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Magnetic Anisotropy and Phase Transitions in Co-Doped Yttrium Iron Garnet Films

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Abstract. YIG:Co,Ca,Ge films grown on (001) plane substrate were investigated down to liquid helium temperatures using torque anisometry technique. Successively lowering temperature spin-reorientational transitions were observed between following easy magnetization axes (EMA) orientations: (i) at room temperature - four EMA inclined to the film plane from [111] directions; (ii) two EMA near the [110] and $[1\bar{1}0]$ directions; (iii) two other EMA near the [100] and [010] directions; (iv) one EMA near the [001] direction at the helium temperature.

The garnet YIG:Co,Ca,Ge films have been intensively investigated at room temperature because of their interesting magnetic and magnetooptical properties [1,2]. Knowledge of temperature dependence of magnetic anisotropy in these samples is very important for understanding of recent results of investigation of photomagnetic effects [3,4] or peculiarities of FMR signal [5,6].

$Y_{3-z}Ca_zFe_{5-x-y}Co_xGe_yO_{12}$ films were grown by liquid phase epitaxy on (001) plane gadolinium gallium garnet GGG substrate. The films were prepared in a form of a disk with diameter of 4mm and thicknesses of 7÷10 μm. The measurements were carried out in the temperature region from liquid helium temperature to room temperature by means of an automatic torquemeter. The period of magnetic field rotation was 6 min. Torque curves were measured in three characteristic planes: (001), (100) and (110) (examples are shown in Fig.1). The contribution of the paramagnetic GGG substrate was determined by measuring the torque as a function of field amplitude. This contribution was numerically subtracted from the total torque.

The analysis of the curves, obtained in this way, displays the orientation of easy magnetization axes. One can distinguish several temperature ranges of different EMA orientation. Four axes EMA_{111} (inclined from the [111]-type directions to the sample plane) were found (Fig.1A) at the room temperature. One of these axes can be described by the angles $54.7° < \vartheta_{111} < \frac{\pi}{2}, \phi_{111} = \frac{\pi}{4}$ (ϑ, ϕ are polar and azimuthal angles measured in the x, y, z co-ordinate system connected with the standard [100], [010] and [001] crystallographic axis). With decreasing temperature an increase of ϑ_{111} was observed. Lowering of the temperature a transition to the configuration with two easy axes EMA_{110} (near [110] and $[1\bar{1}0]$) took place - see Fig.2. Further lowering of the temperature induced the following EMA configurations: (i) the EMA_{100} oriented near [100] and [010]; (ii) the EMA_{001} near [001]. Temperature range of coexistence of the EMA_{110}, EMA_{100} and EMA_{001} configurations depends on small difference of sample chemical composition. Only the EMA_{001} configuration was observed at the helium temperature.

The EMA reorientation could be discussed in the simple case, taking into consideration K_{c1}, K_u - first constants describing cubic and uniaxial anisotropy. For different values of these constants, different EMA orientation could be found out, as follow:

(1) EMA_{001} $K_{c1}<0$; $K_u/|K_{c1}|<-0.5$ $\{\vartheta_{001}=0\}$;

(2) EMA_{111} $-0.5<K_u/|K_{c1}|<1$ $\{\vartheta_{111} = \arcsin\sqrt{\frac{2}{3}(1-\frac{K_u}{|K_{c1}|})};\ \phi_{111} = \frac{\pi}{4}, \frac{3}{4}\pi, \frac{5}{4}\pi, \frac{7}{4}\pi\}$;

(3) EMA_{110} $1<K_u/|K_{c1}|$ $\{\vartheta_{110} = \frac{\pi}{2};\ \phi_{110} = \frac{\pi}{4}, \frac{3}{4}\pi, \frac{5}{4}\pi, \frac{7}{4}\pi\}$;

(4) EMA_{001} $K_{c1}>0$; $K_u/K_{c1}<1$ $\{\vartheta_{001}=0\}$;

(5) EMA_{100} $-1<K_u/K_{c1}$ $\{\vartheta_{100} = \frac{\pi}{2};\ \phi_{100} = 0, \frac{\pi}{2}\}$

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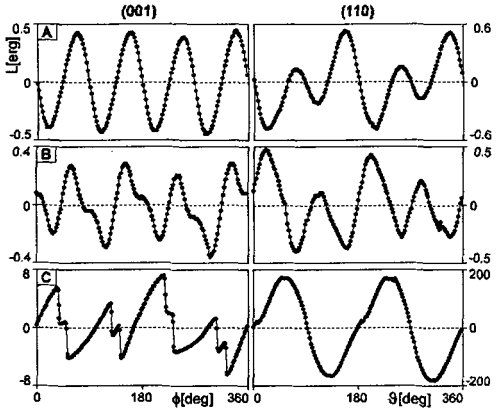

Figure 1: Exemplary torque curves measured for two planes (001) and (110) at the temperature T: (A) 290 K; (B) 140 K; (C) 10 K. H=10 kOe external magnetic field was applied.

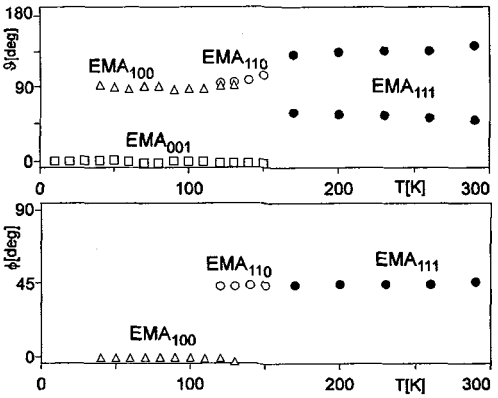

Figure 2: Diagram of easy magnetization axis orientation versus temperature.

Using this simple model we cannot explain the coexistence of EMA_{110} and EMA_{001} configurations even taking into account K_{c2} [7]. Three cubic anisotropy and two uniaxial anisotropy constants were used for description of low temperature torque curves measured in our samples [8].

At room temperature the first cubic anisotropy constant fulfills the relation $K_{c1} < K_{c1\_YIG} < 0$, where K_{c1_YIG} is first anisotropy constant measured for pure YIG sample [9]. Huge contribution to cubic anisotropy was reported [9] for Co_o^{2+} and Co_t^{3+} ions in the octahedral and tetrahedral positions, respectively. At room temperature Co_t^{3+} ions contribution to cubic anisotropy is larger than Co_o^{2+} one. However, for decreasing temperature one can expect [9] a stronger contribution of Co_o^{2+}. The $EMA_{111} \rightarrow EMA_{110}$ transition may be explained assuming an increase of the ratio $K_u / |K_{c1}|$ connected with an increasing contribution of Co_o^{2+} to the cubic anisotropy. The transition $EMA_{110} \rightarrow EMA_{100}$, EMA_{001} can be also connected with Co_o^{2+} ions, for which [110] is the hard magnetization axis [10].

Lowering temperature the increase of ϑ_{111} angle and the transition $EMA_{111} \rightarrow EMA_{110}$ could be also deduced analyzing hysteresis loops, which were measured using magnetooptical set-up [11]. The observed deviation of the measured ϑ_{110} from the theoretically predicted $\pi/2$ may be explained assuming a deviation of the [001] axis from the film normal. Such deviation is also the reason for the asymmetry observed in hysteresis loops, self biasing effect [1].

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