Vol. A43 (1973) ACTA PHYSICA POLONICA No 3

A MAGNETORESISTANCE METHOD OF MEASURING H_k AND H_c OF THIN MAGNETIC FILMS BY A FOUR-POINT RESISTANCE PROBE

By A. Chrząstowski, T. Stobiecki and H. Jankowski

Department of Solid State Physics, Metallurgy Institute, Academy of Mining and Metallurgy, Cracow*

(*Received July 21, 1972; Revised paper received September 20, 1972*)

The paper presents a magnetoresistance method of measuring H_k and H_c of thin magnetic films by means of a four-point probe. It has been found that the results of this method are congruent with those obtained by generally used means.

1. *Introduction*

Magnetoresistance methods of measuring H_k and H_c of thin films have been dealt with by many authors [1, 2, 3, 4] who used, however, specially prepared films in the shape of rectangles with deposited electrodes. Such methods are ill-suited for determining H_k and H_c of many films evaporated on a uniform substrate, *e.g.*, of magnetic storage. The aim of this paper is to present a magnetoresistance method of measuring H_k and H_c by means of a four-point resistance probe.

2. *Theory*

In this paper the model of a polycrystalline, one-domain film with uniaxial anisotropy has been assumed. The free energy per unit value is given by the formula [5, 6]:

$$E = K_u \sin^2 \varphi - MH \cos (\varphi - \vartheta) \quad (1)$$

where K_u is the uniaxial anisotropy constant, M — the magnetization vector and H — the applied field. The angles φ and ϑ are defined in Fig. 1.

By minimizing this energy in order to get the equilibrium state we can find the angle φ as an implicit function of the normalized field h and the angle ϑ:

$$h \sin (\varphi - \vartheta) + \sin \varphi \cos \varphi = 0 \quad (2)$$

* Address: Zakład Fizyki Ciała Stałego, Instytut Metalurgii, Akademia Górniczo-Hutnicza, al. Mickiewicza 30, 30-059 Kraków, Poland.

where

$$h = \frac{H}{H_k} \text{ and } H_k = \frac{2K_u}{M}.$$

The electrical resistance ϱ of thin magnetic films is a function of the angle formed by the vector M and the vector of current density j. When measured in the direction of the current it can be presented by the Voigt-Thomson formula [7]:

$$\varrho(\varphi, \psi) = \varrho_{\perp} + (\varrho_{\parallel} - \varrho_{\perp}) \cos^2 (\varphi - \psi) \tag{3}$$

where $\varrho_{\perp}$ and $\varrho_{\parallel}$ are measured for M being perpendicular and parallel to the current.

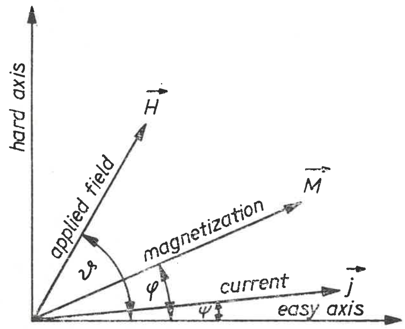

Fig. 1. Definition of angles. The direction of easiest magnetization is chosen as the reference direction

2.1. The measurement of the anisotropy field H_k [1, 8, 9]

a) The necessary condition for the resistance extreme is:

$$\frac{\partial \varrho(\varphi, \psi)}{\partial \varphi} = 0, \tag{4}$$

from where taking into consideration the Eq. (2) we get for $\vartheta = \frac{\pi}{2}$

$$h_{\text{extr}} = \frac{H_{\text{extr}}}{H_k} = \begin{cases} \sin \psi \\ \cos \psi \end{cases}. \tag{5}$$

