

Photoinduced magnetism

V. F. Kovalenko and É. L. Nagaev

T. G. Shevchenko State University, Kiev; Scientific-Production Enterprise "Kvant", Moscow
Usp. Fiz. Nauk **148**, 561–602 (April 1986)

Theoretical and experimental work on the effect of light on the magnetic properties of strongly magnetic materials is reviewed. This phenomenon is caused primarily by the change in the exchange interaction and magnetic anisotropy. The manifestations of photomagnetism are very diverse. Light can affect the long-range order, raising the Curie point of ferromagnetic materials, changing the type of ordering or giving rise to the appearance of magnetization in antiferromagnetic materials. Light can also change the domain structure, affect the motion of domain walls under the action of external forces, and itself give rise to the motion of domain walls. From the theoretical viewpoint, photoinduced order-disorder phase transitions are of special interest as an example of phase transitions in open systems. The review covers works published up to September 1985.

CONTENTS

1. Introduction.....	297
2. Photoinduced long- and short-range magnetic order in ferromagnetic materials..	298
2.1. Photomagnetism of free photoelectrons. 2.2. Photoinduced local centers. 2.3. Photodefekt mechanism of phase transitions. 2.4. Restructuring of the band structure in the field of a light wave and nondissipative photomagnetism. 2.5. Experimental results on photoinduced ordering.	
3. Photoinduced ordering in antiferromagnetic and singlet magnetic materials.....	304
3.1. Photoferron states in antiferromagnets. 3.2. Photoinduced noncollinear antiferromagnetism. 3.3. Exciton mechanism of magnetization of antiferromagnetic materials. 3.4. Exciton mechanism for the change in the type of antiferromagnetic order. 3.5. Long-lived exciton phase. 3.6. Singlet magnetic materials.	
4. Photoinduced change in the domain structure and anisotropy.....	308
4.1. Change in the domain structure in circularly polarized light. 4.2. Effects induced by linearly polarized light. 4.3. Effect of unpolarized light on magnetic anisotropy. 4.4. Effect of light on resonance phenomena.	
5. Effect of light on the motion of domain walls, magnetic susceptibility, and coercive force.....	314
5.1. Experimental data. 5.2. Nature of photopinning of domain walls.	
6. Conclusions.....	318
References.....	319

1. INTRODUCTION

Photoinduced magnetism is the light-induced change in the properties of magnetic materials. Ferromagnetism is essentially the inverse of magneto-optics, which is the study of the effect of magnetic ordering on the optical properties of crystals. Light can affect the magnetic properties for the most diverse reasons, which by no means reduce to the trivial heating of the crystal by the light. Although special studies of the thermal effect of light on magnets have been performed (see, for example, Ref. 1, where the earlier literature on this question is indicated), in this review it will not be specially discussed and will appear only as a parasitic effect, hindering the observation of true photomagnetism.

A discussion of the mechanisms of true photomagnetism should begin with the fact that circularly polarized light has an effect similar to that of a magnetic field, and can therefore magnetize normally unmagnetized bodies, creating a predominant orientation of electron spins. It is caused by the fact that the angular momenta of the photons absorbed by electrons are transferred to the electron spins, and

these momenta in circularly polarized light are oriented in the same direction. Optical orientation does not require exchange interaction between electrons, and it is therefore observed, for example, in a wide class of nonmagnetic semiconductors.² Circularly polarized light has a definite and specific effect on paramagnetic ions in a nonmagnetic crystal (for example, Cr^{3+} in ruby),^{3,5} where light causes transitions between different crystal-field split levels of the d shell, and thereby changes its moment.

Direct magnetization by light can, of course, occur in magnetic materials also. The peculiarity of magnetic materials as compared with nonmagnetic materials lies in the fact that light can affect their magnetic properties even in an indirect manner—via light-induced changes in the exchange interaction or anisotropy. An example of such an indirect mechanism of photomagnetism is the appearance of uniaxial anisotropy in crystals with cubic symmetry under the action of linearly polarized light, which distinguishes an axis in them (the action of the light in this case is similar to a uniaxial deformation). The exchange interaction, however, is also

altered by unpolarized light. Photoinduced changes of the exchange and anisotropy appear for very diverse reasons, and their physical manifestations are just as diverse. This review is primarily concerned precisely with this "indirect" photomagnetism.

One reason for the photoinduced change in the exchange interaction could be the indirect exchange through photoelectrons in magnetic semiconductors, first studied in Refs. 10 and 11. This effect, however, was overestimated in Refs. 10 and 11 by many orders of magnitude as a result of an incorrect application of the Ruderman-Kittel-Kasuya-Yosida (RKKY) theory of indirect exchange to magnetic semiconductors (it is known to be inapplicable to them because the kinetic energy of the photoelectrons is much lower than the s-f exchange energy¹²). In reality, for typical values of the parameters, a shift in the Curie point T_c even by only 0.1 K requires a gigantic photoelectron density $\sim 10^{18}$ cm⁻³.

It is much easier to realize a different mechanism of photomagnetism, when the effect of light is determined by photoelectrons captured in local levels of defects. The trapped electron alters the exchange and anisotropy in the vicinity of the defect. This can be manifested as a change in the susceptibility of the crystal, as an effect of the light on the motion of domain walls, and as a change in the long-range magnetic order. As a rule, the number of defects in magnets is large— if for no other reason than being compounds of transition and rare-earth elements they have a tendency toward nonstoichiometry. At very low temperatures photoelectrons in local levels can have a very long lifetime, so that it is possible to create a high density of photoelectrons.

