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A NEW METHOD FOR ANALYSIS OF MAGNETIC ANISOTROPY IN FILMS USING THE SPONTANEOUS HALL EFFECT

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A new method to determine the easy axis of films with uniaxial magnetic anisotropy using the spontaneous Hall effect is presented. The principle of the method is explained and its validity is verified by the experiments.

There are several methods to determine the magnetic easy axis in films with uniaxial magnetic anisotropy. The typical methods are given as fillows: (1) torque curve analysis; (2) measurement of the M–H loop; (3) domain pattern observation by Lorentz microscopy or polarizing microscopy and Bitter powder method; and (4) measurement of magnetoresistance. Among them, the torque method is most widely used and trusted. However, the torque magnetometer is somewhat unwieldy and insufficiently precise.

The author has recently devised a new method to determine the easy axis of uniaxial magnetic anisotropy films using the Hall effect. This paper presents the method.

In the Hall effect of magnetic films (or plates), Hall voltage V_H is the sum of an ordinary Hall voltage which depends on the applied magnetic field H and a spontaneous (or extraordinary) Hall voltage which depends on the magnetization M. Further, each of these Hall voltages consists of a transverse Hall voltage V_{TH} and a planar Hall voltage V_{PH}. It is known in ferromagnetic substances that the spontaneous Hall voltage is dominant and the ordinary Hall voltage is negligibly small compared with the former. In such cases, it can be considered that V_{TH} is proportional to $M_n = M\cos\theta$ and V_{PH} is proportional to the product of M_p^2 and $\sin 2\phi$, where M_n and M_p are the magnetization components perpendicular to the film plane and parallel to the film plane, respectively, and θ and ϕ are respectively the angle between M and the film normal and that between M_p and the Hall current I. Therefore, the Hall voltage V_H can be represented as follows;

$$V_H = R_s\frac{MI}{d}\cos\theta + k\frac{M^2I}{d}\sin^2\theta\sin 2\phi \quad (1)$$

or

$$\rho_H = R_s M\cos\theta + kM^2\sin^2\theta\sin 2\phi. \quad (2)$$

Here, R_s, k and d are the spontaneous Hall coefficient, a constant and the film thickness, respectively, and $\rho_H(=V_H d/I)$ is the Hall resistivity. In both eqs. (1) and (2), the first term and the second term represent the transverse Hall effect and the planar Hall effect, respectively.

The change of V_H with the applied magnetic field H, namely V_H–H (or ρ_H–H) curve, shows a hysteresis loop, since M shows a hysteresis with respect to H. However, if the film has a perfect uniaxial magnetic anisotropy, the Hall curve will lose hysteresis when H is applied perpendicular to the apparent magnetic easy axis. The reason is that, in such a case, only the rotation of magnetization takes place and the translational movement of magnetic domain walls does not occur. Here, the apparent easy axis is defined as the direction of magnetization in the absence of applied field and it inclines from the true easy axis towards the film plane due to the demagnetizing field H_d. The direction where the hysteresis disappears is supposed to be independent of the change of demagnetizing field with the applied magnetic field. The method to determine the apparent magnetic easy axis in a film described below is based on this idea.

Now, we take rectangular coordinates in a sample film as illustrated in fig. 1. Then, the direction of the apparent easy axis can be described as (ϕ_0, δ_0) or (ϕ_0, θ_0) and that of the applied field H as (γ, β) or (γ, α). Here, ϕ_0 is the angle between the projection of the (apparent) easy axis on the film plane and the $+x$ axis. δ_0 is the angle between the easy axis and the film

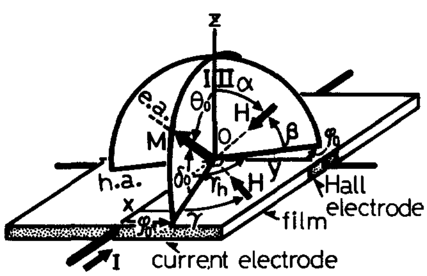

Fig. 1. Definition of normal plane I (NP – I) and II (NP – II) in a uniaxial magnetic anisotropy film and application of magnetic field H in the film plane, in the normal plane I, and the normal plane II (NP-II is vertical to NP-I).

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plane, and θ_0 is that between the easy axis and the $+z$ axis; so that $\theta_0 = 90° - \delta_0$. γ is the angle between the projection of H on the film plane and the $+x$ axis. β is the angle between H and the film plane, and α is that between H and the $+z$ axis; so that $\alpha = 90° - \beta$. Both ϕ_0 and γ are defined as positive in sign when they are measured in the sense $+x \rightarrow +y$. As a general case, let us consider an obliquely magnetized film as illustrated in fig. 1. In this case, we can imagine one normal plane which contains the easy axis and the film normal (z axis) and another normal plane vertical to the former. Here, we denote the former normal plane as NP-I and the latter as NP-II. These two normal planes can be determined by the dependence of Hall curve on the angle γ as follows. The direction of the applied field H is rotated continually in the film (or xy) plane and the Hall curve is recorded on an XY recorder at each time. If the direction of H comes to $\gamma = \gamma_h$ where the NP-II lies, the Hall loop should lose hysteresis because this direction is definitely the magnetic hard direction. Therefore, if this is the case the azimuthal angle of the easy axis ϕ_0 is given by

$$\phi_0 = \gamma_h \pm 90° \tag{3}$$

and thereby the NP-I is determined. Then, the field H is applied parallel with the NP-I and the dependence of the Hall loop on the field direction β (or α) is investigated. Since the direction perpendicular to the easy axis in the NP-I is also the hard direction, hysteresis should disappear from the Hall curve if H is applied in this direction. Let the hard direction be expressed as $\beta = \beta_h$ (or $\alpha = \alpha_h$), then the inclination angle of the easy axis δ_0 is determined by

$$\delta_0 = \beta_h \pm 90°. \tag{4}$$

A simple goniometric sample stage with two rotatable axes enables the above mentioned procedure to be performed.