Hence,

$$H_k = \frac{H'_{\text{extr}}}{\sin \psi} \text{ or } H_k = \frac{H''_{\text{extr}}}{\cos \psi}, \tag{6}$$

where

$$H'_{\text{extr}} = H_{\text{max}}$$
$$H''_{\text{extr}} = H_{\text{min}}.$$

b) For $\vartheta = \frac{\pi}{2}$ there exists such a value $H_{1/2}$ of the magnetic field that

$$\varrho(H_{1/2}) = \frac{\varrho_{||}+\varrho_{\perp}}{2}. \tag{7}$$

For $\psi = \frac{\pi}{2}$ we get from (2) and (3):

$$\left(\frac{H_{1/2}}{H_k}\right)^2 = \frac{1}{2}. \tag{8}$$

The formula (8) allows to determine H_k:

$$H_k = \sqrt{2}\, H_{1/2}. \tag{9}$$

2.2. The measurement of the coercive force H_c [10]

The dependence cos $\varphi(h)$ is obtained from Eq. (2) for $\vartheta = 0$. Then substituting the result in to Eq. (3) we have:

$$\varrho(\varphi(h), \psi) = \varrho_{\perp}+(\varrho_{||}-\varrho_{\perp}) \cos^2 \varphi(h)$$

$$\varrho(\varphi(h), \psi) = \varrho_{\perp}+(\varrho_{||}-\varrho_{\perp}) (1-\cos^2 \varphi(h)) \tag{10}$$

for $\psi = 0$ and $\psi = \frac{\pi}{2}$, respectively.

According to Eqs (10) should occur flips of magnetoresistance for a field equal to H_k which magnetizes the film to saturation in any direction.

The measurement $\varrho(h)$ (see Fig. 5) for real films is disturbed by the motion of domain walls for field $H < H_k$ corresponding to H_c.

3. *Experimental*

3.1. Samples

The films were prepared by vacuum evaporation from the melt of 80% Ni — 20% Fe at the pressure of about 10^{-5} Torr (1.3×10^{-7} N/m^2). During the evaporation the glass substrate was kept at $T_s = 300°$C (573°K) and an external magnetic field of about 200 Oe (1.6×10^4 A/m) was applied in the substrate plane. The films whose parameters are presented in Table I did have different thickness (d). They were evaporated on a glass substrate of the dimensions 16×16 mm. The multilayer system (Table II) consisted of 10 rectangular films of the dimensions 6×9 mm which were evaporated on a uniform glass substrate in the same technological conditions. The thickness of the ferromagnetic materials was registered by a quarz monitor during the evaporation process and it was 1800 Å (1.8×10^{-7} m).

3.2. Apparatus [11]

Changes of magnetoresistance have been registered by the application of a four-point probe. The scheme of the measurement system is shown in Fig. 2. The probe allows to make measurements at any direction of the current in the film. The rotating table on which the films are lying enables an arbitrary choice of the direction of the external magnetic field in respect to the easy axis. The probe which is used here allows to determine H_k

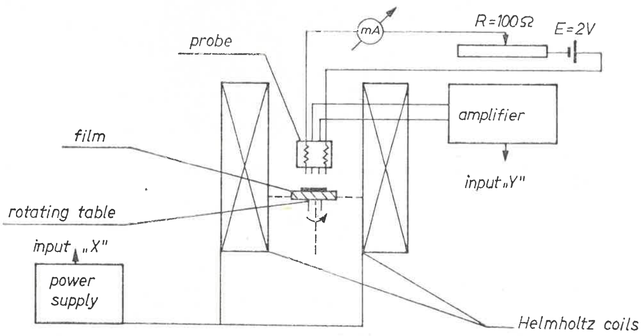

Fig. 2. Scheme of the measurement system

and H_c of any film of arbitrary shape and dimensions over 3 mm using 4 or 2 electrodes, respectively. It has been verified that in both cases the error of measurement was the same. The probe is supplied with a specially sharpened gold electrodes having regulated pressure, so that they touch the film. The point contacts are situated along a straight line. The distance between the current electrodes is 9 mm, and that between the voltage electrodes 3 mm. The direct current was in all measurements about 50 mA. The potential drop is fed into the input of the d. c. integrated circuit of the amplifier μA 609. The introductory stage of the amplifier compensates the Ohm component, and the magnetoresistance component of about 0.1 mV value is amplified 10^3 times and fed into the input "Y" of the X-Y plotter. The potential drop of the Helmholtz coils producing the external magnetic field is given into the input "X".

