Effects of boron implantation in films of iron-nickel

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We have implanted boron ions into films of Fe-Ni alloy composition. A homogeneous distribution of boron was determined from the sputter Auger analysis with a concentration of 18% and 34% for low- and high-dose implantation, respectively. The resistivity of film was increased by a factor of 2 and 4 as a result of low- and high-dose implantation, respectively. The magnetic properties of these films are studied as a function of annealing temperature by using FMR measurements. Both the uniaxial anisotropy field and FMR linewidth are dramatically decreased as a result of annealing at elevated temperatures. The changes of effective magnetization of these films are strongly dependent on implanted boron concentration.

I. INTRODUCTION

A number of techniques, such as melt quenching, vapor condensation in thermal evaporation, or sputtering, have been employed to produce amorphous alloys. Ion implantation is a process that can be used to introduce controlled amounts of foreign atoms into a layer adjacent to a material surface. This technique has been extensively used in magnetic bubble technology, since the first discovery of altering the magnetic anisotropy in garnet crystals. In this study, we have produced amorphous Fe-Ni-B alloys via ion implanting boron into crystalline Fe-Ni films and investigated the changes in magnetic properties of these films after ion implantation and post-annealing treatment. Ferromagnetic resonance (FMR), resistivity, and Auger analysis were performed to characterize the films.

II. EXPERIMENTAL PROCEDURE

Thin films of Fe$_{90}$Ni$_{30}$ and Fe$_{70}$Ni$_{30}$ were thermally evaporated in thicknesses ranging from 1400 to 3100 Å on a quartz or slide glass substrate. The substrate was heated at temperatures from 100 to 1400 °C and 5 × 10$^{-6}$ Torr vacuum during deposition. Boron was implanted into these films at an ambient substrate temperature. The implantation conditions in terms of dose and energy were 4 × 10$^{16}$/cm$^2$ at 20 keV, 5.7 × 10$^{16}$/cm$^2$ at 40 keV, and 9.7 × 10$^{16}$/cm$^2$ at 80 keV for lower-dose implantation and 1.2 × 10$^{17}$/cm$^2$ at 20 keV, 1.7 × 10$^{17}$/cm$^2$ at 40 keV, and 2.9 × 10$^{17}$/cm$^2$ at 80 keV for high-dose implantation. The concentration and distribution of boron was determined after implantation by using a sputter-Auger technique. The depth distribution of boron was deduced from the sputtering rate which was determined by measuring the depth of the crater after sputtering in a given time. The structure of the films after implantation was determined by using reflection electron deflection (RED) analysis revealed that complete amorphous and highly damaged (diffused ring pattern) structure in high- and low-dose implanted samples, respectively.

The changes in resistivity of implanted samples after annealing are shown in Fig. 2. As expected, the values of resistivity are increased four and two times in the high- and annealed state. Resistivity of the film was measured using a four-probe technique. The magnetic properties, effective saturation magnetization ($4\pi M_{eff}$), FMR linewidth ($\Delta H$), and anisotropy field ($H_A$) were determined using the standard in-plane FMR analysis. The FMR experiment was performed in a microwave cavity tuned to 9.5 GHz.

III. RESULTS AND DISCUSSION

The depth distribution of the implanted boron was obtained by using the sputter-Auger technique, as shown in Fig. 1. Boron was uniformly distributed in ranges of 200–2400 Å from the film surface. The concentration of boron was 34% (peak at 1000–1400 Å) and 18% (peak at 750 Å) for high- and low-dose implantation, respectively. Clearly, the distribution of boron is more homogeneous in the high-dose implanted sample. Further, reflection electron deflection (RED) analysis revealed that complete amorphous and highly damaged (diffused ring pattern) structure in high- and low-dose implanted samples, respectively.

The changes in resistivity of implanted samples after annealing are shown in Fig. 2. As expected, the values of resistivity are increased four and two times in the high- and annealed state.
low-dose implanted sample, respectively. Annealing of these films at elevated temperature resulted in slow decrease in resistivity. However, the resistivities of films annealed at 350 °C were still higher than the resistivities of as-grown films. It has to be mentioned that the resistivity of some of high-dose implant samples, especially in permalloy composition, are dramatically increased after annealing. We could not observe ferromagnetic resonance in these samples. Thus, we believed that these samples are magnetically disordered or paramagnetic in these high-dose levels (34% B).

The changes in anisotropy field ($H_A$) are relatively independent of alloy composition or implanted boron concentration, as is shown in Fig. 3. The values of $H_A$ are decreased in all samples as a result of ion implantation and annealing at elevated temperatures. In low-dose implanted permalloy (Fe$_{30}$Ni$_{70}$) films, the $H_A$ are minimum after annealing at 150–200 °C. Annealing these films above 200 °C resulted in a slight increase in $H_A$. In Fe$_{70}$Ni$_{30}$ composition films, the $H_A$

of both high- and low-dose implants show a minimum after annealing films at 200 °C. Annealing these samples above 200 °C resulted in a rapid increase in $H_A$.

A typical plot of effective saturation magnetization ($4\pi M$) as a function of annealing temperature is shown in Fig. 4. The changes in $4\pi M$ are strongly dependent on the alloy composition as well as boron concentration. Thermal post-annealing has little effect on effective magnetization at temperatures lower than 200 °C. Annealing these films above 300 °C resulted in a gradual increase in $4\pi M$. Comparing the values of $4\pi M$ for high- and low-dose implanted Fe$_{70}$Ni$_{30}$ films, it is clear that high-dose boron implantation reduces the effective magnetization. The reduction in $4\pi M$ may be related to a new magnetic ordering or presence of paramagnetic phase. The results of FMR measurements for as-deposited, ion-implanted, and annealed films at 200 °C are summarized in Table I.

**IV. CONCLUSION**

Amorphous thin films of Fe-Ni-B were produced via the ion implantation technique. Uniform distribution of boron

**TABLE I.** Results of FMR measurements for films of Fe$_{30}$Ni$_{70}$ and Fe$_{70}$Ni$_{30}$ composition in as-deposited, boron-implanted, and annealed ($T_a=200$ °C) states.

<table>
<thead>
<tr>
<th></th>
<th>Fe$<em>{30}$Ni$</em>{70}$ (3100 Å)</th>
<th>Fe$<em>{70}$Ni$</em>{30}$ (2500 Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As-dep. Low-dose implant</td>
<td>As-dep. Low-dose implant</td>
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<tr>
<td>$H_A$ (kG)</td>
<td>10.3 10.6 ⋯⋯ 9.5 (?) 15.1 10.4</td>
<td>50 6 ⋯⋯ 75 6 5</td>
</tr>
<tr>
<td>$\Delta H$ (Oe)</td>
<td>62 29 ⋯⋯ 176 98 41</td>
<td></td>
</tr>
</tbody>
</table>
was obtained by implanting this species in three different doses and energies. The minimum values of $H_A$ and $\Delta H$ were obtained after post-annealing these films at temperatures of 200–250 °C. The annealing results were independent of alloy composition. Typically, the values of $H_A$ were measured to be in the range of 2–7 Oe and $\Delta H$ in the order of 30–50 Oe after annealing the films at 200 °C. The value of $4\pi M$ is strongly dependent on alloy composition and relatively independent on annealing treatment temperatures below 300 °C. The low value of $4\pi M$ in high-dose implant Fe$_{70}$Ni$_{30}$ films may indicate the presence of the paramagnetic phase in high boron concentration samples.

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