Some properties of pulsed remagnetization and relaxation in iron garnet films

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A number of new dynamic processes in multilayered single-crystal films of iron garnets grown on (111)-oriented $Gd_3Ga_5O_{12}$ were investigated by high-speed electron-optics photography. It was found that nonuniform rotation of the magnetization vectors can begin in fields that are lower by almost an order of magnitude than the effective uniaxial anisotropy field. It was shown that multilayered ion garnet films can be used to visualize features in the potential distribution due to the effective cubic anisotropy fields. Relaxation processes occurring in iron garnet films after a magnetic-field pulse were examined in detail for the first time. It was found that, in a uniform external field, the relaxation process is, in many ways, similar to direct pulsed remagnetization of a specimen. In particular, both cases involve nonuniform rotation of the magnetization vectors, accompanied by the formation of a magnetic-moment flip wave which transforms into a triangular magnetic domain (TMD). The shape and orientation of the TMD depend on the uniform bias field. Both during the field pulse and afterwards , a "twisting" of the TMD was observed for particular external field strengths. This twisting depends on the orientation of the pulsed field. It is shown that a process close to uniform rotation of the magnetization vectors occurs in the course of relaxation in one or several layers of the specimen.

1. INTRODUCTION

Until now, the dynamics of domain structures in single-crystal magnets, including films of iron garnets, have usually been examined experimentally in a pulsed magnetic field H_p produced by flat single-layer coils. The magnetic field acting on the sample is then irrotational and axially symmetric, which has an important effect on pulsed remagnetization processes in the materials under investigation because of the nonuniform rotation of the magnetization vectors.[1–4] Experiments on the dynamics of domain structures in iron garnet films grown on the (111) plane have revealed that this type of configuration of H_p leads to the formation of a magnetic-moment flip wave (MMFW),[2] which, under certain definite conditions, transforms into a triangular magnetic domain (TMD).[3] The TMD may be formed layer by layer and its orientation is strictly related to the projections of the cubic anisotropy axes onto the plane of the film.[4] Studies of nonuniform rotation in iron garnet films with the minimum possible damping have revealed the excitation of "magnetic vortices" which were interpreted as Rossby solitons.[5] Experiments especially designed to study relaxation processes in magnetic films have not so far been performed, although the dynamics of domain structures after the pulsed fields H_p was studied in Refs. 1, 5, and 6.

This brief review shows that many of the properties of nonuniform rotation of magnetization vectors have evidently not been adequately studied. There is undoubted interest in experimental studies of relaxation processes in single-crystal iron garnet films and in the effect of the layered structure of the specimens on the process of pulsed remagnetization. Such studies have revealed a number of new physical phenomena which are discussed qualitatively in the present paper.

2. EXPERIMENTAL PROCEDURE

Dynamic processes in epitaxial iron garnet films grown on (111)-oriented $Gd_3Ga_5O_{12}$ substrates have been investigated by high-speed electron-optics photography with temporal and spatial resolution of ~ 8 ns and $\sim 0.3\ \mu$m, respectively. A more detailed description of the experimental setup is given in Ref. 1. In its initial state, the specimen was located in a constant bias field H_b parallel to the normal to the film. The bias field could be varied from 0 to 400 Oe. A pulsed magnetic field H_p antiparallel to H_b was produced by a single-layer flat coil with an internal diameter of about 1.3 mm. The dynamic domain configurations were recorded at different times τ_l and τ_t, measured from the midpoint of the leading and trailing edges of H_p. The pulsed field strength was varied between 0 and 5500 Oe. The leading and trailing edges of the field pulse occurred before 25 ns and 30 ns, respectively.

The results reported below were obtained for an iron garnet film of the form $(BiTm)_3(FeGa)_5O_{12}$ of thickness $h \simeq 7.5\ \mu$m. The saturation magnetization was $4\pi M_s \simeq 236$ G, the collapse field of cylindric magnetic domains (CMD) was $H_0 \simeq 131$ Oe, the period of banded domains was $P_0 \simeq 12.6\ \mu$m, and the uniaxial anisotropy field was $H_a \simeq 600$ Oe.

