12 C. E. Fuller, private communication.
13 C. P. Bean and W. H. Meiklejohn: Bull. Am. Phys. Soc. Ser II, **1** (1956) 148.
14 I. S. Jacobs and F. R. Luborsky: Proceedings of the Conference on Magnetism and Magnetic Materials, Boston, (1956).

DISCUSSION

S. METHFESSEL: You suggested that magnetostrictive stress is responsible for the additional anisotropy found in evaporated films. A consequence of this suggestion should be that the type of substrate will influence this anisotropy (e.g. by the value of the coefficient of thermal expansion). And the additional anisotropy should disappear after peeling off the film from the substrate.

K. HOSELITZ: The difference between thermal expansion of substrate and film makes only a contribution to the isotropic property of the film. It may influence the actual value of the magnetostrictive effect to a small extent. I agree that peeled films should not show the stress dependence of uniaxial anisotropy.

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 17, SUPPLEMENT B-I, 1962
PROCEEDINGS OF INTERNATIONAL CONFERENCE ON MAGNETISM AND CRYSTALLOGRAPHY, 1961, VOL. I

Dependence of Magnetic Properties of Thin Iron Films on the Geometry of Evaporation

S. SZCZENIOWSKI, H. RATAJCZAK AND R. GONTARZ

Laboratory of Ferromagnetics, Institute of Physics, Polish Academy of Sciences, Poznań, Poland

The dependence of the uniaxial magnetic anisotropy of thin iron films on the geometry of evaporation was investigated in samples of uniform thickness, as obtained by rotating an appropriately shaped diaphragm in front of the substrate. As the angle of incidence of the metal vapour onto the substrate was made to increase, the anisotropy constant was found to assume higher values, attaining a maximum for an angle of approximately 30° and then decreasing to zero; at still larger angles, a change of the direction of the easy axis occurred.

Moreover, investigation dealt with domain structure of disk shaped films evaporated at an angle. Here, single samples revealed two zones of different structure, namely, an inner zone of conventional structure and an edge zone containing "cross-tie" type walls. The edge zone revealed 90° domain walls.

Introduction

A number of authors[1-8] investigated the magnetic properties of thin ferromagnetic films with uniaxial magnetic anisotropy. In recent years interest is concentrated on the anisotropy of thin films as due to oblique incidence of the metal vapour onto the substrate in the process of evaporation[3-8]. Knorr and Hoffman[3], in iron films, found an increase in uniaxial anisotropy with the incidence angle. Cohen[7] and Kambersky *et al.*[8], who investigated permalloy films throughout a very wide range of angles (80°), found an increase in anisotropy with the angle up to a maximum in the angle range of about 50°, followed at larger angles by a decrease to zero and a change in the direction of the easy axis to perpendicular with respect to its initial direction.

The process of evaporation of the films as applied by Knorr and Hoffman, by Pugh and co-workers[6], by Kambersky and co-workers, and by others, failed to guarantee uniform thickness of the film within the sample. The resulting gradient of the thickness involves a strong gradient of the coercive force[9].

Experimental Part

The present authors investigated the effect of the gradient of thickness on that of the coercive force, by Bitter's technique, observing domain walls on an iron film of diameter 5 mm that had been evaporated at an angle of 40°. The coercive force gradient was found to be 92 Oe/cm. In this situation, the domain walls can be shifted throughout the film by means of the external field, from the edge of lowest coercive force value to the opposite edge where the coercive force of the film is highest. Proceeding in this way, one can introduce several domain boundaries into arbitrary points of the film and retain them there. Fig. 1 shows domain walls set up, on the sample already described, by means of an external field of the strength indicated.

In order to eliminate a possible effect of the thickness gradient of the sample on the value of uniaxial anisotropy, a series of iron films evaporated in vacuum were investigated in such a manner that the thickness of the film was constant over the entire sample. Films of sufficiently homogeneous thickness were obtained by means of a diaphragm resembling a cardioid rotating immediately before the substrate (Fig. 2).

