Photoinduced low-frequency magnetic permeability of silicon-doped yttrium iron garnet

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The photomagnetic properties of yttrium iron garnet—photoinduced change of the magnetic permeability and of the parameters of the magnetic-hysteresis loop—depend strongly on the amplitude of the low-frequency magnetization-reversing field H_m used to measure the photosensitive characteristic. At low values of H_m the permeability of the material exposed to light at 77 K experiences a gigantic Barkhausen jump. This photoinduced jump is accompanied by an unstable equilibrium of the domain structure. A state characterized by a constant permeability and a hysteresis-free magnetization cycle was observed in the illuminated sample. At large values of H_m, a photoinduced increase of the total permeability μ_t is observed. It is shown that the increase of μ_t by the illumination is due to harmonics of higher order.

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The photomagnetic properties first observed in the conducting yttrium iron garnet (YIG)[1,2] were subsequently found in a number of magnetic semiconductors.[3-5] The conducting YIG remains apparently to this day the principal object of photomagnetism research. New regularities of the photoinduced magnetic effects (PIME) were observed recently in this substance.[6-8]

We report here an experimental investigation of singularities observed in the photoinduced magnetic permeability of YIG and due to differences in the effect of light on the total magnetic permeability as a function of the amplitude of the low-frequency field acting on the investigated object.

1. EXPERIMENTAL PROCEDURE

Most investigations of photoinduced changes in the magnetic permeability (PICMP) performed to data[2,6,9] pertain as a rule to the initial permeability. These measurements were made with the aid of an alternating signal of maximum amplitude in the absence of a constant magnetic field ($H=0$). The permeability measured in this manner is indeed close to its initial value

$$\mu_H = \lim_{\Delta H \to 0} \frac{\Delta B}{\Delta H}\bigg|_{H=0} = \frac{dB}{dH}\bigg|_{H=0}.$$

We investigated the total, or maximum, permeability defined in analogy with the initial one ($H=0$) but at arbitrary amplitudes of the alternating signal: $\mu_t = (B_m)_{\text{eff}}/H_m$, where B_m and H_m are the maximum values of the dynamic magnetic induction and magnetic-field intensity. In addition, we investigated the differential permeability ($\mu_{\text{dif}} = \mu_t(H_m \to 0)$) in the presence of a constant magnetizing field ($H \neq 0$) as well as the parameters of the magnetic hysteresis loop.

The investigated substance was single-crystal YIG doped with silicon, with composition $Y_3Fe_{4.96}Si_{0.04}O_{12}$. Two windings were placed on the toroidal samples. H_m was determined by measuring the signal of the primary winding, which had a harmonic variation $H = H_m \sin\omega t$ with various amplitudes $H_m = 0$ to 4 Oe. The signal frequency ranged from 50 Hz to 50 kHz. The value of B_m is proportional to the emf $\mathscr{E}_{\text{II}}$ of the secondary winding, which varies, by virtue of the nonlinearity of $B(H)$, anharmonically. The effective value $(\mathscr{E}_{\text{II}})_{\text{eff}}$ was measured with VZ-6 broadband vacuum-tube voltmeter. The experimental setup has made it also possible to measure, using a U2-6 narrow-band amplifier or an S4-12 spectrum analyzer, the harmonic components of the total permeability. The dynamics of the permeability variation was recorded with a KSP-4 automatic plotter.

In the measurements of the hysteresis-loop parameters the signal from the secondary winding was fed through an integrating network to an oscilloscope. A signal proportional to H_m from the primary windings was applied to the other pair of deflecting plates of the oscilloscope.

All the measurements were made at liquid-nitrogen temperature. The light source was an incandescent lamp producing an illumination of 2×10^3 lux at the sample location.

