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ORIGINAL PAPER

Analysis of the Anisotropy Field and the Saturation Magnetization for Ultrathin Ferromagnetic Films

B. Kaplan · R. Kaplan

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Abstract We study the magnetic in-plane anisotropic fields for a two-dimensional film by including magnetic field in the basal plane for an easy axis film. We present the balance between the applied field and in-plane anisotropic field at equilibrium. We have also investigated the approach to saturation of magnetization and numerically solving the nonlinear equation for equilibrium, and results are discussed in connection with experimental data reported for Co films.

Keywords Magnetic anisotropy · Magnetization curves

1 Introduction

For more than a half a century, the various terms in the expression for the approach to saturation which were observed experimentally in many ferromagnetic materials have long been a topic of interest. In particular, the rotation of the magnetization under the combined influence of the magnetic field and with different kinds of magnetic anisotropies has been intensively studied. Some of them are given below.

It has been shown experimentally that the law of approach to saturation is

$$\frac{M}{M_S} = 1 - \frac{a}{H} - \frac{b}{H^2} + \chi H \tag{1}$$

where M_S is the saturation magnetization and a, b and χ are constants. The χH term is caused by an increase of the spontaneous magnetization itself [1] and may be proportional to $\sqrt{H}$ as suggested by Holstein and Primakoff [2]. In (1), the a/H term is known as the magnetic hardness. The contribution of the dislocation effects to this term was calculated by Brown [3, 4] while in Néel's theory [5] it originated from the stray field.

A calculation is presented by Grady [6] who suggested that residual internal strain contributes significantly to this term and also is effective only in a limited field range. The effect of the magnetic field and crystalline anisotropy torques for the variation of the magnetization of ferromagnets near saturation has been first calculated by Akulov [7] who presented the expression for b in which the internal magnetic field arising from the magnetization itself was neglected completely. However, Akulov's theory has been improved by Holstein and Primakoff [8] by including the internal magnetic field. Herbst and Pinkerton [9] showed that the approach to saturation for cubic and uniaxial polycrystalline, single-domain ferromagnets from the remanent state depends on the initial moment distribution. Nakai [10] observed that the magnetization approaches saturation as a function of $1/\sqrt{H}$ rather than $1/H^2$ for the amorphous alloys at low temperature.

It has been recently shown the approach to saturation in both Co and Fe single crystals by taking into account the field energy and by introducing a new approximation rather than Akulov's approximation [11]. In the computation, $H \leq$ 126,000 Oe, and they found that for the case of the magnetocrystalline anisotropy energy only, the paramagnetism-like process is not occurring, and the a/H, b/H^2 and χH terms all originate from the magnetocrystalline anisotropy. The role of both uniaxial and cubic in-plane anisotropies per atom for a cubic film is not included in this calculation and therefore it raises the important question concerning the strengths of both uniaxial and cubic in-plane anisotropies which are both thickness dependent requiring to dominate over applied field angle in controlling the saturation.

B. Kaplan (✉) · R. Kaplan
Department of Physics, Faculty of Education, University of Mersin, Yenisehir Campus, 33169 Mersin, Turkey
e-mail: bengukaplan@yahoo.com