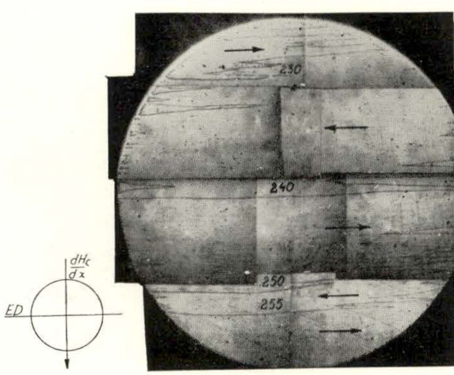


Fig. 1. Domain structure on an iron film with grad H_c=92 Oe/cm.

The samples were evaporated in vacuum of the order of 10^{-5} mm Hg onto a substrate consisting of glass kept at a temperature of 100°C. In advance to evaporation, the substrate was heated for several hours at 300°C, and the heater with the material destined for evaporation at a temperature somewhat below the melting point of iron. The length of the sample was about 15 cm; this yielded incidence angles ranging from 20° to 70°. The rotating cardioid diaphragm method yielded samples whose thickness varied less than by 15%. The thickness was measured and its homogeneity was checked by measuring the absorption of light transmitted by the film.

The dependence of the uniaxial anisotropy constant on the incidence angle of the vapour was investigated in iron films by the method of the longitudinal Kerr effect. The anisotropy constant was computed conventionally from the area, for initial magnetization curves measured in the direction of the easy axis and perpendicular thereto. Freshly evaporated samples were used, immediately after extraction from the vacuum chamber.

Measurements showed the anisotropy constant to increase with the angle of incidence of the vapour onto the substrate, attaining a maximum for an angle of about 30° and than decreasing to zero and changing its sign (Fig. 3); the latter fact is related to a change in the direction of the easy axis in the film.

Fig. 4 shows a number of initial magnetization curves measured for different incidence

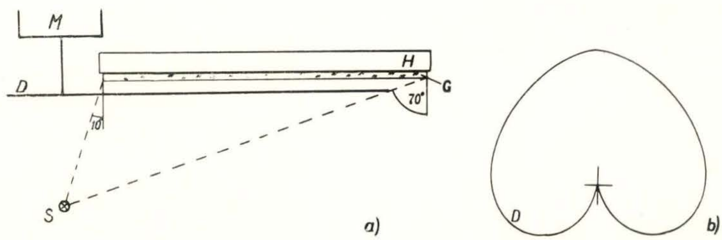


Fig. 2. a) Diagram of deposition arrangement; S denotes source of evaporation, D rotating diaphragm, G glass substrate, H heater, M motor.
b) The diaphragm shape.

angles, in the direction of the easy axis and in the one perpendicular to it. The values of the anisotropy constants for the various angles varied from one sample to another depending on the thickness; however, the shape of the anisotropy constant *versus* incidence angle dependence remained the same.

The curves of the foregoing dependence, as obtained by the present authors, resemble those of Cohen and of Kambersky and coworkers from permalloy films. However, the angle for which the anisotropy of the films investigated attained its maximum value was lesser than that corresponding to maximum anisotropy of the films investigated by the above-mentioned authors.

Investigation of iron films deposited without using the rotating diaphragm, i. e., of films possessing a gradient of the thickness,

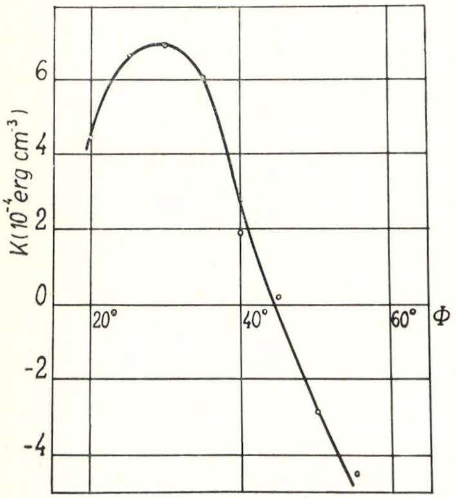


Fig. 3. Dependence of constant of uniaxial magnetic anisotropy on the incidence angle for iron film deposited on glass substrate kept at 100°C using the rotating diaphragm.

