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Optical studies of magneto-electric interactions in yttrium-iron-garnet films

V.E.Koronovskyy, Y.A.Vakyla

Department of Radiophysics, Electronics and Computer Systems, Taras Shevchenko National University of Kyiv, 4-g Prospekt Glushkova Str., 03127 Kyiv, Ukraine

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Magneto-optical properties of epitaxial single-crystalline yttrium-iron-garnet (YIG) films grown on a gadolinium gallium garnet (GGG) substrate are investigated in a low frequency alternating electric field. The magnetoelectric effect, which manifests itself under the combined action of electric and magnetic fields, is revealed. The effect was observed by magneto-optical techniques. The interpretation of the obtained experimental results is given.
Keywords: magneto-electric effect, electric field, magnetic field, domain structure.

Оптичні дослідження магніто-електричних взаємодій у плівках залізо-ітрієвого гранату. *В.Є.Короновський, Ю.О.Вакула*

Досліджувались магнітооптичні властивості епітаксійних монокристалічних плівок залізо-ітрієвого гранату (ЗІГ), вирощених на гадоліній-галієвому гранаті (ГГГ), у низькочастотному електричному полі змінного струму. Виявлено магнітоелектричний ефект, який проявляється при підключені зовнішніх електричного та магнітного полів. Ефект досліджували з використанням магнітооптичних методів. Дано інтерпретацію отриманих експериментальних результатів.

1. Introduction

Among the many magnetic materials in which optical phenomena induced by a magnetic or electric field are possible, thin films occupy a special place. This is due to the wide possibilities of their technological application [1]. As we know, an external magnetic field applied to a magnetic crystal induces in it the Faraday effect or other optical phenomena which depends on the direction of the magnetic field. The optical phenomena in some single crystals and epitaxial films induced by an external electric field also are possible [2, 3].

The relationship between magnetic and electric properties in insulating crystals expressed through the magneto-electric (ME) effect. The magneto-electric effect manifests itself through the change of the direction and (or) the magnitude of magnetization by applied electric field (the electric field induced ME effect). The electric polarization can be induced by an external magnetic field (the magnetic field induced ME effect). One of such ME phenomena induced by an electric field is the effect of rotation of the light polarization plane in crystals. This phenomenon is called the electromagnetic-optical effect (EMOE) [4].

ME materials (especially thin films) may be of practical interest. They are interesting as a basis for creating optical devices with two-channel control by electric and magnetic fields. Among the materials in which optical phenomena induced by an electric field have been experimentally observed are yttrium ferrite garnets (YIG) and rare earth ferrite garnets [5]. Crystals of yttrium iron garnets have inversion symmetry, but the symmetry can be violated in thin YIG films. These films are grown on (111) oriented substrates, and in addition to the dominant uniaxial anisotropy nominally normal to the film plane, they can exhibit cubic and orthorhombic magnetic anisotropies as well as tilting of the easy axis. These additional anisotropies can have striking effects on the dependence of the domain structure on the field. The first observations of the ME effect in yttrium iron garnet was reported in [6, 7].

Controlling the properties of magnetic domains and domain walls (DWs) by electric field opens up great opportunities for technological applications such as spintronics and memory devices [8]. There are several hypotheses to explain the mechanism of the ME effect in magnetic DWs of rare-earth iron garnets:

1) inhomogeneous ME interaction (Dzyaloshinskii-Moriya-like interaction);

2) the local decompensation of the antiferroelectric structure in the DWs, associated with the exchange interaction of rare earth ions and iron;

3) the polarization of DWs is explained by the ME effect arising from ferromagnetic interactions between octahedral and tetrahedral Fe ions at the DWs [9].

The aim of this work was to investigate the influence of a low-frequency AC electric field to the magnetization processes in the ferrite garnet epitaxial films with (110) orientations.

2. Experimental

One of the methods for investigation of the ME effects is the method of optical polarimetry. This method allows us not only to register, but also to visualize the optical phenomena induced by an external electric or (and) magnetic fields in the materials. In particular, the method of optical polarimetry makes it possible to register the change in the Faraday rotation of the plane of polarization of light under the action of an electric field applied to the sample. Our experimental setup consists of a combination of a high-sensitive laser polarimeter and a polarizing microscope [10]. The essence of the experimental method is to register electric field-induced changes in the Faraday rotation, α_{EMO}, in crystals (EMO-effect) as a function of the applied static magnetic field. In the experiment, a probing beam of radiation from a He–Ne laser with a wavelength of $\lambda = 0.63$ μm was used. An epitaxial YIG film 8.4 μm thick grown by liquid-phase epitaxy on a $Gd_3Ga_5O_{12}$ substrate with (110) orientation was studied. Experiments were carried out at room temperature in geometry $E \| k$, where k is the wave vector of light. The external static magnetic field was oriented almost along the film plane and its orientation could change relative to the film plane. The sample was placed between the optically transparent electrodes that created an external electric field. One of the optically transparent electrodes was placed above the surface of the garnet film (i.e. the surface of the film free from external mechanical strains) and the other one was located under the film substrate. An external alternating E-field (ω = 750 Hz) and a constant magnetic field could be applied to the film.