3. EXPERIMENTAL RESULTS AND DISCUSSION

We have carried out an experimental study of nonuniform rotation of the magnetization vectors in multilayered single-crystal films of iron garnets in the presence and absence of a pulsed field. Particular attention was devoted to nonuniform rotation in a uniform external field H_b, i.e., after H_p was shut off. As a rule, the experiments were performed with totally crossed polarizer and analyzer.

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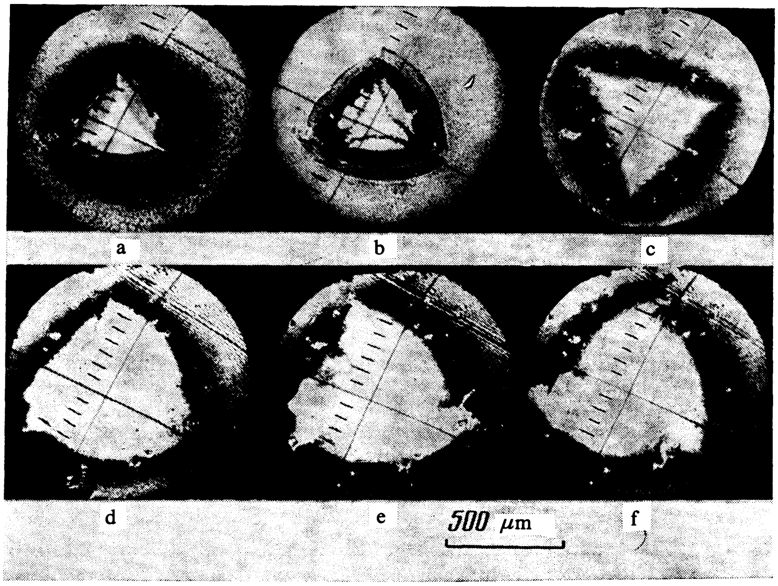

FIG. 1. Typical dynamic domain configurations observed during pulsed remagnetization of iron garnet film and during the relaxation of a local magnetization region (LMR) produced by a magnetic-field pulse; a—pulsed remagnetization, $H_b = 190$ Oe, $H_p = 240$ Oe; delay of light pulse relative to the leading edge of the field pulse $\tau_l = 50$ ns (H_p directed into the substrate); b—same as a but with $H_b = 160$ Oe, $\tau_l = 60$ ns; c—relaxation of the LMR at time τ_t measured from the midpoint of the trailing edge of H_p: $H_b = 350$ Oe, $H_p = 1600$ Oe, $\tau_t = 75$ ns (H_p directed toward the substrate); d—same as c but with $H_b = 0$, $H_p = 1200$ Oe, $\tau_t = 60$ ns (H_p directed along the outward normal to the film); e—same as c but with $H_p = 1600$ Oe, $\tau_t = 170$ ns; f—same as c but with H_p pointing toward the substrate.

Dynamics of domain structures in the presence of the pulsed field

Let us consider the new phenomena in domain-structure dynamics that were discovered in our experiments on direct pulsed remagnetization of iron garnet films, i.e., in the presence of H_p. We have already shown[1-4] that nonuniform rotation of magnetization vectors is possible only when the magnetic field $\Delta H = H_p - H_b$ acting on the sample exceeds the effective uniaxial anisotropy field H_k^*. In the first approximation, this field can be defined by

