JOURNAL OF APPLIED PHYSICS **97**, 10N904 (2005)

Magnetic annealing of plated high saturation magnetization soft magnetic FeCo alloy films

N. X. Sun,[a)] S. Mehdizadeh, C. Bonhote, Q. F. Xiao, and B. York
Hitachi Global Storage Technologies, San Jose, California 95193

(Presented on 10 November 2004; published online 17 May 2005)

Plated high saturation magnetization soft magnetic FeCo films were annealed in magnetic field; their stress, microstructure, and magnetic properties were investigated. The FeCo films consistently showed a reduced tensile stress after magnetic annealing at temperatures above 255 °C. The annealing temperature was found to be the primary factor in reducing the tensile stress, while annealing time was secondary. The FeCo films showed improved soft magnetic properties when subjected to an easy axis annealing with reduced coercivities along both the easy axis and hard axis. Hard axis annealing on these FeCo films caused a switched easy and hard axis in these films when the annealing temperature is above 255 °C. © *2005 American Institute of Physics*.
[DOI: 10.1063/1.1855458]

I. INTRODUCTION

Integrating the thick plated high saturation magnetization B_s FeCo alloy films with a Co content of 30–40 at. % into the write heads has been one of the most important missions for the magnetic recording industry. However, implementation of the plated high moment FeCo into magnetic recording heads has been challenging. As-plated FeCo films usually show high tensile stresses in the range of 400–600 MPa, much higher than the stresses in NiFe films that are generally less than 200 MPa. This high tensile stress in the FeCo films causes formidable challenges in integrating the plated FeCo films into magnetic write heads, such as stress caused film peeling, severe air bearing surface deformation in magnetic recording heads. The high stress in the FeCo films needs to be reduced before the FeCo films can be successfully incorporated into magnetic write heads with improved device level performance.

It is known that stresses in the plated magnetic films are usually tensile, and the tensile stresses increase when the magnetic films are annealed. The reason of the increase of the tensile stress in plated films was attributed to microstructure changes of the magnetic films after annealing, such as the reduction of defect densities of films during annealing.[1] It was reported that the as-plated Permalloy films stress remained the same at ~200 MPa until annealed at temperatures over 200 °C. The Permalloy film stress went up with the increase of the annealing temperature until it saturated at 1.5 GPa at over 400 °C.[1] The longitudinal magnetic recording head processes usually have one or more photoresist hard baking (or annealing) processes, which the plated FeCo films have to go through if they are to be integrated into the magnetic write heads. It would be important to find out how the high tensile stress and their soft magnetic properties evolve after annealing processes. In this work, we report on the magnetic annealing behavior of the plated high saturation magnetization soft magnetic FeCo magnetic films.

[a)]Present address: Electrical and Computer Engineering Department, Northeastern University, Boston, MA 02115; Electronic mail: Nian@ECE.NEU.EDU

II. EXPERIMENT

The FeCo magnetic films were plated onto a thin NiFe seedlayer, which was deposited onto alumina undercoat on the 5 in. diameter AlTiC substrates (a mixture of alumina and TiC). Magnetic field was applied to induce the in-plane magnetic anisotropy during plating. All plated FeCo film thicknesses were 2.0 μm with the Co content of ~40 at. %, with a thickness standard deviation of ~5% across the wafer. Plating condition details were published elsewhere.[2] Electrical resistivity was measured by four-point probe at film surface. Soft magnetic properties were measured with a calibrated B-H looper with a repeatability of better than 1% for saturation flux density measurements. Films stress was measured by using the wafer-curvature method. The wafer-curvature stress measurement relies on the fact that when the thin film is under stress, it imposes a bending moment on the substrate. The curvature change of the substrate before and after deposition can be related to the biaxial stress of polycrystalline thin films.[3] Magnetic annealing was done in a vacuum annealing oven with a pair of hard magnets providing a mean magnetic field of 96 000 A/m (1200 Oe) in the wafer center. The magnetic annealing temperature ranges from 225 to 270 °C, with the upper temperature limited by the annealing oven. The FeCo films were always shiny with a metallic color after the annealing processes, showing no appreciable oxidization.