2. EXPERIMENTAL RESULTS

A. Total and differential permeabilities

At amplitudes $H_m \lesssim 0.6$ Oe of the magnetic fields produced by alternating current in the primary winding, a gigantic Barkhausen jump appears on the plot of the total magnetic permeability $\mu_t(t)$ against the illumination time (Fig. 1). The time of the jump depends on the field amplitude: the larger H_m (but not more than 0.6 Oe for the given sample), the longer the lag of the jump behind the application of the light.

The photoinduced jump is preceded by a region of unstable state of the permeability (Fig. 1). If the light is turned off during this instability, which is obviously due to the unstable equilibrium of the domain structure, then the oscillations can persist for quite a while. They relax within a time ~0.5 – 3 min towards an increased value of the permeability. On the spectrum-analyzer screen this instability of the domain structure is seen as white noise in the region of the higher harmonics of the permeability. The photoinduced instability is an in-

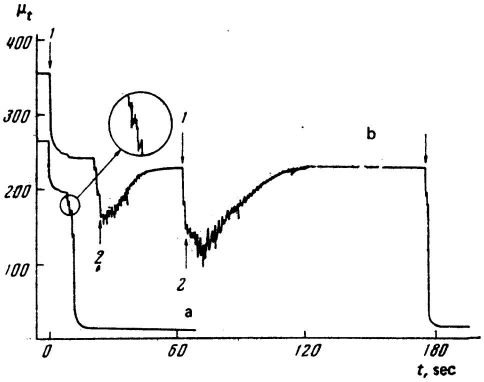

FIG. 1. Time dependence of the total magnetic permeability of single-crystal $Y_3Fe_{4.96}Si_{0.04}O_{12}$ at 77 K: (a) H_m = 0.25 Oe, (b) 0.4 Oe. (1)—light turned on, (2)—off.

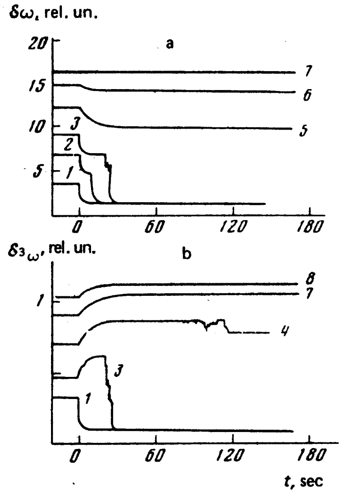

FIG. 3. Dependences of the voltages $\mathcal{E}_\omega$ and $\mathcal{E}_{3\omega}$ proportional to the fundamental (a) and third harmonic (b) of the total magnetization on the illumination time at various values of the magnetic field H_m: 1 – 0.1; 2 – 0.2; 3 – 0.3; 4 – 0.4; 5 – 0.5; 6 – 1.2; 7 – 2.0; 8 – 3.0 Oe. The light is turned on at the instant $t = 0$.

teresting phenomenon and calls for special study.

As seen from Fig. 2, the photoinduced variation of the total permeability depends strongly on the amplitude H_m. The maximum of the effect is observed at optimal values of H_m (at $H_m \lesssim 0.6$ Oe for the given sample). After passing through the maximum, the PICMP, which we shall characterize by the value

$$\Delta\mu = (\mu^d - \mu^l)/\mu^d,$$

(μ^d is the dark permeability and μ^l its value after illumination) decreases strongly with increasing H_m, passes through zero (at $H_m \sim 2.7$ Oe for the given sample), and reverses sign. The increase of the total permeability under the influence of the light, just as the decrease previously observed in YIG at 77 K, is irreversible after the light is turned off. This confirms the non-thermal mechanism of this phenomenon. It will be shown below that the increase of the total permeability by the illumination at large H_m is due to the increased role of the higher harmonics of the permeability.

