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Magnetic properties and high frequency characteristics of sputtered FeAl and FeAlB

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Abstract. The magnetic properties and high frequency characteristics of sputtered Fe₈₁Al₁₉ and Fe₈₁Al₁₀B₉ thin films have been investigated. The above two thin films were sputtered at different oblique deposition angles in order to induce magnetic anisotropy in the film. The saturation magnetization of the films is easily above 12 kG, while the coercivity and the magnetic anisotropy field of the films are increased with increasing the oblique deposition angle, and decreased for the film with B. The residue stress induced by the oblique deposition is presumed the main factor to influence the magnetic anisotropy field of the thin films, the larger the residue stress the higher the magnetic anisotropy field and ferromagnetic-resonance frequency. The ferromagnetic-resonance frequency of Fe₈₁Al₁₀B₉ films can be above 1.3 GHz, while the permeability of the films is as high as 300-750 in the frequency range of 0-1 GHz, depending on the oblique deposition angles.

1. Introduction

Soft magnetic thin films with high saturation magnetization, low coercivity, high permeability and high electrical resistivity are useful for modern inductive devices, such as magnetic recording head and thin film inductors. The ferromagnetic-resonance frequency ($f_{\text{FMR}}$) of such films is proportional to the root of multiplication of saturation magnetization ($4\pi M_s$) and magnetic anisotropy field ($H_k$), i.e. $f_{\text{FMR}} = (\gamma/2\pi)(4\pi M_s \times H_k)^{1/2}$. Therefore, the values of saturation magnetization and magnetic anisotropy field are very crucial for the films to exhibit high ferromagnetic-resonance frequency. Furthermore, the materials with high permeability ($\mu$) can be suitably incorporated into an "air-core" inductor without producing additional loss, and substantially higher inductance and quality factor (Q) would be achievable without increasing the size of the device, or alternatively, for the same inductance value a much smaller substrate area would be needed.² ³

Using an oblique deposition method, FeCoB and FeGaB thin films with high ferromagnetic-resonance frequencies of 1-3.3 GHz have been successfully developed.⁴ ⁶ On the other hand, FeAl alloys have been shown to exhibit high magnetostriction and relatively high saturation magnetization.⁷ It has been reported that Fe-19 at% Al alloy ribbons have a high magnetostriction coefficient of around -700 ppm, while it is 350 ppm for Fe-19 at% Ga single crystal and 270 ppm for FeGa polycrystal.⁸ ¹⁰ It is of interest to see the possibility of FeAl series films to play the same role as that of FeCo or FeGa series films.
Therefore, at first, we deposited the Fe$_{81}$Al$_{19}$ thin films by using oblique deposition method to see if it is suitable for high frequency applications. The impact of oblique angle on the magnetically soft properties was especially investigated. In addition, to reduce the coercivity of the film, part of the Al was replaced with B in preparation of FeAlB thin films because B element is helpful in decreasing the crystallinity in many metallic films. Comparison on the magnetic properties and high frequency characteristics of FeGaB and FeAlB films were reported in this manuscript.

2. Experiment

The Fe$_{81}$Al$_{19}$ and Fe$_{81}$Al$_{10}$B$_9$ thin films, about 110 nm in thickness, were prepared by dc magnetron sputtering onto silicon substrate using oblique deposition method together with an external in-plane magnetic field of 1200 Oe, as show in Figure 1. The base pressure of the sputtering chamber was better than 1×10$^{-6}$ torr, and the working pressure and input power were maintained at 4.5 mtorr and 20 W during the deposition, respectively. The magnetic hysteresis loops along easy axis and hard axis of the films were measured by vibrating sample magnetometer (VSM), respectively. High-frequency permeability characteristics were measured with AC permeance meter (Ryowa: PMF-3000, 0–3 GHz). The crystal structures of the thin films were studied by X-ray diffraction (XRD) with Cu-k$_\alpha$ radiation.