$$H_k^* = H_a - 4\pi M_s.$$

Our subsequent experiments showed that this statement was invalid for a number of specimens. For example (see Figs. 1a and b), the nonuniform rotation process may begin in iron garnet films in fields ΔH much lower than H_k^*. Thus, in the specimen described above, for which $H_k^* \simeq 360$ Oe, the MMFW and TMD were observed even for $\Delta H < H_0$. The resulting MMFW led to the formation of a layered TMD, followed by the rapid growth of TMD and of banded domains. We have thus shown experimentally that nonuniform rotation of the magnetization vectors in multilayer iron garnet films can also begin when the magnetic field ΔH acting on the sample is lower by almost an order of magnitude than the effective uniaxial anisotropy field. It is clear from Figs. 1a and b that the TMD observed in such experiments have a number of interesting features. For example, the inner TMD, which probably occurs in a layer with the minimum field H_k^*, has sharp corners, whereas the outer TMD has much smoother outlines. The bisectors of the angles of the inner sharp-corner TMD are close to the directions of the projections of the cubic anisotropy axes onto the plane of the film (Figs. 2a and b). The small differences between these directions can be due to the influence of a small component with rhombic anisotropy and to the departure of the uniaxial anisotropy axis from the normal to the plane of the film. It is readily seen that the contours of the outer TMD appear to break up along the continuations of the sharp corners of the

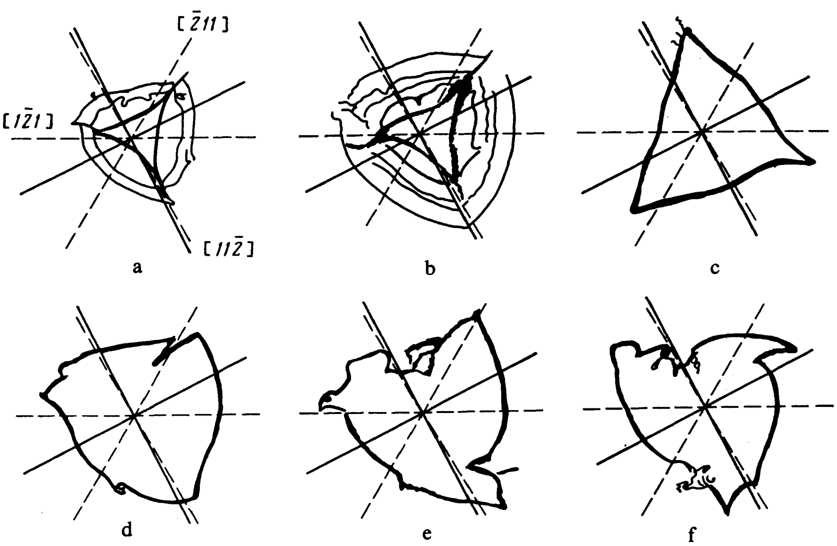

FIG. 2. Orientation of dynamic TMDs relative to easy axes of anisotropy in the plane of the film. The figure also shows the TMD outlines shown of Fig. 1. Broken lines show the projections of the cubic anisotropy axes [1$\bar{2}$1], [$\bar{2}$11], [11$\bar{2}$] onto the plane of the film.

inner TMD. This gives the impression that the outer TMD are "twisted' (see Figs. 1a and b). The direction of this "twist' depends on the orientation of the external fields. For example, when the directions of H_b and H_p are reversed, the twist direction is also reversed. We emphasize that the directions along which the breaks on the contours of the outer TMD were observed practically coincide with the projections of the cubic anisotropy axes on the plane of the film.

An interesting dynamic domain configuration (cf. Fig. 1b) was recorded for certain ratios of H_b and H_p. Instead of the typical TMD picture, one can clearly see the outline of a sharp-corner TMD similar to that shown in Fig. 1a in one of the layers at the center of the coil, next to the layer with the lowest effective uniaxial anisotropy field and against the background of a still unremagnetized part of the sample. When this unusual formation was examined under high magnification, we found that it consisted of a large number of fine CMDs in one of the layers of the sample. Their appearance is probably connected with the fact that, under certain definite conditions, the effective magnetic fields in the iron garnet film produce a complex potential distribution in which it is energetically more convenient for localized CMDs to evolve along certain directions in one or more layers. The effective cubic anisotropy fields then have a controlling influence on the formation of the observed domain structure.

