Physica B 275 (2000) 133–137

PHYSICA B

www.elsevier.com/locate/physb

On the correlation between the widths of minor and major magnetic hysteresis loops

G. Vértesy[a],*, A. Magni[b]

[a]Hungarian Academy of Sciences, Research Institute for Technical Physics and Materials Science, H-1525 Budapest, P.O.B. 49, Hungary
[b]IEN Galileo Ferraris, Corso M. d'Azeglio 42, I-10125 Torino, Italy

Abstract

The widths of the minor and major hysteresis loops were investigated in epitaxially grown uniaxial magnetic garnet films. It was found that minor loops can be wider than the major loop. This relationship can be turned into the opposite in the same sample by its proper processing. The phenomenon was interpreted, showing the difference in the character of the technical coercive force and of domain wall pinning field. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic garnet films; Hysteresis loop; Coercivity

1. Introduction

Coercive properties of materials are commonly considered to be one of the most important parameters in applied magnetism. The influence of microstructure on macroscopic and intrinsic magnetic properties have been studied by several authors (for a review paper, see e.g. Ref. [1]). The coercive field — which is in close correlation to the hysteresis losses of the material — is determined from the width of the hysteresis loop. The technical coercivity, H_c is defined as the external magnetic field necessary to reduce the total magnetic moment of the sample to zero after having been previously saturated. H_c is the half-width of the saturation-to-saturation or major hysteresis loop. It was shown [2] that another characteristic coercive parameter, the domain wall coercive field, H_{cw}, could also be determined from reproducible and well-defined small minor hysteresis loops. Coercivity, determined from the major hysteresis loop was usually found to be significantly higher than the domain wall coercivity [3]. This agrees very well with the usual experience on the great majority of magnetic materials, i.e. the width of the major hysteresis loop is larger than that of any of the minor loops. However, in certain cases — in contrast to the regular and expected case — the minor hysteresis loops were found to be wider than the major loop. The aim of the present work is to investigate and analyse this anomalous phenomenon.

For the investigations epitaxial magnetic garnet films were chosen. These films belong to the most perfect single-crystalline materials, as their growth by liquid-phase epitaxy (LPE) technology and the control of their magnetic properties are very well established processes. Due to the growing conditions they exhibit large uniaxial anisotropy which is perpendicular to the film plane. The magnetisation vector inside all domains is aligned perpendicular to the film plane and the domain structure is the well-known stripe domain structure, with 180° Bloch domain walls.

2. Experimental

The films were grown on 2″ diameter, (1 1 1) oriented gadolinium gallium garnet (GGG) substrate by LPE technology from traditional $PbO–B_2O_3$ melt-solution system. Three different samples were investigated. The chemical composition of samples A and B was $(Y,Sm,Ca)_3(Fe,Ge)_5O_{12}$, while the composition of sample C was $(Y,Ca)_3(Fe,Ge,Co)_5O_{12}$.

---

*Corresponding author. Tel.: + 36-1-169-5165; fax: + 36-1-3959284.
E-mail address: vertesyg@mfa.kfki.hu (G. Vértesy)

PII: S0921-4526(99)00722-X

The thickness of the films were measured by the optical interference method. Magnetization measurements were performed on a vibrating sample magnetometer PAR Model 155 equipped with a helium cryostat. The external magnetic field (up to ± 2 T) was measured by an NMR calibrated, thermally stabilized Hall sensor, and the temperature was determined by a Cu–Constantan thermocouple placed close to the sample. The magnetic contribution of the paramagnetic GGG substrate was always subtracted from the measured magnetic moment. The saturation magnetization, M_S, was determined from the saturation-to-saturation hysteresis loops measured with the external field applied along the easy axis, i.e. perpendicular to the surface of the film, with a relative error less than 1%. The uniaxial anisotropy field, H_A, was determined from the saturation-to-saturation hysteresis loops measured with the external field applied normal to the easy axis, i.e. in the plane of the sample, with an accuracy of 5%.

