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THE EFFECT OF INTERNAL STRESS ON THE SOFT MAGNETIC PROPERTIES OF PERMALLOY THIN FILMS

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Abstract —— The stress in Permalloy thin films fabricated by rf magnetron sputtering on the Si (100) substrates has been investigated with various deposition parameters such as the film thickness, argon pressure, and rf power. The internal stress changes from compressive to tensile with higher input power and argon pressure. The cause of stress variations with these deposition parameters is discussed in terms of thermal and/or intrinsic stress changes. Low coercive force is obtained from Permalloy thin films at a condition of low compressive stress.

I. INTRODUCTION

The relationship between magnetic property and its structure has been investigated extensively for the films fabricated at various deposition conditions [1-2]. However, there are many issues still to be solved. One notable example is the understanding of the effect of internal stress on the magnetic properties. This is particularly important, since the internal stress is known to affect the magnetic properties such as coercivity and permeability quite sensitively [3].

The total stress in a deposited thin film is composed of two major stress components: the thermal stress component which occurs during cooling after the deposition caused by the difference in the thermal expansion coefficients of the film and substrate, and the intrinsic stress component which is caused by an epitaxial misfit between the film and substrate as well as impurities incorporated during the deposition [4-6]. The stresses, whether thermal or intrinsic, may change the mechanical and/or magnetic properties of soft magnetic materials.

In an effort to rectify this situation, we systematically investigate the internal stress and its effects on the soft magnetic properties of NiFe thin films.

II. EXPERIMENTAL PROCEDURES

Permalloy films were deposited by rf magnetron sputtering. The target-to-substrate distance was fixed to 6 cm. The substrate was water-cooled. The rf power was varied from 100 to 600 W, and the argon pressure from 0.5 to 20 mTorr. Permalloy films deposited on the Si (100) wafers with a dimension of 50 mm x 4 mm and 200 mm in thickness.

Internal stress in the thin film was obtained by measuring the radius of curvature of the substrate resulting from the stress in thin film. From the radius of curvature of the substrate, the sign and magnitude of the film stress can be determined by Stoney's equation [7]

$$\sigma = \frac{E_s}{(1-\nu_s)}\frac{t_s^2}{6Rt_f} \qquad (1)$$

where σ = internal stress of the film, E_s = Young's modulus of the substrate, υ_s = Poisson's ratio of the substrate, R = radius of curvature of the substrate, and t_s, t_f = thickness of the substrate and the film, respectively. Coercive force was measured by a vibrating sample magnetometer (VSM).

III. RESULTS AND DISCUSSION

Fig. 1 shows the measured film stress as a function of rf input power at 1 mTorr argon pressure and 1 μm film thickness. For the thermally floating substrate shown in line A in Fig. 1, the stress is tensile over the whole range of the input power and it increases linearly with the input power. For the thermally grounded substrate shown in line B in Fig. 1, the films deposited at low powers less than 500 W have compressive stress whereas those deposited at higher rf powers have tensile stress. The difference of stress between line A and line B is about 1.0 GPa.

To understand the stress variations in the sputtered films, thermal component of total stress will be considered first. The thermal stress is a linear function of temperature and thermal mismatch between the substrate and the film.

$$\sigma_{th} = \frac{E_f}{1-\nu_f}(T-T_r)(\alpha_f-\alpha_s) \qquad (2)$$

where σ_{th} = thermal stress of film, E_f = Young's modulus of the film, n_f = Poisson's ratio of the film, T, T_r = process temperature and room temperature, respectively, and a_f, a_s = thermal expansion of the film and the substrate, respectively. For Permalloy films on silicon wafers, both $(T - T_r)$ and $(a_f - a_s)$ are positive. Therefore, the thermal stress of the film will be a positive value (that is, tensile stress). However, the effect of intrinsic stress is more complicated being strongly dependent on the film nucleation and growth condition. Since the morphology of thin film is dependent on the deposition process, the intrinsic stress becomes a function of process condition. In metallic films, the compressive stress is usually introduced by the bombardment by the energetic particles, including argon ions and sputtered metal atoms, and the incorporation of impurities [8-10]. At low power, these factors have a dominant effect on the film stress and, as a result, the film is in compressive stress. With an increase in rf power, the substrate temperature increases, and the sticking coefficients of gases decreases. Therefore, it is expected that smaller amount of argon or oxygen is incorporated in the film. Furthermore, increasing the rf power, the probability of argon bombarding the film decreases, further increasing the tensile stress. Fig. 2 shows the oxygen content in sputtered Permalloy thin films as a function of input power. The oxygen content is decreased with the input power and this explains the changes of the stress with increasing rf power, as shown in Fig. 2.

