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Domain Structures

On Domain Structure and Magnetization Processes

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In this paper we treated four subjects: 1) Calculation of domain structure of the infinite cylinder with its easy plane normal to the long axis; 2) temperature dependence of domain spacing and exchange constant of magnetoplumbite; 3) dependence of magnetostriction constant of Fe-Ni alloys on elastic stress; and 4) ferromagnetic resonance in thin magnetic films.

1 On the Domain Structure of the Infinite Cylinder

The theory of the domain structure (D.S.) of thin films of uniaxial ferromagnets was worked out by Kittel[1]. In connection with the existence of a number of antiferromagnets showing weak ferromagnetism, which is very strongly held in the basal plane (*i.e.* easy plane) of the crystal in which it is otherwise more or less free to rotate (*e.g.*) alpha-Fe_2O_3, $CoCO_3$, $MnCO_3$), the analogy to the thin film, *i.e.*, the infinite cylinder, is investigated.

The cylinder is placed with its axis normal to the easy plane of the crystal. (Fig. 1). The various energies considered are exchange energy, energy of anisotropy, demagnetizing energy. For vanishing K_3 (hexagonal constant of anisotropy) two possible D.S. may exist. Depending on the radius of the cylinder either the closed flux (Fig. 1a) or the helical magnetization configurations (Fig. 1b) are stable D.S. For radii smaller than a certain critical radius the helical configuration is the more stable, while for larger radii due to the absence of demagnetizing energy we get closed flux configuration.

For $K_3 \neq 0$ there are two analogical cases: The partially closed flux configuration with radial charged Néel walls (Fig. 1c) and the disc D.S. with uncharged Bloch walls parallel to the easy plane (Fig. 1d). In both cases the direction of magnetization in neighbouring domains differs by an angle $\varphi_i = 2\pi/i$ ($i = 2, 3, 6$). The energy of the walls depends on this angle and its values for different i are calculated. The demagnetizing energy of the various configurations is also evaluated and from this and the wall energy the stable

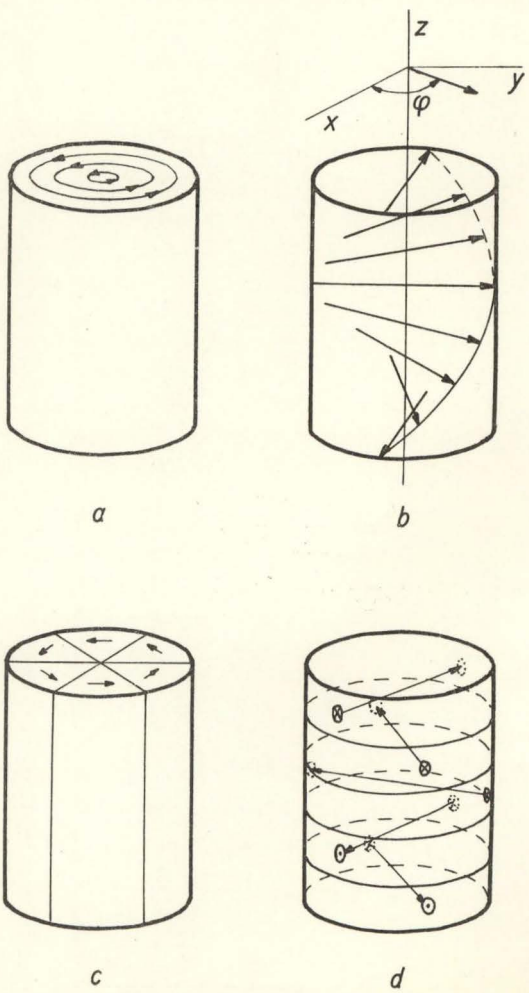

Fig. 1.

D.S. are obtained in the usual way. The equilibrium energy in both cases is a function of the radius. For small radii the partially closed flux configuration is the more stable while for large radii the disc structure is obtained.

