the crystallographic orientation by the Laue method, samples were fabricated that have a $\{100\}_{A1}$ surface. SEM specimens were prepared by mechanical polishing and gentle Ar ion milling. SEM and MFM observations were carried out using FEI Scios and JEOL JSPM-5200 systems, respectively.

3. Results and Discussion

Figures 2a-b show MFM and SEM-ILD images of Fe-r0 at% Pt obtained in the same field of view, and Fig. 2c is a schematic illustration of magnetic domain structures deduced from Fig. 2a. It appears that SEM-ILD image describes domain walls with dark lines in any orientation. Reffering to the spacing of domain patterns in Fig. 2b, the resolution is assessed as on the order of 100 nm or less. Note that the resoultion can be improved further, since it depends on both the lens system that can be optimized further and the complexity of magnetic domain patterns.

To understand the image contrast in the ILD image, we calculated stray field on the surface based on the micromagnetics theory[14]. The model for the calculation is illustrated in Fig. 3 and the results are shown in Fig. 4. It appears that in-plane components of stray field are maximized above the domain walls. Comparing these results with the observations, the magnetic contrasts in Fig. 2b appears to originate from the Lorentz deflection of emitted electrons by in-plane componets of stray field. This is basically the same mechanism as conventional type-I contrast[5,10,11].

When we applied electric stange bias in the range of 0-50 V, the magnetic contrast in the ILD image was weakened, as the stage bias increases. Accordingly, the kinetic energy of signal electrons contributing to the magnetic contrast is estimated as on the order of 0-50 eV, which is typical for secondary electrons[11]. Concequently, the source of magnetic contrast in the ILD image is attributed to secondary electrons, rather than backscattered electrons.

Acknowledgements

We are grateful to Dr T. Sueyoshi of JEOL for his collaboration and instructions on MFM experiments. This research was supported by a Grant-in-Aid for Challenging Exploratory Research (No. 15K14110) from the Japan Society for the Promotion of Science and Kyushu University Interdisciplinary Programs in Education and Projects in Research Development.

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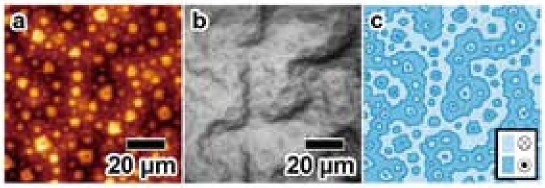

Figure 2. (a) MFM, and (b) ILD images of Fe-40 at% Pt in the same field of view. (c) Schematic diagram of the magnetic domain pattern.

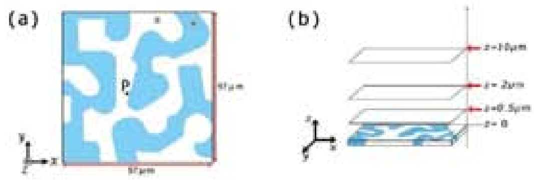

Figure 3. Model for micromagnetic calcuration. The stray magnetic field was calculated on *z*-plane of *z*=0.5, 2, and 10 μm, respectively.

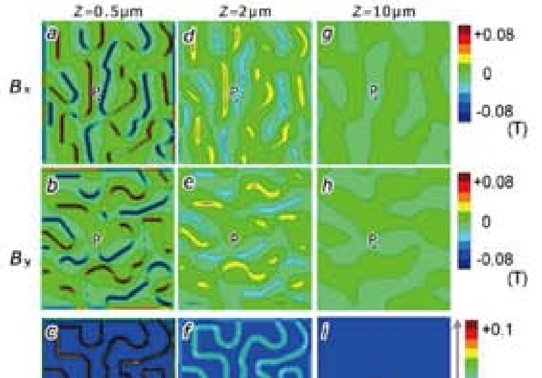

Figure 4. Distributions of (a) *x*-component, (b) *y*-component, and (c) absolute value of magnetic flux at *z*=0.5 μm. (d)-(f) those for *z*=2.0 μm, and (g)-(i) for *z*=10 μm.