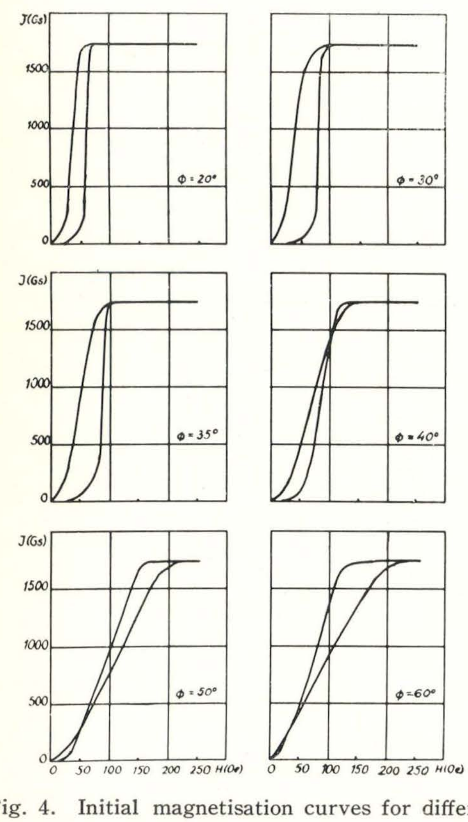


Fig. 4. Initial magnetisation curves for different incidence angles, measured in the direction of the easy axis and perpendicular to it.

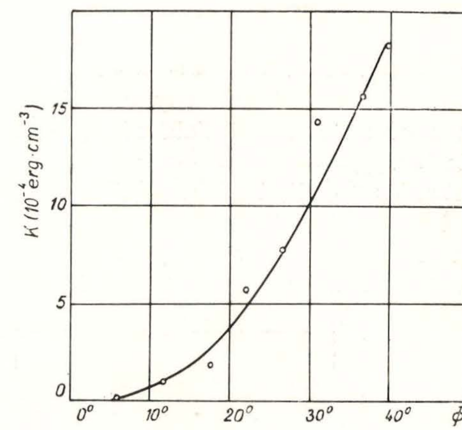
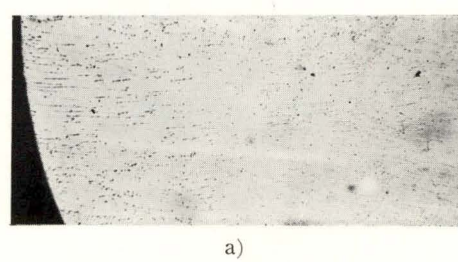
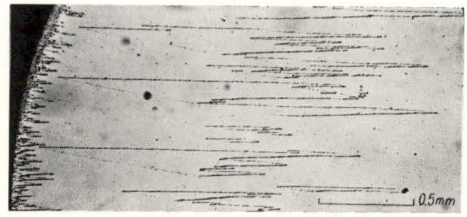


Fig. 5. Dependence of constant of uniaxial anisotropy on the incidence angle for iron films deposited on glass substrate kept at 100° *C*, without using the rotating diaphragm.



a)



b)

Fig. 6. Domain structure on iron films deposited at incidence angles of: a) 15° and b) 40°.

Fig. 7a.

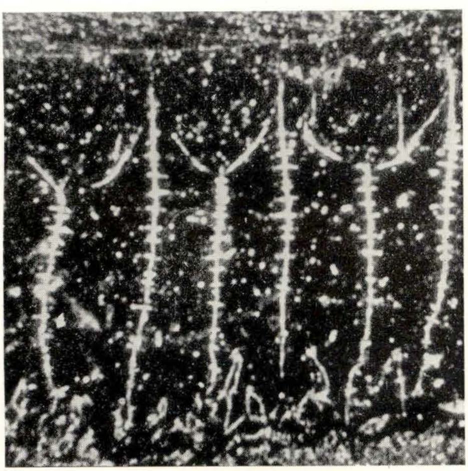


Fig. 7b.

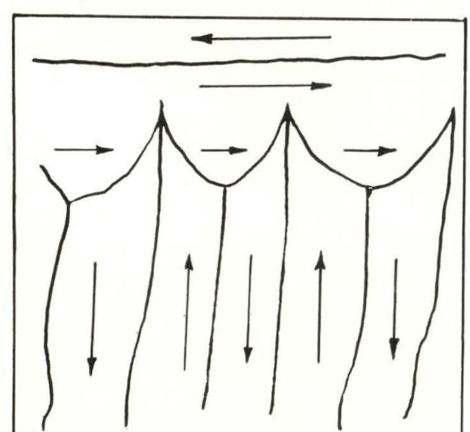


Fig. 7. c. Domain structure of the edge zone of an iron film (×600).

failed to reveal a maximum of the anisotropy constant for incidence angles ranging up to 40°[10] (Fig. 5). Pugh, Boyd and Freedman obtained similar results in iron films, for incidence angles ranging up to 34°. It would seem that the position of the anisotropy maximum depends on the conditions prevailing during evaporation of the films.