III. RESULTS AND DISCUSSION

The as-plated FeCo 40 at. % alloy films were annealed at different temperatures for different dwelling times ranging form 5 to 9 h. No significant stress change differences were observed when the samples were annealed at the same temperature for 5, 7 and 9 h. However, the stress change of these FeCo films was strongly dependent upon the annealing temperature, as indicated in Fig. 1. The as-plated FeCo alloy

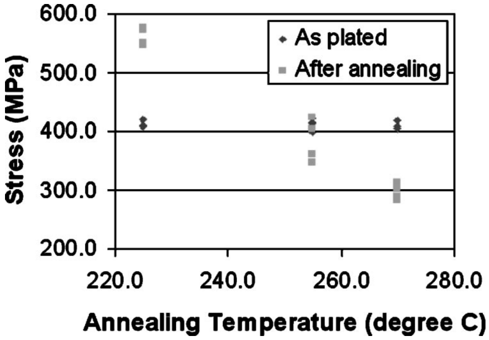

FIG. 1. Plated FeCo film stress before and after magnetic annealing as a function of annealing temperature. As-plated FeCo film stresses were plotted at the temperatures where they were annealed for the purpose of comparison.

films typically had a tensile stress of 400 500 MPa, which was increased by 150 MPa after annealing at 255 °C. When the as-plated FeCo films were annealed at 255 °C or higher temperatures, the FeCo film stresses were reduced. The film stress was reduced further when the annealing temperature was increased. The as-plated film stress reduction amounts to 140 MPa when annealed at 270 °C. This was in contrast to an ever-increasing tensile stress observed in the plated Permalloy films with the increment of annealing temperature.[1] The FeCo film magnetic easy axis orientation was varied with respect to the magnetic field direction in the oven during the annealing process, which was found to have no appreciable effects on the FeCo stress change.

Conventional photoresist hard baking temperatures are about 220 °C/230 °C, the FeCo film stress increase associated with the hard baking process at a temperature of 225 °C will make the plated FeCo film process integration into the recording heads more difficult. If a high temperature anneal is done at temperatures above 255 °C after the FeCo film is plated, the FeCo film tensile stress will be reduced, which can facilitate the plated FeCo films process integration into magnetic recording heads significantly.

The resistivity of the FeCo films drops monotonically with the increase of annealing temperature, as shown in Fig. 2. The as-plated FeCo films show a resistivity of 25 $\mu\Omega$ cm, which drops gradually to 23 $\mu\Omega$ cm when annealed at 225 °C, and 20 $\mu\Omega$ cm when annealed at 270 °C. The rapid drop of resistivity after annealing at temperatures above 225 °C indicates a reduction of defect density in the FeCo films together with a possible increase of grain size.

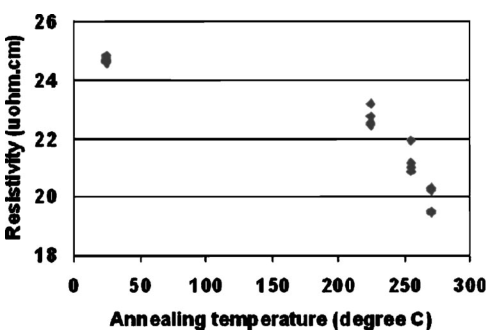

FIG. 2. Resistivity vs annealing temperature for plated FeCo films.

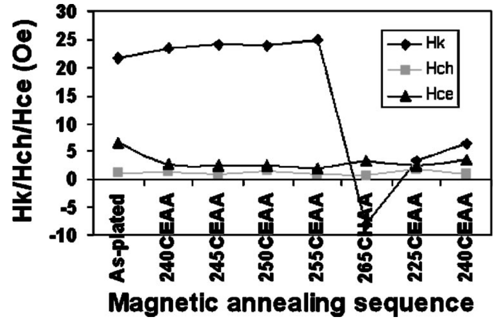

FIG. 3. Anisotropy field H_k, hard axis coercivity H_{ch}, and easy axis coercivity H_{ce} of a FeCo film on AlTiC substrate after a sequence of different annealing steps. EAA, easy axis annealing; HAA, hard axis annealing.

The magnetic softness of the plated FeCo films was improved after the easy axis magnetic annealing processes (i.e., with the magnetic field direction parallel to the *current* magnetic easy axis direction of the films in the oven) as indicated in Fig. 3. The easy axis coercivity dropped from 520 A/m (6.5 Oe) to 168 A/m (2.1 Oe) after a series of easy axis annealing with the temperatures in the range of 240–255 °C, and hard axis coercivity dropped from 96 A/m (1.2 Oe) to 72 A/m (0.9 Oe). The anisotropy field increased slightly from 1760 A/m (22 Oe) to 2000 A/m (25 Oe) after the sequence of easy axis magnetic annealing processes. When the FeCo films went through a hard axis annealing process (i.e., with the applied magnetic field direction parallel to the current hard axis direction in the oven) at 265 °C, the hard axis and easy axis direction was switched, as indicated by the negative H_k in Fig. 3. The switched magnetic anisotropy direction could be switched back by another hard axis magnetic annealing at 225 °C after the hard axis annealing at 265 °C as shown in Fig. 3.