By measuring the value of the domain spacing it should be possible to obtain the values of the wall energy and exchange constant analogously as was done in an earlier paper[2].

2 The Temperature Dependence of the Domain Spacing and Exchange Constant in Magnetoplumbite

The influence of the temperature on the D.S. has been the subject of a number of papers in the last few years. The Kerr effect was used in (1), (2), (3) an adapted powder technique in (6) and a vibrating permalloy probe in (7). All papers contain, however, only qualitative results.

We set out to investigate the temperature dependence of a very simple D.S., *i.e.*, the plate structure found on thin monocrystals of magnetoplumbite. As was shown by us in earlier papers[7),8)], this structure closely follows the theoretical dependence of the domain spacing versus the crystal thickness.

Magnetoplumbite has a very strong uniaxial anisotropy. The measurements were carried out on a monocrystal platelet 2.8 μ thick and about 0.5 mm across. This thickness permits the investigation of D.S. to be carried out in polarized light using the Faraday effect. The transparency of the sample strongly decreases with increasing temperature which together with the decreasing magnetization lowers the obtainable contrast and therefore sets an upper limit to the temperature at which domains could still be distinguished visually. We were, however, able to photograph the D.S. up to 400°C obtaining very good resolution up to 300°C. The Curie temperature of magnetoplumbite is 450°C[9].

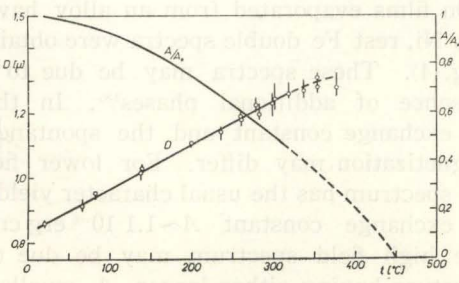

Fig. 2.

The measured temperature dependence of the domain spacing D on the temperature t is shown in Fig. 2.

For the plate D.S. we have according to Kittel[1),10)]

$$D=(\gamma T)^{1/2}/I_s 1.3; \qquad \gamma=4(AK)^{1/2}, \qquad (1)$$

where γ is the Bloch wall energy, T the crystal thickness, I_s the spontaneous magnetization, A the exchange constant and K the first constant of anisotropy.

The temperature dependence of the magnetization and anisotropy was measured by Pauthenet and Rimet[9]. We can calculate the temperature dependence of the exchange constant A. Denoting by the index zero values at room temperatures we get

$$(A/A_0)=(I_s/I_{s0})^4(T_0/T)^2(D/D_0)^4(K_0/K), \qquad (2)$$

with the value of A_0 being $0.61\cdot10^{-6}$ erg cm^{-1}.

If the change in thickness is neglected we obtain from (2) the dependence shown in Fig. 2. The temperature dependence of A was measured using spin-wave resonance on thin permalloy films by Seavy and Tannenwald[12], on Co films by Tannenwald and Weber[13] and also recently by Le Craw and Walker[14] on YIG. The first two papers contain measurements of A at 295°, 77° and 4.2°K and increases with respect to room temperature of 17% and 9% respectively were obtained. Le Craw and Walker, who measured on YIG in the temperature range from 4.2° to 500°K, obtained a slight decrease at temperatures above 400°K, which is in qualitative agreement with our results.

3 The Dependence of the Magnetostriction Constant of Fe-Ni Alloys on Elastic Stress

The magnetostriction constant of polycrystalline wires was determined as 2/3 of the difference between the longitudinal and transversal saturation magnetostriction. The magnetostriction was measured by means of an external resistance tensometer which was calibrated by multiple beam interferency.

