High Frequency Characteristics of $Fe_{65}Co_{35}$ Alloy Cluster-Assembled Films Prepared By Energetic Cluster Deposition

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***Abstract*-Size-monodispersed $Fe_{65}Co_{35}$ alloy clusters whose average sizes ranged between 7 and 12 nm were obtained using a plasma-gas-condensation (PGC)-type cluster deposition apparatus. Positively charged clusters in a cluster beam were accelerated electrically and deposited onto a negatively biased substrate together with neutral clusters from the same cluster source, leading to formation of a high-density $Fe_{65}Co_{35}$ alloy cluster-assembled films with soft magnetic properties. High frequency magnetic characteristics were studied for these films prepared at room temperature by an energetic cluster deposition with and without O_2 gas addition into a cluster deposition chamber.**

Background

There are strong industrial demands for excellent soft magnetic thin films. Their saturation magnetization (M_s), electrical resistivity (ρ), and magnetic anisotropy field (H_k), must be so high as to maintain high magnetic permeability in GHz frequency ranges. Nanocrystalline soft magnetic materials obtained by precipitation processes via heat treatments have been extensively studied [1, 2] because the saturation magnetization is much higher than the intact amorphous state.

Recent we have reported another route for preparing nanostructured soft magnetic materials by an energetic cluster deposition technique [3]. In cluster-assembled films where spherical or polyhedral clusters are generated in gas phases and randomly deposited on substrates to form their porous stacks (low density), ρ is two order larger than that of bulk materials, M_s is low, and the magnetic coercivity (H_c) is also rather high (a few tens kA/m) due to magnetic anisotropy of single domain particles and interparticle dipole interactions. However, density of the cluster-assembled films can be improved by energetic clusters deposition, where electrically charged clusters impinge on electrically biased substrates. High-density Fe [3], Fe-Co [4], and Fe-Ni [5] cluster-assembled films thus obtained reveal a high cluster packing density of about 85%. The ρ values are still one order larger than those of the bulk alloys because a lot of boundaries between clusters can scatter conduction electrons. In these high-density ferromagnetic cluster-assembled films, M_s is large and H_c becomes negligibly small because many ferromagnetic clusters are ferromagnetically coupled by exchange interactions. Such an exchange coupling can suppress both the magnetoelastic and crystalline anisotropy energies, and thus enhanced the magnetic softness.

In this study, we pay attention to high frequency characteristics of $Fe_{65}Co_{35}$ alloy cluster-assembled films prepared by energetic cluster deposition. Using a plasma-gas-condensation (PGC)-type cluster deposition apparatus, $Fe_{65}Co_{35}$ clusters are deposited on substrates. When a bias voltage (V_a = -10 ~ -20 kV) is applied to a substrate, neutral and charged clusters are formed in a plasma region and hard-landed on the substrate, forming dense $Fe_{65}Co_{35}$ cluster-assembled films. We also prepared $Fe_{65}Co_{35}$ cluster-assembled films with and without adding O_2 gas in the cluster deposition chamber to control the degree of oxidization of cluster surfaces. We investigate their structure, morphology, and static and high-frequency magnetic properties through measurements by transmission electron microscope (TEM), electrical resistivity, superconducting quantum interference device (SQUID) magnetometer and high-frequency (0-3GHz) permeameter.

Current Results

The samples were prepared using a new PGC-type cluster beam deposition apparatus (Fig. 1), which basically involves plasma-glow-discharge vaporization (sputtering) and inert gas condensation techniques [6]. As schematically shown in Fig. 1, we used the facing-target-type dc sputtering source, which was a combination of a hollow cathode discharge mode and a magnetron mode for obtaining a high-density metal vapor. We could obtain a high ionization efficiency of Ar and thus a high sputtering rate owing to the magnetic field which was perpendicular to the surfaces of two $Fe_{65}Co_{35}$ alloy targets. We obtained $Fe_{65}Co_{35}$ alloy clusters with the mean cluster diameter from d = 7 to 12 nm with increasing R_{Ar} from 300 to 500 sccm and decreasing R_{He} from 500 to 0 sccm.

Figures 2 shows the in-plane magnetization curves at room temperature for the $Fe_{65}Co_{35}$ alloy cluster-assembled films with d = 7.8 nm prepared on room temperature substrates at several V_a values. The application of V_a leads to a magnetically soft behavior. At V_a = 0 kV, the magnetization is saturated very slowly with a magnetic coercivity (H_c) = 110 Oe. With

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978-1-4244-3544-9/10/$25.00 ©2010 IEEE

increasing V_a, on the contrary, the magnetization is saturated very rapidly and H_c decreases to 35 Oe at V_a = -20 kV. Here, it is important to mention that the saturation magnetization, M_s, for the $Fe_{65}Co_{35}$ alloy cluster-assembled film prepared at V_a = -20 kV is about 2.0 Wb/m^2 (namely, about 81% of M_s (=2.45 Wb/m^2) of bulk bcc-$Fe_{65}Co_{35}$ alloy). That is, if we do not consider the oxidation effect of cluster-assembled film, its packing fraction is about 81%, which exceeds the fcc or hcp packing fraction (74%) in the hard ball model.