Figure 3 shows plots of the voltage picked off the secondary winding at the fundamental frequency, $\mathcal{E}_\omega$, and at the third harmonic, $\mathcal{E}_{3\omega}$, against the sample illumination time at various values of H_m. The main significant difference between the plots of $\mathcal{E}_\omega(t)$ and $\mathcal{E}_{3\omega}(t)$ is that at large values of H_m ($\gtrsim 2$ Oe) the value of $\mathcal{E}$ no longer changes under the influence of the light, while $\mathcal{E}_{3\omega}$ remains photosensitive and increases. The effect of the light on the harmonics of higher order (higher than third) is similar to that on the third harmonic.

The effect of light on the differential permeability (Fig. 4) differs from that on the total permeability (Fig. 2). The dark value $\mu^d_{\rm dif}$ as a function of the magnetizing field has a classical behavior with initial and maximum permeabilities $\mu_{\rm init} = 26$ and $\mu_{\rm max} = 50$. The differential permeability $\mu^l_{\rm dif}$ of the sample after illumination for 120 seconds is practically independent of H. This behavior of $\mu^l_{\rm dif}$ is similar to the behavior of μ^l_t at $H_m < (H_m)_{\rm start} = 0.6$ Oe (Fig. 2).

B. Hysteresis loop

Included among the PIME is the photoinduced change of the hysteresis loop, first observed in single-crystal samples of $Y_3Fe_{5-x}Si_xO_{12}$[2] in the form of an influence of light on the coercive force and on the coefficient of rectangularity of the hysteresis loop. The effect of light on the hysteresis loop has been observed also in other materials.[4,5,10]

We have recorded the effect of light on the parameters of the partial symmetrical hysteresis loop such as the coercive force H_c, the rectangularity coefficient $K_{\rm rec} = B_r/B_m$, the hysteresis loss (the area of the hysteresis loop), and the dynamic permeability (Fig. 5). The magnitude and character of the photoinduced changes of the hysteresis-loop parameters and their settling times

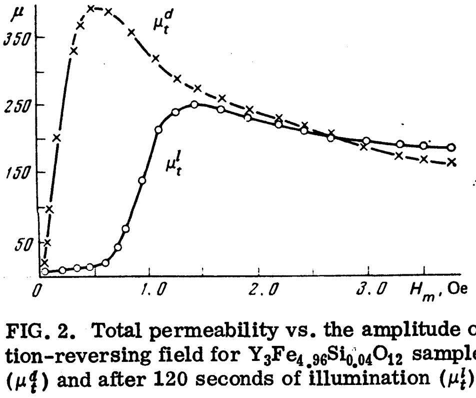

FIG. 2. Total permeability vs. the amplitude of the magnetization-reversing field for $Y_3Fe_{4.96}Si_{0.04}O_{12}$ sample in darkness (μ_t^d) and after 120 seconds of illumination (μ_t^l) at 77 K.

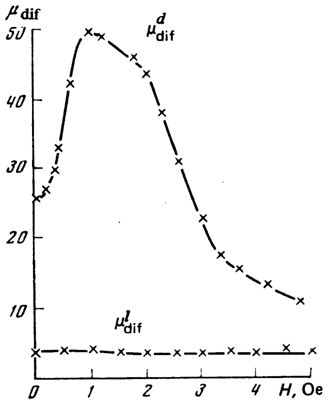

FIG. 4. Differential permeability of $Y_3Fe_{4.96}Si_{0.04}O_{12}$ at 77 K vs. the constant magnetizing field for the sample in darkness ($\mu^d_{\rm dif}$) and after illumination ($\mu^l_{\rm dif}$). $H = H_m \sin\omega t$, $H_m = 0.05$.

