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# Co-based nanogranular thin films on flexible substrate for gigahertz applications

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**Abstract**

The Co-based granular thin films were deposited on the flexible substrate (Kapton) by magnetron sputtering. The films comprise of Co nanocrystallites and small amount of amorphous (Al,O)-rich inter-granular phase and have the electric resistivities in the range 50–120 $\mu\Omega$ cm, depending on the composition and thickness. The as-deposited films with thickness $<80$ nm have low coercivity ($<20$ Oe along hard direction), high permeability (up to 500) and resonance frequency up to 2.5 GHz. Compared to the rigid films, the flexible films have relatively higher coercivity and lower resonance frequency. A comparison between Co-based granular films and FeTaN continuous films has also been discussed.


*Keywords:* Thin film; Granular; Magnetic property; Permeability

## 1. Introduction

Nanogranular systems, i.e. composites comprising metallic grains of nanometer size embedded in an insulating host matrix, exhibit special optical, electrical and magnetic properties [1]. Magnetic granular films have been actively studied due to their potential applications as materials with giant magnetoresistance (MR) [2], hard magnetic properties [3] and high resistivity soft magnetic properties [4]. Granular films for soft magnetic applications receive much attention from the standpoint of low core-loss films for high frequency use [4–6]. Generally speaking, CoAlO-based granular film has relatively high electrical resistivity ($\rho$), large saturation magnetization ($M_s$), large anisotropy field ($H_k$) and low coercivity ($H_c$) [7]; therefore, it has excellent $\mu$–$f$ response and can be seen as an excellent candidate for gigahertz applications. However, most previous investigations [8–10] were based on the films deposited on rigid substrates, such as silicon and glass. No detailed report on the CoAlO thin films on flexible substrate has been reported yet, though some studies on CoCr [11], CoCrTa [12], Fe [13] and NiFe films [14] were witnessed previously. On the other hand, the flexible thin films are extremely useful for practical applications, especially for use as electromagnetic materials. It has been found that the nature of the flexible substrate has an important effect on the structure and soft magnetic properties of the deposited films, which leads to a different performance for a flexible film from a rigid one [11–14]. Following our previous research on the continuous FeTaN films on flexible substrate [15], we now concentrate on other alloy systems, especially nanogranular thin films. Recently, a detailed investigation on the CoAlO-based films deposited on both rigid and flexible substrates has been conducted in our laboratory. Our results on Co- and (CoFe)-based films on the Si substrate will appear on other publications. Here, we report the structure and properties of CoAlO thin films with small amount of (Al,O) contents deposited on plastic substrates and discuss the differences in properties between flexible and rigid films.

## 2. Experiment

Co-based granular thin films were fabricated using RF magnetron sputtering on the flexible plastic substrates at room temperature. There are mainly two types of plastics

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commercially available, i.e., Mylar and Kapton. Due to its high heat resistance [16], we chose Kapton (Goodfellow Co.) as the flexible substrate. For magnetron sputtering, a 2-in. Co disc with various $Al_2O_3$ chips was employed as the target. An alignment magnetic field of ~120 Oe was applied parallel to the substrate surface to induce an in-plane magnetic anisotropy during deposition. The base pressure was $3\times10^{-7}$ Torr. The standard sputtering conditions were ambient Ar-gas pressure of 3.0 mTorr and RF power of 75 W.

The film structure was investigated by X-ray diffraction (XRD), scan electron microscopy (SEM), high-resolution transmission electron microscopy (HRTEM) and energy-dispersive X-ray (EDX). The thickness of the film was also measured in SEM. The electrical resistivity at room temperature and sub-ambient was determined using a conventional four-probe method. The static magnetic property was measured by a *M–H* loop tracer. The permeability spectrum over the frequency range of 0.1–4.5 GHz was characterized by shorted microstrip transmission-line perturbation method using a fixture developed in our laboratory and the measurement error for this method has been found to be less than 10% [17].