A unique form of photomagnetism is the heterophase self-trapping of free photoelectrons, when a photoelectron is spontaneously trapped in some microregion of the crystal, changing the type of magnetic order in that location. For example, self-trapping of a photoelectron in an antiferromagnetic (AFM) semiconductor is accompanied by a local phase transition into the ferromagnetic (FM) state in the region where it is self-trapped.²⁰

Photomagnetism can also be realized as a result of the excitation of Frenkel excitons on the magnetic atoms. When this happens, generally speaking, both the moment of the atom and its exchange interaction with neighboring atoms change. Such excitons can unite into complexes, forming a region with a different magnetic phase. These complexes, owing to the coherence of the exciton states in them, can be anomalously long-lived.¹⁸⁴

Ferromagnetism, being a cooperative phenomenon in a thermodynamically nonequilibrium system, exhibits new characteristics which are fundamentally different from those of equilibrium systems. This concerns especially the photoinduced magnetic transitions, which are essentially an example of self-organization in an open system. For such systems the concept of a thermodynamic potential F becomes meaningless, and therefore a phase transition in them cannot be characterized by the singularities in the derivatives of F . It can, however, be characterized by the singularities in the quantity describing nonequilibrium processes—

the rate of production of entropy.⁷ In jump-like transitions it itself changes in a jump-like manner, and in continuous transitions its derivatives with respect to the temperature and the parameters of the dissipative subsystem (the frequency and intensity of the light) have singularities of the type appearing in the heat capacity in the familiar second-order phase transitions.

We shall briefly consider the status of experimental work. The effect of light on anisotropy, first observed in Refs. 26–29, is manifested most clearly in the restructuring of the domain structure of iron-yttrium garnet (IYG)^{23–25} and in the spin-reorientational phase transition in ErCrO₃.¹⁰⁰ The effect of photoinduced defects on the motion of domain walls was first observed in IYG,^{34,58} and then in CdCr₂Se₄.²⁸ It appears as a drop in the high-frequency susceptibility and expansion of the hysteresis loop, and also as the jump-like nature of the motion of domain walls.⁶¹ An unusual consequence of the openness of the system is the light-induced instability of the domain structure in FeBO₃.⁶²

The photoinduced increase in the magnetization of ferromagnetic materials, which is in agreement with the theoretical models of the photoinduced shift in T_c of these materials, was observed in EuS^{17–19} and in CdCr₂Se₄.⁸⁷ As regards the coherent long-lived states, they are probably realized in ErCrO₃, where a light-induced change in the type of AFM ordering was first observed.^{14,15} Data indicating the self-trapping of photoelectrons in FM regions inside the AFM EuSe and EuTe were obtained in Ref. 21. Finally, we should mention the elegant experiment⁶ on the direct magnetization of the AFM MnF₂ by linearly polarized light by means of the excitation of excitons in one of its two equivalent sublattices. There are a large number of experimental works on the reproduction and detailed study of the effects described above.

2. PHOTOINDUCED LONG- AND SHORT-RANGE MAGNETIC ORDER IN FERROMAGNETIC MATERIALS

2.1. Photomagnetism of free photoelectrons

Photoelectrons can magnetize a crystal both directly and indirectly. Direct magnetization can occur even if the light is not polarized, and is a consequence of the fact that the intensity of generation of photocarriers depends on the direction of their spins relative to the moment of the crystal.^{65,66} For this reason the density of photoelectrons with spins oriented along and opposite to the moment are not equal to one another, i.e., they have a nonzero total moment. This moment is not compensated by the total moment of photoholes, since these two types of carriers have different spin relaxation times. In the limit, when all photoelectrons are completely spin-polarized and all holes are completely depolarized the relative contribution of photoelectrons to the moment of the crystal at $T = 0$ is equal to $na^3/2S$, where n is the total density of photoelectrons, a is the lattice constant, and S is the spin of the magnetic atom. Thus even for $n \sim 10^{19}$ cm⁻³, when breakdown of the crystal can already occur, for $S = 7/2$, as in EuS, this contribution constitutes only $\sim 0.01\%$.

Indirect exchange between photoelectrons can give rise to much larger effects. Its effect on the order-disorder phase transition, which in light becomes thermodynamically non-equilibrium, is of special interest. Such a transition was first studied in Ref. 7 with the use of a microscopic model, valid for a very large direct f-f exchange radius (in the terminology of the s-f model). Although this approach is not accurate enough to obtain reliable estimates in the cases of greatest practical interest, it enabled establishing the main qualitative features of photoinduced phase transitions. We shall present below a simple phenomenological approach to this problem, which enables describing the basic features of such transitions.

The magnetization of the crystal is found from the condition of the minimum of the "synergistic potential" $\tilde{\Phi}$, defined as the sum of the incomplete thermodynamic potential Φ_0 of the f spins in the absence of photoelectrons and the work $E(\eta)$ performed by the photoelectrons in establishing the magnetization of the crystal η :

$$\tilde{\Phi}(\eta) = \Phi_0(\eta) + E(\eta), \quad E(\eta) = \int_0^\eta n(\eta) \frac{d\bar{\epsilon}}{d\eta} d\eta, \quad (2.1)$$

where $\bar{\epsilon}$ is the average energy of the photoelectrons. A rigorous proof of this assertion in the self-consistent field approximation, based on the representation of the photoinduced phase transition as a kinetic phenomenon, is given in Ref. 7. For electrons in thermodynamic equilibrium (2.1), as should be, transforms into the thermodynamic potential of the complete system magnetic material + conduction electrons.

The photoelectron density is determined from the kinetic equation

$$\frac{dn}{dt} = G(\omega, J) - \frac{n}{\tau}, \quad (2.2)$$

where G is the rate of generation of carriers per unit time, τ is the recombination time of the carriers, ω is the frequency of the light, and J is the intensity of the light.

Evidently, $E(\eta)$ can be represented in the form

$$E(\eta) = E(0) - b(\omega, J)\eta^2 + O(\eta^4). \quad (2.3)$$

Substituting (2.3) into the standard Landau expansion for $\tilde{\Phi}_0$, we obtain under stationary conditions

$$\tilde{\Phi} = \frac{\mathcal{A}}{2} \left(T - T_c^0 - \frac{2b}{\mathcal{A}} \right) \eta^2 + \frac{\mathcal{B}\eta^4}{4}, \quad \Phi_0 \equiv \tilde{\Phi}|_{b=0} \quad (2.4)$$

(the contribution of E to the term $\sim \eta^4$ can be neglected, since this term makes the normal contribution to T_c and is thus insensitive to small corrections). As is evident from (2.4) photoelectrons shift T_c relative to its dark value T_c^0 by an amount $\delta T_c(\omega, J) = 2b/\mathcal{A}$.