The fact that, in many iron garnet films, nonuniform rotation of the magnetization vectors can begin in magnetic fields ΔH that are substantially lower than the effective uniaxial anisotropy field H_k^* can be explained qualitatively as follows. At present, the methods used to investigate magnetic anisotropy yield only the uniaxial anisotropy field integrated over the thickness of the specimen (cf., for example, Ref. 7). Naturally, real iron garnet films contain a sufficient number of layers with both very different and very similar integrated parameters. Moreover, multilayer iron garnet film may contain layers with effective anisotropy fields that are substantially smaller than the integrated field H_a. Such layers may be the initiators of the nonuniform rotation process. Since magnetic moments in neighboring layers are coupled by exchange interaction forces, it follows that the uniform rotation process that has begun in one of the layers, can propagate to neighboring layers. In all probability, this process was observed in our experiments. Although the nature of this phenomenon is not entirely clear at present, nevertheless, the fact that the nonuniform rotation process can begin in relatively weak magnetic fields will undoubtedly find extensive practical application.

Relaxation processes in iron garnet films after the field pulse

Let us now consider the relaxation of a local magnetization region (LMR) produced by the flat single-layer coil. In the initial state, the specimen is located in the uniform field H_b, but then a pulse of the magnetic field H_p completely remagnetizes a piece of the film bounded by the pulse-generating coil. The LMR is a region magnetized in the direction antiparallel to H_b. It has a "quasi-Néel" domain wall which lies under the turns of the coil and is due to the configuration of the field H_p. At the end of the field pulse, the nonequilibrium magnetic structure is in an unstable state in the uniform bias field, and relaxes to the stable state determined by H_b. If the inner diameter of the coil producing the pulse is much greater than the width of the turns, the LMR may be looked upon in the first approximation as a macroscopic CMD with quasi-Neel domain wall, produced artificially by the external field. We have examined the relaxation of the LMR produced by pulsed fields H_p of different orientation and strength.

Relaxation processes in the absence of external fields. Let us consider the relaxation of an LMR in the absence of the uniform external bias field ($H_b = 0$; cf. Figs. 1d, e, f). For $H_p < H_0$, the CMD remaining at the end of the field pulse at the center of the coil begin to grow rapidly. This is accompanied by the well-known process of sample magnetization due to the motion of the domain walls. Since $H_b = 0$, the effective field acting on the sample is $\Delta H = H_p$. The most interesting and novel phenomena are observed for $H_p > H_0$. As H_p increases up to the critical value $H_p \simeq 1100$ Oe, the continuous formation and growth of domains on defects occur in the course of the relaxation process. As H_p increases, this process becomes increasingly turbulent, and direct visualization of an increasing number of defects becomes possible. However, when $H_p \simeq 1100$ Oe, there is a radical change in the dynamic picture. Nonuniform rotation begins during the relaxation process near the coil turns, and the MMFW resembling the wave observed during the field pulse is formed (see Fig. 1d). The MMFW is then transformed into the "twisting" TMD whose orientation is similar to that of the TMD observed during the direct remagnetization process (see Figs. 2a and d). As H_p increases, the TMD produced during the relaxation process becomes more twisted (see Figs. 1d and e) and somewhat smaller. However, in contrast to the direct process, the dimensions of the TMD change only slightly, and there is an increasing distortion of its shape with increasing H_p. This is probably due to the fact that, as H_p increases, the formation of a TMD extending right through the specimen becomes energetically less and less convenient, so that the shape of the TMD becomes increasingly transformed under the influence of defects.

The TMD is no longer formed from $H_p \approx 1800$ Oe onward, and the relaxation process proceeds as a result of nonuniform rotation (rapid propagation of the MMFW) in one or several layers of the film. The MMFW is not then axially symmetric and its shape resembles a triangle. It is relatively readily visualized only near the turns of the coil. On the other hand, in the central portion of the coil, the observed process is similar to uniform rotation of the magnetization vectors because, in this region, the magnetic moments rotate practically simultaneously. This can be judged by inspecting the rapid darkening of the region of the sample investigated. An increase in H_p ensures that the relaxation MMFW becomes increasingly more diffuse because the nonuniform rotation process occurs over a large area. As a result, a continuous variation of the magnetic moment integrated over the thickness of the film is observed simultaneously over a large area of the sample. Remagnetization by nonuniform rotation of one or more layers of the sample during the relaxation process is followed with some delay by the rapid growth of banded domains and CMDs over the entire area of the film bounded by the coil. We note that this delay increases somewhat with increasing H_p.

