Formation of stripe antiferromagnetic domains in a Ca–Mn–Ge garnet in a region of interference of orthogonally polarized light beams

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(Submitted 17 August 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **56**, No. 7, 360–363 (10 October 1992)

A stripe structure of time-reversed domains has been formed in an antiferromagnetic crystal lacking an anti-inversion center. Specifically, the structure was formed when a magnetic field was applied to a single-domain platelet of the garnet $Ca_3Mn_2Ge_3O_{12}$ in the optical interference field formed by two coherent, orthogonally polarized light beams. The effect of the polarized light on the magnetization reversal of this antiferromagnetic Ca–Mn–Ge garnet is attributed to light-induced charge-transfer processes involving the magnetic ions of some magnetic sublattices or others of the crystal. The particular ions which are selected depend on the polarization of the light.

Of particular interest among the various types of antiferromagnetic (AFM) domains are the collinear AFM domains (180° or time-reversed domains) and the AFM′ domains, for which the magnetic moments of ions in equivalent crystallographic sites are in opposite directions.[1,2] In an AFM, there are no magnetic mechanisms to stabilize the domain structure, and the stability of the structure is determined exclusively by the coercivity of the domain walls. In all AFMs of the Shubnikov classes, except those which are described by gray magnetic point groups, there is the possibility of arranging a small energy nonequivalence of the AFM and AFM′ states by combining two physical agents. For AFM crystals which are not symmetric under anti-inversion, i.e., under the operation of inverting the spatial coordinates and reversing the time, suitable agents might be a magnetic field and linearly polarized light. We were interested in experimentally investigating the possibility of using these agents to alter the formation of an AFM domain structure and to determine, in particular, whether it is possible to produce an AFM domain structure of a given configuration.

In the AFM crystal of the garnet $Ca_3Mn_2Ge_3O_{12}$, there is a birefringence for linearly polarized light. This birefringence is linear in the magnetic field strength. It changes sign when the crystal undergoes a transition from the AFM state to the AFM′ state.[3] In this case the symmetry thus also allows the inverse effect: a static magnetic moment induced by the field of a linearly polarized light wave. This inverse linear magnetooptic effect can be described by the phenomenological expression

$$m_i=\Lambda_{ijk}(E_jE_k^*+E_jE_k^*)I. \qquad (1)$$

Here I is the light intensity, E_j and E_k are the projections of the Jones vector which determines the polarization of the light, and Λ_{ijk} are the components of the axial

c-tensor, which are related to the components of the tensor of the linear magnetooptic effect. The components Λ_{ijk} have different signs for the AFM and AFM′ states. The appearance, according to (1), of oppositely directed magnetic moments in the AFM and AFM's domains when illuminated with linearly polarized light renders the AFM domains nonequivalent from the energy standpoint in a magnetic field.

In measurements of effects of light, the induced moment which is expected to arise is too small to have any significant effect on the magnetization reversal. During slow relaxation of optically induced states, however, favorable conditions may arise, i.e., conditions which promote a buildup of the light-induced magnetization. Such a situation is expected in the Ca–Mn–Ge garnet, in which a long-lived linear birefringence is observed to be induced by linearly polarized light.[4] The birefringence which arises may be due to a transfer of charge either from Mn^{3+} ions to trapping centers (which could be the Mn^{4+} ions which are usually present in this crystal) or from other impurity ions to Mn^{3+} ions. The same processes should disrupt the cancellation of the magnetic moments of the sublattices after the AFM ordering of the crystal. The direction of the resultant magnetic moment which arises should be determined by the directions of the sublattice magnetic moments and by the polarization of the light. The relaxation time of the light-induced magnetization should be on the same order of magnitude as the relaxation time of the photoinduced birefringence. At low temperatures, the latter time is much longer than the duration of the experiments. Again in this case, the appearance of a moment under the influence of light should be described by an expression like (1).

The experimental procedure was as follows. A twinned platelet of a $Ca_3Mn_2Ge_3O_{12}$ crystal about 90 μm thick, cut perpendicular to the C_4 axis ($\| Z$) and mechanically and chemically polished, was positioned on a cold conductor in a system of mutually orthogonal solenoids. By varying the currents through these solenoids independently, we were able to produce a field of any orientation in a plane passing through a tetragonal axis of the crystal. The sample temperature was held below $T_N = 13.5$ K, specifically, near 5K. The AFM domain structure was observed by means of the linear magnetooptic effect in a longitudinal magnetic field, by a technique like that which has been used[5] to observe domains in AFM cobalt fluoride. To put the sample in a single domain, we made use of the magnetization quadratic in the magnetic field.[6,7] The sample was magnetized in an oblique field with a strength above a certain threshold (about 24 kOe under the experimental conditions at $T = 5$ K).