The hysteresis loops were measured both in the vibrating sample magnetometer and in a magnetooptical setup, using the Faraday effect. Hysteresis loops, measured by the two methods were found completely equivalent to each other. The technical coercive field, H_c, was determined from the saturation-to-saturation hysteresis loop, the external field being normal to the film surface. The domain wall coercive field, H_{cw}, was determined as the half-width of the minor hysteresis loops measured in the external field applied along the easy axis, only in the close vicinity of zero applied field [3]. The minor loops were always recorded after demagnetization of the sample by an AC magnetic field with an amplitude decreasing to zero. This procedure was to ensure that we always started from the domain structure with the lowest energy, anhysteretic equilibrium period, p_0. The coercive field can be determined with an accuracy of ± 20 A/m.

Sample A was cut into 5×5 mm pieces, and the reference measurements were performed on one of these pieces. Another piece of the sample was annealed in oxygen atmosphere at 980°C, through 2.5 h, and measurements were performed after the heat treatment. Sample B was cut into a large (about 2000 mm^2) and into a small (40 mm^2) piece, and measurements were done on both pieces. A 50 mm^2 piece of sample C was measured.

Table 1
Measured parameters of the samples (h, film thickness, M_S, saturation magnetization, H_A, uniaxial anisotropy field, p_0, zero field stripe domain period)

Sample	h (μm)	$\mu_0 M_S$ (mT)	H_A (A/m)	p_0 (μm)
A	5.3	19.7	57000	9.0
B	12.6	5.2	233500	165.0
C	11.8	16.3	140400	56.0

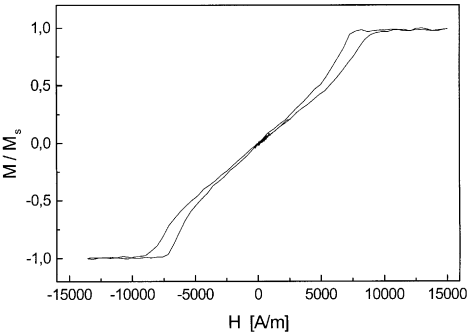

Fig. 1. Major and minor hysteresis loops of sample A at room temperature.

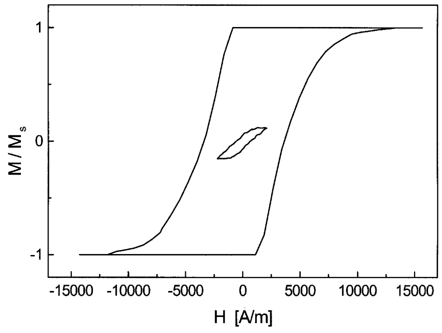

Fig. 2. Major and minor hysteresis loops of sample A at $T = 82$ K.

3. Results

The measured parameters of the investigated samples (at room temperature) are given in Table 1. The room temperature saturation-to-saturation hysteresis loop, measured on sample A, is shown in Fig. 1, together with minor hysteresis loops (in the middle of the curve). The width of minor loops are smaller than that of the major loop, however it is not seen clearly in the figure, because of the narrow loops. The ratio of the widths of the major and minor loops is seen much better at lower temperature, where the hysteresis loops are significantly wider. This low temperature case is illustrated in Fig. 2, for the same sample. This sample (sample A) represents the standard garnet samples, its behaviour is typical for the great majority of materials.

Samples B and C show anomalous behaviour from the point of view of the ratio of major and minor hysteresis loops. The widths of the minor hysteresis loops,

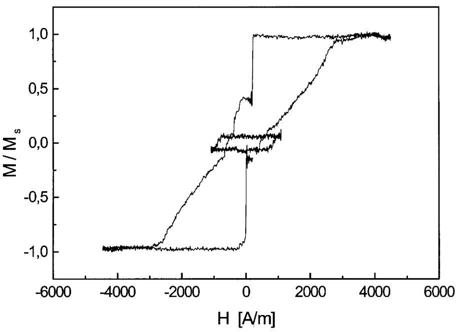

Fig. 3. Major and minor hysteresis loops of sample C at room temperature.

