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THE INFLUENCE OF SAMPLE GEOMETRY ON THE MAGNETORESISTANCE OF Ni–Fe FILMS

J. H. J. FLUITMAN

Department of Electrical Engineering, Twente University of Technology, Enschede (The Netherlands)
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The magnetoresistance of Ni–Fe (81–19) films has been measured as a function of film geometry (thickness to width ratio N). It has been found that under the condition of large magnetization dispersion the behaviour of films with a high value of N differs distinctly from that of films with $N \approx 0$. Moreover, the easy axis coercive force H_c increases markedly when the width of the film is of the order of 20 µm and less.

INTRODUCTION

The magnetoresistance of uniaxial ferromagnetic films is utilized in many ways: it is used in the study of the magnetic properties of ferromagnetic films[1–3]; it may be employed to sense magnetic fields[4–6], with special application in magnetic memories[7, 8]; and it has been used in the study of magnetic coupling in multilayer films[9]. In all these cases the film geometry must be chosen according to the requirements of the application. In particular, when miniaturization is required it could be important that the width of the film cannot be chosen to be "infinite", so that demagnetizing fields in the plane of the film might occur. This might influence the magnetoresistance behaviour. It has been the purpose of our experiments to check whether or not the sample geometry influences the magnetoresistance curves. We have investigated a number of Ni–Fe (81–19) films which were in the form of strips with thicknesses varying from 200 Å to 1 µm and widths varying from 2 to 1000 µm. The main results are reported in this paper.

The strips were produced by vacuum evaporation onto glass at 250 °C in a magnetic field of about 3200 A/m (40 Oe). The masking procedure to obtain the narrowest films is described elsewhere[6]. The magnetoresistance was measured with the aid of a standard d.c. potentiometric circuit. The small resistance variation, as a function of the applied magnetic field, was plotted on an X–Y recorder. We refer to these plots as R–H plots (R for resistance, H for magnetic field). An R–H plot could be produced in approximately 1 min.

The geometry of the strips is illustrated in Fig. 1. The thickness is t and the width w, where $t \ll w$ is consistently valid. For simplicity, we consider the cross section of the strip to be elliptic so that demagnetizing factors N_α can be

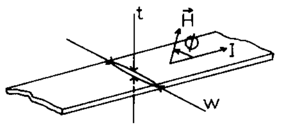

Fig. 1. Cross section of a strip, which is considered to be elliptic, with thickness to width ratio t/w. $\boldsymbol{H}$ is in the plane of the strip.

assigned to the three principal axes. These demagnetizing factors are[10]: $N_w = t/(t+w) \approx t/w = N$ in the direction of w; $N_t = w/(t+w) \approx 1$ in the direction of t; and zero along the axis of the strip. The values of N_w for our samples lay in the range from 0.00 to 0.04. Since the magnitude $M_s \equiv |\boldsymbol{M}_s|$ of the saturation magnetization was 8×10^5 A/m a demagnetizing factor N_w as small as 10^{-4} could give rise to a demagnetizing field of 80 A/m (1 Oe) when the film was saturated in the direction of w. The applied magnetic fields were constantly chosen in the plane of the film so that N_t was of no further relevance. The R–H plots presented here are characterized by the angle ϕ between the direction of $\boldsymbol{H}$ and the strip axis.

THEORY

The direction of the magnetization $\boldsymbol{M}_s$ in the film can be calculated by minimizing the expression for the free energy of the system[11]. In the single domain model this calculation leads to the well-known astroid with its simple procedure for constructing the direction of $\boldsymbol{M}_s$ when $\boldsymbol{H}$ is given. The astroid also determines the theoretical values of $\boldsymbol{H}$ for which the magnetization rotates in the alternative direction. These values do not coincide with experimental observations. In fact, the magnetization reverses at critical values $\boldsymbol{H}_{crit}$ determined by the formation of domains, which depends on a variety of film parameters[11].

