Effect of rapid thermal annealing on microstructural, magnetic, and microwave properties of FeGaB alloy films


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We have performed rapid thermal annealing (RTA) experiments on crystalline and amorphous (Fe_{70}Ga_{30})_{1-x}B_x films in order to understand and reduce the linewidth of ferromagnetic resonance (FMR). In the absence of cubic anisotropy in amorphous films, the effective anisotropy is small, resulting in a narrow FMR linewidth. The FMR linewidth in both crystalline and amorphous films can be further reduced by RTA. In crystalline films, a minimum FMR linewidth can be achieved by annealing the samples at a relatively high temperature for a short time. The effect is attributed to the reduction in the uniaxial anisotropy. In amorphous films, the reduction in FMR linewidth is achieved at low temperature and short annealing time. Elevated temperatures and prolong time may crystallize the amorphous structure and introduce a much large cubic anisotropy, resulting in a large FMR linewidth. © 2010 American Institute of Physics.

I. INTRODUCTION

Materials with strong magnetoelectric coupling and low loss at microwave frequencies are the focus of research due to their potential use in microwave magnetic devices. The loss is related with the linewidth of ferromagnetic resonance (FMR). Earlier reports on the effect of metalloid doping in FeGa alloy films have shown high saturation magnetization and low FMR linewidth when B doping is higher than 14%. In B doped Fe based alloys, due to the presence of interstitials, they often form distorted bcc D0_3 structures. Therefore, there are limited approaches to reduce the FMR linewidth. On the other hand, a narrow FMR linewidth can be obtained in an amorphous phase with more than 14% B addition in Fe_{70}Ga_{30}. To further reduce their FMR linewidth, one can try to reduce the strain in the films without crystallizing the amorphous structures. For this reason, we study the effect of rapid thermal annealing (RTA) on the magnetic and microwave properties of these (Fe_{70}Ga_{30})_{1-x}B_x films.

For a better comparison, RTA is performed on both the crystalline and amorphous phases at different temperatures and annealing durations. Study of (Fe_{70}Ga_{30})_{0.8}B_{0.2} films (crystalline) and (Fe_{70}Ga_{30})_{0.82}B_{0.18} (amorphous) annealed at 180 and 380 °C has been undertaken to investigate the effects of RTA on magnetic softness, magnetization dynamics, and the role of anisotropy in the observed behaviors of the FeGaB thin films.

II. EXPERIMENTAL DETAILS

Thin films of (Fe_{70}Ga_{30})_{0.8}B_{0.2} and (Fe_{70}Ga_{30})_{0.82}B_{0.18} were grown on a Si/SiO_2 substrate via reactive magnetron sputtering from two separate targets of Fe_{70}Ga_{30} (Angstrom Sciences, Inc.) and boron (CERAC). (Fe_{70}Ga_{30})_{0.9}B_{0.1} and (Fe_{70}Ga_{30})_{0.82}B_{0.18} films of 100 nm thickness were deposited at room temperature under 3 mTorr pressure of Ar. The films were capped with further 20 nm Ta layer. Thermal annealing was performed using a RTA system in Ar atmosphere at 180 and 380 °C. Structures were characterized using x-ray diffraction (XRD) with Cu Kα radiation (λ = 1.5405 Å). Magnetic measurements were carried out using a vibrating sample magnetometer (Lake Shore). The dc magnetic data are extracted from the in-plane magnetization hysteresis (M-H) loops which were measured both along the easy and the hard axes. Microwave properties were measured using a custom designed coplanar waveguide based FMR magnetometer. The FMR measurements were carried out at x band (7 GHz) with the applied magnetic field along the easy axis of the magnetization.