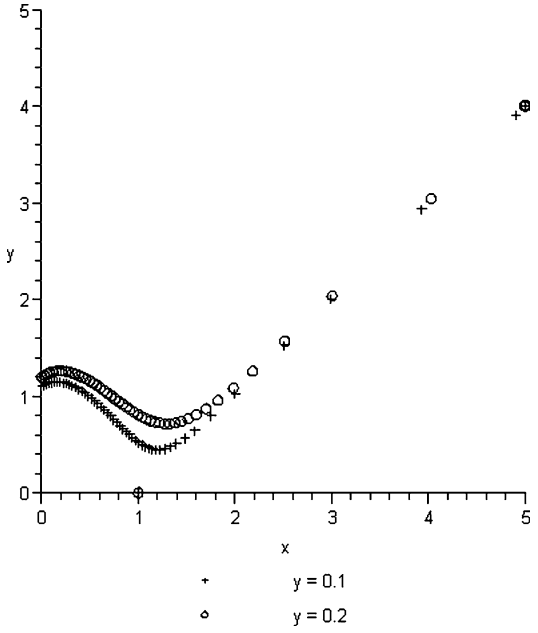

Fig. 1 The variation of y vs. x. Beyond $x = 3$, y shows a linear increase

In framework of our theory, we focus on the balance between the applied field and in-plane anisotropic field at equilibrium and the approach to saturation of magnetization. The magnetic properties of epitaxial Fe single films on GaAs substrates were found to vary continuously with film thickness (L) [12]. A thickness-dependent uniaxial in-plane magnetic anisotropy whose strength was of the order of the cubic in-plane anisotropy was observed. A uniaxial and a cubic in-plane anisotropies showed a different thickness dependence leading to a directional change of the easy and hard magnetization axes with respect to the crystallographic axes in the film plane as the Fe layers grow thicker. As the film thickness increases, the cubic in-plane anisotropy and the magnetization clearly approach the values for bulk Fe. Recently, the structure and magnetic anisotropy of thin Co films have been studied as a function of thickness [13]. Xu et al. have investigated the fourfold anisotropy field of bcc Co as well as hcp Co at a series of growth temperatures. The experimental data of Xu et al. [13] are well suited for our theoretical results. Representative longitudinal-MOKE loops for 1.4 nm bcc Co only show twofold symmetry implying that the in-plane uniaxial anisotropy plays a dominant role and the estimated fourfold anisotropy field is −152 Oe. A 2-nm Co film shows a fourfold dominant anisotropy which corresponds to a positive fourfold anisotropy field. We assume the presence of both the out-of-plane and the uniaxial in-plane anisotropy energy contributions for a cubic film.

2 Calculation

As a starting point, we consider a film in the (x, y) plane and assume that the ground state energy is a function of the magnetization direction $\varepsilon(\theta, \varphi)$. The anisotropy energy may be written as:

$$\varepsilon_a(\theta,\varphi) = K_{1\text{eff}}\cos^2\theta + \frac{K_v}{4}\sin^2 2\theta + \frac{K_u}{4}\sin^4\theta\sin^2 2\varphi + K_{\text{in}}\sin^2\theta\sin^2\varphi \tag{2}$$

where $K_{1\text{eff}}$ is the effective perpendicular uniaxial anisotropy constant including shape anisotropy of the film, K_v and K_u are the modified fourth-order cubic anisotropy constants associated with the crystal symmetry, and K_{in} is the uniaxial in-plane anisotropy constant, and all of them depend on thickness L. The equilibrium angles found from $\frac{\partial\varepsilon_a}{\partial\theta} = \frac{\partial\varepsilon_a}{\partial\varphi} = 0$ are $\theta_0 = \pi/2$ and $\varphi_0 = 0$, where θ is the polar angle with respect to the film normal and φ is the azimuthal angle between magnetization easy axis and in-plane magnetization component. We generalize this to include a magnetic field H orientated in the plane at angle ψ to the easy direction.

$$\varepsilon(\theta,\varphi) = \varepsilon_a(\theta,\varphi) - HM_S\sin\theta\cos(\psi-\varphi). \tag{3}$$

Firstly, at equilibrium $\theta = \pi/2$, as before, and for $\psi = \pi/4$:

$$\left.\frac{\partial\varepsilon}{\partial\varphi}\right)_{\theta_0,\varphi_0} = 0 = \frac{K_u}{2}\sin 4\varphi_o + K_{\text{in}}\sin 2\varphi_o - HM_S\sin\left(\frac{\pi}{4}-\varphi_o\right). \tag{4}$$

This equation defines φ_o as a function of H. For $K_{\text{in}} = 0$ then this equation is always satisfied for $\varphi_o = \pi/4$. This solution is stable if $M_S \geq 2K_u$. For $K_{\text{in}} \neq 0$ the angle φ_o approaches $\pi/4$ for large fields as:

$$\varphi = \frac{\pi}{4} - \varphi_o = \frac{K_{\text{in}}}{HM_S - 2K_u}. \tag{5}$$