When the demagnetizing factor N_w differs from zero and $\boldsymbol{H}$ is in the plane of the film, the expression for the free energy reads (SI units):

$$F = -\mu_0 M_s H_x \cos\theta - \mu_0 M_s H_y \sin\theta + \tfrac{1}{2}\mu_0 N_w M_s^2 \sin^2\theta + K \sin^2(\theta+\psi) \tag{1}$$

H_x and H_y are the components of the external magnetic field related to axes parallel and perpendicular to the specimen axis (Fig. 2). θ is the angle between

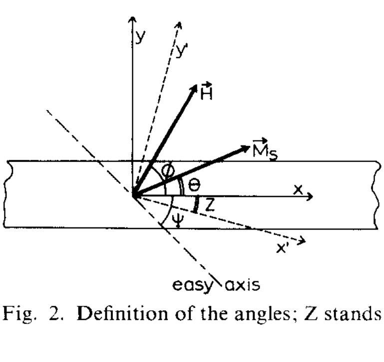

Fig. 2. Definition of the angles; Z stands for ζ in the text.

M_s and the strip axis, ψ is the angle between the axis of uniaxial anisotropy (in general not parallel to the strip axis) and the strip axis, and K is the anisotropy constant intrinsic to the film material.

$$K^* = \tfrac{1}{2}\mu_0 N_w M_s^2$$

can be interpreted as a geometrical anisotropy constant. In order to collect the two anisotropy terms, expression (1) can be transformed into

$$F = -\mu_0 M_s H_{x'} \cos(\theta+\zeta) - \mu_0 M_s H_{y'} \sin(\theta+\zeta) + C + R\sin^2(\theta+\zeta) \tag{2}$$

using

$$\begin{aligned} K^* + K\cos 2\psi &= R\cos 2\zeta \\ K\sin^2\psi &= C + R\sin^2\zeta \\ K\sin 2\psi &= R\sin 2\zeta \end{aligned} \tag{3}$$

$H_{x'}$ and $H_{y'}$ are the components of $\boldsymbol{H}$ relative to coordinate axes which are rotated through an angle ζ relative to the strip axis.

Expression (2), except for the irrelevant constant C, is of the same form as the expression for F when no demagnetizing fields are present; the astroid concept remains valid and the usual procedure to determine θ may be followed. Introducing the anisotropy fields $H_K = 2K/\mu_0 M_s$, $H_K^* \equiv 2K^*/\mu_0 M_s = N_w M_s$ and $H_K^{tot} \equiv 2R/\mu_0 M_s$ eqns. (3) are reduced to

$$\begin{aligned} \mathrm{tg}\, 2\zeta &= \frac{H_K \sin 2\psi}{H_K^* + H_K \cos 2\psi} \\ H_K^{tot} &= (H_K^{*2} + H_K^2 + 2H_K^* H_K \cos 2\psi)^{1/2} \end{aligned} \tag{4}$$

If N_w is large, $H_K^* \gg H_K$, from which it follows that $\zeta \approx 0$ and $H_K^{tot} \approx H_K^*$ or, in other words, the geometrical anisotropy dominates. When $\zeta \approx 0$, which is generally the case in practice, eqns. (4) are reduced to

$$H_K^{tot} = H_K + H_K^* = H_K + N_w M_s \tag{5}$$

When the magnetization vector $\boldsymbol{M}_s$ is constant throughout a strip (single domain), the resistance is determined by the angle θ between $\boldsymbol{M}_s$ and the current direction (strip axis)[2, 12]:

$$R = R_0 - \Delta R \sin^2 \theta(\boldsymbol{H}) \tag{6}$$

in which the dependence of θ on $\boldsymbol{H}$ is determined by the procedure outlined in the preceding text. In the particular case when the axis of uniaxial anisotropy (easy axis) is directed along the strip axis ($\psi = 0$) and $\boldsymbol{H}$ is perpendicular to it (transverse magnetoresistance, $\phi = 90°$) it is found that[1]

$$\begin{aligned} R(\boldsymbol{H}) &= R_0 - \Delta R (H/H_K)^2 \qquad & H < H_K \\ R(\boldsymbol{H}) &= R_0 - \Delta R \qquad & H \geqq H_K \end{aligned} \tag{7}$$

R_0 and ΔR are constant for a given sample. Generally the magnitude of ΔR is of the order of 1 % of R_0.

An important phenomenon in ferromagnetic films is magnetization dispersion: the direction of $\boldsymbol{M}_s$ is generally not a constant in a single domain but varies from place to place[11]. This variation is characterized by the dispersion angle α, which may have a magnitude of a few degrees for small dispersion films and up to ten or twenty degrees for large dispersion films. In the last case in particular, it cannot be expected that the single domain theory is valid and a deviation from eqns. (7) will result as a consequence of the fact that θ is no longer a constant but varies roughly between $\theta-\alpha$ and $\theta+\alpha$.