Further increase in H_p does not produce a substantial change in the picture of the relaxation processes. Their distinctive feature is the absence of the "layered" TMD, characteristic for the direct magnetization of the multilayer sample, although the layered nature of the sample does have an essential effect on the nonuniform rotation process. The basic properties of the relaxation process as a whole are found to remain unchanged as the direction of the external field H_p is varied, with the important difference that the direction of twist of the TMD is reversed (see Figs. 1e and f).

In our experiments, there are no external fields acting on the sample after the end of H_p. Nevertheless, the magnetic system behaves during the relaxation process approximately as if it were located in an axisymmetric irrotational pulsed field. It is important to note, however, that the nonuniform rotation begins during the relaxation process after the end of the field pulse of strength exceeding by an order of magnitude the threshold field ΔH for the onset of nonuniform rotation in the presence of H_p. It would appear that this unusual phenomenon can be explained as follows. In a strong pulsed field ($H_p > H_a$), the magnetic moments in the iron garnet film should follow the configuration of the field produced by the coil. When H_p shuts off, they are in a state that is unstable in the absence of H_p. Consequently, the nonequilibrium LMR contains stored energy which must be dissipated during the relaxation process. Under certain definite conditions, this energy is probably sufficient to produce the MMFW and TMD in one or more layers. This is supported by the fact that the TMD was produced during the relaxation process only near the turns of the pulse-generating coil where, by virtue of the configuration of the H_p, the deviation of the magnetic moments from the uniaxial anisotropy axis is greater than that at the center of the coil. Naturally, in this region and under the coil turns, the energy density stored in the nonequilibrium magnetic system is substantially greater than at the center of the LMR, and this is responsible for the formation of the MMFW and TMD in this particular region.

Experiments have shown that direct remagnetization (for $H_b > H_0$) and relaxation (for $H_b = 0$) are accompanied by the twisting of the TMD corners, the direction of the twist depending on the orientation of the external magnetic field. We note that the directions of twist of the TMD corners are different for direct remagnetization and for relaxation after the end of H_p (see Figs. 1a, b, and d–f). At present, the nature of this phenomena is not clear to us. We can only suggest that detailed examination of the forces acting on the magnetic moments should lead to the correct explanation of the observed phenomenon.

Relaxation processes in a uniform bias field. Let us now consider some of the properties of LMR relaxation in the presence of the bias field, but confine our attention to those cases where the region can be looked upon as a single-domain region at the end of the H_p pulse. An increase in H_b produces a substantial change in the LMR relaxation process described above for $H_b = 0$. There is a sharp change in the shape of the relaxation TMD and, for $H_b \simeq 10$ Oe, we can no longer be certain that we are observing strictly oriented TMD against a background of the complex domain structure formed on defects. Nothing resembling the TMD is observed for fields H_b up to approximately 40 Oe. However, for $H_b \simeq 40$ Oe, we can again visualize the TMD, oriented as for $H_b = 0$, in one of the sample layers. The characteristic feature of this TMD is the presence of regions at its corners, which run through the entire thickness of the sample. These regions vanish as H_p increases further and, for H_b between ≈ 90 Oe and ≈ 140 Oe, the TMD cannot be visualized again.