The magnetization lies in plane so the effective in-plane anisotropy energy K_S may be defined by [14]

$$2K_S = \left.\frac{\partial^2\varepsilon}{\partial\varphi^2}\right)_{\theta=\pi/2,\varphi_0}. \tag{6}$$

A plot of (6) vs. (4) is shown in Fig. 1. It has a little minimum, and beyond $x = \frac{HM_S}{2K_u} = 3$, $y = \frac{2K_S}{2K_u}$ shows a linear increase. For large H, φ goes to $\pi/4$ and we consider the approach to saturation of magnetization originating from the uniaxial and the cubic in-plane magnetic anisotropies for a two-dimensional film by including magnetic field in the basal plane for an easy axis film. We extend the results [11] to the case of (3) at equilibrium. In the computation, $H \leq 60$ Oe for 1.4 nm Co and $H \leq 350$ Oe for 2 nm Co and also ψ varies from 0 to $\pi/4$.

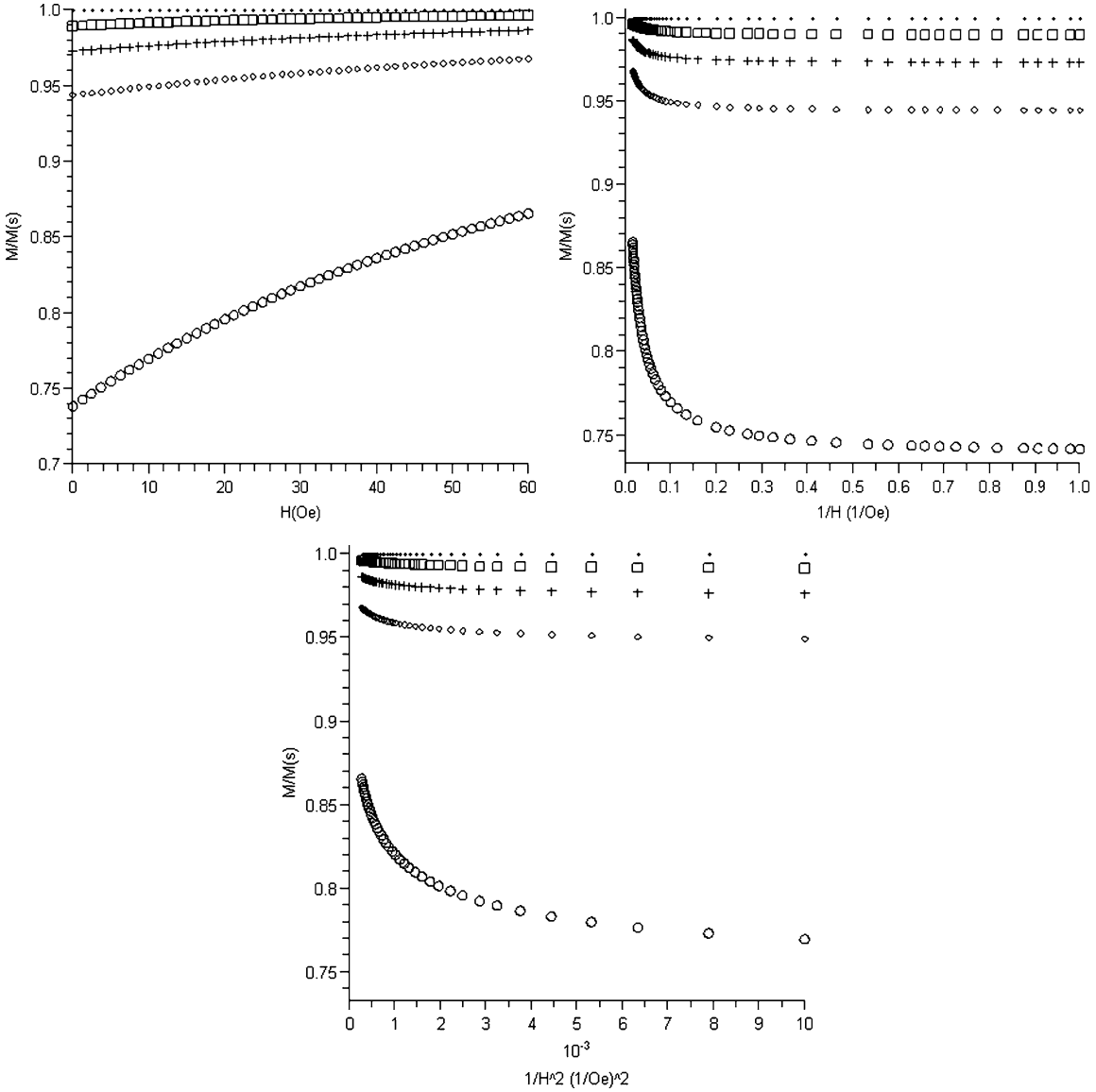

Fig. 2 Calculated M/M_S against the applied fields H (part (**a**)), $1/H$ (part (**b**)) and $1/H^2$ (part (**c**)) with the different directions defined by ψ for 1.4 nm Co film. ($\psi = 0°$ (*point*), 10° (*box*), 20° (*cross*), 30° (*diamond*), 45° (*circle*).) $H = 60$ Oe

The equilibrium direction of the saturation magnetization is obtained by the extremum energy condition from (3):

