ANGULAR DEPENDENCE OF MAGNETORESISTANCE IN THIN Ni-Fe FILMS

By T. Stobiecki and A. Paja

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

(*Received September 3, 1971*)

The magnetoresistance of thin ferromagnetic film is calculated for the case when both the directions of the current and of magnetization vector are changed independently. The validity of the expression obtained is examined for the planar evaporated sample of 80–20% Ni–Fe. A new method of magnetoresistance measurement is applied. The agreement between theoretical calculations and experimental results is good.

1. *Introduction*

The phenomenon of interest to us is the magnetoresistance of thin ferromagnetic films. This effect has been the subject of many investigations [1–7]. Our aim was to determine the behaviour of magnetoresistance while the angles between current and easy axis as well as between saturation magnetization vector and easy axis were both changed. The formula predicted theoretically provides a new method for measuring the anisotropy field H_K. In the present paper we shall only compare our theoretical curves with experimental ones.

2. *Theory*

Consider a thin film in which the current i makes an angle θ with the easy axis, the saturation magnetization vector $\boldsymbol{M}_s$ an angle φ and the external magnetic field $\boldsymbol{H}$ is applied along the hard axis (Fig. 1). The free energy per unit volume is given by the well-known formula [1]:

$$E = K_u \sin^2\varphi - M_s H \sin\varphi \tag{1}$$

where K_u is the uniaxial anisotropy constant. By minimizing this energy in order to get the equilibrium state we can find the angle φ as an implicit function of the field H or, equivalently, of a normalized field h

$$\sin\varphi = \frac{H}{H_K} \equiv h \tag{2}$$

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

where

$$H_K = \frac{2K_u}{M_s}. \tag{3}$$

The resistivity of a polycrystalline ferromagnet in isothermal conditions depends upon the angle between the direction of the measurement (*i. e.* the direction of current

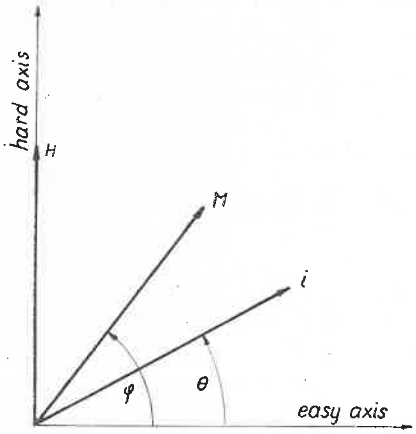


Fig. 1. Definition of angles; the reference direction is the easy axis direction

for measuring the resistance) and that of magnetization only. That dependence is given by the well-known Voigt-Thomson formula [2]

$$\varrho(\varphi, \theta) = \varrho_{\perp} \sin^2(\varphi-\theta)+\varrho_{||}\cos^2(\varphi-\theta) \tag{4}$$

where $\varrho_{\perp}$ and $\varrho_{||}$ are measured for M_s being perpendicular and parallel to the current, respectively. We define a quantity λ

$$\lambda \equiv \frac{\varrho(\varphi, \theta)-\varrho_{\perp}}{\varrho_{||}-\varrho_{\perp}} \tag{5}$$