## 3. Results and discussion

CoAlO thin films with various compositions and thicknesses were successfully fabricated on the Kapton substrate. As mentioned earlier, the film composition was adjusted by changing the number of $Al_2O_3$ chips. Three compositions were obtained by adding 2, 4 and 6 pieces of $Al_2O_3$ chips ($5\times10$ mm) on the Co disc. Due to much lower sputtering rate of $Al_2O_3$ than that of Co, the (Al,O) concentration was controlled to quite low level, which was verified by magnetic measurement. Large values of saturation magnetizations ($M_s$; in the range of 1.4–1.6 T) were obtained in the films fabricated using these three target compositions, which indicates that the Al content in our films is less than 6 at% based on other researchers' work [4]. As expected, $M_s$ was decreasing with increasing $Al_2O_3$ content in the target. In the following sections, for discussion purpose, the film compositions obtained using 2, 4 and 6 pieces of $Al_2O_3$ chips are denoted as compositions A, B and C, respectively. It has been found that the deposition rates for composition A, B and C are around 80, 60 and 40 Å/min, respectively.

### 3.1. Film structure

A shining and smooth surface was observed for all films, as shown in Fig. 1(a). The adhesion between the film and the plastic substrate was found very strong through testing by repeatedly bending the films. SEM image of the side-view for a selected film with a relatively large thickness is shown in Fig. 1(b), demonstrating a fairly smooth surface and uniform thickness.

The granular structure of the film was confirmed by HRTEM investigation. As shown in Fig. 2, the film with composition C has a granular structure, consisting of Co nanocrystallites and amorphous (Al,O) phase. The latter is distributed in the inter-grain boundary. This has been supported by EDX investigations (not shown here); qualitative element analysis revealed that the concentrations inside and between the nanograins were Co-rich and (Al,O)-rich, respectively. The Co grains have a mean size of ~20 nm and have been determined as a FCC structure with (1 1 1) d-spacing of ~2.05 Å (Fig. 2(b)). The FCC Co phase was also verified by XRD (Fig. 2(a), inset), where only a Co (1 1 1) peak was found. The relatively large grain size for present films may result from the low thermal conductivity of the Kapton substrate.

### 3.2. Electrical properties

The room temperature electric resistivities for the films are shown in Fig. 3(a), where resistivity $\rho$ is plotted against film thickness $t$ for three compositions. The values of $\rho$ are around 100 μΩ cm. This value is slightly higher than the results reported by Shintaku et al. [10] for (Fe/Co)Al–O with 0–2 at% $Al_2O_3$ but it is much smaller than most of CoAlO films reported previously [8,9], also indicating the low (Al,O) contents in the films in the present work. TEM images (Fig. 2) show that the amount of (Al,O) phases is not enough to isolate all adjoining Co grains, which leads to, in some degree, a semi-continuous metallic film. Hence, the film has lower resistivity. Fig. 3(a) also shows that $\rho$ slightly decreases with increasing $t$, especially for the films with small thicknesses, implying the effect of interface

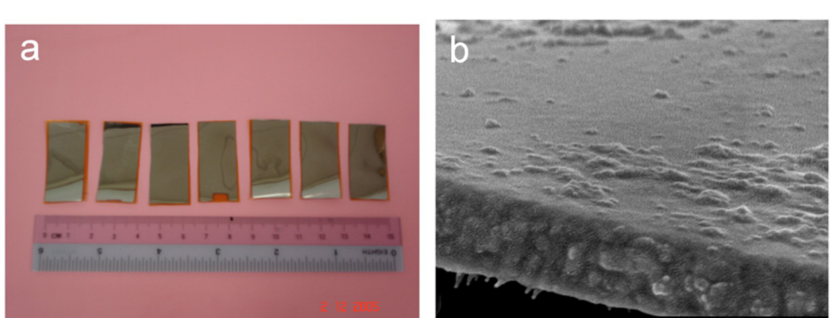


Fig. 1. CoAlO films on the plastic substrate (a) and SEM image for cross-section (b).