The rate of production of entropy $\dot{\mathcal{L}}$ is expressed in terms of the amount of the light energy absorbed per unit time:

$$\dot{\mathcal{L}} = \frac{\delta Q}{T} = \hbar\omega \frac{G(\eta)}{T}. \quad (2.5)$$

The generation of carriers in (2.5) can also be expanded in terms of η :

$$G(\eta) = G_0 + g\eta^2. \quad (2.6)$$

Substituting into (2.5) and (2.6) the value of η^2 determined from the condition that $\tilde{\Phi}$ in (2.4) be minimum, we obtain

$$\dot{\mathcal{L}} = \frac{\hbar\omega}{T} \left[G_0 + \frac{\mathcal{B}}{\mathcal{A}} g(\omega, J) (T_c - T) \theta(T_c - T) \right], \quad (2.7)$$

where $\theta(x)$ is the unit step function.

It follows from (2.7) that in the approximation adopted the derivatives of $\dot{\mathcal{L}}$ with respect to T and the parameters of the system, whose energy transforms into heat, undergo jumps:

$$\Delta \frac{\partial \dot{\mathcal{L}}}{\partial T} = -\frac{\hbar\omega g \mathcal{B}}{\mathcal{A}T} \equiv \lambda, \quad (2.8)$$

$$\Delta \frac{\partial \dot{\mathcal{L}}}{\partial J} = -\lambda \frac{\partial T_c}{\partial J}, \quad \Delta \frac{\partial \dot{\mathcal{L}}}{\partial \omega} = -\lambda \frac{\partial T_c}{\partial \omega}.$$

According to (2.2) and (2.4), analogous jumps also occur in $\partial n/\partial T$, $\partial n/\partial J$, $\partial n/\partial \omega$, as well as in the corresponding second derivatives of $\tilde{\Phi}$ ($\partial^2 \tilde{\Phi}/\partial T^2$, $\partial^2 \tilde{\Phi}/\partial T \partial \omega$ etc.).

A microscopic calculation,^{185,203} carried out under more realistic assumptions than in Ref. 7, yields the following dependence of δT on n :

$$\delta T_c \approx 0,2 \{A[S(S+1)]^{1/2}\}^{2/3} W^{1/3} \left(\frac{a}{r}\right)^{2/3} (na^3), \quad (2.9)$$

where A is the s-f exchange integral, $W \approx 12\hbar^2/m^*a^2$ is the width of the conduction band, and r is the f-f exchange interaction radius. According to (2.9), for $W = 5$ eV, $AS = 0.5$ eV, $r = a = 5A$, $n = 10^{18}$ cm⁻³ the shift in T_c is equal to 0.2 K, i.e., it exceeds 1% of T_c in EuS. The fact that indirect exchange via the photoelectrons raises T_c is a consequence of the general properties of the indirect exchange in magnetic semiconductors, established in Refs. 63 and 74.

Light can also induce first-order phase transitions, if it lies in the transmission band of the crystal, when the crystal is unmagnetized and is absorbed when the crystal is magnetized.⁷⁻⁹ Then indirect exchange through photoelectrons is switched on only for quite high values of η . The phase transition from the unmagnetized into the magnetized state is accompanied by a jump in the magnetization equal to $4(E_g - \omega)/A$, where E_g is the width of the optical gap at $\eta = 0$. The rate of entropy production $\dot{\mathcal{L}}$ undergoes a jump at the same time. Such a magnetized state can be produced if the crystal is first magnetized by an external field and then illuminated; the illumination will maintain the magnetization also in the absence of the field.

The foregoing analysis was based on the assumption that the state of the ferromagnetic material with photoexcited electrons is homogeneous. In principle, it is possible to have a situation when the ferromagnetic material spontaneously transforms into a state which is inhomogeneous with respect to the magnetization and density of current carriers.⁶⁷ This is based on the tendency of photoelectrons to collect in regions with an elevated degree of FM order and to increase this order.^{20,63,74} Indeed, the energy of the electrons decreases as η increases, and the increase in their local density intensifies the FM indirect exchange through them. However, the criterion for the instability of the homogeneous state, obtained in Ref. 67, is not in agreement with the very rigid condition of self-trapping of an individual electron in the FM semiconductor near T_c .^{63,74} It is therefore not yet

clear whether or not an inhomogeneous state of the ferromagnetic material can be realized under conditions of practical interest. In any case, in analogy with Ref. 68, where the analogous phenomenon was studied in ferroelectric semiconductors, it may be expected that the characteristic length of the inhomogeneity which appears is of the order of the diffusion length. For this reason, small samples obviously exist in uniform states.

2.2. Photoinduced local centers

In photomagnetism, determined by the conduction electrons, the defects play a secondary role, appearing as recombination centers for nonequilibrium carriers. But before the nonequilibrium carriers recombine they reside for a long time in localized states on recombination or attachment centers (i.e., defects, which trap carriers of only one sign and thereby prevent their recombination). The number of trapped nonequilibrium carriers can be many orders of magnitude larger than the number of free carriers. For this reason, defects which trap photoelectrons can themselves strongly affect the magnetic properties of a crystal. Such defects can be both point defects and extended defects (dislocations, etc.).

We must first clarify the nature of the electron states on local centers. In the case $W \gg |A|S$, corresponding to magnetic semiconductors such as EuO and EuS, the situation is clearer. At $T = 0$ the state of the trapped electron in the FM semiconductor is the same as in an ordinary semiconductor: the electron is smeared over the magnetic atoms in the vicinity of the defect, and the radius of its orbit is proportional to $\varepsilon^{1/2}$, where ε is the depth of the level. As the temperature is raised, FM ordering in the vicinity of the defect breaks down more slowly than far away from the defect, since the moving electron realizes FM indirect exchange between the magnetic atoms in the vicinity of its localization and, thereby, strengthens the FM coupling between them. The trapped electron thus increases the degree of local FM order in the vicinity of the defect ("localized ferron").