and we see from (4) that

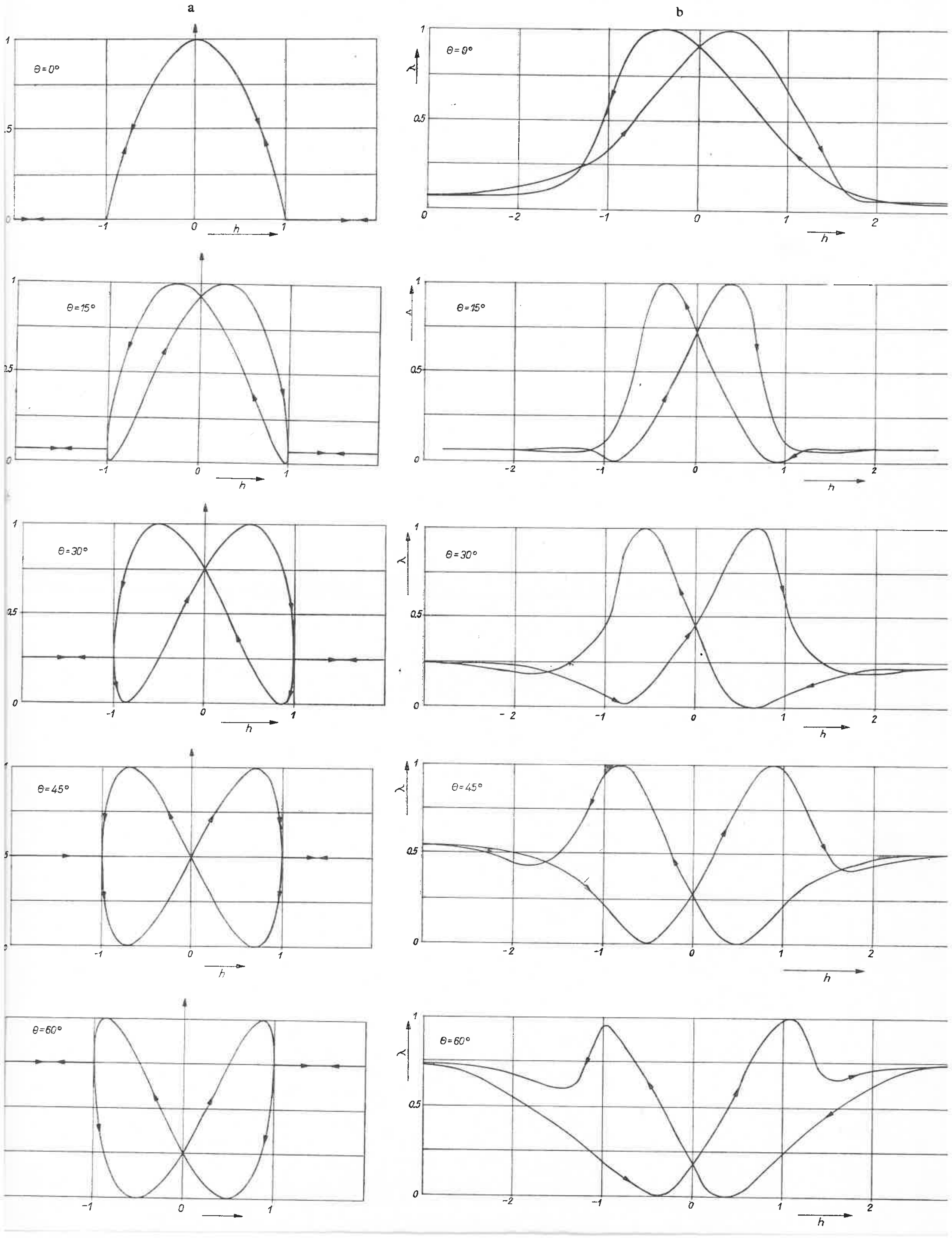
$$\lambda = \cos^2(\theta-\varphi) \tag{6}$$

where

$$\varphi = \arc\sin h. \tag{7}$$

In the cases when the current is parallel or normal to the easy axis ($\theta = 0°$ or $\theta = 90°$ respectively) our formulae (6) and (7) give the same results as those obtained by West [3]. Nevertheless, in the other cases, a plot of λ against h should not be a parabola, but a curve of a more complicated shape. In the range of h for which (7) is valid for a given film (*i. e.* $H \leqslant H_K$) the plot should correspond to the function