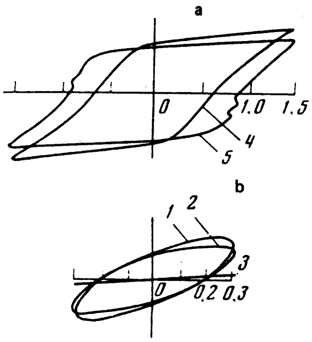

FIG. 5. Magnetization reversal curves $B(H)$ for various amplitudes of the field H_m: *a*—1.5 Oe, *b*—0.3 Oe; Curves 1 and 4 were obtained for a $Y_3Fe_{4.96}Si_{0.04}O_{12}$ sample at 77 K in darkness, 2—after 5 seconds of illumination, 3—20 sec, 5—100 sec.

depend strongly, just as in the case of the permeability, on the amplitude of the magnetization-reversing field H_m (see Fig. 5). At the optimal values of H_m, all the loop parameters undergo photoinduced changes with little time delay. Included among the parameters strongly influenced by the light is in this case the remanent magnetic induction B_r (Fig. 5b). A case when B_r is not photosensitive (the region of non-optimal values of H_m) was apparently observed in preceding studies.[2,7,11]

In the optimal H_m region in which a photoinduced jump of the permeability is observed (Fig. 1), the hysteresis loop experiences a similar jump (Fig. 5b). This jump occurs during the sample illumination and manifests itself in a shrinking of the hysteresis loop to a hysteresis-free magnetization-reversal cycle.

3. DISCUSSION OF EXPERIMENTAL RESULTS

The PICMP singularities observed by us as functions of the amplitude H_m can be attributed to the effect of the light on the domain-wall (DW) pinning (stopping) centers. In the absence of a constant field but in the presence of an alternating one of low amplitude H_m the permeability of the medium is determined by the reaction of the domain walls rather than that of the magnetic moments. In a demagnetized samples the DW are located at minima of the free energy. The potential relief inside the crystal is produced by all kinds of crystal-lattice defects. (The possible nature of defects that act as light-sensitive DW-pinning centers in YIG was considered by us earlier.[9]) Electronic transitions induced by the light produce highly anisotropic DW pinning centers at the expense of the less anisotropic centers. Naturally, the centers of the two types interact differently with the DW. The increased degree of DW pinning manifests itself macroscopically in a decrease of the permeability.

At low temperatures without a perturbing action, the domain walls in the samples may remain in their wells.[12] It is necessary to produce a drawing (starting) field with amplitude $(H_m)_{\text{start}}$ to move the DW out of their traces and make them occupy places in new potential wells (Fig. 6). This transition manifests itself in the form of a photoinduced jump of the magnetic characteristics of the medium (Figs. 1–5).

The decrease of the PICMP with increasing H_m in the region $H_m > (H_m)_{\text{start}}$ can be interpreted in several ways:

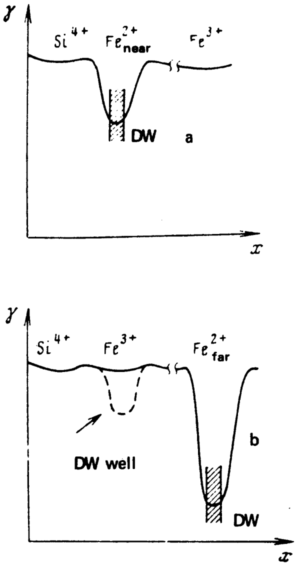

FIG. 6. Change produced in potential relief of silicon-doped YIG crystal by exposure to light, assuming the model with a "near" and "far" site with Fe^{2+} ion: *a*—sample in darkness, *b*—sample after illumination (γ is the free energy).

1) At DW swing amplitudes comparable with the crystal dimensions, the crystal boundaries can serve as the DW pinning centers.

2) The amplitude of the remagnetizing field may be sufficient to take the magnetization of the crystal into a region in which the crystal becomes single-domain (it is known that the main contribution to the PICMP is made by the light via its influence on the DW, and not on the rotation of the magnetic moments).

3) At large swing amplitudes the DW can leave the potential wells (their kinetic energy becomes larger than the potential energy of the defect field). In this free above-the-barrier motion the DW are weakly affected by the potential relief, meaning also by photoinduced changes in it.

