JOURNAL OF APPLIED PHYSICS **97**, 10F906 (2005)

Stress, microstructure, and magnetic softness of high saturation magnetization (B_s) FeCoN films

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(Presented on 10 November 2004; published online 10 May 2005)

High saturation magnetization soft magnetic FeCoN films were deposited under different conditions. Their soft magnetic properties and microstructures were characterized. Good magnetic softness with a low coercivity of ~240 A/m (3 Oe) was achieved in FeCoN films on glass with a thickness of up to 640 nm. A correlation was found to exist between the FeCoN film coercivities and their compressive strains, with higher coercivities corresponding to larger compressive strains. FeCoN film coercivities were lower for samples with larger grain sizes, exhibiting a typical $1/D$ relationship with D being the mean grain size, a mechanism that is different from the reported fine grain size-induced magnetic softness in FeCo thin films. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853102]

I. INTRODUCTION

High saturation magnetization FeCoN and FeCo films with Co content in the range of 30–40 at. % show a high B_s of ~2.4 T and have been widely used in magnetic write heads. These FeCoN and FeCo alloys show a large saturation magnetostriction constant in the range of $(40-65)\times 10^{-6}$, and a relatively high anisotropy constant K_1 of ~10 kJ/m^3,[1] which make it difficult to achieve good magnetic softness in the FeCo and FeCoN alloys.[2–11] Consistent process control of the soft magnetic FeCo and FeCoN alloy film deposition process has been challenging, particularly for the rf diode deposition processes.

Hard axis coercivities of ~800 A/m (10 Oe) or less were achieved in the deposited FeCoN and FeCo alloy films in several reports.[2–11] A coercivity of 960 A/m (12 Oe) was achieved in a 30-nm-thick FeCo50 at. % alloy film seeded with a thin CoO layer.[3] The soft magnetism in the CoO-seeded FeCo film was believed to be due to the fine grain size induced by the CoO seedlayer.[3] A coercivity of 400 A/m (5 Oe) was achieved in the 100-nm-thick FeCoN (with ~30 at. % Co) films.[4] A very thin ~2.5-nm-thick Permalloy alloy film was used as a seedlayer for the FeCoN film with a thickness of 100 nm, which resulted in a low coercivity of less than 80 A/m (1 Oe).[4,5] Similar magnetic softness was achieved in 50-nm-thick FeCo35 at. % alloy films seeded with a thin layer of NiFe, Cu, and Ru, which showed a low coercivity of 80–240 A/m (1–3 Oe) in the hard axis;[6,7] and in a thin NiFe- and NiFeCr-seeded 100-nm-thick FeCo25 at. % and FeCo30 at. % films which showed a coercivity of 215 A/m (2.7 Oe).[8] The mean grain sizes of the NiFe-, Cu-, and Ru-seeded 30-nm-thick FeCo35 at. % films were found to be in the range of 10 nm, which was in contrast to the mean grain size of ~50 nm in the Ta-seeded FeCo film that did not show good soft magnetic properties. The magnetic softness in the FeCo films on NiFe, Cu, and Ru was attributed to the fine grain sizes induced by the seedlayers.[6,7] A low coercivity of 720 A/m (9 Oe) was reported in a single-layer FeCo film, which was also attributed to a small mean grain size of 7.2 nm.[11]

The mean grain size usually increases with the film thickness, which often causes deteriorated soft magnetic properties, as shown in the FeCo50 at. % films.[2] Stripe domain forms when the film thickness reaches a certain limit in a soft magnetic film which degrades the magnetic softness.[12,13] Most of the published data on soft magnetic FeCo and FeCoN films showed a thickness of 30–100 nm.[2–8] One exception is the recently reported 200-nm-thick FeCo40 at. % soft magnetic films.[9]

Achieving soft magnetic FeCo or FeCoN films with large thicknesses, e.g., over 200 nm, can lead to improved overwrite if the thick soft magnetic FeCo films are incorporated into magnetic write heads. This is important with the ever-increasing areal density in longitudinal magnetic recording. In this work, process condition variations for the FeCoN film deposition processes were explored. The FeCoN films soft magnetic properties and microstructures were examined. A good correlation was found between the coercivities of the FeCoN films, their strains, and mean grain sizes.