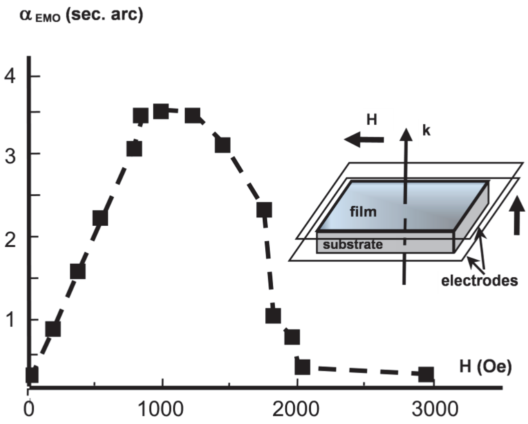

Fig.1. Magnetic-field dependence of α_{EMO} for local site of YIG film, when E = 2,2 kV/mm. The insertion presents the geometry of experiments.

3. Results and discussion

According to the results of our optical measurements, we have already reported [10–13] that the ME effect in local regions of magnetic domains and in multi-domain regions of garnet films was observed in a wide range of magnetic field variations. The investigated yttrium-ferrite-garnet films were deposited on the (111) $Gd_3Ga_5O_{12}$ substrates.

This paper reports the results of the experimental investigation of the ME effect manifestations in the iron garnet films with the (110) substrate orientation. The electric field-induced changes in the Faraday rotation in a garnet film (α_{EMO}) as a function of an applied static magnetic field are shown in Fig. 1. As can be clearly seen from the dependence on the magnetic field, an increase in the H-field led to a significant increase in the EMO signal even at weak fields. In this case, the orientation of the external magnetic field was chosen in such

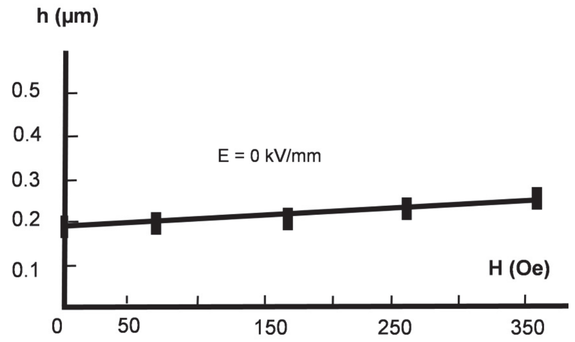

Fig.2. Approximate dependence of a DW width (h) of the local straight segment DW from magnetic field value.

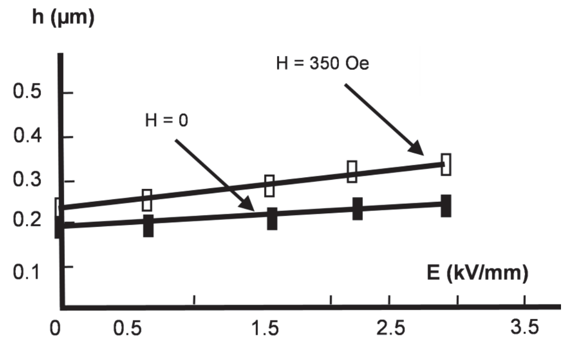

Fig.3. Approximate dependences of a DW width (h) of the local straight segment DW from electric field value

a way that the magneto-optical Faraday effect was close to zero (H-field was oriented at an angle $\alpha \sim 14°$ to the film plane). I.e., the orientation of the magnetic field in this case was perpendicular to the easy magnetization axis of the film.

In the range of changes in the H-field from about 800 to 1200 Oe, the effect reaches its maximum values and has an insignificant instability in the change in the value of α_{EMO}. Starting approximately from $H = 1200$ Oe, we registered a sharp non-uniform decrease in the α_{EMO} values.

The direct visual observation of the domain structure using a polarizing microscope under such experimental conditions showed a clearly observed reaction of domain structure on these external influences. Even with a relatively weak applied magnetic field, one could visually observe the loss of contrast by the domain structure of the film.