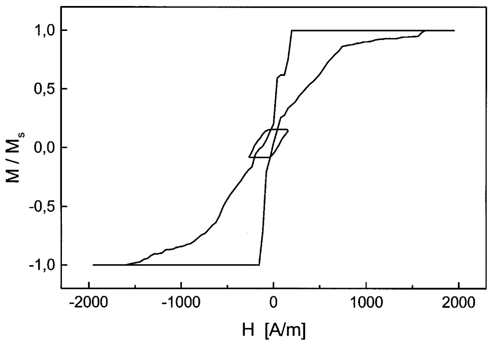

Fig. 4. Major and minor hysteresis loops of sample B, measured on a large piece (room temperature).

measured around zero external normal field, are definitely wider, than the width of the major loop. The room temperature hysteresis loops of samples C and B are shown in Figs. 3 and 4, respectively.

The temperature dependence of H_{cw} was measured in the as-grown, reference piece of sample A, and on another piece of the same sample, which was previously annealed through 2.5 h at 980°C in oxygen atmosphere. It was found that in a certain temperature range (between 100 and 200 K), the domain wall coercive field was modified (increased), compared with the original values of H_{cw}. In this region, where an increase of H_{cw} was found, the width of the minor loops around the zero field became larger, than the width of the major loop, similar to the case which is illustrated in Fig. 3. However, the heat treatment did not measurably modify the width of the major loop in the whole temperature range.

The major and minor hysteresis loops were measured at room temperature on two pieces of sample B. The result of the measurements, performed on a large (2000 mm^2) piece of the sample is shown in Fig. 4, while Fig. 5 shows the result of the measurements, performed on a small (40 mm^2) piece of the same sample. The value of H_{cw}, determined from the minor loop, is the same ($H_{cw} = 143$ A/m) in both cases, while the value of H_c was increased by cutting the sample, from the original $H_c = 80$ to 260 A/m. On decreasing the size of the sample, H_c increases even further, without significant modification of H_{cw}.

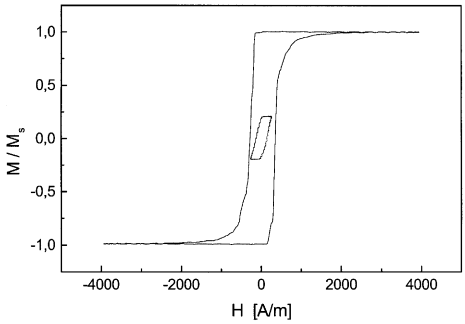

Fig. 5. Major and minor hysteresis loops of sample B, measured on a small piece.

4. Discussion

Measuring the magnetic hysteresis loops, two characteristic parameters can be determined from the width of the loops, each of them characterizing different properties of the measured specimen. One of them, the so-called coercive force, or technical coercivity (H_c) is one of the most frequently used parameters for the characterization of magnetic materials. Even though such a parameter is important in technical applications, it is generally difficult to find its direct link with individual micromagnetic processes which take place in the material during the complete change in the magnetic state of the sample. These processes can include rotation of the vector of magnetization, nucleation of magnetic domains and translation of domain walls within the bulk of the material. The other one, the domain wall coercive field, H_{cw}, which characterizes the interaction between translating domain walls and the actual structure of the material [3–5], is defined as the minimum mean external magnetic field necessary to irreversibly move the walls in the sample. H_{cw} can be measured only in certain cases, where the change in magnetization takes place only by domain wall displacement. Uniaxial epitaxial magnetic garnets are a very good model material for studying this parameter.