$$\left.\frac{\partial \varepsilon}{\partial \varphi}\right)_{\theta_0,\varphi_0} = 0 = \frac{K_u}{2}\sin 4\varphi_o + K_{\text{in}}\sin 2\varphi_o - HM_S\sin(\psi-\varphi). \tag{7}$$

By putting $\delta = \psi - \varphi_0$ and then substituting into (7), we obtain

$$0 = \frac{K_u}{2}\sin 4(\psi-\delta) + K_{\text{in}}\sin 2(\psi-\delta) - HM_S\sin\delta. \tag{8}$$

It is useful to introduce the anisotropic fields $H_{\text{in}} = \frac{2K_{\text{in}}}{M_S}$ and $H_u = \frac{2K_u}{M_S}$. Using the approximation from [11], we expand the first and second terms in (8), and neglecting terms of order δ^2, we obtain

$$\delta \approx \frac{1}{4}\left\{\frac{1H_{\text{in}}\sin 2\psi + H_u\sin 4\psi}{H + H_{\text{in}}\cos 2\psi + H_u\cos 4\psi}\right\} \tag{9}$$

Then the component of magnetization in the direction of the field is given by

$$M = M_S\cos\delta \approx M_S\left(1-\frac{\delta^2}{2}\right). \tag{10}$$

In the computation, the observed twofold and fourfold anisotropy fields are 220 Oe and −152 Oe for 1.4 nm Co and also 62 Oe and 132 Oe for 2 nm Co films, respectively. Samples thinner than the structure transition thickness show negative fourfold anisotropy field [13].