![Figure 1. Schematic diagram of oblique deposition method.](image)

3. Results and discussion

Previous studies have shown that using the oblique deposition method can effectively enhance the residue stress of the magnetically soft thin films and, consequently, increase the magnetic anisotropy field and magnetic resonance frequency of the films. Same trial has been made to prepare Fe$_{81}$Al$_{19}$ film at first in this study. Figure 2 shows the downward part of magnetic hysteresis loops along the hard magnetization axis of the Fe$_{81}$Al$_{19}$ films prepared at different oblique deposition angles.

Figure 3 shows the change of magnetic properties of the Fe$_{81}$Al$_{19}$ thin films as a function of oblique deposition angle. It can be found that with increasing the oblique deposition angle the saturation magnetization of the films decreased rapidly, from 12.8 kG for $\delta = 15^\circ$ to 11.3 kG for $\delta = 40^\circ$. Meanwhile, the coercivity measured along easy axis ($H_{ce}$) and along hard axis ($H_{ch}$) increased with the increase of oblique deposition angle. The Fe$_{81}$Al$_{19}$ film deposited at $\delta = 15^\circ$ had $H_{ce}$ of 66.5 Oe and $H_{ch}$ of 15.7 Oe, whereas higher coercivity, $H_{ce}$ = 143.3 and $H_{ch}$ = 51.3 Oe, appeared for the film deposited at $\delta = 40^\circ$. In addition, the magnetic anisotropy field, obtained from the interception of hysteresis loops along the easy axis and along the hard axis of the film, increased effectively from 68 Oe for $\delta = 15^\circ$ to 191 Oe for $\delta = 40^\circ$. The residue stress induced by the oblique deposition is presumed the main factor to influence the magnetic anisotropy field of the films, the larger the oblique deposition angle the larger the residue stress and induced magnetic anisotropy field. Based on the above magnetic data, the ferromagnetic-resonance frequency can be estimated following the formula of $f_{\text{FMR}} = (\gamma/2\pi)(4\pi M_s H_k)^{1/2}$, it increases from 2.6 GHz for $\delta = 15^\circ$ to 4.2 GHz for $\delta = 40^\circ$ for Fe$_{81}$Al$_{19}$ films.

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For high frequency applications, small coercivity of thin films is requisite in order to reduce the hysteresis loss. To reduce the coercivity and improve the permeability for the studied films, the third element B is adopted to add into FeAl alloy based on Inoue’s empirical rules for the alloys with high glass forming ability. Fig. 4 displays the XRD patterns of the Fe\textsubscript{81}Al\textsubscript{19} and Fe\textsubscript{81}Al\textsubscript{10}B\textsubscript{9} thin films prepared at different oblique deposition angles. From the change of full width at half maximum (FWHM) of α-Fe (110) peak in Fe\textsubscript{81}Al\textsubscript{19} films, it is obvious that FWHM value increased with the increase of oblique angle, whereas the diffraction peak of α-Fe (110) almost vanished in Fe\textsubscript{81}Al\textsubscript{10}B\textsubscript{9} films. As expected, B substitution for Al did decrease the crystallinity of the films effectively, which is helpful for reducing the coercivity of the films.
Figure 5 shows the variation of magnetic properties of the Fe$_{81}$Al$_{10}$B$_{9}$ films prepared at different oblique deposition angles. The trend of the variation of magnetic properties for Fe$_{81}$Al$_{10}$B$_{9}$ films prepared at different oblique deposition angles is similar to those of Fe$_{81}$Al$_{19}$ thin films. With increasing the oblique deposition angle, the saturation magnetization of the thin films decreased from 13.3 kG for $\delta = 15^\circ$ to 12.7 kG for $\delta = 40^\circ$, while the anisotropy field was enhanced from 17 Oe for $\delta = 15^\circ$ to 121 Oe for $\delta = 40^\circ$. The coercivity of the hysteresis loops increased from $H_{ce} = 14.7$ and $H_{ch} = 5.5$ Oe for $\delta = 15^\circ$ to $H_{ce} = 62.3$ and $H_{ch} = 25.4$ Oe for $\delta = 40^\circ$, respectively. The calculated ferromagnetic-resonance frequency of the films could be improved from 1.3 GHz for $\delta = 15^\circ$ to 3.5 GHz for $\delta = 40^\circ$ for Fe$_{81}$Al$_{10}$B$_{9}$ films.