RESULTS FOR FILMS WITH SMALL VALUES OF $N_w(H_K^* \lesssim H_K)$

The magnetoresistance of films with a small or zero value of N_w has been treated before[1,2]. For the sake of clarity, and to contrast with the results described in the next section, we give an R–H plot in Fig. 3, which represents the case $\psi \approx 0°$ (and thus $\zeta \approx 0°$), $N_w = 18 \times 10^{-6}$, $t = 180$ Å, $\alpha \approx 10°$ and $\phi = 90°$ (transverse magnetoresistance). The deviation from the theoretical behaviour (eqns. (7)) has been explained by West[1] as being a consequence of magnetization dispersion.

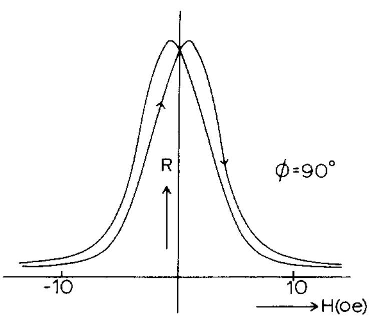

Fig. 3. R–H plot for a sample with $t = 180$ Å, $w = 1$ mm, $\psi = \zeta = 0°$, $\alpha \approx 10°$ and $\phi = 90°$. The zero on the R axis is chosen arbitrarily.

If a saturating transverse field is switched on, $\boldsymbol{M}_s$ will be directed perpendicular to the strip axis. On release of the field, $\boldsymbol{M}_s$ will rotate back to the longitudinal direction. There are, however, two ways to rotate to this direction (clockwise and anticlockwise) and the tendency to rotate back to the local easy axis will cause a reversion into different regions with $\boldsymbol{M}_s$ pointing in almost opposite directions when $H = 0$ again. In this situation a remanent magnetic moment results in the transverse direction giving rise to a value of R which is smaller than R_0. A magnetic field in the opposite direction is needed to pull $\boldsymbol{M}_s$ into longitudinal directions in order to give the strip the maximum resistance R_0. This scheme is a rather simplified one. Other processes are involved, that refer principally to the formation of and changes in domain wall structures which appear as the boundaries between regions (domains) having opposite directions of $\boldsymbol{M}_s$[11,13]. These processes generally contribute to the remanence and to the magnetoresistance behaviour as depicted in Fig. 3. The same behaviour is found in films which have other thicknesses, or in cases when ϕ is not exactly 90°. As long as $|\phi-90°|<\alpha$ the tendency of the magnetization to fall back into different directions is present, as has been observed.

RESULTS FOR FILMS WITH LARGE VALUES OF $N_w(H_K^* \gg H_K)$

When the value of N_w is large, the anisotropy of the strip is governed by H_K^* and the resulting easy axis will be parallel to the strip axis. In small dispersion strips (*i.e.* in which α is a few degrees) we have not found results that differ qualitatively from those with N_w small. However, when α is not small the magnetoresistance curves have an appearance which differs from that for small N_w. A large value of α may be recognized from the longitudinal magnetoresistance, $\phi=0°$, which is shown in Fig. 4(a). Figure 4(b) and (d) show the R–H plots for the same sample, but now with ϕ very close to 90° (90° ± 1.5°). As $|\phi-90°|\ll\alpha$ a behaviour similar to that of Fig. 3 is expected. This is not the case however: as H decreases after saturation a maximum value of R is reached before H reaches the value $H=0$.

