A new guideline for the improvement of soft magnetic properties of crystalline films deposited on tilted substrates

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A new guideline for the improvement of soft magnetic properties of crystalline films deposited on tilted substrates

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The coercive forces and anisotropy fields of Fe-Ru-Ga-Si films deposited on 30° tilted substrates were measured for varying chemical compositions and crystal orientations. The minimum coercivity and minimum in-plane magnetic anisotropy were observed at an iron-rich composition corresponding to a substantial magnitude of anisotropy constant: $K_1=6\times10^3$ (J/m^3). From an orientation analysis of the crystal aggregate, this optimization with the large K_1 was understood to be a result of the cancellation of the shape anisotropy by the crystalline anisotropy.

I. INTRODUCTION

Soft magnetic characteristics of crystalline films have been optimized by minimizing both crystalline and stress-induced magnetic anisotropies. Chemical compositions with null crystalline anisotropy and null magnetostriction for the best magnetic softness are known for the Fe-Al-Si (Sendust)[1] and Fe-Ru-Ga-Si (SOFMAX®)[2] systems. However, films of even these materials do not always possess soft magnetic properties, particularly when they are deposited on tilted substrates. This is due to shape anisotropy arising from the anisotropic microstructure formed by the oblique incidence of the deposition beam on the substrate. Our study is motivated by the increasing importance of such anisotropic deposition processes in industrial applications. For example, metal film is deposited on the tilted slopes of grooves cut on a substrate in the production of TSS-type magnetic heads.[3]

Since the shape anisotropy often becomes the predominant component in soft magnetic films, canceling this anisotropy by other components might be a better approach than minimizing the individual anisotropies separately.

II. EXPERIMENTAL

Soft magnetic Fe-Ru-Ga-Si alloy films with the thickness of 1.3 μm were prepared by rf magnetron sputtering. The crystalline anisotropy constant K_1 of the films was varied, keeping the Ru content 8 at.% by controlling the chemical composition of the alloy target. We assumed each specimen to have the value of K_1 from Okamoto's mapping[4] corresponding to the film specimen determined by WDX. To eliminate stress-induced anisotropy, not only were the compositions of the specimens chosen such that the magnetostriction λ of the films became small[5] but also glass ceramic substrates (PEG(R)-3130 of HOYA Corp.) with almost the same thermal expansion as that of the metal film, 1.3×10^{-5} (1/K), were used. The substrate tilting was varied between 0° and 30°.

With a view to controlling the crystal orientation of the magnetic layer, a gold or chromium base layer was formed by sputtering before depositing FeRuGaSi. After film deposition, the specimens were annealed at 550 °C in vacuum for 1 h and furnace cooled.

The coercive force and the anisotropy field of B-H loop was measured to evaluate magnetic softness. The (110) and (200) diffractions of the bcc phase were measured by Schulz's reflection method, and the pole distribution in the region with latitude $15°<\alpha<90°$ was obtained.

III. MAGNETIC PROPERTIES

Figure 1 shows B-H loops of FeRuGaSi/Au specimens with different values of K_1. The X and Y axes of the tilted substrate were taken parallel and perpendicular to the incident plane of the deposition beam. It was natural that the coercive force, H_c, increased with K_1 for specimens on horizontal substrates. However, as is seen in Fig. 1, the H_c of a specimen with $K_1=6\times10^3$ (J/m^3) was the smallest of specimens formed on 30° tilted substrates. The dependence of H_c on K_1 for specimens on horizontal and tilted substrates showed split curves, as shown in Fig. 2. This implies that the best composition for soft magnetic performance depends on the substrate tilting.

The magnitudes of the in-plane magnetic anisotropy of films formed on tilted substrates were estimated from the B-H loops by the difference of anisotropy field, $\Delta H_K = H_K(X \text{ direction}) - H_K(Y \text{ direction})$ and summarized in Fig. 3. Specimens with small K_1 had ΔH_K around 120 (A/m) regardless of their base layers. The anisotropic magnetization energy in the film plane, -70 (J/m^3), evaluated from this anisotropy field gave an estimate for the shape anisotropy.