The importance of argon pressure and substrate cooling condition on both magnitude and sign of stress in rf-sputtered Permalloy films is clearly

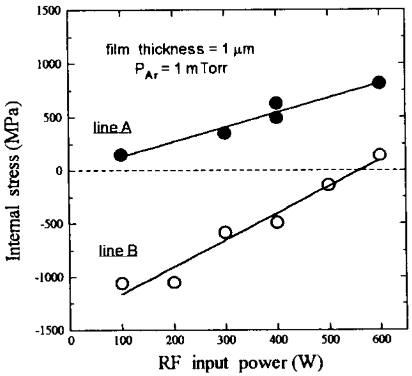


Fig. 1 Internal stress in sputtered Permalloy thin films as a function of input power.

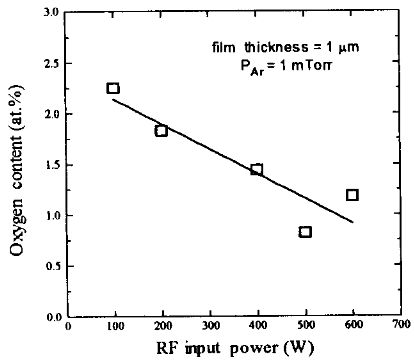


Fig. 2 Oxygen content in sputtered Permalloy thin film as a function of input power.

illustrated in Fig. 3. It shows the variation of the film stress as a function of argon pressure at 400 W rf input power and 1 mm film thickness. For the thermally floating substrate shown in curve A in Fig. 3, the stress is tensile over the whole range of argon pressure. As the argon pressure increases, the tensile stress increases. For the thermally grounded substrate shown in curve B in Fig. 3, the compressive stress changes to tensile stress at the argon pressure of 5-10 mTorr.

This is possible because the temperature of thermally grounded substrate increases more slowly than that of thermally floating substrate. Hence, the large tensile stress of thermally floating substrate is mainly attributed to the thermal stress due to high substrate temperature during deposition. The shape of the curves agrees well qualitatively with the data from sputter-deposited Cr, Mo, Ta and Pt film by Hoffman et al [11].

For curve B, the film stress changes from compressive at 0.5 mTorr pressure to tensile at 20 mTorr. Since the level of argon incorporation in the film depends on the energy of argon atoms (or ions) bombarding the substrate, it is expected that a higher argon pressure would lead to a smaller mean-free-path, lower energies of impinging argon atoms and therefore, a smaller argon concentration in the film. Conversely, as the argon pressure is reduced, argon level in the film should increase and lead to compressive stresses [11-12].

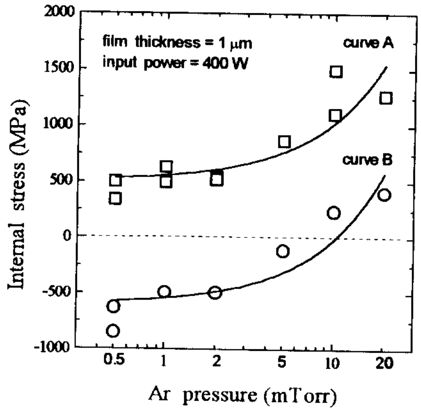
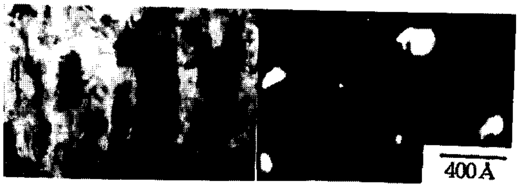


Fig. 3 Internal stress in sputtered Permalloy thin film as a function of Ar pressure.



(a) B.F. (b) D.F.

(A) P_{Ar} = 0.5 mTorr

(a) B.F. (b) D.F.

(B) P_{Ar} = 10 mTorr

Photo. 1 Cross sectional TEM microstructure of Permalloy thin films deposited at the Ar pressure of (A) 0.5 mTorr, (B) 10 mTorr.

The present results for the argon dependence of stress are understood by referring to the Thornton's zone structure of sputtered films [13]. According to the Thornton's zone structure model, elevated working pressures are conducive to the columnar structure with intercrystalline voids. Such structures exhibit high resistivity, low optical reflectivity, and tensile stress. At lower pressures the development of the columnar structure is suppressed.

