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FMR studies of $\text{Y}_3\text{Fe}_5\text{O}_{12}/\text{Gd}_3\text{Ga}_5\text{O}_{12}$ (YIG/GGG) superlattices and YIG thin films

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Abstract

We have employed ferromagnetic resonance to obtain magnetic anisotropy information in a series of YIG/GGG superlattices and a single YIG thin film with temperature variations. The Curie temperature of these samples increases with the YIG layer thickness, reaching saturation beyond a specific YIG thickness. As temperature rises, the magnitude of the calculated magnetocrystalline anisotropy constant decreases while the uniaxial anisotropy constant exhibits growing behavior. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The study of thin film type and superlattices of ferromagnetic materials, either metallic or oxide is of interest from both the fundamental and the technological points of view. Many efforts have been devoted to investigating the dimensionality effects, anisotropy, interfacial properties, and giant magnetoresistance (GMR), etc. in these materials (for a review see [1]). When the constituent magnetic layers in the superlattices become very thin, many interesting phenomena take place due to the new low-dimensional magnetic interactions. In general, most ferromagnetic thin films, independent of their methods of preparation, show uniaxial magnetic anisotropy [2]. The anisotropy energy arises due to various causes (imperfections, stress induced magnetostriction, etc.). According to the macroscopic symmetry, the anisotropy energy can be

classified and experimentally observed with respect to some specific axis [3,4].

Although superlattices of magnetic oxides are less studied compared to metallic superlattices, their importance in the role of technological applications can not be ignored. Iron garnets are a large class of ferro-magnetic oxides with wide applications in magnetic-optical and memory devices [5]. In this study, ferromagnetic yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, YIG), and paramagnetic gadolinium gallium garnet ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$, GGG) are chosen because of their very small lattice mismatch, and therefore the energy associated with magnetostriction can be neglected. High quality ultrathin superlattices of alternating YIG and GGG are made by pulsed laser deposition (PLD) and their anisotropy property is studied by ferromagnetic resonance (FMR) [6,7]. Magnetic thin film samples deposited on specific substrates have their characteristic anisotropy constants [8]. The dependence of anisotropy constants on temperature and film structure results in a characteristic FMR feature. The results are discussed in terms of the combined effects of magnetocrystalline and uniaxial anisotropy.

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2. Samples and FMR measurements

The superlattices were deposited onto GGG(111) substrates by PLD at 650°C in a 200 mTorr oxygen atmosphere using an ArF (193 nm, 23 ns pulse length) excimer laser with energy of 200 mJ per pulse and a fluence of 2 J m^{-2} at the target. Details of the sample preparation were stated elsewhere [6]. The deposited film thickness was calibrated by grazing angle X-ray reflectivity (GAXR) measurements. A series of superlattices was made with the YIG layer thickness varied from one unit cell to six unit cells, i.e. $[\text{YIG}(n)/\text{GGG}(1)]_m$, where $n = 1-4$, and 6; and m is the number of bilayers. A single YIG film of 29 unit-cell layer thickness was also made.

We carried out FMR measurements at 9.48 GHz on the samples using the Bruker EMX system from 110 to above 500 K. The experiments were performed with the DC applied field H fixed in one direction and the sample rotated such that the plane of the film was varied from an orientation (φ) parallel to the field ($\varphi = 0^\circ$) to perpendicular to the field ($\varphi = 90^\circ$). The resonance frequencies of uniform precession for the perpendicular and parallel configurations are given by [6]

$$\frac{\omega}{\gamma} = H_{\perp} + \frac{2K_u}{M_s} - 4\pi M_s - \frac{4}{3} \frac{K_1}{M_s},$$

$$\left(\frac{\omega}{\gamma}\right)^2 = \left\{ H_0 \left(H_0 - \frac{2K_u}{M_s} + 4\pi M_s - \frac{K_1}{M_s} \right) - 2 \left(\frac{K_1}{M_s} \right)^2 \cos^2 3\alpha \right\},$$

where γ , M_s , α , K_1 , and K_u are the gyromagnetic ratio, saturation magnetization, in-plane azimuthal angle (measured from the $[11\bar{2}]$ azimuth), magnetocrystalline anisotropy constant, and uniaxial anisotropy constant. H_0 and $H_{\perp}$ are the resonance fields at $\varphi = 0^\circ$ and $\varphi = 90^\circ$, respectively.