Magnetic annealing can be used to induce uniaxial anisotropy in soft magnetic amorphous alloys and switch the in-plane magnetic anisotropy.[4–6] Similar switching of magnetic anisotropy direction by hard axis magnetic annealing was also observed in other high B_s soft magnetic alloy films, like the crystalline FeTaN films.[7] It is interesting to note that no phase change is detected for the bcc FeCo films after magnetic annealing at 270 °C, and the magnetic softness was improved, unlike what was observed in the FeTaN films,[8] indicating a good thermal stability of the plated FeCo films.

After easy axis annealing with temperatures in the range of 225–270 °C, both easy axis saturation flux density B_{se} and hard axis saturation flux density B_{sh} were improved by a small amount of around 2%, reaching 2.45 T at easy axis and 2.4 T at hard axis. When the FeCo films went through hard axis annealing, the hard axis and easy axis could be switched, as shown in Fig. 3 by the negative anisotropy field H_k. An interesting phenomenon occurred, as indicated in Figs. 4(a)–4(c). The as-plated FeCo films showed a well defined hard and easy axis hysteresis loop, with the easy axis parallel to the applied field direction during the plating of the FeCo films. The easy axis saturation flux density B_{se} was clearly higher than the hard axis saturation flux density B_{sh} in the as-plated state by about 5%, as shown in Fig. 4(a). After

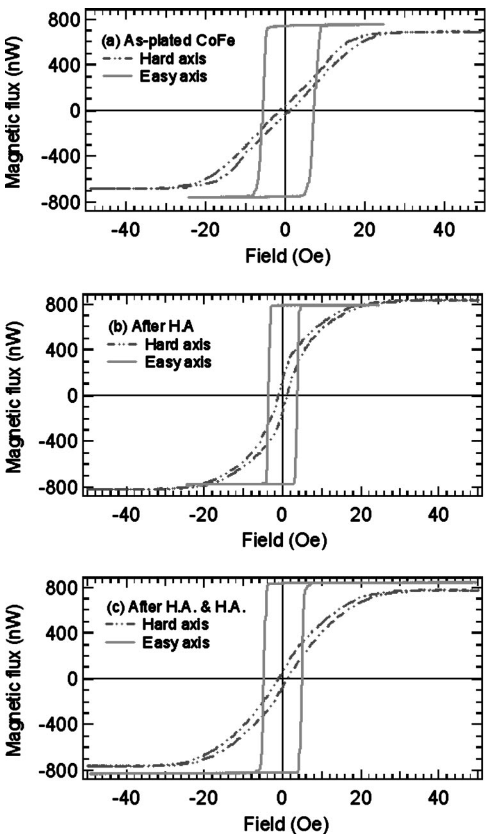

FIG. 4. B-H loops of FeCo films at different states. (a) As-plated; (b) after hard axis annealing; (c) after hard axis annealing and another hard axis annealing.

the hard axis annealing, the easy axis and hard axis were switched, and the B_{sh} was higher than the B_{se}, as shown in Fig. 4(b). A second hard axis annealing after the first hard axis annealing switched the easy axis back to the original as-plated magnetic easy axis direction, and the B_{se} was higher than B_{sh} again after the two hard axis annealing steps, as shown in Fig. 4(c). This indicates that the saturation flux density along the in-plane FeCo film direction that is parallel to the applied magnetic field direction during the plating process, i.e., the original magnetic easy axis direction in the as-plated state, is always higher than the magnetic saturation flux density along the as-plated hard axis direction, which stays valid even when the easy axis and hard axis is switched back and forth after the magnetic annealing processes.

IV. SUMMARY

The high tensile stress of the plated thick FeCo films were successfully reduced by annealing these FeCo films under a temperature of 255 °C or above, and magnetic softness is also improved after an easy axis annealing. The amount of the tensile stress reduction increases with the increment of annealing temperature when the annealing temperature is above 255 °C. This reduced tensile stress facilitates the successful integration of the thick high B_s FeCo films into magnetic recording heads. The mechanism of the tensile stress reduction of the FeCo films, however, is not well understood and more work is needed.

[1] A. S. Kao and P. Kasiraj, J. Appl. Phys. **27**, 4452 (1991).
[2] C. Bonhote, H. Xu, E. I. Cooper, and L. T. Romankiw, ECS Proceedings, 2002.
[3] W. D. Nix, Metall. Trans. A **20**, 2217 (1989).
[4] P. Allia, F. E. Luborsky, G. P. Soardo, and F. Vinai, J. Appl. Phys. **52A**, 3553 (1981).
[5] B. S. Berry and W. C. Pritchet, Phys. Rev. Lett. **34**, 1022 (1975).
[6] M. K. Minor and T. J. Klemmer, J. Appl. Phys. **93**, 6465 (2003).
[7] M. K. Minor and J. A. Barnard, J. Appl. Phys. **85**, 4565 (1999).
[8] B. Viala, V. R. Inturi, and J. A. Barnard, J. Appl. Phys. **81**, 4498 (1997).