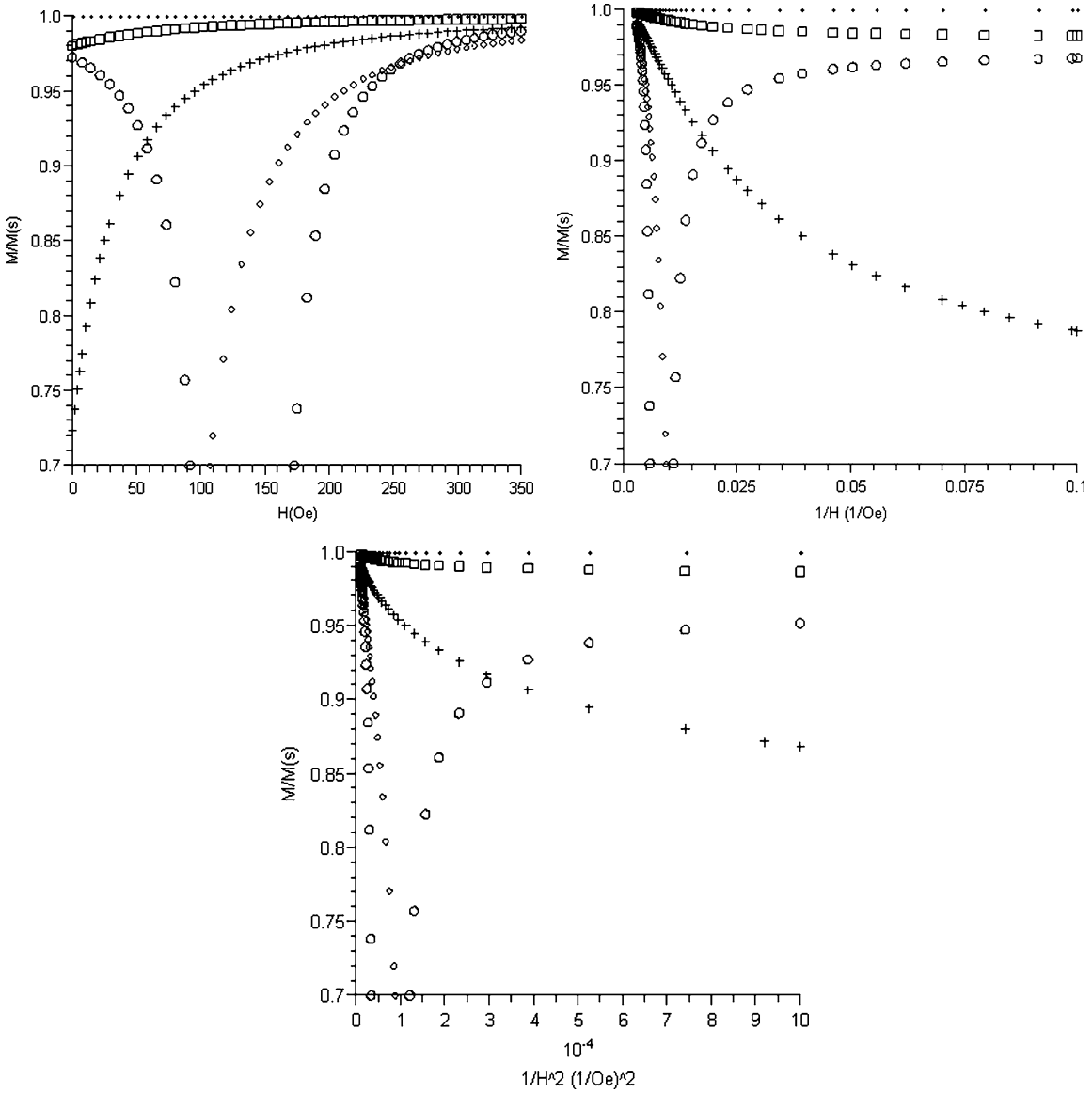

Fig. 3 Calculated M/M_S against the applied fields H (part (**a**)), $1/H$ (part (**b**)) and $1/H^2$ (part (**c**)) with the different directions defined by ψ for 2 nm Co film. ($\psi = 0°$ (*point*), 10° (*box*), 20° (*cross*), 30° (*diamond*), 45° (*circle*).) $H = 350$ Oe

Parts (a), (b) and (c) in Fig. 2 show the M/M_S vs. H, $1/H$ and $1/H^2$, respectively, with the field applied along different directions defined by ψ for the 1.4 nm Co film. It can be seen that the approach to saturation is strongly dependent on the angle ψ. It can be fully saturated by the field along the easy or hard axes. The magnetizations are rotated into the field direction and also the critical fields are identical and determined by the small in-plane and cubic anisotropy fields. The approach to saturation for $\psi = 10°$ is different from that for $\psi = 45°$ because of difficulty to be magnetized for the directions far away from the non-easy (or hard) axes.