However, in a number of materials now known, exhibiting photoinduced photomagnetism (IYG, CdCr_2Se_4), the opposite situation with $W \ll AS$ is apparently realized. This gives rise to misunderstandings in the interpretation of their properties.

Starting with the pioneering works on photomagnetism, it has become traditional to regard the appearance of the extra electron on the transition-metal ions M^{n+} in a crystal as an indication of the transition of one of them into the $M^{(n-1)+}$ state without a change in the state of the remaining ions. It is precisely in these terms (for example, the appearance of localized Fe^{2+} ions amongst Fe^{3+} ions in IYG, the appearance of Cr^{2+} amongst Cr^{3+} in CdCr_2Se_4) that the photomagnetic effects are customarily explained. Thus it is actually thought that d-d exchange on an ion localizes the extra electron on a definite ion and prevents it from moving to other ions. Because this interpretation has been widely accepted it should be critically analyzed.

In reality d-d exchange cannot cause the localization of the extra electron on a definite ion. No ion is capable of

confining this electron, and it moves to other ions for the same reason that the wave packet spreads out in quantum mechanics: the localized state is not an eigenstate of the Hamiltonian of the system, since it contains terms which transfer the electron from one ion to another. But, regardless of the ion on which the extra electron is located at any given moment, its spin is combined with the spin of this ion into one spin equal to $S \pm 1/2$ (the sign is the same as the sign of A). At very low temperatures the motion of the electron is equivalent to the motion of the "incorrect" spin $S \pm 1/2$ amongst "correct" spins. In a perfect crystal such a quasiparticle will move about as a band electron, and its effective mass will either coincide with or, in the worst case, will exceed by only a factor of $\sqrt{2}$ that of the electron whose spin is not coupled by d-d exchange with the spins of the ions.^{63,69-73} When the number of such current carriers is high enough they will also bring about FM indirect exchange between spins, raising their value of T_c by an amount $\sim Wv$.

If the extra electron under the same condition $W \ll AS$ is localized near defects, then this must once again be understood in the sense that the electron does not reside on any one ion in the vicinity of the defect, but is smeared over all equivalent ions. Because of the transitions of the electron from one ion to another the same tendency for establishing local FM order near a defect appears as in the case of $W \gg AS$.

In models in which the extra electrons are each regarded as being "pinned" to their own ion, this effect, which is of fundamental importance, is lost. These models also do not describe correctly the effect of the extra electron on the local magnetic anisotropy: if the electron is localized on some one ion, then it can only change the single-ion anisotropy. If, on the other hand, it moves from ion to ion, then it also changes the multi-ionic anisotropy. In a correct model one must not talk about an $M^{(n-1)+}$ ion amongst M^{n+} ions, but rather about the fact that all N ions on which the extra electron can be localized have a valence which falls between n and $(n-1)$. (If the extra electron has the same probability for being located on each ion, then the valence of the ion is equal to $n - N^{-1}$.)

We note in conclusion that, in principle, if the electron polarizes the lattice very strongly and if the conduction band is very narrow, then a polaron with a small radius should be formed. Such a quasiparticle may be regarded as being localized on a definite atom, since its mobility is extremely low (several orders of magnitude lower than $1 \text{ cm}^2/\text{V}\cdot\text{s}$). This is determined by the fact that as the electron moves from atom to atom the lattice polarization which it induces should move together with it. The mobility of such a quasiparticle increases exponentially with the temperature. It should be kept in mind, however, that the conditions for the existence of a polaron with a small radius are extremely stringent, and materials in which these conditions hold have not yet been found. In particular, the analysis performed in Ref. 74 (and in a different variant in Ref. 63), shows that it is impossible to have a polaron with a small radius in CdCr_2Se_4 , since the polarizability of the lattice of this crystal is very low. The existence of a polaron with a small radius can also be judged from whether or not the mobility of the carriers is low and

whether or not the mobility increases exponentially with temperature. The experimental data collected in Refs. 63 and 74 show that the mobility does not grow exponentially in $n\text{-CdCr}_2\text{Se}_4$, and it has a quite high magnitude of $1\text{--}10\text{ cm}^2/\text{V}\cdot\text{s}$. It is therefore meaningless to talk about the coexistence of Cr^{3+} and Cr^{2+} ions in this material. Larsen and Metseelaar⁷⁵ arrived at an analogous conclusion that one should avoid talking about the coexistence of Fe^{2+} and Fe^{3+} ions in IYG, based on an analysis of their own experimental data and the data of others on the electric properties of IYG, though previously they held the opposite point of view.^{76,77}

2.3. Photodeflect mechanism of phase transitions

It is entirely obvious that photodeflects of the localized ferron type substantially affect the short-range magnetic order and the effects which depend on this order, such as, for example, the magnetization in an external field. But it is no less important that photodeflects can also affect the magnetic long-range order, giving rise to an increase in T_c . Since, as already indicated, the density of photodeflects is normally many orders of magnitude higher than the density of free photoelectrons, this mechanism can be much more efficient than exchange via free electrons (see Sec. 2.1). Besides, these mechanisms can coexist and transform into one another.

In particular, at sufficiently high light intensities, when all trapping centers are filled, further increase of the light intensity will give rise to pumping of only the free carriers, and a free-electron density at which the free electrons will substantially affect the ordering can be achieved. On the other hand, if the radius of the electron state on the impurity is large enough, then a Mott transition can occur in the system of photoelectrons trapped by defects: an impurity band, lying below the bottom of the conduction band and coalescing with it, forms instead of impurity levels. The collectivized electrons of the impurity centers participate directly in establishing long-range order. In both cases, in the presence of high light intensities the conductivity must increase with the intensity more rapidly than in the presence of low intensities.