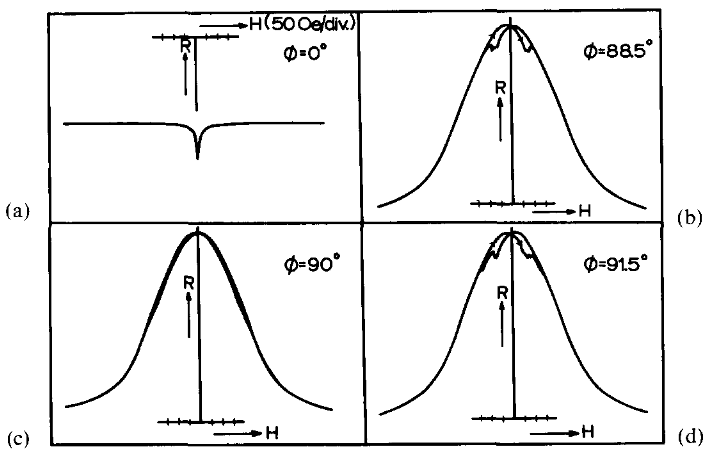

Fig. 4. R–H plots for a sample with $t=6000$ Å, $w=18$ μm, $\zeta=0$, $\alpha\approx25°$ and $H_K^*=330$ Oe (26 400 A/m): (a) $\phi=0°$; (b) $\phi=88.5°$; (c) $\phi=90°$; (d) $\phi=91.5°$. The zero on the R axis is chosen arbitrarily.

If it is first assumed that the specimen consists of one single domain, the zero-field value of θ can be calculated from $R(0)$ and $R(\infty)$ with the help of eqn. (6) (situation of Fig. 4 (a), $\phi=0°$). For the sample of Fig. 4 ($t=6000$ Å, $N_w=33\times10^{-3}$) we have calculated a value for θ of approximately 25° in this way. However, since for $H=0$, $\theta=\zeta$, and since ζ must be very close to 0° in a sample having such a large value of N_w, the apparently large value of θ can only be interpreted as a consequence of dispersion with $\alpha\approx25°$ (*cf.* Fig. 5(b)). In order that this large dispersion is possible and is not suppressed by the demagnetizing field from the edge of the specimen, the wavelength of the zigzag structure (Fig. 5(b)) must be small compared with the width w of the strip. If an external field is applied in a nearly transverse direction the mean magnetization tends to rotate, building a net magnetic charge density at the edges of the strip and giving rise to a demag-

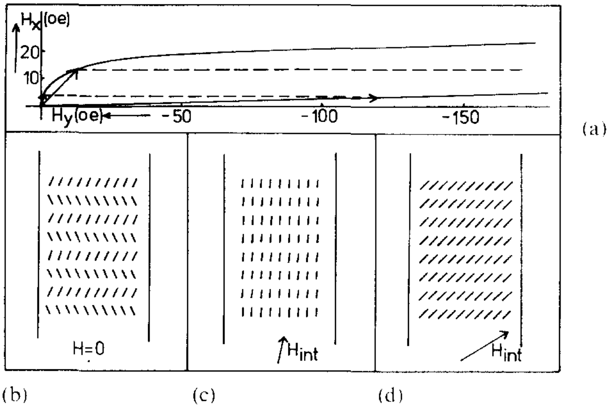

Fig. 5. (a) Relationship between $\boldsymbol{H}_{int}$ and $\boldsymbol{H}_{ext}$ for the sample of Fig. 4(d) with $\phi = 91.5°$. The coordinates of $\boldsymbol{H}_{int}$ form the upper curve and the coordinates of $\boldsymbol{H}_{ext}$ form the straight line (having an angle of 1.5° with the H_y axis). Horizontal (broken) lines connect related vectors $\boldsymbol{H}_{int}$ and $\boldsymbol{H}_{ext}$ (sample axis is oriented vertically). (b) (c) (d) Schematic representation of the magnetization in the strip with. (b) $H_{ext} = 0$, (c) $H_{ext} \approx 50$ Oe and (d) $H_{ext} \approx 250$ Oe.