II. EXPERIMENT

FeCoN films with the thicknesses of 150–650 nm were deposited onto bare glass coupons and onto metal seedlayers by rf diode deposition under different conditions. Microstructures of the films were characterized with a four-circle diffractometer x-ray difraction (XRD) system with a primary parallel-beam polycapillary optic and a secondary LiF monochromator. The strains of the FeCoN films were measured with the (310) peak using the "d vs $\sin^2 \psi$" method with ψ tilting from 0° to 88° with a step of 8°. Average in-plane grain sizes were measured with multiple diffraction peaks of (110), (211), (220), and (222), with the assumption of a Cauchy profile for size broadening and a Gaussian profile for microstrain broadening.[14]

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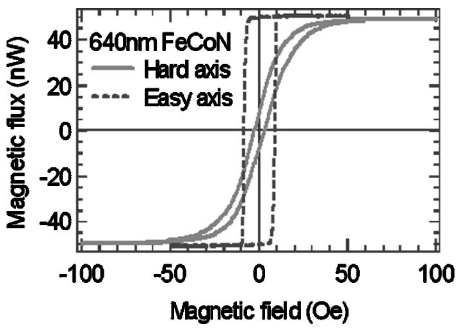

FIG. 1. Easy axis and hard axis hysteresis loops of a 640-nm-thick FeCoN films under condition A.

III. RESULTS AND DISCUSSION

FeCoN samples were deposited under different deposition parameters and different substrates, which were designated as conditions A, B, C, and D. Excellent soft magnetic properties were achieved in the FeCoN films under conditions A and D. As shown in the *B-H* loop in Fig. 1 for a 640-nm-thick FeCoN film deposited under condition A, a low hard axis coercivity of 240 A/m (3 Oe), an easy axis coercivity of 640 A/m (8.5 Oe), and a decent uniaxial anisotropy were achieved. The hysteresis loop shows an M_r/M_s of 0.98 along the easy axis and 0.15 along the hard axis. Saturation flux density of these films was determined by a calibrated *B-H* looper to be 2.4 T. FeCoN samples deposited under conditions B and C show widely dispersed hard axis coercivities of 800–7200 A/m (10–90 Oe). As shown in Fig. 2 for the out-of-plane theta-2 theta XRD scans, the FeCoN films from condition A show a much stronger and narrower (110) diffraction peak but a weaker (211) peak compared to the FeCoN samples from condition B. The typical rocking curves of the (110) peak of these FeCoN films are shown in Fig. 3, indicating a strong peak at film plane normal direction for the samples produced under condition A, which contrasts the two small satellite peaks at $\pm 10°-20°$ away from the film plane normal for the rocking curves for samples from condition B. The double satellite (110) peaks in the rocking curves for samples from condition B indicate that they have less (110) fiber texture than condition A, which is consistent with Fig. 1.

The FeCoN films deposited under the same process condition usually show similar XRD patterns except one notable difference, which is the shifted diffraction peak position at high two theta angles. The FeCoN samples with high coercivities generally show shifted (220) and (310) diffraction peaks to lower angles in the out-of-plane theta-2 theta XRD scans. The shifted diffraction peaks indicate that there are different levels of strains in these samples. The FeCoN films strains deduced from the lattice spacing at different tilt angles are shown in Fig. 4, exhibiting widely dispersed strains for the same deposition condition. There is an interesting correlation with the coercivities of the FeCoN films shown in Fig. 4, that is, high compressive strains correspond to high coercivities, while a low compressive strain or a tensile strain corresponds to a low coercivity in the strain range we studied. The FeCoN film strains range from −1.2%–0.6%, corresponding to a stress in the range of −3–1.5 GPa if a Young's modulus of 250 GPa is used.[9] The coercivities of the FeCoN samples are shown in Fig. 5 as a function of the mean grain sizes of the FeCoN films deposited under different conditions. Clearly the coercivity drops with the increase of mean grain size for all the samples, exhibiting a typical $1/D$ like behavior with D being the mean grain size, similar to what is theoretically predicted.[15]

It is notable that the coercivity versus strain, and coercivity versus mean grain size trends, as shown in Figs. 4 and 5 for the FeCoN films, are also valid for FeCo films deposited on different seedlayers,[16] including a ~3-nm-thin seedlayer that is known to promote better magnetic softness in the FeCoN and FeCo films, such as Permalloy,[4,5,8] Cu,[6,7] Ru,[6,7] NiFeCr,[8] etc. FeCo films with a thickness of 150 nm deposited on such ~3-nm seedlayers show large mean grain sizes of 30±5 nm and relatively low coercivities of 800 A/m (10 Oe). A similar correlation between the coercivity and the macroscopic compressive stress was observed

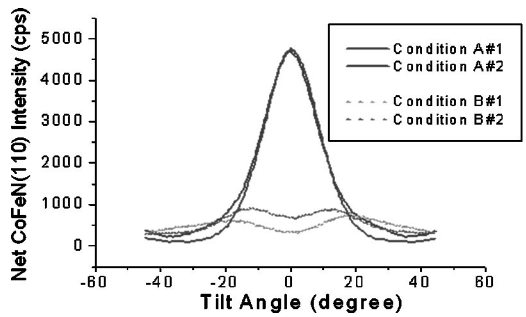

FIG. 3. Rocking curves of the FeCoN samples under conditions A and B.