3.3. Measurements

The measurements were performed at room temperature, and the earth magnetic field was compensated.

In determining H_k the equation (6) was applied. For this purpose the d. c. formed a respective angle with the easy axis. The external magnetic field H was perpendicular to the easy axis. The dependence of the magnetoresistance on the external magnetic field, which was registered on the X-Y plotter, is shown in Fig. 3 for $\psi = 5\,\pi/6$. The equation (9) was also applied, in order to compare the measured values of H_k. The magnetoresistance changes and the method of determining H_k is shown in Fig. 4.

For the measurement of H_c the external magnetic field should be parallel to the easy axis. The d. c. should be parallel or perpendicular to the easy axis. The magnetoresistance changes and the method of determining H_c is shown in Fig. 5.

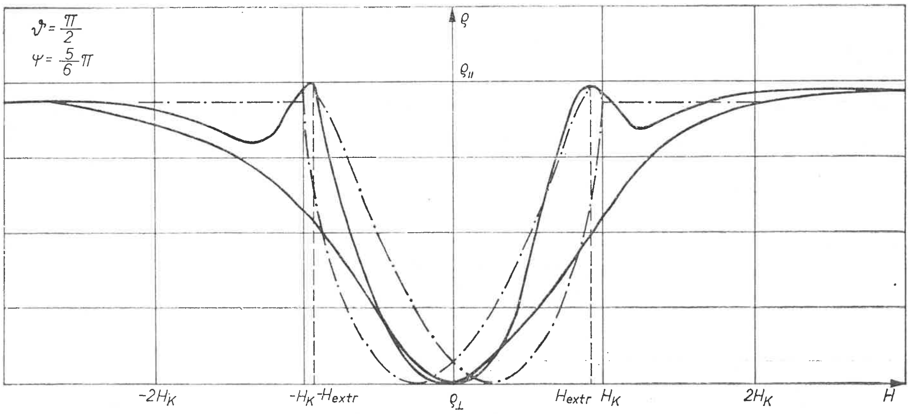

Fig. 3. The plot of magnetoresistance changes as function of the magnetic field for $\vartheta = \frac{\pi}{2}$ and $\psi = \frac{5}{6}\pi$

(– · – theoretical, —— experimental)

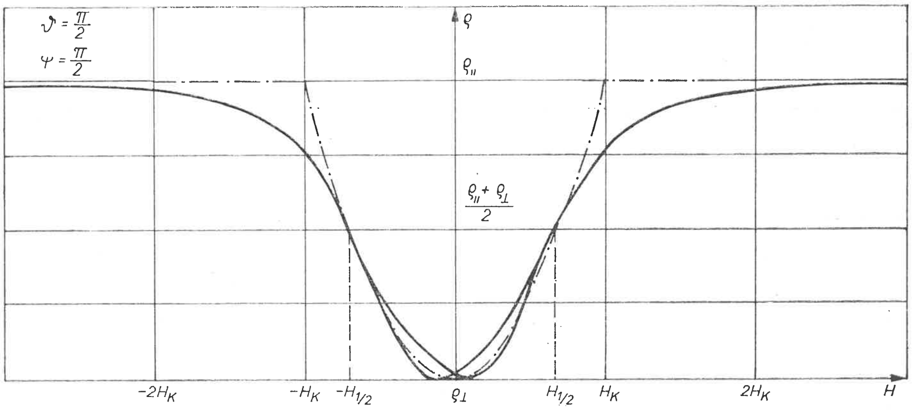

Fig. 4. The plot of magnetoresistance changes as function of the magnetic field for $\vartheta = \frac{\pi}{2}$ and $\psi = \frac{\pi}{2}$

(– · – theoretical, —— experimental)

