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Manifestations of the effects of a "weak" sublattice in an YIG film with the replacement of yttrium by Gd ions

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Abstract. Ferrite-garnet films of submicron thickness were investigated by ferromagnetic resonance method and by the autodyne oscillator method. Compensation of the magnetization of such a film is detected on the curve of its temperature dependence, which is associated with the inclusion of gadolinium ions from the gadolinium-gallium garnet substrate in its composition. It was found that the magnetization of the sample in perpendicular to the surface of the film magnetic field showed an abnormal change in the magnetization and also rotation of the magnetic axis. This behaviour of a ferromagnetic material in the presence of a magnetic field can be explained by the expressions for the linear magnetostrictive effect, and the piezomagnetic effect arising from the para-processes operating within a “weak” rare-earth magnetic sublattice which is located inside a unidirectional exchange field of “strong” iron sublattice.

1. Introduction

Gadolinium ferrite-garnet shows the unique characteristic of unidirectional anisotropy of the exchange interaction, which influences the “weak” gadolinium sublattice. It is shown [1] that the presence of the 'weak' sublattice in rare-earth ferrite-garnets leads to manifestation of abnormal phenomena. In particular, in gadolinium ferrite-garnet a breach of magnetostriction “evennies” and also magnetoresistance and magnetocaloric effect are observed. Magnetostriction shows linear dependence of magnetization due to the influence of unidirectional exchange anisotropy. To the linear magnetostriction is associated a thermodynamically opposite effect, namely piezomagntetism (the occurrence of the magnetization under the action of elastic stresses in the absence of a magnetic field). The occurrence of these phenomena is solely attributed to the paraprocess [1]. For yttrium iron garnet, which is far from the point of magnetic ordering, magnetostriction is a quadratic function of the magnetization. The aim of the present study was to detect piezomagnetic and other related effects given rise to by the presence of a 'weak' sublattice in ferrite.

2. Samples

The samples were synthesized by the two-crucible liquid-phase epitaxy technique from wetting melt-solution [7] on (111)-oriented substrate of gadolinium-gallium garnet. In the first crucible containing a superheated melt-solution of yttrium iron garnet (YIG), overgrazing (dissolution) of the upper layer of the substrate forms so that the various surface defects can be gotten rid of. Then the substrate, which spent almost the entire time in the hot zone, was transferred to second pot. During the transfer time of the substrate a submicron YIG type thin film grows from the remaining on it solution-melt of YIG and partially etched and dissolved substrate. In second pot was grown a uniaxial film with the required thickness for bubbles magnetic domain devices. Both these and earlier investigations [5,6] were conducted on this film of submicron thickness, which was grown on the substrate during the transfer time of it from the first crucible to another. The width of ferrimagnetic resonance (FMR) line for these films was ~30-40 Oe, while that for pure YIG was ≤ 0.5 Oe. The saturation magnetization for these films was 1250 Gs, while that for YIG was 1760 Gs. The film thickness was in the range 0.1- 0.2 μm, and the cubic anisotropy field was ~36 Oe.

It is known [4] that if impurity ions are present in the rare-earth sublattice the width of the FMR line of pure YIG increases. In this case, such impurity ions are magnetic gadolinium cations, which have diffused from the dissolved substrate (non-magnetic gallium ions dilute iron sublattice) [8]. Increased width of the line by nearly two orders of magnitude and decreased magnetization of the sample indicate a significant concentration of these ions. Thus, the total magnetization of the films arises due not only to the “iron” sublattice, but also to “weak”

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(yttrium diluted by gadolinium) sublattice. Therefore, unusual phenomena may occur in them.

3. Experiment

The details pertaining to the FMR apparatus that was used to carry out studies on the thin films are given in [4,5]. Experiments were performed at the ambient temperature. Figure 1 shows the frequency-field dependence of the fundamental mode of the FMR for the negative (H-) and positive (H+) external magnetic fields that are normal to the surface of the film (Higher-order modes, detected for this sample in [6], were not generated in this experiment).

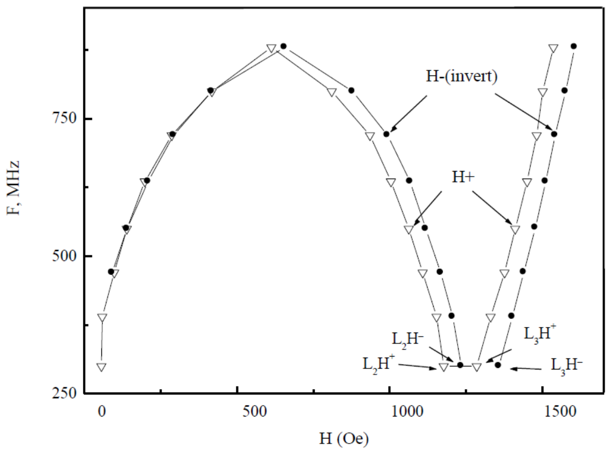

Fig.1. Experimental frequency-field dependence of FMR lines. The field is perpendicular to the surface of the film. (Dependence with a negative field is inverted to the positive axis).