The reasons that one can talk about an increase in T_c owing to photoelectrons is that in Heisenberg magnetic materials defects do not smear the phase transition and do not change the critical indices.⁷⁸⁻⁸¹ The mechanisms by which they directly affect T_c can, however, be different. It should be pointed out first that the fact that the local exchange in localized ferrons increases is itself directly reflected on T_c . We shall assume that this indirect exchange via trapped photoelectrons is so strong that the spins of the atoms in the vicinity of the effect are bound into one moment. The reason that such gigantic moments raise T_c is that the degree of their polarization is much higher than the degree of polarization of the spins of regular atoms. If the full polarization of the moments of the defects were to remain at all temperatures T , then the defects would act as an external magnetic field and the phase transition would not be possible at all.

In reality they become depolarized as the temperature T is raised, but much more slowly than regular spins. This is a consequence of the fact that the energy of the moments of the

defects in a molecular field is much higher than that of regular spins. For example, in the Ising model the energy of a regular spin in a molecular field is $\pm zJ\eta$, where z is the number of nearest neighbors and J is the exchange integral between them. The energy of the defects, however, is $\pm N_R J\eta$, where N_R is the number of bonds between the atoms within the defect and their nearest neighbors outside the defect. For example, if the moment of the defect consists of the spin of the central atom and its nearest neighbors, then $N_R = z(z-1)$. In this case the interaction of the defect with the molecular field is $(z-1)$ times stronger than that of the regular atom.

Calculations^{185,205} show that in the presence of a very strong bond inside the defect the relative shift in T_c of a Heisenberg magnetic material owing to n_d defects, trapping the electron, in the nearest neighbor approximation is equal to

$$\frac{\delta T_c}{T_c} = \frac{S}{S+1} \left(\frac{N_R}{z} \right)^2 n_d a^3. \quad (2.10)$$

This shift, unlike (2.9), is independent of AS , because s-f exchange, which unifies the spins near a defect into one moment, cannot be manifested in the magnetic properties of the crystal without defects. Since $AS \gg T_c^0$, δT_c (2.10) can exceed (2.9) only if the number of trapped photoelectrons is several orders of magnitude higher than the number of free electrons. As already discussed above, such a situation is entirely realistic.

The deformation of the lattice accompanying trapping of electrons in traps makes an additional contribution to the shift in T_c . In the presence of randomly distributed defects the lattice undergoes a uniform deformation.¹⁸⁸ The change in the lattice constant is accompanied by a change in the direct f-f exchange in the entire crystal uniformly, independent of the position of the atoms relative to the defects. This gives rise to the following shift in T_c :

$$\frac{\delta T_c}{T_c} = -\frac{C}{3Ms^2} \frac{d \ln T_c}{d \ln a} n_d a^3, \quad (2.11)$$

where C is the constant in the deformation potential, M is the mass of the unit cell, and s is the sound velocity. Under typical conditions $d \ln T_c / d \ln V \sim -5\text{--}10$, so that for $C \sim 10\text{ eV}$, $M \sim 10^{-23}\text{ g}$ the relative shift in T_c owing to the defect-induced deformation of the crystal can be of the order of $(1-10)m_d a^3$.

It is not difficult to verify that with this mechanism of photoinduced transition the derivatives of the rate of production of entropy with respect to the temperature and the frequency and intensity of the light at the point of the transition have precisely the same singularities as in the case of indirect exchange via free photoelectrons (Sec. 2.1).

2.4. Restructuring of the band structure in the field of a light wave and nondissipative photomagnetism

In preceding sections we studied photomagnetism determined by the excitation of current carriers in the crystal. Naturally, excitation is possible only as a result of the absorption of light. The energy of the light is therefore dissipated. However, light-induced change in the magnetization without dissipation of the light energy can occur when the

frequency of the light lies in the transmission band of the crystal.^{13,189} Generation of current carriers by light is in this case impossible if multiphoton processes are neglected. Photomagnetism is determined by the virtual transitions of electrons from the valence band into the conduction band, as a result of which virtual conduction electrons and holes appear. (These terms describe the change in the state of the valence band under the action of the light, which mixes the states of the conduction band with the states of the valence band. But the electrons which were present in the valence band before the illumination remain there, though the band itself is altered.)

In many magnetic semiconductors (for example, EuO ^{63,74}) the states of the valence band are constructed primarily from the p -orbitals of nonmagnetic anions, while the states of the conduction band are constructed from the outer orbitals of the magnetic cations. The overlapping of the orbitals of the partially filled shells of the cations with the orbitals of the outer shells of the same cations is much larger than the overlapping with the orbitals of the anions. For this reason, the exchange interaction of localized d and f moments with conduction electrons is much stronger than with electrons in the valence band. Under these conditions the light-induced mixing of the states of the conduction band with the states of the valence band markedly intensifies the exchange between electrons in the valence band and the localized moments.

The intensification of exchange can either decrease or increase the energy of the electron, depending on the orientation of the electron spin relative to the moment of the crystal. If the degree of mixing were independent of the orientation of the electron spin, then the total change in the energy of the exchange between electrons in the completely filled valence band and the localized moments would be equal to zero. In ferromagnetic semiconductors, however, the degree of mixing depends on the orientation of the electron spin. This is because in the presence of a nonzero moment in the crystal the energy bands are spin-split (the Zeeman splitting of the energy of the electron $\epsilon_{\mathbf{k}}$ in the molecular field of the crystal):

$$\epsilon_{\mathbf{k}\sigma} = \epsilon_{\mathbf{k}} - A\sigma\eta \quad (2.12)$$

(\mathbf{k} is the quasimomentum). As a result of this, the size of the gap between the valence band and the conduction band, which is determined by the degree of mixing, also depends on the spin orientation. In terms of the virtual conduction electrons one can talk about the fact that they are spin-polarized; in addition, the virtual electrons whose spin projection ensures a gain in their exchange energy with localized moments dominate. The latter increases with the magnetization of the crystal. For this reason, the virtual electrons appearing under the action of the light strive to establish and maintain ferromagnetic ordering in the crystal.

