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Thin Solid Films 505 (2006) 90 – 92

thin solid films

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Soft magnetic layers for low-field-detection magnetic sensors

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Abstract

We have investigated a wide variety of soft magnetic layers as sense layers for magnetic-field sensors. We find that in thin-film form, some of these soft materials can have susceptibilities (χ) approaching those of the corresponding bulk material. In general, the highest χ values occur in trilayer structures with a non-magnetic film separating two soft magnetic films. The alloy $Ni_{77}Fe_{14}Cu_5Mo_4$ of the mu-metal family is the softest thin-film material we have found, and we can achieve hard-axis χ values above 10^5 in trilayer structures. The hard axis is preferred for magnetic sensors due to its near-linear response. The major impediment we have found to using these very soft layers in low-field sensors is that the χ value decreases by almost two orders of magnitude when the soft structure is incorporated in a standard spin valve or tunnel junction. The problem appears to be stiffening of the soft layer by the stray field from ripple in the pinned layer. A partial solution is found in the use of a synthetic antiferromagnetic as the pinned film. The antiferromagnetic alignment appears to have a canceling effect on the stray field.

Keywords: Sensors; Thin films; Susceptibility; Ripple

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1. Introduction

Sensors for the detection of magnetic fields below 100 pT (picoTesla)in the frequency range 1 to 1000 Hz are largely dominated by the technologies of fluxgates and superconducting quantum interference devices (SQUIDs) [1]. Unfortunately, these sensors are bulky and expensive. Above 100 pT, small inexpensive solid-state thin-film sensors provide a more attractive alternative [1]. A major challenge is thus to extend the range of thin-film sensors below 100 pT. One promising approach is to make the sense layer softer.

In recent decades, a wide range of soft magnetic materials have been developed that have very small coercivity ($\sim 10^{-2}$ milliTesla(mT)) in the easy axis and very large χ ($\sim 10^5$) in the hard axis [2]. The major driving force for this development has been the demand for higher efficiency in electrical transformers. Because of this application, these soft materials have been developed in bulk form with relatively little attention having been given to reproducing the properties in thin-film form.

The hard-axis saturation field of the soft layer in commercial thin-film sensors is typically several tenths of a mT which corresponds to χ values on the order of 10^3 [1,3,4]. It would seem there is the potential to improve the χ of the soft layer by about a factor of 100 if the properties of the best soft materials can be achieved in these sensors.

2. Experimental

All films were deposited on Si(100) wafers with 250 nm of thermal oxide. Wafers were cleaved into ~ 1 cm^2 pieces, cleaned ultrasonically in a glassware cleaning solution, rinsed in distilled water, blown dry with inert gas, and installed in the deposition chamber. After bakeout, the deposition chamber has a base pressure of 7×10^{-8} Pa (5×10^{-10} Torr), of which 90% is H_2. The films were deposited at room temperature by dc-magnetron sputtering in 0.3 Pa (2 mTorr) Ar at a typical rate of ~ 1 nm/min and by ion-beam sputtering using foil targets in 0.07 Pa (0.5 mTorr) Ar at a typical rate of 4 nm/min.

The magnetic hysteresis loops shown here were recorded in air using a BH looper. The absolute magnetization of the

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doi:10.1016/j.tsf.2005.10.014

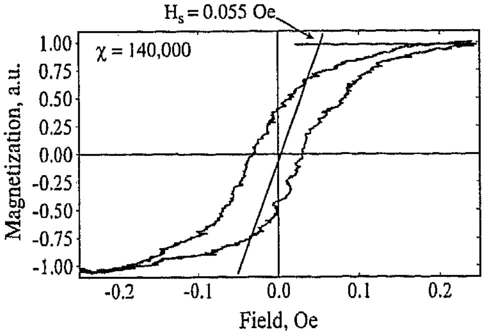

Fig. 1. A plot of the magnetization of the structure 25 nm $Ni_{77}Fe_{14}Cu_5Mo_4$/10 nm Au/25 nm $Ni_{77}Fe_{14}Cu_5Mo_4$ versus field. The extrapolated saturation field corresponds to $\chi = 140,000$.

samples was calibrated using a vibrating sample magnetometer. The estimated accuracy is ±3%.

3. Results and discussion

We have concentrated in this work on large-area (1 cm^2) films because it is unlikely that the softness of the sense layer will improve as a result of device fabrication. The softest possible sense layer is thus an important initial goal.