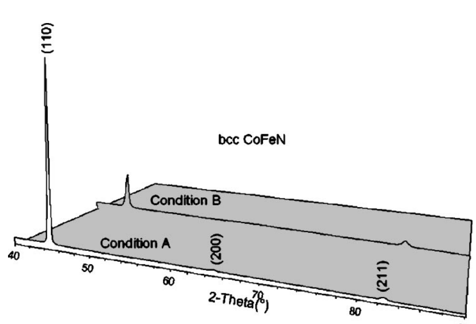

FIG. 2. Out-of-plane theta-2theta XRD scans of FeCoN films under conditions A and B.

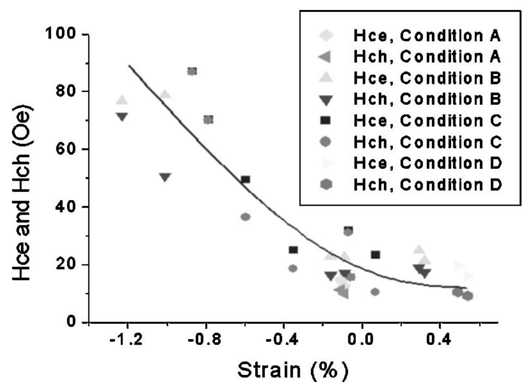

FIG. 4. Coercivities vs strain for FeCoN films under different conditions.

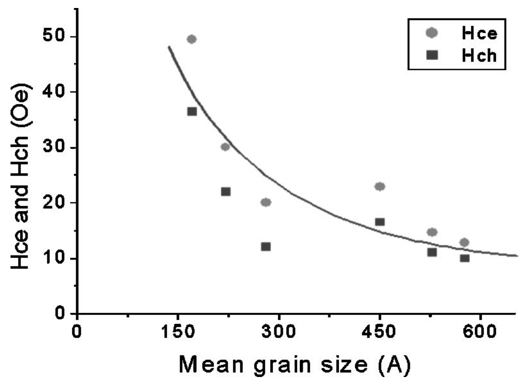

FIG. 5. Coercivities as a function of mean grain sizes for FeCoN films with different deposition conditions.

in FeCo films with a thickness of 200 nm, and the FeCo alloy films with larger grain sizes seemed to correlate with lower coercivity,[9] similar to the $1/D$ correlation we observed for the coercivities of the FeCoN and FeCo films with thicknesses >150 nm. This is in contrast to the observed phenomenon that these thin seedlayers, such as Permalloy, Cu, and Ru, induced fine grain sizes of ~ 10 nm and good magnetic softness in the FeCo films with a thickness of 50 nm.[6,7]

It is predicted that when the mean grain size D is larger than the domain-wall width, which is about πL_{ex}, the coercivity H_c scales $1/D$.[15] The ferromagnetic exchange length is about $L_{ex}=(A/K_1)^{1/2}=32$ nm for FeCo30 at. % alloy with $K_1=10$ kJ/m^3 and $A=1\times 10^{-11}$ J/m;[1] the domain-wall width is on the order of 100 nm. The mean grain sizes of the FeCoN films are in the range of 17–60 nm, which is obviously *lower* than the domain-wall width.

It is notable that the random anisotropy model used to derive the $H_c \sim D$ relation was intended for bulk magnetic materials with randomly orientated crystallites, and the magnetoelastic anisotropy was neglected in deriving the H_c vs D relations.[15] This is valid for magnetic materials with low magnetostriction constants and/or low stresses, which is not true for the FeCo and FeCoN films. Considering a typical compressive strain of −0.5% from Fig. 4, and a saturation magnetostriction constant of $\lambda_s=45\times 10^{-6}$ for FeCo and FeCoN films with 30 at. %Co,[17] the magnetoelastic anisotropy term is $K_\sigma=3/2\sigma\lambda_s=-95$ kJ/m^3, which pushes magnetization out of plane and degrades the magnetic softness. The magnetoelastic anisotropy is an order of magnitude higher than K_1 and scales linearly with strain, which may be the reason why the FeCo and FeCoN film stresses or strains correlate well with the coercivities when their film thicknesses are high and their mean grain sizes are large.

In summary, excellent soft magnetic properties were achieved in thick FeCoN films (150–640 nm) with large grain sizes and optimized strains. The FeCoN film coercivity was found to correlate well with the strain of the FeCoN films, and scales with $1/D$, with D being the mean grain size, showing a mechanism that is different from what is observed for the thin FeCo films when the thickness is 50 nm or less.

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