$$\lambda(h) = \cos^2(\theta-\arc\sin h), \quad H \leqslant H_K \tag{8}$$



a
b
θ = 0°
θ = 15°
θ = 30°
θ = 45°
θ = 60°
λ
h
0.5
-2
-1
0
1
2

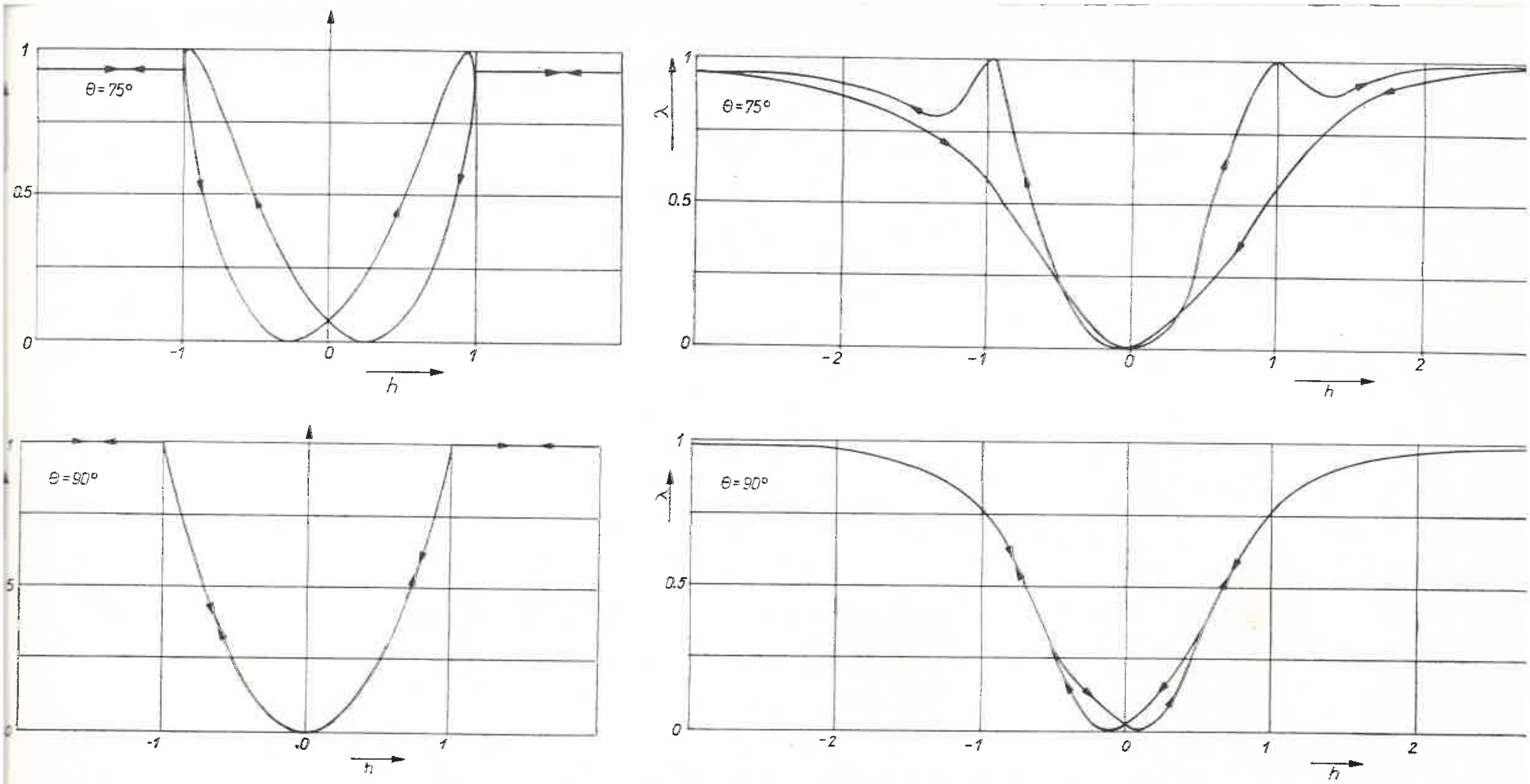


Fig. 2a. Theoretical, b. experimental plots representing the relative magnetoresistance λ as a function of the normalized magnetic field h

where θ is treated as a parameter. Outside this range the function should be constant because the external field $H > H_K$ gives the same position of magnetization vector as H_K:

$$\lambda(h) = \lambda(1) = \sin^2\theta, \quad H \geqslant H_K. \tag{9}$$

The curve has a minimum for

$$\arcsin h = \theta - 90° \tag{10}$$

and a maximum for

$$\arcsin h = \theta. \tag{11}$$

Thus the distance between extremal points is

$$\Delta h = \sqrt{2}\cos(\theta - 45°). \tag{12}$$

The theoretical plots for different angles θ are shown in Fig. 2a. Negative values of h (also H) have only the meaning of direction reversal.