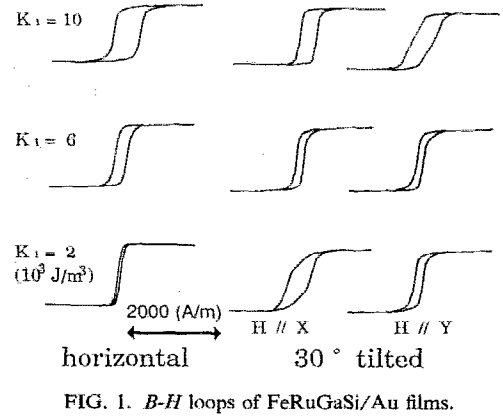

FIG. 1. B-H loops of FeRuGaSi/Au films.

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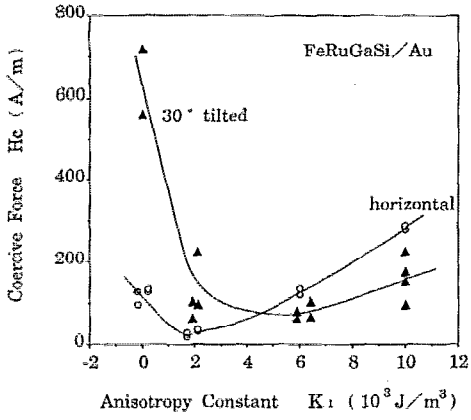

FIG. 2. Coercive force H_c of FeRuGaSi/Au films deposited on horizontal and 30° tilted substrates.

As for FeRuGaSi/Au films on tilted substrates, a monotonic decrease of ΔH_K with increasing K_1 was observed, as shown in Fig. 3. The intersection of this descending line at $K_1 = 6 \times 10^3$ (J/m^3) is consistent with the minimum H_c in Fig. 2.

IV. CRYSTAL ORIENTATION

As shown in Fig. 4, the specimens deposited on horizontal glass ceramic substrates showed a (110) fiber structure with axial symmetry. However, this axial symmetry disappeared when the film was formed on a tilted substrate. A concentration of (200) poles at a low latitude in the incident plane was characteristic of the specimens on 30° tilted PEG® substrates.

A Au base layer sharpened the (110) fiber structure of the magnetic films, as shown in Fig. 5. A specimen with a Au base layer kept its (110) fiber axis nearer to the normal direction of the film plane even when the film was deposited at oblique incidence. Taking into consideration the high density of (200) poles at $\alpha = 45°$ in the Y-Z plane in Fig. 5(b), the dominant crystal orientation has its (110) plane parallel to the film plane and its ⟨001⟩ axis in the X direction. Since this (200) pole distribution does not consist of points but arcs, there exist crystallites with rotated (110)⟨001⟩ orientations around the normal direction of the film. The estimated volume fraction of crystallites with this anisotropic orientation is about 1/9 with rotation ranging between ±45°.

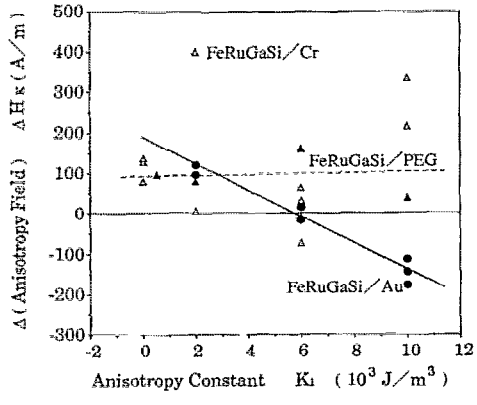

FIG. 3. Difference of anisotropy fields, $\Delta H_K = H_K(X) - H_K(Y)$, for FeRuGaSi films deposited on 30° tilted substrates.

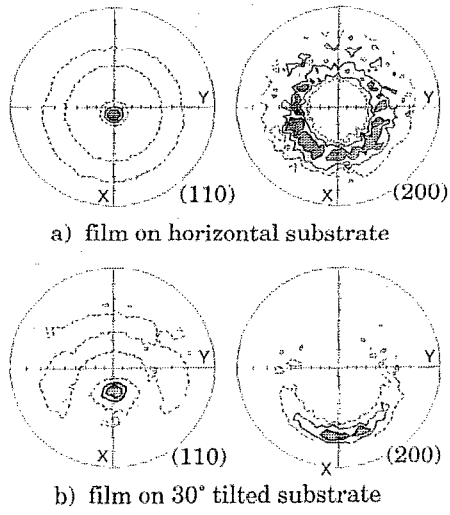

FIG. 4. Pole figures of FeRuGaSi films deposited on PEG® substrates.