Usually H_c is larger than H_{cw}; it is well known from the everyday experience and from the basic handbooks dealing with magnetic phenomena. The same general relationship was found also in the case of epitaxial magnetic garnet films, systematically investigating and comparing the results of different methods for coercivity [3]. However, in certain cases, which are represented by samples B and C of the present work, the opposite relationship can exist between H_c and H_{cw}. The $H_{cw} > H_c$ relationship was reproducibly found on these samples. The reason can originate in the extraordinary magnetic parameters of these samples, compared with the standard samples (see Table 1). It is thought that the shape of the major hysteresis loop is determined mainly in the epitaxially grown magnetic garnet films by the domain wall nucleation. The saturation magnetization of samples B and C is small, compared with the uniaxial anisotropy field. The nucleation of the domain walls is difficult in the previously saturated sample, because the nucleation is poorly assisted by the low value of the saturation magnetization (low value of the demagnetization energy) and at the same time strongly opposed by the large value of the domain wall energy density, $\sigma_w = 4(AK_u)^{1/2}$, where A is the exchange constant, and K_u is the uniaxial anisotropy constant.

If a thin film of thickness h is considered, with large uniaxial anisotropy perpendicular to the film plane, the nucleation field can be expressed by the following formula, applying dipolar-random field Ising model to garnet films [6]. Here a is the cell size of the magnetically saturated area and the magnetic moment of a single cell is $m = a^2 h I_s/\mu_0$.

$$H_n = \left(4\frac{\sigma_{DW}}{I_s} - 9\frac{I_s h}{4\pi\mu_0}\right)\frac{1}{a} = wa. \tag{1}$$

The difference in the parenthesis of the nucleation field formula has been shown as an important parameter in Ref. [6]. It has been verified, that for non-standard samples (B,C), $w > 0$, while $w < 0$ for standard samples. w depends just on physical quantities, while a is the lattice cell side we choose. The nucleation field goes to zero with a from negative values (standard) or from positive values (non-standard).

Considering that H_c and H_{cw} represent two different types of characteristics of the material, it is not surprising that these parameters can be modified independent of each other. In the extreme case, the proper processing of the sample can turn over the originally existing $H_c/H_{cw} > 1$ or $H_c/H_{cw} < 1$ relationship. As seen in the previous chapter, we have managed to find experimental evidence for both cases, i.e. in a standard sample (sample A), due to annealing, the originally experienced $H_c/H_{cw} > 1$ relationship was reversed in a certain temperature range, and in an irregular sample (sample B) the original $H_c/H_{cw} < 1$ relationship was also reversed into $H_c/H_{cw} > 1$ by cutting the sample.

Modification of magnetic parameters such as uniaxial anisotropy due to the heat treatment in O_2 atmosphere was reported in Ref. [7], and the phenomenon was attributed to the climbing motion of the vacancy pairs formed by dodecahedral site cations and oxygen vacancies from the film interior to the surface. The heat treatment had an influence also on the domain wall coercive field. In the 100–200 K temperature range, H_{cw} was increased due to the annealing in the oxygen atmosphere, while H_c did not change measurably. The reason is, that H_{cw} is much more sensitive to any fine modification of the sample's magnetic parameters, and also to any change in the defect structure. The observed phenomenon, the modification of H_{cw} only in a certain temperature range, instead of the full range, can be interpreted on the basis of a model, describing the temperature dependence of coercivity of garnet films [8–10]. According to this model, different types of wall-pinning traps (material defects) coexist in the sample, each of them prevailing in different temperature regions. From the measurement results it can be concluded, that the heat treatment modified only the strength of a certain type of defects, leaving the others unchanged.