One can see that extremal points give the value of anisotropy field H_K. We have *e. g.*

$$H_K = H_{max} \operatorname{cosec}\theta \tag{13}$$

where H_{max} denotes the value of the external field H for maximum in the non-normalized plot. The results of this new method of measuring H_k and a comparison of them with those obtained with other methods will be presented in our next paper.

3. *Experimental*

3.1. Sample

The film was prepared by vacuum evaporation from a melt of 80–20% Ni–Fe at the pressure above 10^{-5} Torr (1.3×10^{-7} N/m²). During the evaporation the glass substrate was kept at 200°C (473°K) and the external magnetic field of about 200 Oe (1.6×10^4 A/m) was applied to the substrate plane. The thickness of the film was 1400 Å (1.4×10^{-7} m). Its planar size is not important — it must be only bigger than the distance between the electrodes used in the measurement.

3.2. Measurement

The measurements were performed with the specimen at room temperature. The external magnetic field H was applied to the substrate plane perpendicularly to the easy axis. The magnetoresistance signal was obtained from the film with the electrodes touching its surface [8]. A constant current of about 50 mA was passed through the film. The potential drop between the electrodes was measured by a constant current amplifier. The change in resistance was recorded on an X–Y plotter as a function of the magnetic field. The ground new of this method is a possibility of continuous change in the angle θ and a performing of the measurements with the planar films of any shape.

3.3. Results

The measurements were made for θ varying from 0° to 90°. The obtained plots were normalized and they are shown in Fig. 2b together with the theoretical curves.

4. *Conclusions*

To obtain the angular dependence of the magnetoresistance effect we have assumed the coherent rotation model. As seen in these figures the agreement between theoretical and experimental curves is fair. A slight shift of extrema for $\theta = 0°$ and $\theta = 90°$ observed also by West [3] was explained as ordinary hysteresis effect. It also appears for the other cases, as expected. The edges of the plot for $h = \pm 1$ are not sharp, due to various factors as dispersion, intrinsic structure etc. which cause that saturation in the hard axis direction is obtained later than H reaches H_K and disappears earlier before H decreases to H_K. For the applied field H a little greater than H_K the normalized magnetoresistance comes closer to the calculated value $\sin^2 \theta$. This theory is valid only for low saturation fields [3] because the strong magnetic field disturbs the current. According to the Lorentz force namely, the field makes the current go nearer to its own direction and thus the magnetoresistance tends to grow. The clearest example is seen in Fig. 2b for the angle $\theta = 75°$ because the angle between field and current is 15° only, so that the disturbing influence of the field is the strongest among investigated cases. Hence λ reaches its maximum value for the field much greater than H_K.

The remaining slight differences between the experimental and theoretical values should not be considered as significant because the measurement of resistance is so sensitive that a small change in external conditions (*e. g.* temperature) can appreciably influence the results.

In conclusion we can say that the experimental results confirm our model of change in resistance caused by rotation of the magnetization vector. The deviations discussed above will be the subject of further investigations and the results will be published in later papers.

The authors wish to thank Professor dr L. Kozłowski for many profitable discussions. The authors are also very indebted to Engineer H. Jankowski for his help in constructing of apparatus.

REFERENCES

[1] V. dinh Ky, *Izv. Akad. Nauk SSSR, Ser. Fiz.*, **30**, 27 (1966).
[2] J. P. Jan, *Solid State Phys.*, **5**, 1 (1957).
[3] F. G. West, *Nature*, **188**, 129 (1960).
[4] G. Kneer, *IEEE Trans. Magnetics*, **2**, 747 (1966).
[5] K. Kuwahara, *Trans. Japan Inst. Metals*, **6**, 192 (1965).
[6] K. Kuwahara, F. B. Humphrey, *Japan. J. Appl. Phys.*, **5**, 1 (1966).
[7] K. Kuwahara, S. Shinzato, *Mem. Fac. Eng., Hiroshima Univ.*, **3**, 1 (1969), Serial No 11.
[8] H. Jankowski, T. Stobiecki, *Polish Patent Application*, No P 147577.