It was evidenced that the coercivity along easy axis and hard axis and the magnetic anisotropy field were all decreased by the substitution of B for Al. The coercivity of the films deposited at $\delta = 20^\circ$ decreased from $H_{ce} = 74.0$ and $H_{ch} = 15.7$ Oe for Fe$_{81}$Al$_{19}$, to $H_{ce} = 24.8$ and $H_{ch} = 6.3$ Oe for Fe$_{81}$Al$_{10}$B$_{9}$. Besides, the magnetic anisotropy field of the films decreased from 77 Oe for Fe$_{81}$Al$_{19}$ to 27 Oe for Fe$_{81}$Al$_{10}$B$_{9}$. Meanwhile, the calculated ferromagnetic-resonance frequency of the films was decreased from 2.8 GHz for Fe$_{81}$Al$_{19}$ film to 1.7 GHz for Fe$_{81}$Al$_{10}$B$_{9}$ film sputtered at $\delta = 25^\circ$.

Figure 6 shows the frequency dependence of permeability for the Fe$_{81}$Al$_{10}$B$_{9}$ films with an oblique deposition angle of (a) $\delta = 15^\circ$, (b) $\delta = 20^\circ$, and (c) $\delta = 25^\circ$. Table I lists the calculated and experimental ferromagnetic-resonance frequency, and the average maximum permeability at frequencies below 1 GHz of Fe$_{81}$Al$_{10}$B$_{9}$ films. It can be seen that the ferromagnetic-resonance frequency of Fe$_{81}$Al$_{10}$B$_{9}$ films increased from 1.3 GHz for $15^\circ$ to 2.2 GHz for $25^\circ$ because of the increase in magnetic anisotropy field of the films, and the average permeability at frequencies below 1 GHz of Fe$_{81}$Al$_{10}$B$_{9}$ films prepared at the above three oblique angles is 780, 590 and 300, respectively.

It was also shown that the calculated and experimental ferromagnetic-resonance frequencies are quite closer, reflecting that the former adopted formula is acceptable for estimating the magnetic-resonance frequency in the present alloy films.
Table 1. The calculated and measured ferromagnetic-resonance frequencies, and the average permeability of the Fe$_{81}$Al$_{10}$B$_{9}$ films prepared at different oblique deposition angles.

| $\delta$ (°) | $f_{\text{FMR, cal.}}$ (GHz) | $f_{\text{FMR}}$ (GHz) | $\mu_{\text{ave}}$ (< 1 GHz) |
|-------------|---------------------------|-------------------|------------------|
| 15          | 1.3                       | 1.3               | 780              |
| 20          | 1.7                       | 1.8               | 590              |
| 25          | 2.4                       | 2.2               | 300              |

As shown in the previous results, it is found that the average permeability of Fe$_{81}$Al$_{10}$B$_{9}$ film at the frequencies below 1 GHz is above 500 and the ferromagnetic-resonance frequency is about 1.7 GHz for $\delta = 20$°, which are identical to the values that obtained in FeGaB films. In short, Fe$_{81}$Al$_{10}$B$_{9}$ thin films prepared at suitable oblique deposition angle may display identical or even better soft magnetic properties than those of FeGaB thin films. Inasmuch as the element Al is much cheaper than the element Ga, FeAlB film has the potential to be an alternative material for high frequency applications.

4. Conclusions

The effect of oblique deposition angles on soft magnetic properties and high frequency characteristics of Fe$_{81}$Al$_{10}$ and Fe$_{81}$Al$_{10}$B$_{9}$ thin films were examined. The magnetic properties and high frequency characteristics of the Fe$_{81}$Al$_{10}$ and Fe$_{81}$Al$_{10}$B$_{9}$ thin films can be monitored by different oblique deposition angles. Furthermore, B substitution for Al decreased the crystallinity of the films and magnetic anisotropy field, resulting in the decrease of coercivity. Nevertheless, high permeability of the thin film is obtainable by decreasing the oblique angle. In addition, high ferromagnetic-resonance frequencies between 1-3 GHz can be attained by increasing the oblique deposition angle.

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