The frequency-field dependence with a negative field is inverted to the positive axis H and is shown as curve H-(invert) in Fig. 1. Figure 1 shows that both for the negative and positive directions of the field the plots of frequency vs. field start from the zero value of the field, and with increasing absolute value of the field, the curves gradually diverge from each other to the field of orientation of the magnetization along the external field, which is ~1250 Oe. (In zero field the magnetization lies almost on the plane of the film due to the demagnetizing energy). Such behavior of the curves can be explained by the change in the demagnetizing field during the magnetization of the sample.

With increasing field along one direction, the demagnetizing energy grows greater, and in another increases less. Upon the sample reaching to the maximum in magnetization, the change of the demagnetizing energy is terminated. Thus, for one direction of the field, normal to the plane of the film, the saturation magnetization increased, while it decreased for the opposite direction.

Let us estimate the magnitude of change of magnetization in order to evaluate the differences in frequency-field dependence shown in Fig. 1. The difference is found to be 36 Oe near the saturation point. This means that for a change of magnetization of 1.43 Gs the demagnetizing field changes to 18 Oe along each direction.

In the next experiment, the external magnetic field was allowed to subtend an angle (θ) of 1 degree with the normal to the surface of the film. Consider the behavior of two FMR lines at a field strength that is closer to saturation at a frequency of 300 MHz and is dependent on the azimuthal angle, φ, lying on the surface of the film. This line is L2H-in the negative field up to the saturation point; and after the saturation point it changes to $L3H^-$, whose position in the frequency-field space (Fig. 1) is indicated by arrows. In the positive field, lines $L2H^+$ and $L3H^+$ correspond to this behavior.

Since the field is tilted from the normal, which is represented by a diagonal of a cubic crystal in a single-crystal film, i.e. the direction of type {111}, then at the azimuthal sample rotation, the cubic magnetic anisotropy is due to the presence of the other three diagonals (one of the methods for determining the cubic anisotropy [3]). For a given geometry and experimental conditions, the explanation for cubic magnetic anisotropy is as follows: during rotation of the sample and passing of the magnetic moment near one of the three edges of the cube, the distance between the FMR lines reaches its the maximum. At a distance from the edges, they approach and disappear. This fact is illustrated in Fig. 2, which shows the dependence of the derivatives of the absorption lines on the magnetic field for a number of azimuthal angles close to the direction {112}, which is representative of the projection of both the diagonal and the edge of the cube on the plane of the film [3].

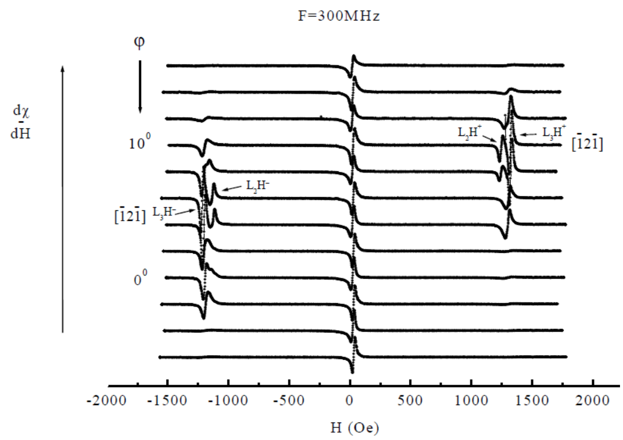

Fig. 2. Variation of the derivative of magnetic susceptibility with quasinormal external ($\theta_H = 1$ degree) field for a range of azimuthal angles (φ_H) separated by an interval of 2 degrees. (F = 300 MHz and T= Ambient).

By rotating the azimuthal angle to 360 degrees, there are three such ranges of FMR line appearing at a distance of 120 degrees from one another. One of them is shown in Fig. 2. From this figure it follows that if we define the direction of the crystallographic axes in accordance with the FMR spectra, they are dependent on the direction of the field. This difference is about 4 degrees.

Consequently, there is an effect, which depends on the magnetic field, which changes the magnetization of the sample apart from rotating the magnetic axis.