The foregoing mechanism also operates in cases when generation of current carriers is possible under the action of light. If the relaxation time of the magnetization is less than other characteristic times, then the contributions of the virtual and real photoelectrons to photomagnetism can be sepa-

rated according to their relaxation times (the relaxation of the virtual photoelectrons is instantaneous, while the relaxation time of the real photoelectrons is the same as that of the photoconductivity).

The evaluation of the effect made in Ref. 13 showed that when the frequency of the light is quite close to the absorption edge and the intensity of the field of the unpolarized electromagnetic wave is $\sim 10^6$ V/cm, the shift in T_c is ~ 0.1 – 1 K.

2.5. Experimental results on photoinduced ordering

Photoinduced change in the magnetization was observed in IYG:Si at 150 K in a magnetic field rendering the sample single-domained. The surface of the sample was illuminated with $3 \cdot 10^3$ ln of light from a white source for 2 min. The change in the magnetization was recorded based on the Faraday rotation of the plane of polarization of the probing beam. A change in the magnetization by 1 G with a saturation magnetization of 180 G was observed.¹⁶ Unfortunately, the sign of the effect was not explicitly indicated in Ref. 16, but from the interpretation presented it follows that the magnetization increases.

A light-induced rise in the magnetization was observed under laser illumination in the FM semiconductor EuS with $T_c = 16$ K.¹⁷⁻¹⁹ To avoid heating, which gives rise to an effect with the opposite sign, in these works the high-frequency modulation of the laser beam with a frequency of several MHz was employed. The excitation density of the pumping light was equal to 10^{24} – 10^{25} cm⁻³ sec⁻¹.

The magnetization M of a sample placed in a magnetic field of 1.2 kOe at a temperature of $T = 12$ – 14 K was measured directly in Ref. 19: the change in the magnetization ΔM , caused by the illumination, was detected by the emf induced in the detecting coil. Judging from the phase of this emf the light-induced magnetization increased. Because of the domain structure of the sample the relative change in its magnetization was by a factor of $4\pi\chi$, i.e., three orders of magnitude lower than the relative change in the true magnetization in the domains $\Delta M/M_0$ (χ is the susceptibility, equal to 200 in EuS). For this reason the observed change $\Delta M/M \sim 10^{-5}$ corresponded to a change $\Delta M/M_0 \sim 10^{-2}$, which, in terms of the Curie temperature, under the assumption of a Brillouin temperature dependence of M_0 , gives a photoinduced increase of ~ 0.1 K.

The conclusion that the magnetization of EuS increases under laser illumination is confirmed by a study of the optical absorption,¹⁸ carried out under the same conditions. The coefficient of absorption \tilde{k} was studied at a probing wavelength of $\lambda = 0.63$ μm (naturally, not the same wavelength as the irradiating laser). The idea of the method consisted of the following. In this part of the spectrum the coefficient of absorption increases monotonically with the distance from the absorption edge, while the absorption edge itself shifts with increasing magnetization toward longer wavelengths.^{63,74} The distance between the absorption edge and the wavelength at which \tilde{k} was measured thereby increases, i.e., \tilde{k} increases with the magnetization. Therefore the obser-

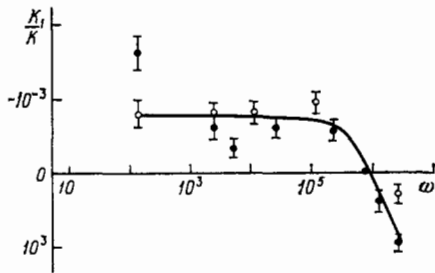


FIG. 1. The modulation of the coefficient of absorption of EuS as a function of the frequency of modulation of the intensity of the illumination.¹⁸

vation of a photoinduced increase in \bar{k} could indicate the appearance of photoinduced magnetization.

The experimental study showed that with a low beam modulation frequency (up to 10^5 Hz) heating dominates and \bar{k} decreases under illumination, as should occur as the magnetization decreases. But at frequencies above 10^6 Hz, \bar{k} does indeed increase with illumination (Fig. 1). The study of optically induced dichroism in Ref. 17 also leads to the conclusion that photoinduced magnetization exists. The same estimate of T_c as in Ref. 19 was obtained in both Ref. 17 and Ref. 18.

Unfortunately the data of Refs. 17–19 do not make it possible to separate unequivocally the action of light into long- and short-range order. A change in the short-range order can lead to the same effects, for example, in the following manner. The excited photoelectrons are transferred to attachment levels, creating localized ferrons (Sec. 2.2). Their local moments are manifested as an increase in the magnetization of the crystal in an external field, as observed in Ref. 19, while electronic transitions from them into the conduction band increase the absorption coefficient. At the same time, as discussed in Sec. 2.3, such localized ferrons also affect the long-range order, thereby working in the same direction as photoelectrons. We note that a photoinduced change in the optical absorption was also observed in FeBO_3 ,⁴⁸ IYG:Si ,¹⁷⁵ and IYG:Ca ,¹⁷⁶ where this absorption is not associated with interband transitions.

Afanas'ev *et al.*^{17–19} believed that they were able to obtain very high electron densities of $\sim 10^{17} - 10^{19} \text{ cm}^{-3}$. More definite conclusions regarding this could have been drawn, if in Refs. 17–19 the photoconductivity and spectral dependence of the photoinduced absorption of the sample studied were measured.

Investigations of the magnetization near T_c in an external field, analogous to Ref. 19, were then carried out on samples of Ga-doped CdCr_2Se_4 .⁸⁴ The conclusion that a photon-induced increase in the magnetization occurred was drawn in Ref. 84 based on the fact that the induced emf changes sign with a reduction of the power of the laser pulse, characterized by a change in the surface energy density from $3 \cdot 10^{-2} \text{ J/cm}^2$ to $3 \cdot 10^{-3} \text{ J/cm}^2$. The increment to the magnetization then was equal to 4–6 G. According to Ref. 85, with a laser power corresponding to $6 \cdot 10^{-4} \text{ J/cm}^2$ the magnetization increased by ~ 0.3 G. The factors responsible for the fact that the thermal effect decreases with a drop in the pulse power

much more strongly than true photomagnetism are not clear. One would expect that both effects are proportional to the pumping power, which is confirmed by a comparison of the data presented above from Refs. 84 and 85. It would be desirable to study CdCr_2Se_4 by the procedure of Refs. 17–19, where everything depends on the difference between the characteristic times for heating and true photomagnetism.