The early stages of this work concentrated on nanocrystalline and amorphous alloys such as $Fe_{62}Co_{26}Zr_7B_4Cu_1$, $Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$, and $Co_{65}Fe_4Ni_2Si_{15}B_4$ (at.%). In general, the magnetic properties of these alloys are quite sensitive to stoichiometry, and that makes them unsuitable for deposition by magnetron sputtering. The pressure of Ar is high enough to scatter the light components such as B to the side, reducing their concentration in the deposited film. Heavier atoms tend to pass through the Ar relatively unimpeded. Therefore, we chose ion-beam sputtering for alloys of this type. The lower Ar pressure and a shorter target-substrate distance preserve stoichiometry much better than magnetron sputtering.

Nanocrystalline and amorphous alloys generally require very specific annealing conditions to achieve soft properties [5]. However, these conditions have been optimized for alloys in bulk form. We found that these conditions did not work for films of the thickness appropriate for thin-film sensors (a few tens of nanometers). Among the likely causes of this problem are segregation of some components to the surface, which would alter the stoichiometry, and stresses remaining in the magnetic film due to different thermal expansion of the Si substrate. In fact, annealing often reduced the χ of the films.

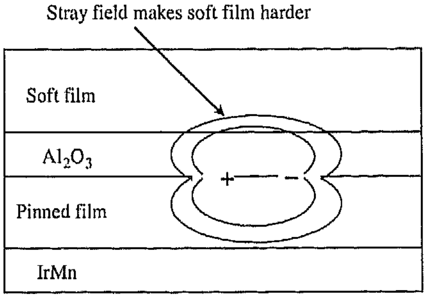

Fig. 2. An illustration of how ripple in the pinned film due to polycrystalline IrMn creates a stray field that reduces χ in the soft film.

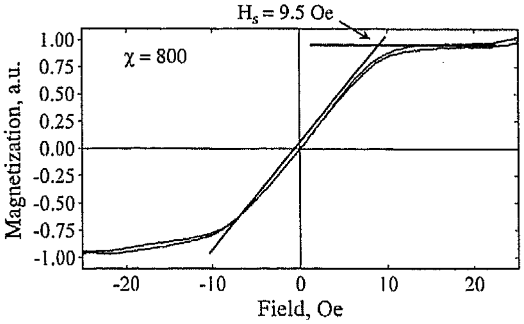

Fig. 3. An illustration of the typical reduction in χ caused by the stray field from the pinned layer.

Fortunately, there are alloys that do not require annealing to be magnetically soft. Among these are $Ni_{80}Fe_{20}$, $Ni_{80}Fe_{15}Mo_{4.2}Mn_{0.5}Si_{0.3}$, $Ni_{80}Fe_{15.5}Mo_4Mn_{0.5}$, $Ni_{80}Fe_{15.8}Mo_{4.2}$, and $Ni_{77}Fe_{14}Cu_5Mo_4$. Although there are annealing conditions that can, in some cases, make bulk forms of these alloys softer, we found again that in thin-film form no improvement seems attainable.

The well-known alloy $Ni_{80}Fe_{20}$ is not particularly soft because its stoichiometry does not simultaneously tune the magnetocrystalline anisotropy and the magnetostriction to zero [6]. Alloys that do attempt to tune both to zero include $Ni_{80}Fe_{15}Mo_{4.2}Mn_{0.5}Si_{0.3}$, $Ni_{80}Fe_{15.5}Mo_4Mn_{0.5}$, $Ni_{80}Fe_{15.8}Mo_{4.2}$, and $Ni_{77}Fe_{14}Cu_5Mo_4$. Of these, we found $Ni_{77}Fe_{14}Cu_5Mo_4$, a member of the mu-metal family, to be the softest. In single films, it had typical χ values of ~80,000 and as high as 140,000 in trilayer films of the type illustrated in Fig. 1. While not equal to the best bulk values of 500,000 these results are at least of the same order.

The largest χ values are achieved by spinning the sample during deposition to improve uniformity. As deposited, such samples show little evidence of hard and easy axes. The reason the trilayer structure has a larger value of χ is not known. However, a reasonable guess would be that it is due to coupled Neel walls which lower the energy barriers both to the nucleation of reverse domains and to rotation of the magnetization.