In order to examine the magnetic power loss of a high-density $Fe_{65}Co_{35}$ alloy cluster-assembled films at a high operation frequency, we measured their initial permeability. Figure 3 shows the frequency (f) dependence of permeability for high-density $Fe_{65}Co_{35}$ alloy cluster-assembled films with d = 7.8 nm prepared at V_a = 0, -10, -15, and -20 kV. Clearly, the f dependence of permeability for low-density (packing fraction of about 30%) $Fe_{65}Co_{35}$ alloy cluster-assembled films prepared at V_a = 0 kV shows a heavy noise and is incapable of measurement. When $|V_a| \geq 10$ kV, $Fe_{65}Co_{35}$ alloy cluster-assembled films reveal obvious f dependence of permeability. The real part (μ') of permeability has the values of 100, 100, and 135 and flats up to 200MHz, 1 GHz, and 1.5 GHz for the films at V_A = -10, -15, and -20 kV, respectively. It is also notable that the permeability of the $Fe_{65}Co_{35}$ alloy cluster-assembled films prepared at V_a = -20 kV still maintains such a large value of μ' = 135 at f = 1.5 GHz, and imaginary part (μ'') of permeability has a maximum ($\mu'' \approx 190$) at about 2.5 GHz, being corresponding to ferromagnetic resonance frequency (f_r). Such cluster-assembled film materials can become potential candidates for microwave absorbers.

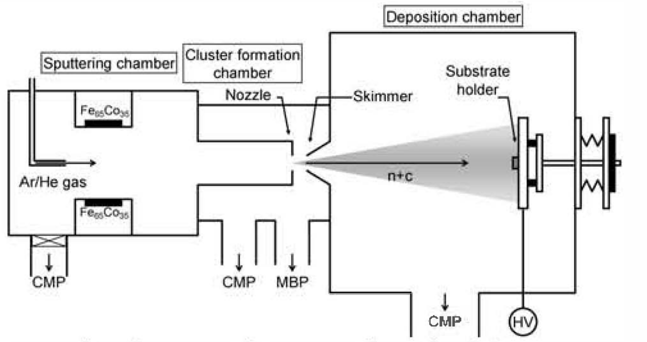

Fig. 1. Schematic set-up of PGC-type cluster deposition apparatus and energetic cluster impact method. HV represents a high voltage applied to metal substrate holder. Charged or ionized clusters (c) in the cluster beam were accelerated electrically and deposited onto the substrate holder together with neutral clusters (n) from the same cluster source.

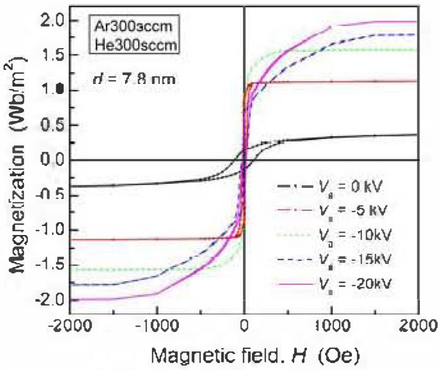

Fig. 2. In-plane magnetization curves at room temperature for the $Fe_{65}Co_{35}$ alloy cluster-assembled films with d = 7.8 nm prepared on room temperature substrates at several V_a values.

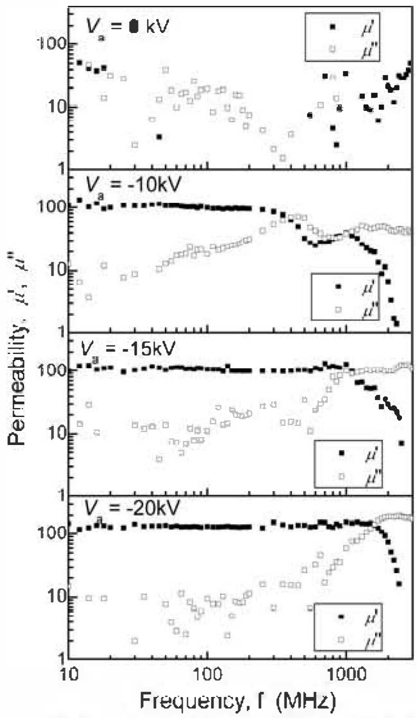

Fig. 3. Frequency (f) dependence of permeability for high-density $Fe_{65}Co_{35}$ alloy cluster-assembled films with d = 7.8 nm prepared at V_a = 0, -10, -15, and -20 kV.

ACKNOWLEDGMENT

This work was partly supported by the National Natural Science Foundation of China under Grant No.50671087 and No. 50825101, and by the Intellectual Cluster Project of the Ministry of Education, Culture, Sports, Science, and Technology, Japan, Aichi Prefecture, Nagoya City and Aichi Science and Technology Foundation.

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