Nevertheless the point of view taken in Ref. 84, according to which the photoinduced magnetization is determined by local centers, appears to be completely reasonable. It is also confirmed by the fact that the photoconductivity of $\text{CdCr}_2\text{Se}_4:\text{Ga}$ near T_c unlike EuS, is negligibly small.⁸⁶ For this reason the effect obviously cannot be explained by the indirect exchange through free electrons in this case.

As regards the specific mechanism for the action of the localized photoelectron on the exchange, for some reason Rudov and Veselago reduce it to local changes in the intracrystalline fields and the covalence of the bonds, which, in their turn, affect the superexchange. These effects are significant for unfilled traps. Trapping of an electron, however, gives rise immediately to the appearance of a much more powerful mechanism—local indirect exchange through the localized electron.

According to Ref. 84, the binding energy of an electron on a trap is not very high (~ 0.1 eV). It is clear that for such a binding energy the electron is smeared over a large group of magnetic ions, between which it gives rise to an indirect FM exchange, i.e., this result indicates the existence of local ferrons in CdCr_2Se_4 (see Sec. 2.2). The existence of photoinduced local moments, experimentally confirmed in Ref. 84, essentially indicates that models in which the action of the light reduces to the appearance of Cr^{2+} ions with a fixed position among regular Cr^{3+} ions and a concomitant change in the local anisotropy are unsatisfactory (unfortunately, this interpretation was also adopted in Ref. 84; see Sec. 3 below).

In Ref. 87, where the procedure of Faraday induction of magnetization was employed, analogously to Ref. 16, the photoinduced magnetization in pure CdCr_2Se_4 far from T_c was studied. The source of light with $\lambda = 1.06 \mu\text{m}$ had an intensity of 1.6 W/cm^2 ; the temperature of the sample was measured directly, which enabled separating the heating and true ferromagnetism. At 43 K the increase in the magnetization in unpolarized light is the same as would occur with a reduction of the temperature of the sample by 5K. (This does not mean that the magnetization changes substantially, since at 43 K it is already close to saturation and is virtually independent of the temperature.) Measurements at 78 K showed that circularly polarized light increases the magnetization by an order of magnitude more strongly than does unpolarized light, and when the direction of rotation of the plane of polarization changes the light reduces the magnetization.

This effect is attributed in Ref. 87 to the photon-induced high density of photoelectrons. Depending on the direction of rotation, the electrons fall either into the bottom or top subband (2.12); in the first case, they maintain the magnetization and in the second case they destroy it. The effect of

unpolarized light, however, is described in Ref. 87 on the basis of the RKKY theory, which, as already pointed out in the introduction, is unsuitable for magnetic semiconductors, overestimating by several orders of magnitude the intensity of the indirect exchange in them. It is possible that the relatively high value of the photomagnetization observed in Ref. 87 is associated with the accumulation of a large number of long-lived photoelectrons in the attachment levels. In any case, magneto-optical measurements⁸⁷ should be supplemented by an investigation of the photoelectric properties of samples. Further studies of CdCr₂Se₄ according to the procedure of Refs. 16 and 87 are carried out in Ref. 88.

It was found in Ref. 186 that illumination of the ferrites Mn_{1-x}Zn_xFe₂O₄ with circularly polarized light in a magnetic field at $T = 273$ K induces in them an additional magnetization, which persists indefinitely after the light is switched off.

3. PHOTOINDUCED ORDERING IN ANTIFERROMAGNETIC AND SINGLET MAGNETIC MATERIALS

3.1. Photoferron states in antiferromagnets

As discussed in Sec. 2, photoelectrons strive to establish FM ordering. From estimates of the intensity of indirect exchange via photoelectrons, however, it is obvious that normal antiferromagnetic materials with $T_N \sim 10$ – 100 K cannot become FM—this would require completely unattainable photoelectron densities $\sim 10^{20}$ – 10^{21} cm⁻³. Metamagnetic EuSe, which becomes FM when $\sim 10^{19}$ cm⁻³ conduction electrons are injected into it, could be an exception.^{63,74} The possibilities for this are even more favorable, if pressure is applied to EuSe: according to Ref. 89 and 90 a pressure of 4.5 kbar at $T \sim 4$ – 5 K transforms the crystal into the FM state. Substitution of S for part of the anions in EuSe could lead to the same result; 13% S is sufficient for the crystal to become FM.⁹¹ If the pressure or the S concentration is close to but less than the critical value, then an experimentally completely attainable photoelectron density will be required to establish FM ordering.

The transformation of EuSe into the FM state can also occur owing to trapping of photoelectrons in local levels, since this will decrease the volume of the crystal. According to (2.11), with a compressibility of $k \sim 10^{-6}$ kbar⁻¹ and a defect density of $\sim 10^{20}$ cm⁻³ the compression of the crystal is the same as under a pressure of $\sim 10^4$ kbar.

A fundamentally important fact is that with relatively low photoelectron densities in AFM semiconductors with low values of T_N separate FM regions, predicted theoretically in Refs. 20 and 63, cannot arise. The electrons create inside the crystal microregions of the FM phase and stabilize them by their localization in them. Such complexes consisting of the electron plus the FM microregion created by it are essentially quasiparticles of a special type, called ferrons.

The size R of a ferromagnetic microregion can be found by minimizing the total energy of the system. If the effective mass of the electron is not too high, then for $R \gg a$ the energy is given by the expression

$$E = -\frac{AS}{2} + \frac{\hbar^2}{2m^*} \left(\frac{\pi}{R}\right)^2 + \frac{4\pi}{3} D \left(\frac{R}{a}\right)^3, \quad (3.1)$$

where the first term is the lowering of the bottom of the conduction band as a result of the replacement of AFM ordering by FM ordering, the second term is the kinetic energy of the electron, and the third term is the energy of magnetic control expended on creating the FM region (for Heisenberg magnetic materials $D \sim JS^2$).