In addition, domain structure of thin iron films evaporated under different angles was subjected to observation. This was carried out by Bitter's technique on samples having the shape of circular spots 5 mm in diameter, subsequent to demagnetisation by means of an AC field of amplitude (3/2) H_c applied in the easy direction. Fig. 6 shows the domain structure on films that had been obtained by evaporation at angles of 15° and 40°, whose anisotropy constant amounted to $K=0.5\cdot10^4$ erg/cm^3 and $5.8\cdot10^4$ erg/cm^3, respectively. Herein, the areas of the domains are seen to grow with the anisotropy constant, and the domain boundaries tend to straighten out. However, the magnetic properties of the edge over a breadth of about 100μ differ considerably from those of the rest of the film. Throughout the edge zone, the directions of magnetization are distributed radially independent of the direction of the easy axis of the film and, moreover, the coercive force is lesser. In films of low anisotropy, "cross-tie" walls appear in the edge zone (Fig. 7 a, b). If the "cross-tie" walls subtend an angle with the easy axis, these walls go over into normal 180°-walls as we proceed away from the edge zone. If the easy axis is perpendicular to the "cross-tie" walls, the latter branch and close up by means of 90°-walls (Fig. 7b). Fig. 7 c shows schematically the orientation of the vectors in the edge zone domains. The considerable inhomogeneity of orientation of the easy axis and the lesser coercive force in the edge region are due to the wedge-shapedness and inhomogeneity of the stresses.

Conclusions

Numerous experiments on thin films proved their magnetic properties to be strongly dependent on the conditions prevailing during evaporation. In order to eliminate the effect of wedge-shapedness on the value of uniaxial anisotropy, films of the greatest possible homogeneity of thickness as obtained by applying a rotating diaphragm were used. The results obtained in iron prove films produced by evaporation in such conditions to possess a uniaxial anisotropy maximum for an incidence angle of about 30°. Such a behaviour obviously differs from that of the anisotropy in iron films evaporated by the usual method, as these failed to reveal an anisotropy maximum at incidence angles lesser than 40°.

The domain structure depends strongly on the magnetic anisotropy of the film. Thus, as the anisotropy increases, the domain pattern becomes more regular, the walls straighten out, and the domain increases in area. Moreover, domain structure observation revealed considerable inhomogeneity in easy axis orientation, owing to wedge-shapedness of the edge of the film and to the presence of stress inhomogeneity in the edge zone.

References

1 D. O. Smith: J. Appl. Phys. **29** (1958) 264.
2 C. D. Olson and A. V. Pohm: J. Appl. Phys. **29** (1958) 274.
3 T. G. Knorr and R. W. Hoffman: Phys. Rev. **113** (1959) 1039.
4 D. O. Smith, E. E. Huber Jr., M. S. Cohen and G. P. Weiss: J. Appl. Phys. **31** (1960) 295S.
5 E. W. Pugh, J. Matissoo, D. E. Speliotis and E. L. Boyd: J. Appl. Phys. **31** (1960) 293S.
6 E. W. Pugh, E. L. Boyd and J. F. Freedman: IBM J. Res. Dev. **4** (1960) 163.
7 M. S. Cohen: J. Appl. Phys. **32** (1961) 375.
8 V. Kambersky, Z. Malék, Z. Frait and M. Ondris: Czech. J. Phys. **B11** (1961) 171.
9 L. Néel: J. Phys. Radium **17** (1956) 250.
10 H. Ratajczak: Nauka Polska, in print.

DISCUSSION

D. O. SMITH: The oblique-incidence anisotropy shown in Fig. 3 of the author's paper is caused by two different aspects of film structure induced by the oblique incidence:

1) The positive anisotropy is due to chains of crystallite forming perpendicularly to the direction of the incident beam (Smith, Cohen and Weiss: J. Appl. Phys. **31,** 1755 (1960)) and occurs because of the shadow cast by a growing crystallite.

2) The negative anisotropy which occurs at high incident angle is caused by growth of the individual crystallite in the direction of the incident beam (refer to the author's paper).