The modification of the size of the sample has no influence on any basic magnetic material parameter, which determines the behaviour of the domain walls, through the domain wall energy density and domain wall thickness. Cutting of the sample into smaller pieces has no influence on the originally existing defect structure of the material as well. Because of this, no change in H_{cw} can be expected due to samples cutting, in good agreement with the experiments. (The sample size, however, has a small and opposite sign influence on the domain wall coercivity, as was found previously [11]. This effect becomes significant only in the case of very small, some mm^2 size pieces, and H_{cw} was found to decrease with the sample size. This effect was attributed to the sample-size-dependent derivatives of the total free energy with respect to the domain wall positions. In the case of the sample B, this change in H_{cw} due to the decrease in the sample size was negligible.) On the other hand, the nucleation of the domain wall becomes even more difficult, if the sample size is decreased, because of the change of the demagnetizing field. The magnetostatic term in the expression of H_c (see e.g. Ref. [12]),

$$H_c = \alpha\frac{2K_u}{\mu_0 M_S} - N_{\text{eff}} M_S, \tag{2}$$

makes it clear that magnetostatic effects give a significant contribution to the coercivity. (Here is α phenomenological parameter, and N_{eff} is the effective demagnetizing factor.) This is the reason why the modification of the demagnetizing field by cutting the sample can have such a large influence on H_c.

Preliminary experiments showed as well, that the value of H_c depends significantly on the value of the magnetic field, by which the sample was previously saturated. In the case of the non-standard samples, anomalous behavior of H_c, as a function of the saturating field, was experienced. This phenomenon is being studied, and will be published later.

5. Conclusions

The widths of minor and major hysteresis loops were investigated in epitaxially grown uniaxial magnetic garnet films. It was shown that in certain cases minor loops can be wider than the major loop. Both the widths of major and minor loops can be modified in the same sample, independent of each other, by suitable processing of the specimen. These results revealed the different characteristics of the macroscopic coercive field, determined from the major loop, and of the domain wall coercive field, determined from minor loops, close to zero magnetic field. H_c was found to be a sample parameter, while H_{cw} to be a material parameter. H_{cw} is a very stable quantity, it cannot be modified easily (only by rough processing of the specimen), and the modification (if there is any) is small and valid only in a limited temperature range. This parameter is the real physical characteristic of the interaction between the moving domain wall and the defect structure of the material. On the other hand, H_c depends very much on the actual size of the sample (the difference can be larger than one order of magnitude), and it depends also on the magnetic prehistory of the sample.

Acknowledgements

The authors are indebted to the Magnetic Department of Institute of Physics (Prague), Academy of Sciences of the Czech Republic, for making it possible to use the VSM for the measurements. This work was partially supported by Hungarian Scientific Research Fund (T-026153).

References

[1] H. Kronmüller, in: G.C. Hadjipanayis (Ed.), Magnetic Hysteresis in Novel Magnetic Materials, Kluwer, Dordecht, 1997, pp. 84–108.
[2] G. Vértesy, L. Pust, I. Tomáš, J. Paces, J. Phys. D 24 (1991) 1482.
[3] G. Vértesy, M. Pardavi-Horváth, L. Bódis, I. Pintér, J. Magn. Magn. Mater. 75 (1988) 389.
[4] H. Krause, J. Theile, R. Dahlbeck, J. Engemann, J. Magn. Magn. Mater. 95 (1991) 95.
[5] A.N. Grigorenko, S.A. Mishin, E.G. Rudashevskii, Fiz. Tver. Tela 30 (1988) 2948.
[6] A. Magni, G. Vértesy, Phys. Rev. B, in press.
[7] M. Mikami, K. Suzuki, H. Makino, J. Crystal Growth 49 (1980) 381.
[8] G. Vértesy, I. Tomáš, L. Pust, J. Paces, J. Appl. Phys. 71 (1992) 3462.
[9] G. Vértesy, I. Tomáš, J. Appl. Phys. 77 (1995) 6426.
[10] J. Kadlecová, K. Metlov, I. Tomáš, G. Vértesy, J. Phys. IV 8 (1998) 307.
[11] G. Vértesy, M. Pardavi-Horváth, I. Tomáš, L. Pust, J. Appl. Phys. 63 (1988) 1694.
[12] G. Bertotti, Hysteresis in Magnetism, Academic Press, New York, 1998.