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# Magnetic properties of ion-beam sputter-deposited Fe-Ni-B-Si films

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We have produced  $\text{Fe}_x\text{-Ni}_{80-x}\text{-B}_{15}\text{-Si}_5$  ( $x = 20, 40, \text{ and } 75$ ) and permalloy thin films on a silicon substrate using ion-beam sputtering technique. Four-point probe measurement indicated that quarternary films had 3–4 times higher resistivity than permalloy films, and this ratio was not changed after thermal annealing. The values of saturation magnetization were determined to be 5–13 kG depending on Fe concentration. The anisotropy fields of these films were in the ranges of 2–15 Oe after deposition, however, these values were reduced by more than 50% after annealing with field. The lowest value of the anisotropy field was 1.3 Oe for the permalloy film after thermal annealing without field.

## I. INTRODUCTION

High saturation magnetization ( $4\pi M_s$ ) and low uniaxial anisotropy field ( $H_K$ ) are essential for microwave frequency application of magnetic materials. Magnetic oxide films have been used extensively for microwave devices. The values of saturation magnetization of the oxide films are typically only half those of the metal films. Recently, high  $4\pi M_s$ , low  $H_K$ , and relatively high-resistivity amorphous Fe-Ni-B-Si ribbons<sup>1</sup> were prepared in various compositions by using the melt-quench technique. For microwave device application, it may be essential to develop these materials in thin-film form. In this study, we have produced thin films of Fe-Ni-B-Si alloy on a Si substrate via the ion-beam sputtering technique. In addition, permalloy films ( $\text{Fe}_{20}\text{-Ni}_{80}$ ) were prepared for the purpose of comparison.

## II. EXPERIMENTAL PROCEDURE

An apparatus as shown in Fig. 1 was used for deposition of Fe-Ni-B-Si as well as Fe-Ni films. The target of desired composition was mounted on a water-cooled holder and a 3-cm beam diameter Kaufman-type ion source was used for sputter deposition. The compositions of the targets used are  $\text{Fe}_{20}\text{-Ni}_{80}$  and  $\text{Fe}_x\text{-Ni}_{80-x}\text{-B}_{15}\text{-Si}_5$  ( $x = 20, 40, \text{ and } 75$ ) in atomic percent. Since the film composition was not determined, compositions described in this paper referred to the target composition. The deposition chamber was initially pumped down to lower than  $2 \times 10^{-6}$  Torr, then purified Ar

gas was introduced into the ion source. The pressure of the chamber during growth was maintained at  $3 \times 10^{-4}$  Torr. Silicon substrate was mounted parallel to the target at a 4 in. distance. The substrate was not heated, but was rotated at 2 rpm speed to enhance the uniformity of the film. The voltage and current of the ion beam were 1 keV and 50–60 mA, respectively. Under these conditions, the deposition rate was 3–4 Å/s. The thickness of the film, measured by using a surface profilometer, was in the range of 2400–2800 Å. After deposition, one set of films was annealed in vacuum lower than  $2 \times 10^{-5}$  Torr at 275 °C for 30 min using a quartz lamp heater. The other set of films was annealed in a magnetic field of 300 Oe applied along the hard axis of the film which was determined from vibrating sample magnetometer (VSM) measurement. For resistivity and magnetic property measurements, specimens were cut into disk shape (6 mm in diameter). Resistivity of the film was measured by the four-point probe technique. The saturation magnetization and the coercive field  $H_c$  were measured with a vibrating sample magnetometer. In addition, the magnetic anisotropy was determined by measuring the VSM hysteresis loops along both easy and hard axis and corroborated by FMR technique.

## III. RESULTS AND DISCUSSION

Typical hysteresis loops of the permalloy and Fe-rich ( $x = 75$ ) quarternary films in the as-deposited state are shown in Fig. 2. Although these two films have nearly the same coercive field, permalloy film has much smaller anisot-

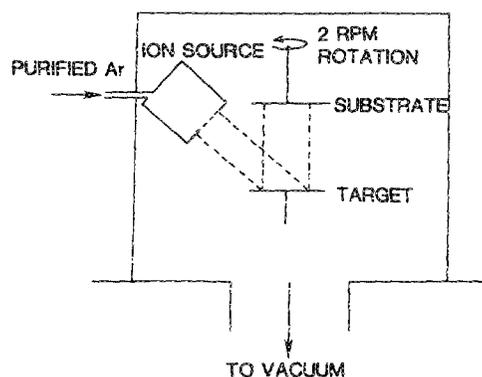


FIG. 1. Schematic diagram of the ion-beam sputter-deposition system.