In order to examine the validity of this Hall method,

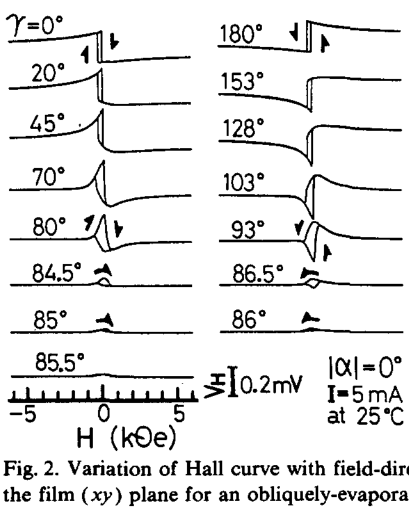

Fig. 2. Variation of Hall curve with field-directional angle γ in the film (xy) plane for an obliquely-evaporated Ni film.

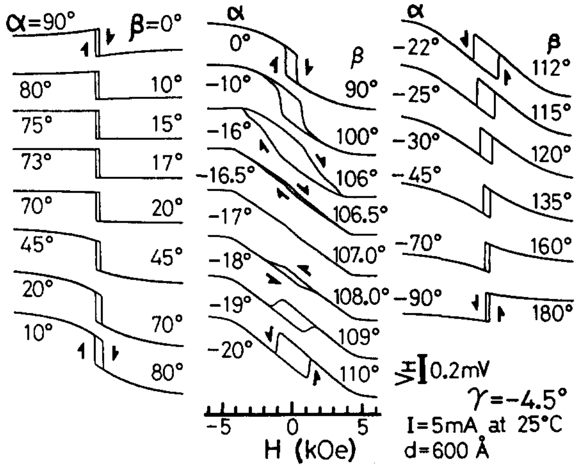

Fig. 3. Variation of Hall curve with field-directional angle β (or α) in the NP-I for the same sample in fig. 2. ($\alpha = 90° - \beta$)

Ni films with oblique magnetic anisotropy were prepared by oblique incidence vacuum evaporation. Fig. 2 shows the field-directional dependence of the Hall loop in the film plane, or V_H–H–γ characteristics, obtained on a Ni film with thickness about 600 Å, 2×4 mm^2 in effective area, deposited onto a glass substrate ($7 \times 7 \times 0.8$ mm) in a vacuum of $8\text{–}9 \times 10^{-3}$ Pa ($6\text{–}7 \times 10^{-5}$ Torr) at an incident angle of $\lambda = 60°$ (measured from the film normal). As is obvious from fig. 2, the hysteresis loop disappears in one direction, namely $\gamma = 85.5°$. This means from eq. (1) that the normal plane-I which contains the easy axis lies in the direction $\phi_0 = 85.5° - 90° = -4.5°$. Then the dependence of V_H–H curve on the field-directional angle $\beta(\alpha)$ was measured in the NP-I. Fig. 3 shows the result. It can be seen from fig. 3 that hysteresis disappears when H is applied in one direction i.e. $\beta = 107.0°$ ($\alpha = -17.0°$) and this indicates that the easy axis lies in the direction $\delta_0 = 107.0° - 90° = 17.0°$ in the NP-I. Consequently, it is concluded that the film is a uniaxial oblique anisotropy film whose apparent easy axis lies in the direction $(\phi_0, \delta_0) = (-4.5°, 17.0°)$. Actually, if H is applied in this easy direction, a completely saturated rectangular Hall loop is observed as can be seen in fig. 3 ($\beta = 17.0°$) and fig. 4 (low field data), and this loop should be called the true magnetization loop of this film. Thus the results shown in figs. 2–4 verify the validity of the Hall method presented here.

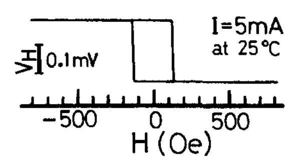

Fig. 4. Hall curve obtained by H applied along the easy axis ($\gamma = -4.5°$, $\beta = 17.0°$) of the same sample as in fig. 2.

It should be noted in fig. 3 that the disappearance of hysteresis is very sensitive to any fractional change of β as small as 0.1°. That is, if $\beta = 106.9°$ or $\beta = 107.1°$, hysteresis appears in the Hall curve. This fact suggests hat the method described in this paper enables us to determine the easy axis of magnetic films with high accuracy better than 0.1°. It is also noted in fig. 3 that the Hall loop is normal (or regular) type for $\beta < 107.0°$ but it changes into an anomalous (or irregular) one with negative magnetization loop for $\beta > 107°$. Such an anomalous Hall loop has already been reported in ref. [1]. The occurrence of an anomalous loop is considered to be attributed to the type-2 magnetic domains [2] which are supposed to exist in the Ni film. The detailed explanation will be published elsewhere.

The method presented in this paper is useful not only for the high-accuracy measurement of the magnetic easy axis but also for the investigation of the spin configuration of magnetic film. Again, the method is effective in checking the uniaxial magnetic anisotropy of so-called perpendicular magnetic anisotropy films like rare earth–transtion metal alloy films or MnBi film, and is also applicable to the usual in-plane magnetic films like Permalloy.

References

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