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DETERMINATION OF MAGNETIC PROPERTIES IN (111) ORIENTED MAGNETIC GARNET FILMS WITH THE TORQUE METHOD

M. D. Guo, J. Z. Feng and L. Y. Jiang

Shanghai Institute of Metallurgy, Academia Sinica, 865 Chang Ning Road, Shanghai 200050, China

Abstract. — The torque curve analysis of a (111) magnetic garnet film is described. In this way, it is possible to obtain simultaneously magnetic properties the magnetization \( M_s \), the cubic anisotropy \( K_1 \) and the uniaxial anisotropy \( K_u \) from only one torque curve by the simple experiment and calculation.

Introduction

It is well known that the torque \( (L) \) — magnetic field \( (H) \) date can be recorded using a sensitive torque magnetometer. Some torque measurements and analytical methods for the four magnetic films iron, nickel, cobalt and permalloy were reported. Similar measurement has been used to the garnet films \([I]\), but all of the methods have a basic supposition in which the torque only depends the magnetization \( M_s \) and the uniaxial anisotropy \( K_u \) of the films.

In fact, the structure of the garnet is cubic. The garnet films exhibit the combination of the cubic magnetocrystalline and uniaxial anisotropy. For \( K_1 < 0 \) the easy direction of magnetization is \((111)\) and for \( K_1 > 0 \) it is \((100)\) if the higher order term magnetocrystalline anisotropies can be ignored. In general only the first order anisotropy \( K_1 \) and uniaxial anisotropy \( K_u \) are given consideration. Measurement of the anisotropies of the magnetic garnet films is usually carried out from ferromagnetic resonance (FMR) technique and torque method. However, the magnetization \( M_s \) can not be obtained in FMR \([2]\) since \( K_u \) term and \( M_s \) term have the same angular form. In the present paper, a new torque method is described. We report on torque curve analysis for (111) magnetic films to determine the magnetic properties \( M_s \), \( K_u \) and \( K_1 \).

Torque curve analysis

Consider a discoid (111) oriented garnet sample (see Fig. 1). If the external magnetic field is high enough, the film will become a single domain state. When the saturant magnetization \( M_s \) is rotated in the same plane. In this case the directions of the magnetic field \( H \) and magnetization \( M_s \) with reference to \((111)\) are defined by angles \( \theta_H \) and \( \theta \), respectively.

The total energy density \( E_T \) per unit volume can be written as

\[
E_T = -M_sH \cos(\theta_H - \theta) + 2\pi M_s^2 \cos^2 \theta + K_u \sin^2 \theta + K_1 \left( \sin^4 \theta / 4 + \sin^4 \theta / 3 + \sqrt{2} \sin^3 \theta \cos \theta / 3 \right) \text{ (1)}
\]

where the first term is the Zeeman energy density, the second corresponds to the demagnetizing energy density, the third and forth are due to the energy densities of the uniaxial and cubic anisotropy.

In the equilibrium condition the torque per unit volume is obtained by setting \( \partial E_T / \partial \theta = 0 \). It is particular convenient by taking \( \theta_H = \pm \pi / 4 \). The result is found by the relations

\[
L = M_sH \sin \alpha \text{ (2a)}
\]

\[
L = (K_u - 2\pi M_s^2) \cos 2\alpha - K_1 P(\alpha) \text{ (2b)}
\]

where \( P(\alpha) = \cos 2\alpha / 12 + 7 \sin 4\alpha / 24 - \sqrt{2} (\sin 2\alpha + \cos 4\alpha) / 6 \), angle \( \alpha \) between \( M_s \) and \( H \) is the equilibrium orientation of \( M_s \). It shows that the two torque curves merge into one when the magnetic fields are in the two specific positions.

In order to solve equations (2a) and (2b), the least square fitting has been used. A computer program has been made to determine the combination of \( M_s \), \( K_u \) and \( K_1 \). It is based on the following procedure.

Putting a \( M_s \) value to calculate \( \alpha_i \) corresponding to \( (L_i, H_i) \) value through equation (2a), with the least square fitting method \( K_u \) and \( K_1 \), then \( L_i^{\text{calc}} \) values can be calculated through equation (2b). Setting the error \( E = \frac{1}{n} \sum_{i=1}^{n} (L_i^{\text{calc}} - L_i^{\text{exp}})^2 \) and finding \( E_{\text{min}} \), the best fitting combination of \( M_s \), \( K_u \) and \( K_1 \) is determined.

Fig. 1. — Coordinate system for (111) film. \( H \) is applied in (111).

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Experiment and results

Magnetic garnet films CaGe:YIG grown on (111) - oriented substrates of Gd₃Ga₅O₁₂ by the LPE method. The torque curves of 1 cm diameter disc cut from the as-grown sample were recorded with a sensitive torque magnetometer in applied field up to 25 kOe. The normal of the sample was along the torque magnetometer axis. The magnetic field direction was π / 2 from the [110] direction and ±π / 4 from the [111] direction of the sample. The two L·H curves can be perfect coincidence, otherwise the sample misalignment should be corrected.

Miyakini et al. [3] have developed standard method for the simultaneous measurements of $M_s$ and $K_u$. Following the analysis, an example of $(L/H)^2$ versus $L$ plot of experimental date of a CaGe:YIG film for θ$_H$ = π / 4 is shown figure 2. We can not find a simple linear relation. It clearly shows that the cubic magnetocrystalline anisotropy of the garnet film should be taken into consideration.

![Figure 2](image.png)

Fig. 2. – A plot of $(L/H)^2$ versus $L$ for a CaGe:YIG film.

By using the above mentioned analysis, the fitting material parameters of $K_u$ and $K_1$ corresponding to $M_s$ is found from ten groups of experimental values $(L,H)^{\text{exp}}$. In figure 3 the error $E$ is obtained as a function of $M_s$. Figure 3 also shows the calculated plot for $K_u$ and $K_1$. The best fitting magnetic properties of $M_s$ = 14.9 G, $K_u$ = 11 000 erg/cm$^3$ and $K_1$ = −3 400 erg/cm$^3$ can be determined as E is minimized.

![Figure 3](image.png)

Fig. 3. – $K_u$, $K_1$ and error $E$ as a function of $M_s$. The best combination $(M_s, K_u$ and $K_1)$ is determined, which gives smallest $E$.

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