netizing field. Therefore the tendency to rotate is suppressed. Only the (relatively) small longitudinal component of the external field has free play in stretching the zigzag structure (Fig. 5(c)). In Fig. 5(a) we have plotted the internal field H_{int} $(= H_{ext} + H_{demag})$ as a function of the external field H_{ext} for the configuration of Fig. 4(d). Although the strip cannot be considered as a single domain the dependence of the magnitude of the demagnetizing field on the mean rotation of $\boldsymbol{M}_s$ from the zero position is comparable with that of a single domain. This statement is the basis of the calculation of the curve depicted in Fig. 5(a). It can be seen that for a large value of N_w the internal field starts almost parallel to the strip axis even when ϕ is very close to 90°. The background leading to the behaviour demonstrated in Fig. 4(b) and (d) can now be easily understood with the help of Fig. 5(b), (c) and (d), where from right to left the situation is given for a decreasing field with $\phi = 91.5°$. As the field decreases the local magnetization vectors rotate to a nearly longitudinal position, giving rise to a maximum value of R, and then split up as a consequence of magnetization dispersion when H is further lowered to $H = 0$. When the field increases in the same direction again, the same procedure is followed from left to right. (An increasing field in the opposite direction causes the magnetization to reverse its direction first, giving rise to an irregular dip in the curve.) When $\boldsymbol{H}$ is exactly transverse ($\phi = 90°$) the magnetization, starting from saturation, has no preferential direction to rotate back to the longitudinal position. The film will probably split up into regions tending to have opposite directions of $\boldsymbol{M}_s$, but a situation such as was described in the preceding section cannot arise since self-demagnetization forces the mean direction of $\boldsymbol{M}_s$ to be parallel to the strip axis. In this situation (Fig. 4(c)) the maximum value of R should occur when H is zero (or very close to it). It must be said, however, that R–H loops in these cases (as is sometimes observed for small values of N_w as well) often show irregularities and sometimes cannot be reproduced satisfactorily. This must be ascribed to the fact that the demagnetization process is accompanied by sudden and irreversible changes in the structure of domains and/or domain walls.

The behaviour described in this section has been observed, apart from in the given example, in strips with $t \approx 550$ Å, $N_w \approx 30 \times 10^{-3}$ and $t = 1400$ Å, $N_w \approx 15 \times 10^{-3}$ respectively.

EASY AXIS COERCIVE FORCE H_c

The dependence of the easy axis coercive force H_c on the film parameters has been the subject of many experiments[11]. We have added one, in which the dependence of H_c on the width w and the demagnetizing factor N_w is considered. The values of H_c which we ascribed to our strips were derived from the longitudinal magnetoresistance data in the way described in ref. 2. In Fig. 6 H_c is plotted as a function of w for several series of extremely narrow strips (all with $t \approx 450$ Å). The strips in each series were produced in the same deposition cycle, following the method described in ref. 6, and may be compared directly. There is a clear rise in the curves at low values of w (high values of N_w).

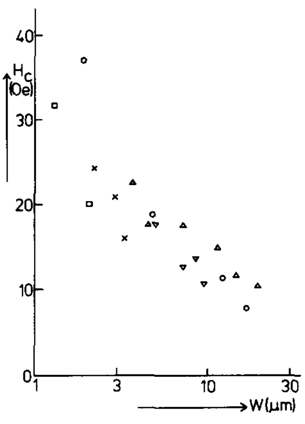

Fig. 6. H_c as a function of the width w for five series of samples, all having $t \approx 450$ Å. Each series was produced at the same deposition and is characterized by one of the symbols □, △, ▽, x or o.

In order to decide whether this rise is a consequence of the low value of w or of the high value of N_w, it is necessary to compare these results with H_c values of films having both N_w and w large and both N_w and w small. In the first case, in which necessarily rather thick films are involved, we have found no evidence of H_c being markedly enhanced over the values found in the literature, while in the latter case we found a value of $H_c = 10$ Oe for a sample having $t \approx 150$ Å and $w = 12$ μm. Consequently the rise is related to w rather than to N_w. However, our experimental data concerning these extreme geometries are rather scarce. In addition, a comparison of films which have very different thicknesses is rather unreliable since the character of the domain walls depends strongly on the film thickness, so that our conclusion can only be regarded as a tentative one.

On the other hand, an increase in H_c on reducing w to the micrometre range is to be expected, since the wall energy will increase as the film width reaches the order of magnitude of the width of the domain walls.

CONCLUSION

It has been found that the geometry of small Ni–Fe (81–19) films can influence the magnetoresistance behaviour. Large dispersion films occur even for high values of the demagnetizing factor N_w; this can be derived from the longitudinal magnetoresistance data. In such a case the nearly transverse magnetoresistance behaviour deviates from the case with $N_w \approx 0$.

The characteristic points marking the value of H_c in the longitudinal magnetoresistance curves (see ref. 2) show a clear shift to higher values for decreasing width of the specimens. This can be ascribed to the fact that small strips behave more and more like single domain systems.

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