Fig. 2 shows the results of our observations of the local rectilinear section of the change in the DW width in a magnetic field at the initial stage of the magnetization process ($E = 0$). In this case, we limited the range of variation of the magnetic field to the limiting values at which there is still no significant loss of contrast in the domain structure of the film. Fig. 3 presents the results of our observations of the local rectilinear segment in the DW width which varies in an electric field at the above magnetic field values. The local region of the DW was chosen in an arbitrary way.

We can see from Fig. 2 and Fig. 3 that a width of the selected segment of the DW varies in both magnetic and electric fields. At the same time, we can see from Fig. 1 that in the given range of the magnetic field variation, a near-linear growth of the α_{EMT} signal is observed.

The results of our studies of ME interactions under the combined action of two factors, an alternating electric field and a permanent magnetic field, can be explained as follows. In our experiments, we measured the Faraday rotation angle of the light polarization plane. When scanning local regions of the domain structure of the YIG film, the Faraday angle of rotation is sensitive both to the magnetization in these regions and to the internal magnetic field averaged over local values, which depends on local demagnetizing fields. The magnitude of the magnetization in an electric field practically does not change. This can be seen from our experimental results: the values of αEMT in the magnetic saturation region of the film are close to zero. That is, changes in α_{EMT} in an electric field are determined by changes in local demagnetizing fields, the sources of which can be not only DWs (in the domain phase), but also various local inhomogeneities of the domain structure of the films. In particular, demagnetizing fields also exist in places of a sharp change in the magnetization vector near defects [14], where the direction of magnetization can differ significantly from the crystallographic direction of easy magnetization.

As we mentioned in a previous article [10], an external electric field can change the parameters of the magnetic anisotropy of thin YIG films. The reason for the induced magnetic anisotropy in epitaxial films is the specific local arrangement of ions (or vacancies, interstitial atoms, etc.) in the crystal lattice [14]. Induced anisotropy stabilizes any arbitrary spatial distribution of magnetization in the sample, regardless of whether it is uniform or non-uniform.

An external electric field changes the parameters of the magnetic anisotropy and, therefore, violates the mentioned stabilization. The domain structure of the film is very sensitive to the symmetry of the magnetic anisotropy. Its changes lead to a change in the local values of the demagnetization fields, which in turn leads to a change in the value of the Faraday rotation angle of the light polarization plane, which we registered (Fig. 1).

Here, it is important to recall the conditions of our experiments. In this paper, we discuss the experimental conditions under which the magnetization of a film in a magnetic field (of the corresponding orientation) occurs due to the rotation of the magnetization vector. That is, there is no movement of the DW in magnetic field. If the electric field changes the magnetic anisotropy of the film, the DW can react accordingly to these changes. In particular, the observed effect of changing the DW width (Fig. 3) in the YIG film is due both to the corresponding orientation of the magnetic and electric fields, and to the film itself, grown on a substrate with the (110) crystallographic orientation. As already mentioned, the easy axis of magnetization of the film is inclined with respect to the normal to the film surface. This causes the existence of weak rhombic anisotropy and the appearance of an easy axis in the film plane [14]. In this case, the magnetization vector in the domain wall goes beyond the film plane. The electric field changes the parameters of the magnetic anisotropy of the film, which leads to the reaction of domain walls, as the element of the domain structure that is most sensitive to such changes.

It should be taken into account the instability of the DW profile of epitaxial films can manifest itself differently on its surface with a change in the E-field strength. This is due to the fact, that the parameters of the near-surface layers of epitaxial films at the boundaries with the substrate and with the free space differ significantly [15]. Thin transition layers appear at the film-substrate and the film-free space interfaces. The parameters of these layers (in particular, he values of the uniaxial anisotropy constant) differ significantly from the parameters of the internal volume of the film and, accordingly, magnetization processes under an external field can occur in different ways. Probably, this is one of the reasons why we detected small fluctuations in the value of αEMT during magnetization in the domain phase of the film (Fig. 1). In addition, local fluctuations in the direction of magnetization within domains (from the region of optical probing) can cause variations in the value of αEMO. They are due to structural inhomogeneities and associated changes in the exchange, crystallographic, and magnetoelastic energies.

4. Conclusion

Thus, our results demonstrate the possibility of the influence of an alternating electric field on the magnetization processes in YIG films. The discussed ME effect is actually determine by changes in the parameters of the magnetic anisotropy of the garnet film in an external electric field. In this case, the main mechanism of the ME effect in garnet films under the considered experimental conditions of two-factor action is an additional rotation of magnetization due to an external electric field, caused by a change in the anisotropy energy.

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