III. RESULTS AND DISCUSSION

The crystal structure, dc magnetic, and microwave behavior of (Fe_{70}Ga_{30})_{0.8}B_{0.2} and (Fe_{70}Ga_{30})_{0.82}B_{0.18} films are observed to change with the addition of B as shown in Table I.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Structure</th>
<th>4πMs (kOe)</th>
<th>Hc/Hk (Oe)</th>
<th>FMR linewidth/Hz &lt;sub&gt;res&lt;/sub&gt; (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe_{70}Ga_{30}B_{0.1}</td>
<td>bcc (110)</td>
<td>15.5</td>
<td>227/33</td>
<td>172/344</td>
</tr>
<tr>
<td>Fe_{70}Ga_{30}B_{0.18}</td>
<td>Amorphous</td>
<td>13</td>
<td>45/2</td>
<td>48/400</td>
</tr>
</tbody>
</table>
XRD analysis shows that the (Fe$_{70}$Ga$_{30}$)$_{0.9}$B$_{0.1}$ film is crystalline having distorted bcc structure of D0$_3$. The lattice constant and grain size calculated from the bcc FeGa lattice symmetry and uniaxial anisotropy shows that RTA releases stress and improves magnetic softness. The magnetic data, shown in Table I, are extracted from the in-plane M-H loops which were measured both along the easy and hard axes. The results show that the values of $H_c$ and FMR linewidth for the (Fe$_{70}$Ga$_{30}$)$_{0.82}$B$_{0.18}$ film are smaller than that of (Fe$_{70}$Ga$_{30}$)$_{0.9}$B$_{0.1}$ film, indicating that B addition in FeGa improves magnetic softness and FMR linewidth. Analysis of the XRD data of (Fe$_{70}$Ga$_{30}$)$_{0.9}$B$_{0.1}$ films annealed at 380 °C [Figs. 1(a) and 1(b)] shows that the lattice constant of the bcc lattice structure sharply decreases from 2.945 to 2.89 Å in about 100 s of annealing. Furthermore, the grain size has been observed to increase with annealing time and attain its maximum at 300 s of annealing.

Static and dynamic magnetic measurements shown in Figs. 2(a)–2(c) illustrate several interesting features, (i) both dc magnetic and microwave properties show similar trends, (ii) high temperature is more effective in reducing the FMR linewidth, and (iii) minimum values of $H_c$, $H_k$, and FMR linewidth are obtained in a short annealing of 60 s at 380 °C. The minimum values of $H_c$ and FMR linewidth obtained for (Fe$_{70}$Ga$_{30}$)$_{0.9}$B$_{0.1}$ films with RTA at 180 °C are 23 Oe and 115 Oe, respectively, whereas for the same film with RTA at 380 °C, these values are 7 Oe and 100 Oe, respectively.

Analyses of structure, dc, and microwave properties show that RTA releases stress and improves magnetic softness. In these films, there can be two dominant contributions to the in-plane anisotropy, cubic anisotropy ($K_c$) originating from bcc FeGa lattice symmetry and uniaxial anisotropy ($K_u$) induced due to stress induced during the film deposition. The process of RTA is expected to reduce the stress and thus reduce the uniaxial anisotropy. Consequently, minimum anisotropy can be achieved at certain annealing time, further annealing increases the cubic anisotropy and thus the in-plane anisotropy ($H_k$). High anisotropy gives rise to high $H_c$ and broad FMR linewidth.

Similar experiments have been performed on (Fe$_{70}$Ga$_{30}$)$_{0.82}$B$_{0.18}$ amorphous films. The XRD data show that (Fe$_{70}$Ga$_{30}$)$_{0.82}$B$_{0.18}$ films are amorphous and no apparent structural changes after RTA. Static and dynamic magnetic measurements performed on (Fe$_{70}$Ga$_{30}$)$_{0.82}$B$_{0.18}$ films, shown in Figs. 3(a) and 3(b), again show that both dc and microwave properties have similar trends with annealing time. Unlike the crystalline films, samples annealed at 380 °C have much larger $H_c$ and FMR linewidth than those annealed at 180 °C. More importantly, minimum FMR linewidth can still be achieved in films treated at 180 °C for about 100 s.

Similar to (Fe$_{70}$Ga$_{30}$)$_{0.82}$B$_{0.18}$ films, RTA performed at lower temperature (180 °C) results in stress reduction and improves magnetic softness. At 380 °C annealing, we suspect that amorphous films start to crystallize, which will induce cubic anisotropy. The cubic anisotropy increases rapidly with annealing time, resulting in much larger $H_c$ and FMR linewidth.

### IV. SUMMARY

We have performed RTA experiments on crystalline (Fe$_{70}$Ga$_{30}$)$_{0.9}$B$_{0.1}$ and amorphous (Fe$_{70}$Ga$_{30}$)$_{0.82}$B$_{0.18}$ films in order to reduce the FMR linewidth. The FMR linewidth is directly related with the effective anisotropy which comes from cubic anisotropy and uniaxial anisotropy. The latter is small and arises from the stress in the films. In the absence of
cubic anisotropy in amorphous films, the effective anisotropy is small, resulting in a narrow FMR linewidth. The FMR linewidth in both crystalline and amorphous films can be further reduced by RTA. In crystalline films, a minimum FMR linewidth can be achieved by annealing samples at a relative high temperature for a short time. The effect is attributed to the reduction in uniaxial anisotropy. In amorphous films, the reduction of FMR linewidth is achieved at low annealing temperature for a short time. Elevated temperatures and prolong time may crystallize the amorphous structure and introduce a much large cubic anisotropy, resulting in a large FMR linewidth.

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