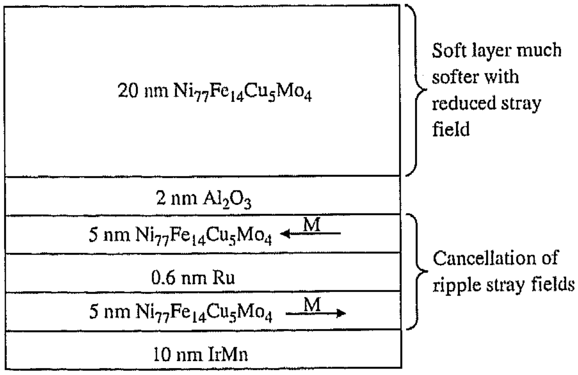

Fig. 4. A typical application of a SAF to reduce the stay field from the pinned layer by cancellation of the stray field components.

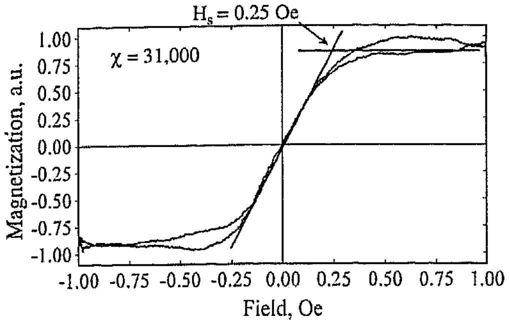

Fig. 5. A typical result of using a SAF to reduce the stray field from the pinned film in the MJT structure of Fig. 4.

We found that the use of $Ni_{77}Fe_{14}Cu_5Mo_4$ films in giant magnetoresistance (GMR) spin valves is not practical. The $Ni_{77}Fe_{14}Cu_5Mo_4$ films generally need to be about 20–25 nm thick enough to be as soft as possible, and at this thickness the GMR is quite small due to current shunting.

It seems more likely that these films will actually be used in sensors based on magnetic tunnel junctions (MJTs). However, MJTs are also not without problems. Fig. 2 illustrates a key challenge that must be met, the reduction of the stray field from magnetic ripple in the pinned film. As illustrated in Fig. 3, this effect reduces χ sharply.

Note that the coercivity drops to zero in Fig. 3. This result is typical. Even a slight pinning by a stray field can suppress the small coercivity seen in Fig. 1, and produce a nonhysteretic linear transfer curve so valuable in sensors.

Tondra et al. first suggested using a synthetic antiferromagnet (SAF) as a pinned layer to reduce the effect of the stray field on the sense layer [3]. In this work, we investigated that suggestion and found that it is indeed useful although not a complete solution. Fig. 4 illustrates a typical structure and Fig. 5 a typical result.

The χ value in Fig. 5 (31,000) is a promising result. If fine tuning of the thicknesses can reduce the stray field further, it may be possible to develop $Ni_{77}Fe_{14}Cu_5Mo_4$ films with more sensitivity than the films available in commercial thin-film sensors today.

4. Conclusions

1) Alloys that have a stoichiometry that simultaneously tunes the magnetocrystalline anisotropy and the magnetostriction to zero can exhibit large susceptibilies in thin-film form.
2) The best alloy we have found is $Ni_{77}Fe_{14}Cu_5Mo_4$.
3) The annealing conditions that make bulk alloys magnetically soft do not, in general, work for the same alloys in thin-film form.
4) When such alloy films are thick enough to have a large susceptibility they shunt too much current to be practical as GMR spin valves.
5) The stray field from the pinned layer in a MJT creates problem by reducing the susceptibility of the sense layer.
6) Even a slight pinning by a stray field can suppress the small coercivity in the sense layer and produce a nonhysteretic linear transfer curve so valuable in sensors.
6) The stray-field problem can be sharply reduced by using a synthetic antiferromagnet as the pinned layer.

References

[1] N.A. Stutzke, S.E. Russek, D.P. Pappas, M. Tondra, J. Appl. Phys. 97 (2005) (Art. No. 10Q107).
[2] C.-W. Chen, Magnetism and Metallurgy of Soft Magnetic Materials, Dover, New York, 1986.
[3] M. Tondra, J.M. Daughton, C. Nordman, D. Wang, J. Taylor, J. Appl. Phys. 87 (2000) 4679.
[4] X. Liu, C. Ren, G. Xiao, J. Appl. Phys. 92 (2002) 4722.
[5] M.E. McHenry, M.A. Willard, D.E. Laughlin, Prog. Mater. Sci. 44 (1999) 291.
[6] F. Pfeifer, C. Radeloff, J. Magn. Magn. Mater. 19 (1980) 190.