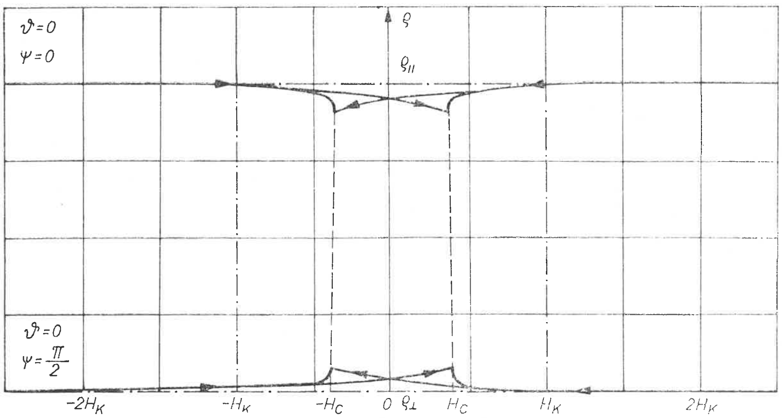

Fig. 5. The plot of magnetoresistance changes as function of the magnetic field for $\vartheta = 0$ and $\psi = 0, \frac{\pi}{2}$

(– · – theoretical, —— experimental)

3.4. Results

Table I and II show the obtained values, the measurement error being ± 19 A/m. For comparison, the parameters of single films (each of them on a separate substrate) have also been determined by using the method described in the papers [12, 13, 14, 15].

The method of the magnetoresistance probe has also been applied in determining H_k and H_c for the multilayer system. The results are shown in Table II. There are satisfied that experimental data are repeatable.

TABLE I

No	$d \times 10^{-8}$m	T_s °K	H_c A/m		H_k A/m			
			[12, 13]	Sec. 2.2	[12, 13]	[15]	(6)	(9)
1	15	573	152	144	496	496	504	504
2	36	573	104	96	312	320	312	304
3	44	573	64	64	410	400	400	402

TABLE II

No	Multilayer system No 2	
	H_c A/m	H_k A/m
1	410	530
1a	187	276
2	208	415
2a	208	505
3	340	570
3a	300	710
4	487	735
4a	225	672
5	224	528
5a	300	675

4. *Conclusions*

In this paper we assumed the applicability of the coherent rotation theory and of Voigt-Thomson's formula. Both describe fairly well the magnetization process the knowledge of which is necessary for determining H_k and H_c.

The magnetoresistance method of the four-point probe allows to determine H_k and H_c of a multilayer system, *e. g.*, of a magnetic storage.

The results for H_k and H_c obtained by using the magnetoresistance probe have shown good agreement with the values obtained by generally used methods. One should note that there is a possibility of a surface flow of the film when touching it with sharpened electrodes, which can be eliminated by applying mercury contacts.

The authors wish to thank Professor L. Kozłowski and Dr L. Maksymowicz for many useful discussions.

REFERENCES

[1] Z. Sczaniecki *et al.*, *Phys. Status Solidi*, **7**, 597 (1971).
[2] F. G. West, *Nature*, **188**, 129 (1960).
[3] G. Kneer, *IEEE Trans Magnetics*, **2**, 747 (1966).
[4] E. F. Kuritsyna, Vu Dinh Ky, *Izv. Akad. Nauk SSSR, Ser. Fiz.*, **29**, 580 (1965).
[5] E. C. Stoner, E. P. Wohlfarth, *Phil. Trans Roy. Soc. London*, **A240**, 599 (1948).
[6] Vu Dinh Ky, *Izv. Akad. Nauk SSSR, Ser. Fiz.*, **30**, 27 (1966).
[7] J. P. Jan, *Solid State Phys.*, **5**, 1 (1957).
[8] T. Stobiecki, A. Paja, *Acta Phys. Polon.*, **A41**, 343 (1972).
[9] T. Stobiecki *et al.*, *Polish Patent Application*, No P 153524.
[10] W. Hellenthal, *Z. Naturforsch.*, **14a**, 1077 (1959).
[11] H. Jankowski, T. Stobiecki, *Polish Patent Application*, No P 147577.
[12] E. Feldtkeller, *Z. Phys.*, **176**, 510 (1963).
[13] L. Maksymowicz, E. Schabowska, *Rev. Sci. Tech. A.M.M. s. H.*, **13**, No 21, 5 (1968).
[14] E. C. Crittenden *et al.*, *Rev. Sci. Instrum.*, **22**, 872 (1957).
[15] H. Lachowicz, *Phys. Status Solidi*, **16**, 313 (1966).