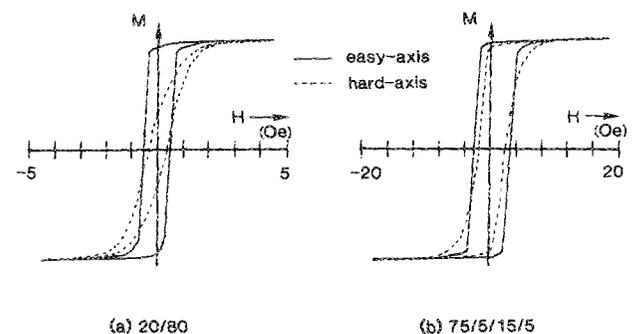


FIG. 2. Typical hysteresis loops of the as-deposited (a) permalloy and (b) Fe-rich quarternary films.

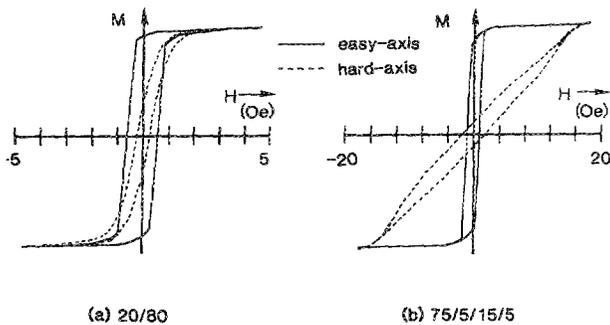


FIG. 3. Typical hysteresis loops of the annealed (a) permalloy and (b) Fe-rich quarternary films. Note the squareness ( $M_r/M_s$ ) of the Fe-rich films is greatly increased as a result of field annealing.

ropy field. In Fig. 3, the hysteresis loops for the same samples after 275 °C annealing in a magnetic field of 300 Oe along the hard axis are shown. Comparing Figs. 2 and 3, the hysteresis loops for the as-deposited and the annealed permalloy film are almost identical. However, in the Fe-rich ( $x = 75$ ) quarternary film, the squareness ( $M_r/M_s$ ) of hysteresis loops increased remarkably as a result of field annealing. This increase in squareness of the hysteresis loop was observed in all quarternary films. The highest  $M_r/M_s$  values obtained for the  $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{15}\text{Si}_5$  films after annealing were 98% and 88% along the easy and hard axis, respectively. Furthermore, in some Ni-rich ( $x = 20$ ) films, square-shaped hysteresis loops were obtained in all orientations of applied magnetic field. No particular easy or hard axis of magnetization existed in these films. One notable feature observed was that annealing the film at 275 °C in a magnetic field of 300 Oe along the hard axis resulted in a complete rotation of magnetic easy axis in all samples.

The values of  $4\pi M_s$  and resistivity as functions of nominal film compositions as well as annealing conditions are

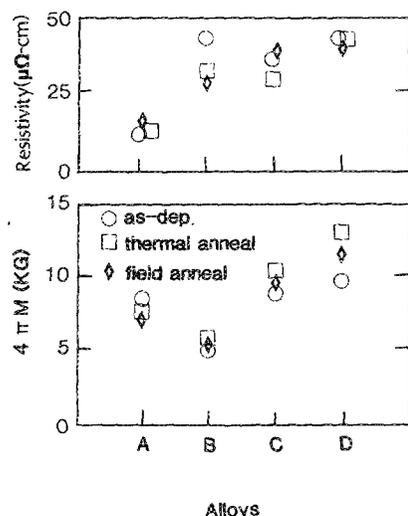


FIG. 4. Values of saturation magnetization ( $4\pi M_s$ ) and resistivity ( $\rho$ ) as functions of alloy composition and annealing condition. A, B, C, and D represent  $\text{Fe}_{20}\text{Ni}_{80}$ ,  $\text{Fe}_{20}\text{Ni}_{60}\text{B}_{15}\text{Si}_5$ ,  $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{15}\text{Si}_5$ , and  $\text{Fe}_{75}\text{Ni}_{15}\text{B}_{15}\text{Si}_5$  films, respectively.

