VERY THIN Fe-Si FILMS WITH SOFT MAGNETIC PROPERTIES

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Abstract-- Fe-Si films epitaxially grown on GaAs(111) substrates exhibit low H_c and high permeability when their thickness is in the range 150~1000 Å. Calculations on the initial permeability of (111) oriented single crystal thin films are presented and the results are compared to the experiments.

INTRODUCTION

It has been reported by the authors that crystal orientation of Fe alloy polycrystalline films is one of the main factors to determine the magnetic softness¹⁾. Results of calculation on the fundamental properties of the polycrystalline films with various orientation indicate that (111) orientation is favorable to the magnetic softness. Experimental evidences were also given on the advantage of (111) orientation in terms of coercive forces and permeability.

However, some difficulties arose in fabrication of the films with (111) orientation. The orientation was realized only in the films deposited on ZnSe underlayer and H_c of those films are lower than the films with other kinds of orientation although the crystal size of the films on ZnSe is relatively large. But it was also found that ZnSe underlayer must be as thick as 2000 Å for good (111) orientation. This thickness brings about rough surface of the underlayer and works unfavorably for the magnetic softness of Fe alloy films deposited on it.

In this paper fabrication of Fe-Si films epitaxially grown on (111) of single crystal GaAs substrates and their soft

magnetic properties are reported. The results are compared with the calculated H_c and μ_i assuming magnetization rotation.

CALCULATION AND EXPERIMENTS

In the calculation reported in the previous publication, the magnetization was assumed to be parallel to the film plane, namely perfectly confined in the (111) plane in the (111) oriented films. This seems to be valid because of the very large demagnetizing field caused by the shape anisotropy. Under this assumption, the initial permeability was estimated to be very high and a disagreement was found between the experimental results and the calculated values. Here, deviation of the magnetization out of the film plane due to the crystalline anisotropy is taken into account. Figure 1 shows the coordinate system for the calculation. The magnetization is out of the (111) plane with small angle ϵ , which is determined by the crystalline anisotropy and the shape anisotropy.

The anisotropy energy (E_a), the magnetostatic energy (E_m) and the demagnetizing energy (E_d) are

Fig.1

$$E_a = K_1 \left[\left(\frac{1}{4} \right) - \left(\frac{1}{2\sqrt{2}} \right) (\cos 3\psi + \cos \psi) \epsilon + \left(\frac{1}{6} \right) (2\cos 2\psi - 1) \epsilon^2 \right] + K_2 \left[\left(\frac{1}{108} \right) (\cos 6\psi + 1) - \left(\frac{1}{36\sqrt{2}} \right) * (\cos 5\psi + 3\cos 3\psi + \cos \psi) \epsilon - \left(\frac{1}{36} \right) * (\cos 6\psi - 2\cos 4\psi - 2\cos 2\psi - 2) \epsilon^2 \right] \quad (1)$$

$$E_s = -M_s h \cos(\psi - \beta) (1 - (1/2) \epsilon^2) \quad (2)$$

$$E_d = 2\pi N M_s \epsilon^2 \quad (3)$$

The Landau-Lifshitz equation for the dynamic behavior of the magnetization under a very weak high-frequency field($\mathcal{H}$) was used to obtain the permeability. For the detailed process of the calculation, refer to 2). The static initial permeability of the (111) oriented single crystal film is calculated as

$$\mu_i = 4\pi M_s B \sin^2(\psi - \beta) / (AB - C^2) \quad (4)$$

where

$$A = (\delta^2 E_0 / \delta \psi^2) \text{ for } \psi_0, \epsilon_0 = 0$$

$$B = (\delta^2 E_0 / \delta \epsilon^2) \text{ for } \psi_0, \epsilon_0 = 0$$

$$C = (\delta^2 E_0 / \delta \epsilon \delta \psi) \text{ for } \psi_0, \epsilon_0 = 0$$

$$E_0 = E_a + E_s + E_d$$

According to eq.(4) it is expected that for Fe-Si(1.5wt.%) single crystal film with (111) orientation the permeability will be about 2200 at maximum.

Fig.2 The substrate temperature is (a):500,(b):400,(c):300,(d)200 and (e):R.T.

Films with orientation of (111) were fabricated by using GaAs single crystal substrates. Fe-Si(1.5wt%) alloy films

were deposited on GaAs substrates with (111) orientation by sputtering. Film thickness ranges from 150 to 6000 Å with the substrate temperature from R.T. to 500°C.

The Fe-Si films fabricated in this way exhibit good orientation of <111> axis perpendicular to the film plane. Figure 2 shows X-ray diffraction patterns of the films deposited at various substrate temperatures. While the intensity ratio of the X-ray diffraction peak from (110) to that from (222) is about 16.6 in the homogeneous polycrystalline Fe, it is zero in Fig.2, indicating that the films have good orientation of (111).

As seen in Fig.2, the substrate temperature is an important factor to determine the orientation. At 400°C the orientation is the best and at 500°C an unidentified peak is observed. This is probably due to interdiffusion between the substrate and the film.

Figure 3 shows a result of the torque measurement. The crystalline anisotropy is triaxial and very weak in (111) plane. The torque curve in the figure indicates triaxial anisotropy. Since the crystalline anisotropy energy which makes the magnetization deviate out of the (111) plane is not negligible compared to the demagnetization energy due to the film shape, the magnetization deviates slightly from the film plane and the absolute value of the torque does not necessarily agree with the calculation which assumes the magnetization always lie parallel to the film plane. However, the triaxial curve gives clear evidence of epitaxial growth of the Fe-Si crystals.

Fig.4 is H_c of the films as a function of the film thickness. $\Delta \theta_{so}$ is also shown. H_c is minimum at 300 Å but increases rapidly as the thickness becomes higher than 2000 Å. This indicates that good epitaxial growth occurs for a thickness

Fig.3

Fig.4

less than 1000 Å. High H_c for thicker films may be due to formation of grain boundaries and some other internal structures such as columns.

Permeability was measured for 1000 Å films by using a LCR meter, and, for high frequencies, an 8 figure coil system.⁹⁾ While the calculation expects the initial permeability to be triaxial with the maximum value of 2500, no clear triaxial symmetry was available for the films and the maximum experimental values are about 1400. A reason for this disagreement is that the films exhibit a very weak uniaxial in-plane anisotropy in addition to the crystalline

anisotropy: An example of the B-H loops is shown in Figure 5.

REFERENCES

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Fig.5

Since the uniaxial anisotropy is relatively weak, dominant factors determining the initial permeability are unknown at present. However, the permeability is constant against frequency change up to 100MHz. This indicates that the permeability is caused by magnetization rotation rather than domain wall displacements.

CONCLUSION

Very thin Fe alloy films with good magnetic softness were obtained by using (111) single crystal GaAs substrates. The measured initial permeability is high but lower than the theoretical prediction.

Although some ambiguity still remains concerning the influence of the in-plane crystalline anisotropy and uniaxial anisotropy to the initial permeability, the films are of interest from the standpoint of material research for the main pole head, where magnetic softness of very thin films has always been required.