The measurement shows the magnetostriction constant to be a linear function of stress; the slope of the lines being different for samples having different crystallographic texture at the outset, *i.e.*, different magnetostriction constants for zero stress (Fig. 3). The lines for samples of differing texture intersect

in one point where the material becomes magnetostrictive isotropic. We assume that the magnetostriction constant of a polycrystal

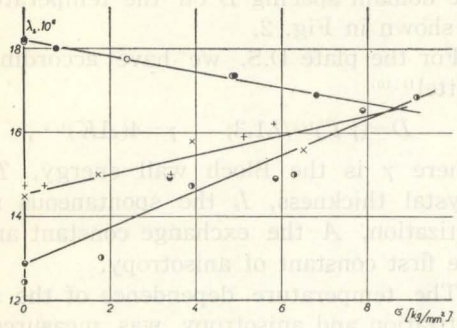

Fig. 3.

with arbitrary texture can be expressed as a linear combination of the magnetostriction constants of the monocrystal

$$\lambda_s = a\lambda_{100} + b\lambda_{111} , \qquad (3)$$

where the coefficients a and b are independent of stress and $a+b=1$. The values of a and b are determined from λ_s, λ_{100} and λ_{111} given by Bozorth[15]. Assuming that the magnetostriction constants of the monocrystal change linearly with stress, *i.e.*,

$$\lambda_{100}(\sigma) = \lambda_{100}(0) + (\Delta\lambda_{100}/\Delta\sigma)\sigma ,$$
$$\lambda_{111}(\sigma) = \lambda_{111}(0) + (\Delta\lambda_{111}/\Delta\sigma)\sigma \qquad (4)$$

we can determine $\Delta\lambda/\Delta\sigma$ from our measurements and thus arrive at the dependence of the magnetostriction constants of the monocrystal on stress.

For n different textures we obtain n equations with two unknowns which, within the limit of experimental error, must give a unique solution. The experimental points deviate from the linear interpolation at the most by 5%. The same error is obtained for $\Delta\lambda/\Delta\sigma$ for the monocrystal. Because, however, λ_{100} and λ_{111} for the materials in question are not exactly known this error may be somewhat larger even though the point of intersection was determined with a precision of 1%.

The following table gives the measured results:

Table I.

Sample	Composition+)			Point of intersection		Slope	
	Ni	Fe	Mn	$\lambda_s \cdot 10^6$	σ	$(\Delta\lambda_{100}/\Delta\sigma)\cdot 10^6$	$(\Delta\lambda_{111}/\Delta\sigma)\cdot 10^6$
PY 36	37.23	62.20	0.37	16.6	8.7	1.4	−0.5
PY 65	63.87	34.30	1.92	13.2	5.7	−1.65	0.25

+) rest Si, C, S, P.

Even though Takaki and Hayashi[16] did not obtain any changes of the magnetostriction constants of iron up to 0.65 kg mm^{-2}, we are of the opinion that with Fe-Ni alloys having a f.c.c. lattice the situation is different. The measured changes are thought to be due to changes in spin-orbital interaction in the elastically deformed lattice.

4 Ferromagnetic Resonance in Thin Films

The ferromagnetic and spin-wave resonance on Ni, Co and permalloy films in the thickness range 2000 Å to 7000 Å evaporated onto glass substrates was measured[17]. The wavelength was around 3 cm. The following values were determined; g-factor, line-width, effective isotropic stress, magnetization, induced uniaxial anisotropy and the exchange constant. With spin-wave resonance a shift of the spectra was observed towards lower fields for materials having negative magnetostriction (Co, Ni) and towards higher fields for permalloy 78% and 64%. Because the value of the isotropic stress determined from this value is smaller for films evaporated onto heated substrates we assume that the stresses are produced on cooling from the condensation temperature by the film not being able to shrink. By heating the substrates during evaporation the necessary shrinkage and also the stress is lowered.