Beginning with $H_b \approx 140$ Oe, an MMFW of triangular shape is excited again during the LMR relaxation time. However, its orientation is opposite to that observed previously (cf. Figs. 1c and 2c). Further increase in H_b ensures that the MMFW is transformed into a regular sharp-cornered untwisted TMD in one of several layers (cf. Fig. 1c). It is clear from Figs. 1 and 2 that this TMD is practically a mirror reflection of the TMD observed in the presence of the pulsed field H_p. The special feature of the TMDs that appears for bias fields $H_b \simeq 140$ Oe is their very short lifetime (~ 10–20 ns). High-contrast regular TMD shapes are then produced only in a relatively narrow range of external fields ($H_b \gtrsim 300$ Oe, $H_p \simeq 1500$–2000 Oe). Low-contrast TMD with diffuse sides or triangular MMFW with practically unaltered orientations are observed for $H_b > 140$ Oe and $H_p \gtrsim 1500$ Oe. Under certain definite conditions (in particular, for $H_b \sim 250$ Oe), one can observe at the center of a TMD formed in one of the layers the outlines of a TMD analogous to those shown in Fig. 1b, but with a much lower contrast.

When the directions of H_b and H_p are reversed, the overall picture of the relaxation processes and the TMD orientation are found to remain unaltered. It is thus quite clear that the cubic anistropy of the sample has an essential effect on the dynamics of the main structures, both when the field pulse is on and when it is off. The essential feature of relaxation processes in a uniform external field is that MMFW or TMD running right through the thickness of the sample were not observed in any of the fields that we have used ($H_b > 40$ Oe, $H_p > 1100$ Oe). Since magnetic moments in neighboring layers are coupled to one another by the exchange interaction, it follows that, after magnetization in fields $H_b > H_0$, nonuniform rotation in one of the layers produces a process close to uniform rotation in neighboring layers. When the polaroids are accurately crossed, the image of the interior of the coil becomes much darker and then brightens up again. The time occupied by this process depends on the fields H_b and H_p and, as a rule, does not exceed 100 ns.

4. CONCLUSION

Our basic results can be summarized as follows.

Nonuniform rotation of magnetization vectors in multilayer iron garnet films can begin in magnetic fields ΔH acting on the sample that are lower by an order of magnitude than the effective uniaxial anisotropy field H_k^*. This phenomenon is probably connected with the presence in the specimen of one or more layers with effective anisotropy fields much lower than H_k^*. Studies of the dynamics of the main structures in multilayered iron garnet films have demonstrated the possibility of visualizing the spatial distribution of the potential associated with the effective cubic anisotropy fields.

Relaxation processes occuring in iron garnet films after the field pulse is over have been examined in detail for the first time. We have shown that, in the absence of external fields, nonuniform rotation of magnetization vectors begins after a field pulse exceeding ΔH by more than an order of magnitude. The formation of MMFW and TMD is possible just as in the presence of the field H_p. We have found that, both in the presence of H_p and during the subsequent relaxation, the TMD tends to have twisted corners, the direction of twist being a function of the orientation of the external magnetic fields. We note that, after the H_p pulse is over the TMD is not observed simultaneously in different layers. We have shown that something akin to uniform rotation of magnetization vectors is observed during the relaxation process over the large sample area bounded by the pulse-generating coil. We have thus demonstrated that many of the features characteristic for direct pulsed remagnetization are observed during LMR relaxation in the absence of external fields.

Relaxation processes occurring in a uniform bias field have a number of properties. In relatively low bias fields H_b (between ~ 40 Oe and ~ 90 Oe), a TMD oriented in the same way as for $H_b = 0$ is observed in one of the layers. However, in strong external fields ($H_b \gtrsim 140$ Oe), there is a radical change in the picture of relaxation processes. The twisting of the TMD corners is then almost completely absent, and the TMD itself is practically the mirror image of the TMD observed in the presence of the field pulse. A process similar to uniform rotation of the magnetization vectors was clearly observed both in the presence and absence of the uniform field.

We note in conclusion that, in many ways, the nature of the observed phenomena is still unclear, and further experimental and theoretical studies will be necessary. Nevertheless, the experimental demonstration of the new features in the dynamics of domain structures may well find extensive application in microelectronics, including, in particular, magnetooptical devices for different applications.

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