Photo 1(A),(B) shows the cross sectional TEM microstructure of Permalloy thin films deposited at the Ar pressure of 0.5 and 10 mTorr, respectively. A equiaxed grain is shown in Photo 1(A), whereas a columnar grain is shown in Photo 1(B).

Fig. 4 shows the dependence of coercive force of Permalloy films on the internal stress. In this figure, the curve A and B exhibit the values of coercive force as a function of argon pressure at 400 W rf power, and of power at 1 mTorr argon pressure, respectively.

For curve A and curve B, the coercive force is large when high compressive stress is present. As the compressive stress decreases, the coercive force reaches a minimum of 1.38 Oe at the compressive stress of 580 MPa, and of 0.07 Oe at 110 MPa,

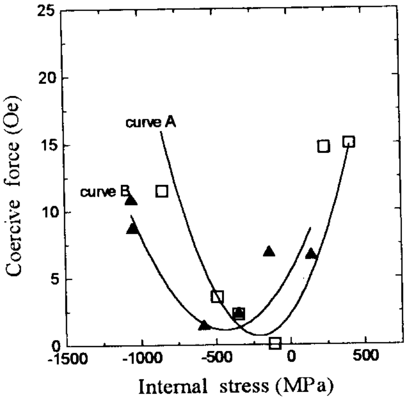


Fig. 4 Coercive force of sputtered Permalloy thin film as a function of internal stress.

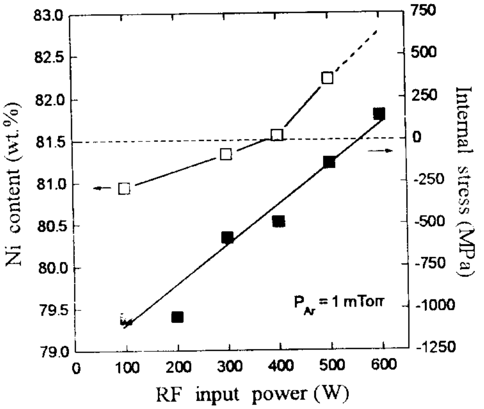


Fig. 6 Ni content and internal stress of Permalloy thin films as a function of rf input power.

respectively, and then increases with the internal stress. The change of coercive force with the stress in curve B is more steep than in curve A.

This suggests that the stress changes induced by the argon pressure have more significant effect than rf power on the coercive force of Permalloy thin film.

According to the magnetoelastic anisotropy, the good soft magnetic property is obtained at the condition of $K_\sigma \approx \lambda_s \sigma = 0$. Here K_σ is the magnetoelastic anisotropy, λ_s is the saturation magnetostriction, and σ is the internal stress.

Fig. 5 and Fig. 6 show the Ni content and internal stress of Permalloy thin films as a function of argon pressure and RF input power, respectively. As shown in Fig. 5, the internal stress is about zero at 5~10 mTorr, where the lowest coercive force is obtained (refer to the curve A of Fig. 4). Meanwhile, as shown in Fig. 6, zero internal stress appears at 500~600 W, but the lowest coercive force is obtained at the zero magnetostriction condition of 300~400 W (refer to the curve A of Fig. 4)..

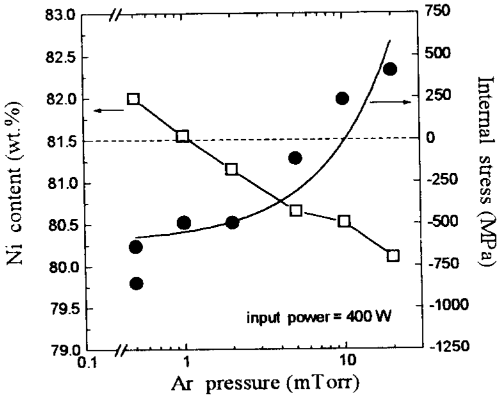


Fig. 5 Ni content and internal stress of Permalloy thin films as a function of Ar pressure.

IV. CONCLUSION

The sign and magnitude of the internal stress in the rf sputtered Permalloy thin film is strongly dependent on the deposition process such as film thickness, argon pressure, and rf power. With increasing the argon pressure and rf power the internal stress is changed from compressive to tensile. These variation of internal stress is attributed to the changes of thermal stress and intrinsic stress with deposition condition. It is noted that the internal stress in the films is not affected directly by the deposition rate. The soft magnetic properties of thin films are strongly affected by the internal stress, and good soft magnetic properties are obtained at a condition of low internal stress and zero magnetostriction.

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