After the uniform AFM state was produced, the sample was exposed to the interference field of two linearly and orthogonally polarized coherent light beams with identical intensities of about 0.1 W/Cm^2. The beam axes lay in a plane normal to the sample, symmetric with respect to this normal. The largest angle (2θ) between these axes was approximately 4°. In the beam interference region, the polarization of the light varied in a spatially periodic manner. The direction and strength of the magnetic moment induced in the sample by the light should also have varied periodically. Under these experimental conditions, the light beams were polarized along the [100] $\| X$ and [010] $\| Y$ directions. The change in the z projection of the light-induced magnetic moment along the line of intersection of the plane of incidence of the light with the plane of the platelet should be described by

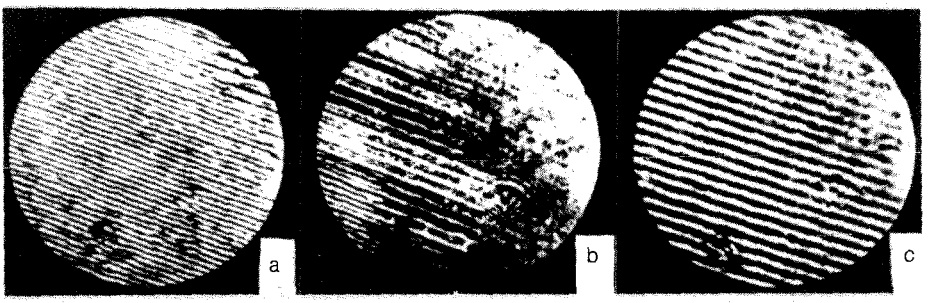

FIG. 1. Formation of a stripe structure of 180° antiferromagnetic domains in a Ca–Mn–Ge garnet platelet in the interference field of two linearly and orthogonally polarized light beams. The sample temperature was 5 K. a: Relief of the photoinduced birefringence established in the sample. A linear polarizer crossed with a linear analyzer was used for the observations. The narrow dark stripes are images of regions of the sample which were illuminated by light with an approximately circular polarization. The axes of the optical scattering function in the bright stripes are orthogonal and parallel to the [110] and [1$\bar{1}$0] directions. b: Appearance of antiferromagnetic domains in the illuminated sample in a magnetic field $H=\{H_\perp \approx 1$ kOe, $H_z=24$ kOe$\}$. The original antiferromagnetic state in the sample was uniform. c: Stripe antiferromagnetic domain structure which formed in the case $H=\{H_\perp \approx 1$ kOe, $H_z=24.2$ kOe$\}$. The period of the stripe structure is about 9 μm.

$$m_z = \pm m_{z0}\cos[4\pi\lambda^{-1}\xi\sin\theta + (\delta_1 - \delta_2)], \qquad (2)$$

where $(\delta_1-\delta_2)$ is the initial phase difference between the light beams, λ is the wavelength of the light, and ξ is the coordinate.

Figure 1b shows the results of the experiment. Frame *a* shows the birefringence relief established in the single-domain sample as visualized with a linear polarizer. A magnetic field in the direction opposite that used to put the sample in a single-domain state was applied to switch the AFM state of the sample. In the sample illuminated in the manner described above, the magnetization reversal of the AFM state, AFM→AFM′, occurred in a nonuniform way. At first, the reversal occurred in only those stripes of the sample which were illuminated by linearly polarized light with $E\|$ [110]. The reversal of the stripe regions began in a field just below the threshold field for the switching of the sample. It was possible to see an abrupt increase in the stripe domains as the structure became established (Fig. 1b). Increasing the field by several hundred oersteds resulted in the formation of a well-defined stripe domain structure (Fig. 1c).

After the induced optical anisotropy (of the periodic birefringent background) was erased by circularly polarized light, the sample looked uniform in the absence of a field, but the stripe structure of the AFM domains remained, invisible in the absence of a field. This structure was visualized, as usual, during observation of the AFM domains after the application of a magnetic field. Only a further increase in the field, to a point several hundred oersteds above the threshold, or a heating of the sample above the Néel point annihilated the domain structure. After the domains were destroyed and the entire procedure repeated, it was again possible to produce a stripe AFM domain structure. The period of the structure could be varied by varying the

angle between the light beams. In the particular geometry of these experiments, it was possible to produce structures with a period of about 9 μm.

The light-induced additional nonequivalence of the AFM and AFM′ states in a magnetic field as outlined above may not be the sole reason why the threshold field for the AFM→AFM′ switching depends on illumination with linearly polarized light. Such a dependence may also stem from a change in the field for the nucleation of a more favorable AFM state in the illuminated regions, as the result of a light-induced redistribution of local deviations from AFM order near photoactive centers and the formation of new nucleation centers, or as the result of a partial annihilation of existing centers—depending on the orientation of the light polarization axis.

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Translated by D. Parsons