3. Results and discussion

The first-derivative FMR spectra of all samples show a main resonance signal resulting from the ferromagnetic YIG layers. The resonance field (H_{res}) increases as φ is varied from 0° , reaching a maximum value at $\varphi = 90^\circ$, and decreasing to its original value as φ is set to 180° . H_{res} versus temperature for both parallel ($\varphi = 0^\circ$) and perpendicular ($\varphi = 90^\circ$) configurations is plotted in Fig. 1 for $[\text{YIG}(6)/\text{GGG}(1)]_4$. In all these samples, the perpendicular resonance field ($H_{\perp}$) decreases with increasing temperature, whereas the parallel field (H_0) evolves the opposite way. The two field curves bend toward each other and are expected to coincide near Curie temperature. The extrapolated Curie tem-

Fig. 1. The FMR resonance field (H_{res}) versus temperature for both parallel and perpendicular configurations for the $[\text{YIG}(6)/\text{GGG}(1)]_4$ multilayer sample.

Table 1

The Curie temperature (T_C), the calculated magnetocrystalline and uniaxial anisotropy constants (K_1 and K_u) at 300 K, and the cross-over temperature (T_0) of uniaxial anisotropy constant for the YIG/GGG samples

	T_C (K)	$T = 300 \text{ K}$		T_0 (K)
		K_1 (erg cm $^{-3}$)	K_u (erg cm $^{-3}$)	
$[\text{YIG}(1)/\text{GGG}(1)]_{12}$	433	−1500	−9600	405
$[\text{YIG}(2)/\text{GGG}(1)]_6$	525	−3500	−21500	420
$[\text{YIG}(3)/\text{GGG}(1)]_8$	547	−5000	−18900	420
$[\text{YIG}(4)/\text{GGG}(1)]_6$	540	−6200	−15400	387
$[\text{YIG}(6)/\text{GGG}(1)]_4$	538	−7800	−8300	340
YIG(29)	526	−9800	−1300	344

peratures are consistent with the SQUID measurements and are listed in Table 1. As expected, the Curie temperature of these samples increases with the YIG layer thickness, reaching saturation when the YIG unit-cell layer number is beyond three.

Assuming that the g factor is equal to 2, and $\gamma = 1.76 \times 10^7 \text{ s}^{-1} \text{ Oe}^{-1}$ [5], from the resonance measurements we calculate K_1 and K_u for the six films, and the results are also listed in Table 1 for temperature $T = 300 \text{ K}$. Except for $[\text{YIG}(1)/\text{GGG}(1)]_{12}$, the magnitude of the negative K_u is roughly proportional to the inverse of the YIG layer thickness, implying that the origin of the negative K_u comes from the interface. K_1 and K_u versus temperature for $[\text{YIG}(6)/\text{GGG}(1)]_4$ are plotted in Fig. 2. The magnitude of the negative K_1 decreases with increasing temperature, approaching zero near Curie temperature as the magnetocrystalline anisotropy ceases to be effective. K_u , however, crosses

Fig. 2. The calculated magnetocrystalline anisotropy (K_1) and uniaxial anisotropy (K_u) constants versus temperature for the [YIG(6)/GGG(1)]₄ sample.

over from negative to positive values at a temperature ranging from 340 to 420 K for different samples. The origin of this change of sign and continuing growth behavior is not yet clear to us. We have included the cross-over temperatures (T_0) for the six samples in Table 1. Except for the first sample, T_0 is higher for those with thinner YIG layers and larger bilayer number, indicating that interfacial anisotropy is more profound in these samples.

4. Conclusion

We have performed FMR measurements on a series of YIG/GGG samples. The variation of resonance field

with temperature is shown to be an effective way of determining Curie temperature, and the Curie temperature of these samples increases with the YIG layer thickness, reaching saturation when the YIG unit-cell layer number is beyond three. As temperature rises, the magnitude of the magnetocrystalline anisotropy constant decreases, while the uniaxial anisotropy constant increases and crosses over from negative to positive values at a temperature ranging from 340 to 420 K for different samples.

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References

- [1] J.C.A. Bland, B. Heinrich (Eds.), *Ultrathin Magnetic Structures I, II*, Springer, New York, 1994.
- [2] U. Gradmann, J. Mueller, *Phys. Stat. Sol.* 27 (1968) 313.
- [3] M.J. Pechan, *J. Appl. Phys.* 64 (1988) 5754.
- [4] J.W. Feng, et al., *J. Magn. Magn. Mater.* 152 (1996) 27.
- [5] A.H. Eschenfelder, *Magnetic Bubble Technology*, Springer, New York, 1981.
- [6] M.Y. Chern, C.C. Fang, J.S. Liaw, J.G. Lin, C.Y. Huang, *Appl. Phys. Lett.* 69 (1996) 854.
- [7] B. Heinrich, J.F. Cochran, *Adv. Phys.* 42 (1993) 523.
- [8] C. Chappert, K. Le Dang, P. Beauvillain, H. Hurdequint, D. Renard, *Phys. Rev. B* 34 (1986) 3192.