# Artificial fabrication and characterization of $L1_0$-FeNi thin films for rare-earth-free permanent magnets

M. Mizuguchi, T. Kojima, T. Y. Tashiro and K. Takanashi
Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

Large uniaxial magnetic anisotropy materials are extremely promising for the application to rare-earth-free permanent magnets. As one of the materials, $L1_0$-ordered FeNi alloy is attracting attention because it reveals large $K_u$ (uniaxial magnetic anisotropy energy) value in bulk[1]. However, it is difficult to obtain the $L1_0$ phase by conventional techniques because the order-disorder transformation temperature of $L1_0$-FeNi is too low (320 ˚C) and the migration of atoms is not fully promoted to form the ordered phase. From this reason, the artificial fabrication of $L1_0$-FeNi films from seems to be one of the scarce solutions to realize this material. In this study, we successfully obtained $L1_0$-FeNi thin films with a large $K_u$ by alternate monatomic layer deposition using molecular beam epitaxy (MBE)[2-8]. FeNi films including $L1_0$ phase were also fabricated by sputtering and post-annealing[9]. Structural and magnetic properties were systematically investigated for FeNi thin films, and clarified the origin of the large magnetic anisotropy in $L1_0$-FeNi.

FeNi films were fabricated by MBE employing an alternative monatomic deposition of Fe and Ni layers on several underlayers. They were fabricated also by sputtering on a MgO(001) substrate and subsequent rapid thermal annealing (RTA). Structural properties were investigated by X-ray diffraction (XRD) using synchrotron radiation and transmission electron microscope observation. Magnetic properties were characterized by a superconducting quantum interference device or a vibrating sample magnetometer.

$K_u$ of FeNi this film fabricated by MBE was evaluated to be about 0.7 MJ/m$^3$ from the magnetization curves, and it is confirmed that large magnetic anisotropy is induced by the formation of $L1_0$ type FeNi structure. The relationship between $K_u$ and chemical order parameter ($S$), which was estimated from XRD measurements, was investigated. $K_u$ was roughly proportional to $S$, indicating clear correlation between $K_u$ and $S$ as shown in Fig. 1. On the other hand, XRD patterns of FeNi films fabricated by sputtering drastically changed depending on the condition of RTA. Magnetization curves also changed with the annealing temperature and the annealing time, which implied the successful formation of $L1_0$-FeNi. In addition, the enhancement of coercivity ($H_{c\perp}$) and remanent magnetization ($M_{r\perp}/M_S$) with $S$ was observed associated with the appearance of $L1_0$ phase as shown in Fig. 2. The effect of the other-element-addition for FeNi on crystallographic and magnetic properties was also investigated for both MBE and sputtered FeNi films, and enhancement of $S$ or increase of the order-disorder transformation temperature was clarified.

The part of this work was supported by the Elements Strategy Initiative Project under the auspice of MEXT.

Reference

1) J. Paulevé *et al*., J. Appl. Phys., **39** (1986) 989.
2) T. Shima *et al*., J. Magn. Magn. Mater., **310** (2007) 2213.
3) M. Mizuguchi *et al*., J. Appl. Phys., **107** (2010) 09A716.
4) M. Mizuguchi *et al*., J. Magn. Soc. Jpn., **35** (2011) 370.
5) T. Kojima *et al*., Jpn. J. Appl. Phys., **51**(2012) 010204.
6) T. Kojima *et al*., J. Phys.: Conden. Matter, **26** (2014) 064207.
7) T. Kojima *et al.*, J. Phys. D: Appl. Phys., **47** (2014) 425001.
8) T. Kojima *et al.*, Thin Solid Films, **47** (2016) 348.
9) T. K. Tashiro *et al.*, J. Appl. Phys., **117** (2015) 17E309.

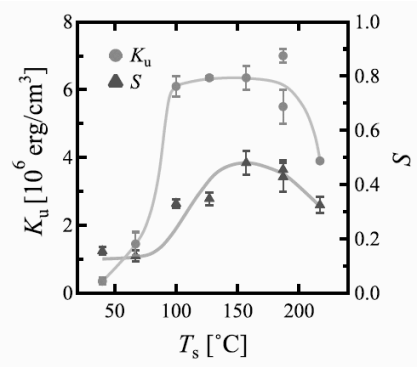


Fig. 1 Growth temperature ($T_s$) dependence of $K_u$ and $S$ [5].

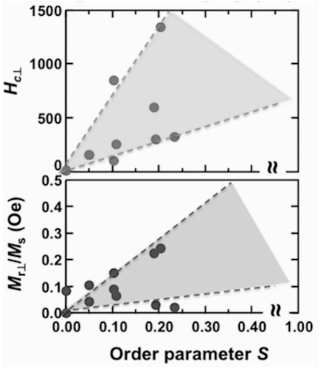


Fig. 2 $S$ dependence of $H_{c\perp}$ and $M_{r\perp}/M_S$.