For 2 nm Co film, parts (a), (b) and (c) in Fig. 3 show the M/M_S value as a function of H, $1/H$ and $1/H^2$, respectively, at different directions defined by ψ. As seen from these figures, the dependence of M/M_S on H can be satisfied in the high field region for all directions. However, for only $\psi = 45°$, it cannot be satisfied at low field region. For this case, the M/M_S decreases very sharply at the beginning with increasing field until at about 100 Oe, and after this value, it changes direction to the increase and approaches saturation at about 250 Oe as we have expected. The difference between Figs. 2 and 3 is in the opposite signs of magnetocrystalline anisotropy and different film thickness. According to the present day experiments of the magnetization reversal of uniaxial Co films as a function of the applied field orientation, while stable intermediate domain states exist for most field directions, their occurrence is suppressed for field

orientations along the easy axis of magnetization [15]. For field angles of 20° and 40° away from the easy axis, Idigoras et al. have observed the creation of stable or metastable domains during magnetization reversal. If the external field is aligned along the easy axis, magnetization reversal proceeds by means of a sample-size domain-wall avalanche, so that the magnetization reversal is completely correlated in the whole sample of 30-nm thick Co film with in-plane uniaxial anisotropy without creating intermediate metastable or stable multi-domain states.

In (9), the $\cos 2\psi$ and $\cos 4\psi$ terms which originate from the twofold and fourfold symmetry play a dominant role in the approach to saturation. For $\psi = 0°$, these terms do not contribute to the magnetization process and full saturation of the magnetization is achieved. For $\psi = 45°$, the sign of the $\cos 4\psi$ term can change from '+' to '−'. With a very strong applied external field, the terms of $\cos 2\psi$ and $\cos 4\psi$ are very small and thus can be neglected. In spite of this, the approach to saturation comes from the uniaxial in-plane and fourth-order cubic anisotropies in origin and also depends strongly on the film thickness.

3 Conclusion

In this study we have shown that the small in-plane anisotropies cannot be neglected for ultrathin ferromagnetic films. The ultrathin films can reach complete saturation when they are magnetized by a field along the easy or hard directions, while they will follow the law of approach to saturation if the field is applied along the non-easy (or hard) directions. The reason is that depending on the film thickness as well as the applied field angle, the twofold and fourfold anisotropy symmetries can impede or facilitate the magnetization of the ultrathin film. No paramagnetic process occurs, and thus the a/H, b/H^2 and χH terms in (1) arise from the twofold and fourfold anisotropies in origin and depend on the film thickness. By using the experimental data at room temperature, in which the Co films were deposited on GaAs(001) substrates at different growth temperatures from 60 and 160°C, we derived good qualitative results.

References

1. Chikazumi, S.: Physics of Magnetism. Willey, New York (1964)
2. Holstein, T., Primakoff, H.: Phys. Rev. **58**, 1098 (1940)
3. Brown, W.F. Jr.: Phys. Rev. **58**, 736 (1940)
4. Brown, W.F. Jr.: Phys. Rev. **60**, 139 (1941)
5. Neel, L.: J. Phys. Radium **9**, 184 (1948)
6. Grady, D.E.: Phys. Rev. B **4**, 3982 (1971)
7. Akulov, N.S.: Z. f. Physik **69**, 822 (1931)
8. Holstein, T., Primakoff, H.: Phys. Rev. **59**, 388 (1941)
9. Herbst, J.F., Pinkerton, F.E.: Phys. Rev. B **57**, 10733 (1998)
10. Nakai, I.: J. Magn. Magn. Mater. **177**, 117 (1998)
11. Zhang, H.: Zeng. D., Liu, Z.:. J. Magn. Magn. Mater. **322**, 2375 (2010)
12. Gester, M., et al.: Thin Solid Films **275**, 9 (1996)
13. Xu, X.Y., et al.: Phys. Rev. B **77**, 052403 (2008)
14. Bland, J.A.C., et al.: J. Phys., Condens. Matter **7**, 6467 (1995)
15. Idigoras, O., et al.: J. Magn. Magn. Mater. **322**, L57 (2010)