On films evaporated from an alloy having 48% Ni, rest Fe double spectra were obtained (Fig. 4). These spectra may be due to the presence of additional phases[18]. In these the exchange constant and the spontaneous magnetization may differ. For lower fields the spectrum has the usual character yielding an exchange constant $A \sim 1.1 \cdot 10^{-6}$ erg cm^{-1}. The high field spectrum may be due to a structure having either larger A, smaller I_s

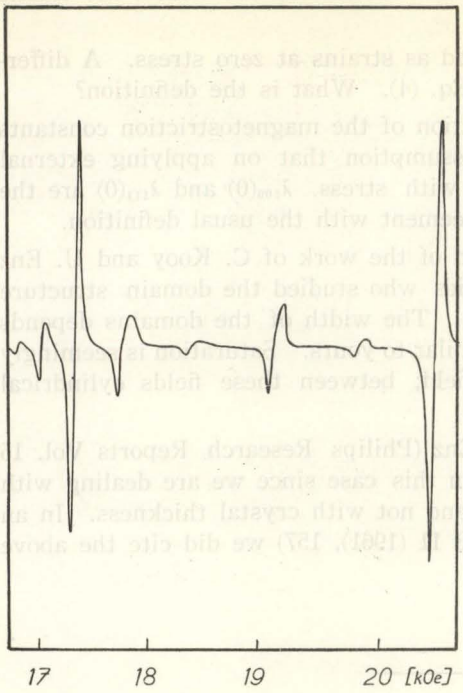

Fig. 4.

or both. The uniform distance of the modes points to the existence of antiferromagnetic ordering. The main peaks of both spectra are 3300 Oe apart, which for the frequency used corresponds to $g=2$. This shift could also be explained by the presence of a second phase having equal I_s but g in the neighbourhood of unity. The existence of a surface layer due to interaction with the atmosphere can also not be excluded. With films containing 37% Ni we observed besides the spin-wave resonance a peak at 24 kOe, pointing to precipitated iron in the film.

The frequency dependence of ferromagnetic resonance in Fe-Ni alloys in the 7 to 10 kMc/s range was also investigated on PY78, PY48, PY37, mumetal and Mo-permalloy in the shape of thin (0.05 to 0.1mm) electrolytically polished and annealed discs magnetized normal to their plane. It was possible to determine the g-factor from the slope of the linear dependence of the resonance field on the frequency. For these materials $g<2$ was obtained. This can only be explained by assuming an additional frequency-dependent effective field.

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DISCUSSION

H. Takaki: I think the two constants a and b in equation (3) should change in such a high stress region in your experiment, because a plastic deformation will begin at about 1 kg/mm², and the crystal orientation of grains in your samples will change as the stress increases.

Authors: The measuring equipment permitted the determination of any plastic flow the effect of which was much larger than the measured effect. Also points measured while exceeding the plastic limit were considerably outside the linear dependence. As an additional check-up the zero-stress values of the magnetostriction constants before and after straining were equal if no substantial plastic strain occur-

red. We therefore believe that the measurements were carried out within the elastic limits.

W. F. BROWN: λ_{100} and λ_{111} are usually defined as strains at zero stress. A different definition is evidently being used here, in Eq. (4). What is the definition?

AUTHORS: We start out from the usual definition of the magnetostriction constants at zero stress. Equation (4) expresses our assumption that on applying external elastic strain these constants change linearly with stress. $\lambda_{100}(0)$ and $\lambda_{111}(0)$ are the values of these constants for zero stress in agreement with the usual definition.

E. W. GORTER: I see you made no mention of the work of C. Kooy and U. Enz Physica 1960 of the Philips Research Laboratories who studied the domain structure of thin ($\sim 3\,\mu$) single-crystal plates of $BaFe_{12}O_{19}$. The width of the domains depends on thickness according to an extended theory similar to yours. Saturation is seemingly obtained at a field below H_A, the anisotropy field; between these fields cylindrical domains exist in accordance with theory.

AUTHORS: The paper by C. Kooy and U. Enz (Philips Research Reports Vol. 15 (1960), 7) which you mention is not relevant in this case since we are dealing with the change of domain width with temperature and not with crystal thickness. In an earlier paper of ours (see Czechosl. J. Phys. B 11 (1961), 157) we did cite the above paper.