The ferromagnet state wherein the permeability remains constant in weak fields and there is now magnetic hysteresis is known in the literature as the "Perminvar effect".[13] This effect is attributed to stabilization of the DW under the influence of the induced magnetic anisotropy. The DW stabilization increases the starting field $(H_m)_{\text{start}}$ at which the DW is released from the potential well.

The permeability of a medium in the Perminvar state remains constant up to a certain starting magnetic field $(H_m)_{\text{start}}$. In fields $H_m > (H_m)_{\text{start}}$ the permeability increases sharply and the hysteresis loop opens up. In fields $H_m < (H_m)_{\text{start}}$ the DW displacements are reversible and there is no hysteresis (the magnetization-reversal cycle reduces to a straight line). All the foregoing pertains to the illuminated sample. In darkness, a YIG sample doped with silicon has no Perminvar effect at 77 K.

The Perminvar effect is present in media in which the induced magnetic anisotropy can compete in magnitude with magnetocrystalline anisotropy. The fact that this effect is observed in the conducting YIG agrees with investigations made by a number of workers,[1,9,14,15] who explain the induced anisotropy in YIG with the aid of a model with four types of Fe^{2+} ion sites. However, primarily on the basis of the concentration dependence of the PICMP, which has an extremal character, we give preference to an explanation of the PICMP with the model using "near" and "far" sites with Fe^{2+} ions,[2,9] a model that takes account also of the stabilization of the DW.

Our results of the investigation of the photoinduced stabilization of the DW agree with the results of Halsma and Robertson,[16] who observed directly the effect of light on the DW mobility and have shown that the DW light stops the motion of the DW in weak alternating magnetic fields. In contrast to the previously observed PICMP, which proceed smoothly without jumps and in which the light influences the properties (mobility) of the DW but does not change the domain structure, the photoinduced jump observed by us should cause also a change in the domain structure of the crystal.

The photoinduced increase of the higher harmonics of the total magnetic permeability, observed here for the first time, cannot be regarded as an obvious consequence of the previously observed photoinduced change in the rectangularity coefficient of the hysteresis loop. There exists a region of small values of H_m in which light decreases both the fundamental and the higher harmonics of μ_t. The photoinduced increase of the contribution of the higher harmonics to the total permeability attests to light-induced distortion of the symmetry of the potential wells and can be taken into account by introducing nonlinear terms in the equation of motion of the DW.

We note that the role of the DW pinning centers can probably be played by magnetic polarons, the possible formation of which under the influence of light was indicated by Belov, Koroleva, and Batorova.[17]

The results are of importance for a more complete understanding of the mechanism of the PICMP and its practical applications. The observed phenomena can be used to investigate the dynamics of domain walls and to analyze the crystal defects that serve as DW pinning centers.

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Nature of the dislocation charge in ZnSe

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A physical model is proposed to explain the experimentally observed anomalously large electric charges of moving dislocations in II–VI semiconductors. The model is based on the idea that broken bonds in the core of a dislocation are filled with electrons from point centers swept through by the dislocation during its motion. The theoretical predictions are compared with the experimental data for ZnSe.

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INTRODUCTION

The presence of electric charges at dislocations has been detected experimentally in many II-VI compounds: ZnS,[1-4] ZnSe,[4] CdS,[5] and CdSe.[4] A surprising feature is the very high linear density q of such charges, reaching one electronic charge per interatomic distance. The following interesting physical phenomena are associated with the motion of such strongly charged dislocations: the photoplastic effect,[6,7] deformation-induced luminescence,[2,8] influence of electrical boundary conditions on plastic deformation processes,[1] electroplastic effect,[9,10] and influence of dislocation motion on conduction current and photocurrent.[10,11] However, in spite of the importance of the nature of such high dislocation charges in these physical phenomena, the magnitude of the charge is accepted—with some exceptions[3,5]—in the cited papers simply as an experimental fact without interpretation. Osip'yan and Petren-

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