As for specimens with Cr base layers, the (110) fiber structure was somewhat sharpened when the substrate was horizontal. However, no common feature to all the specimens was observed when tilted. This variation in crystal orientation may be related to the widely scattered ΔH_K shown in Fig. 3.

V. DISCUSSION

The magnetocrystalline anisotropy of the FeRuGaSi/Au specimens is suitable for further discussion because the (110)⟨001⟩ orientation was common, to some extent, to all the FeRuGaSi/Au specimens on tilted substrates.

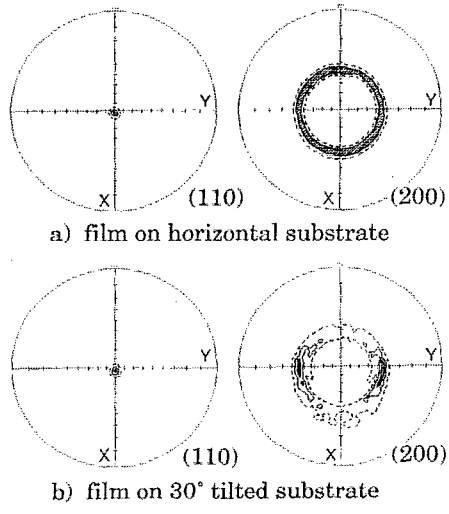

FIG. 5. Pole figures of FeRuGaSi films deposited on Au base layers.

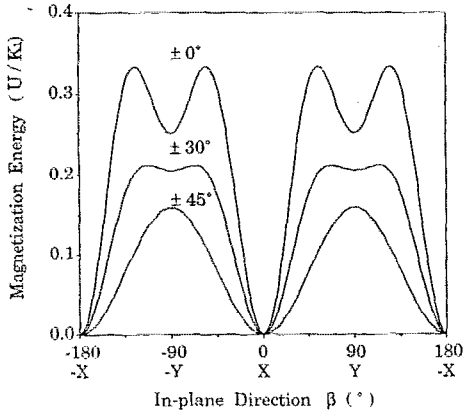

FIG. 6. Calculated magnetization energy for crystal aggregates with (110)⟨001⟩ orientation.

The value of the potential energy, U, for a crystallite with its magnetization having direction cosine (l,m,n) is given by the formula $U(l,m,n)=K_1(l^2m^2+m^2n^2+n^2l^2)+\cdots$.[6] The magnetization energy of the crystallites with the (110)⟨001⟩ orientation is drawn in Fig. 6 as a function of in-plane direction β. The curve has minima in both the X and $-X$ directions and the deviation reaches $(1/3)K_1$, which is the largest value available from the above equation. Of course, the deviation decreases when the specimen includes crystallites rotated away from the exact (110)⟨001⟩ orientation.

Considering the breadth of the distribution, ±45°, and its volume fraction, 1/9, of the quasi-(110)⟨001⟩ component of the FeRuGaSi/Au specimen, the anisotropic magnetization energy is expected to be $(1/9)\times0.16\times K_1$. A magnetocrystalline anisotropy thus obtained from a value of $K_1=6\times10^3$ (K/m^3) is 107 (J/m^3). This amount and sign is sufficient to cancel the shape anisotropy of −70 (J/m^3). Increasing K_1 in this model calculation would reproduce the monotonic decrease of ΔH_K seen in Fig. 3.

VI. CONCLUSION

The soft magnetic properties of obliquely deposited films optimized at a Fe-rich composition with larger K_1 can be understood as the result of the mutual cancellation of the shape anisotropy and the crystalline anisotropy.

This principle of cancellation is also applicable to Sendust, a more popular material, and nanocrystalline materials[7] whose crystallites have a larger crystalline anisotropy.

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