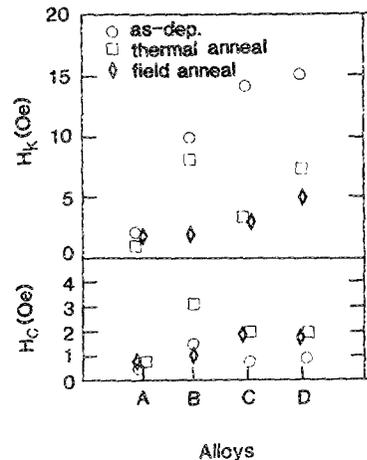


FIG. 5. Values of coercive field ( $H_c$ ) and anisotropy field ( $H_k$ ) as functions of alloy composition and annealing condition. A, B, C, and D represent  $\text{Fe}_{20}\text{Ni}_{80}$ ,  $\text{Fe}_{20}\text{Ni}_{60}\text{B}_{15}\text{Si}_5$ ,  $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{15}\text{Si}_5$ , and  $\text{Fe}_{75}\text{Ni}_{15}\text{B}_{15}\text{Si}_5$  films, respectively.

plotted in Fig. 4. As expected, the Fe-rich ( $x = 75$ ) film showed the highest  $4\pi M_s$ . After annealing without field, the values of  $4\pi M_s$  for all but permalloy films increased slightly, and this trend was more significant in the Fe-richer films. The highest value of  $4\pi M_s$  is 13 300 G, obtained for the  $\text{Fe}_{75}\text{Ni}_{15}\text{B}_{15}\text{Si}_5$  film after thermal annealing without field. The resistivity of all but the Ni-rich ( $x = 20$ ) films was not sensitive to annealing treatment. In the Ni-rich film ( $x = 20$ ), the resistivity decreased from 44 to 32  $\mu\Omega$  cm as a result of annealing. Generally, the resistivities of the quarternary films, in as-deposited as well as annealed states, were 3–4 times higher than that of permalloy film. However, the resistivity of our quarternary films (about 40  $\mu\Omega$  cm) is much less than the values obtained from the amorphous ribbons ( $\rho = 100\text{--}200 \mu\Omega$  cm) (Ref. 2) or the amorphous films<sup>3</sup> of similar compositions. This low-resistivity value indicates that our films may contain crystalline structure, although they have a high concentration (20%) of glass-forming elements, boron and silicon.

The values of coercive field ( $H_c$ ) and  $H_k$  were determined from the hysteresis loops. The results are shown in Fig. 5. While the change in  $H_c$  for the permalloy films is negligible,  $H_c$  in all the quarternary films increased about 100% as a result of annealing. An increase in  $H_c$  of the quarternary films tends to indicate that crystallization occurred during annealing. The value of  $H_k$  for the permalloy films was not changed after anneal with field, however, this value decreased 30% after annealing without field. In all quarternary films, the values of  $H_k$  drastically decreased as a result of annealing.

#### IV. CONCLUSION

The Fe-Ni-B-Si system exhibits the following properties: (1) The saturation magnetization,  $4\pi M_s$ , can vary between 10 000 and 13 000 G for the iron-rich ( $x = 75$ ) films. This is to be compared to 7000–8000 G for the permal-

loy film. (2) The  $H_K$  values for the as-deposited films are always higher than  $H_K$  values obtained for annealed films. The lowest values of  $H_K$  are 1.3 and 5 Oe for the permalloy and the iron-rich ( $x = 75$ ) quaternary films, respectively. The system also exhibits square loop properties. The remanence magnetization is relatively high and is in the order of 94%–98% after field annealing. (3) Finally, we observed

complete rotation of magnetic easy axis as a result of annealing the films in a magnetic field along the hard axis of magnetization.

<sup>1</sup>L. T. Kabacoff, M. Wun-Fogel, and F. Bucholtz, *IEEE Trans. Magn. MAG-21*, 2014 (1985).

<sup>2</sup>R. Hasegawa and J. A. Dermon, *Phys. Lett.* **42A**, 407 (1973).

<sup>3</sup>R. J. Kobliska, J. A. Aboaf, A. Gangulee, J. J. Cuomo, and E. Klokholm, *Appl. Phys. Lett.* **33**, 473 (1978).