To determine the form of the dependence of the saturation magnetization on temperature and the search for the compensation point, measurements of the values of the normal field of the transferring film to the saturation state were made for different temperatures. Such measurements were made to supplement and confirm the results and conclusions [6]. The measurements were performed from the records of the change in the magnetic susceptibility of the sample at a frequency of 5 MHz using the autodyne oscillator method [9]. The recording of the signal of absorption of high-frequency energy in a film with an increase in the normal field by an acute maximum (minimum in the inset in Fig. 3) fixes its transition to the saturation state. Such records were made for a sequence of stabilized temperatures. The obtained dependence (Fig. 3) on the temperature of the measured values of the transition field to the saturation magnetization has an acute deep minimum at a temperature of 57 °C. By recording the high-frequency energy absorption signal in such a film, as a function of temperature, the Neel point is determined to be 248 °C. The detected minimum is determined by the corresponding magnetic compensation point. Its appearance is due to the entry of gadolinium ions from the GGG substrate into a thin transition layer between the substrate and the YIG film and the formation of a mixed yttrium-gadolinium iron garnet in which a compensation point is possible. The magnetization of a very thin YIG film does not overlap this minimum by its monotonic decrease in magnetization with increasing temperature.

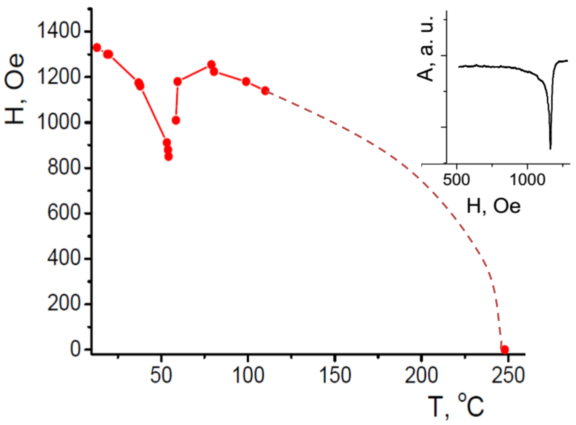

Fig. 3. Temperature dependence of the measured values of the transition field of the film to the saturation state.

4. Discussion

Based on the concepts developed in [1], the features observed during a study on the film using the FMR method can be explained as follows. The technique of fabrication of the ferromagnetic film involves a rare-earth sublattice incorporating ions of gadolinium (magnetic) and yttrium (nonmagnetic) with the iron sublattice being diluted with gallium ions. The exchange interaction between gadolinium ions at room temperature is so weak that it does not lead to their ordering. ("weak" sublattice). Their ordering occurs due to influence of strong (about 200 kOe) negative exchange field from the iron sublattice (paraprocess). The interaction of the rare-earth sublattice with iron is weak. This unidirectional exchange interaction leads to a linear rather than a quadratic dependence of magnetostriction on magnetization. Consequently, when the sample is magnetized in a direction that is parallel to the field, it gets elongated, while it gets compressed when it is aligned in a direction that is perpendicular to the field. As the symmetry analysis shows, the accounting of the linear magnetostrictive effect and piezomagnetic effect under cubic symmetry [1,8], in a coordinate system with the axis [111] along the normal leads to the appearance of non-diagonal components in the strain tensor. In turn, this may lead not only to the anisotropic stretching of the sample (without changing its volume), but also to a purely mechanical torsion of crystallographic axes. Moreover, with respect to the applied external field, this effect also shows unidirectionality. Since thermodynamically it is the opposite effect, piezomagnetism corresponds to the linear magnetostriction. Such deformation of the sample in a magnetic field causes an increase in magnetization due to tension and a decrease in it due to compression and also to the rotation of the magnetic axes by twisting. Thus, as determined from the experiment the change in magnetization and the rotation of the magnetic axes in the magnetic field are interrelated and are defined by the simultaneous manifestation of two effects, namely linear magnetostriction and piezomagnetic effect.

5. Conclusions

A deep minimum was found that marks the compensation point for the magnetization of thin YIG films on the curve of its temperature dependence. The presence of compensation is associated with the entry of gadolinium ions from the GGG substrate into the transition layer between the substrate and the YIG film during liquid-phase epitaxy from the wetting melt - solution of the YIG and from the GGG substrate dissolved in it, which results in the formation of a mixed yttrium-gadolinium iron garnet. The total magnetization of such a film is due to the "iron" and "weak" sublattices with a possible point of its compensation. It has been found that during magnetization in a normal magnetic field of such a film an abnormal change in the magnetization of the sample as well as rotation of the magnetic axes occur: i.e., in the straight (one) field direction the magnetization increases and the axis of the magnetic field rotates to align with it; on the other hand, in the opposite external field direction, magnetization decreases and the axis rotates to align with it in the opposite direction. This ferromagnetic behavior in a magnetic field can be explained by the simultaneous manifestation of the linear magnetostriction and the piezomagneticeffect that operate due to the paraprocess in a “weak” magnetic sublattice, wich is located in a unidirectional exchange field of the “strong” sublattice.

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