For very low values of D , from (3.1) we obtain the following expression for the number of atoms in the FM region:

$$N_{FM} = \frac{4\pi}{3} \left(\frac{\pi}{4m^*a^2D}\right)^{3/5}. \quad (3.2)$$

For EuTe there are hundreds and for EuSe there are thousands of atoms in the FM region. The stability of the ferrons is additionally raised by the polarization of the crystal lattice by them.^{63,74}

Ferrons are normally randomly distributed over the crystal. As their density increases, they begin to coalesce into drops, to which, owing to the Coulomb forces, holes are also attracted (an analogous phenomenon in ferroelectric semiconductors was studied in Ref. 68). In typical cases s-f exchange for holes is negligibly small compared with exchange for electrons. For this reason the position of the bottom of the hole band in the drop is the same as outside the drop, while the bottom of the conduction band is lower in the drop by $AS/2$. Thus the photoinduced appearance of drops indicates the appearance of photoinduced heterojunctions. Such junctions can in principle also appear near the surface of the crystal, if all of the light is absorbed near the surface and a density sufficient for establishing FM ordering appears there.^{8,9}

The number of nonequilibrium carriers evidently increases with the recombination time. This time can be increased by spatially separating the electrons and holes. Thus if a quite strong electric field is applied to the crystal, then the nonequilibrium electrons will appear on one surface and the holes will appear on another surface. For this reason, in a field it is easier to collect on a surface the number of carriers required for transforming it into the FM state. The nonequilibrium current carriers can also be separated by a p-n junction.

Finally, it should be pointed out that localized ferrons form in the presence of traps in AFM semiconductors^{63,74}: near defects AFM ordering is replaced by FM ordering. Unlike analogous formations in FM semiconductors, localized ferrons must lower the Néel temperature of the crystal.

Photoinduced ferrons have been observed experimentally in EuSe and EuTe²¹ crystals illuminated at liquid-helium temperatures. This conclusion was drawn in Ref. 21 on the basis of the anomalous dependence of the photoconductivity and luminescence on the magnetic field. The strong luminescence is usually attributed to the presence of defects, operating as carrier traps. The luminescence of EuSe, however, did not weaken when the samples were cleaned. At temperatures $T \gg T_N$ the magnetic field has virtually no effect on the luminescence, but at 4.2 K a field of 11 kOe, which magnetizes the sample to 80%, weakens the luminescence by a factor of 5 and simultaneously sharply intensifies the photoconductivity (Fig. 2). This indicates that the magnetic field destroys the local levels, through which electron

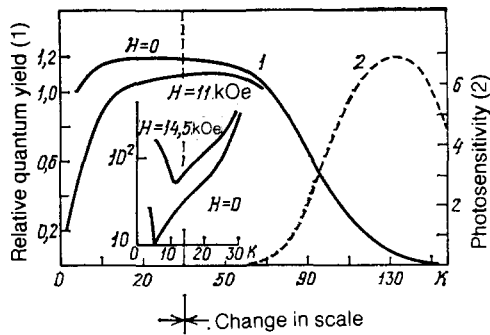


FIG. 2. Temperature dependence of the relative quantum yield of luminescence of EuSe in the absence of a field and in a field of 11 kOe (solid lines).²¹ The inset and the broken curve show the photosensitivity (in arbitrary units).

transitions proceeded in its absence. These levels, not related with defects, existing only at not too high temperatures and vanishing in a magnetic field, are precisely the ferron levels. An investigation of the degenerate semiconductors EuSe⁹² and EuTe⁹³⁻⁹⁶ confirm directly that the localization of electrons in definite regions of the crystals induces FM order there (for a more detailed discussion see Refs. 63 and 74¹¹).

3.2. Photoinduced noncollinear antiferromagnetism

A different situation arises in AFM crystals with high Néel temperatures T_N , where ferron formation is impossible. Ferron formation is also inhibited in crystals with FM layers, whose moments are ordered antiferromagnetically. In this case photoinduced formation of a tilted AFM structure, in which the moments of the sublattices M_1 and M_2 are oriented not opposite to one another, but rather at some angle 2θ differing from π , becomes possible.^{8,9} With actually attainable photoelectron densities the magnetization M realized must be very weak. This phenomenon is in no way related to the weak equilibrium ferromagnetism of AFM crystals of definite symmetry, in which it is caused by the weak relativistic Dzyaloshinskii interactions. In the case under study it is entirely determined by the non-Heisenberg nature of the indirect exchange through the conduction electrons, which is determined by the fact that in magnetic semiconductors the condition of applicability of the RKKY theory $\varepsilon \gg AS$, where ε is the characteristic energy of an electron, does not hold. As a result of the non-Heisenberg nature of the indirect exchange, in the expansion of the energy of such a system in power of the magnetization η

$$E = E_0 + A\eta^2 + B\eta^4 + \dots; \quad (3.3)$$

the term proportional to η^4 turns out to be nonzero.^{8,9,63,74, 2)} As regards the coefficient A , at $n = 0$ this coefficient is positive, but as the carrier density n increases it decreases and vanishes at

$$\frac{n_A}{N} \sim \frac{T_N \varepsilon}{A^2 S^2}. \quad (3.4)$$

If the electron gas is not degenerate, then ε should be interpreted as its temperature T_c , which, generally speaking,

can substantially exceed the temperature of the lattice. If, on the other hand, the electron gas is degenerate, then ε is the Fermi energy μ . Assuming for estimates that $AS = 1$ eV, $T_N = 100$ K, $\varepsilon = \mu$, we obtain from (3.4) the critical concentration n_A at which the magnetization appears: $n_A \sim 10^{18} - 10^{19}$ cm⁻³. As n increases further the moment increases as $(n - n_A)^{1/2}$. The conditions for the appearance of photomagnetization in a crystal can be made more favorable if the crystal is first doped, making the carrier concentration in it approach n_A .

3.3. Exciton mechanism of magnetization of antiferromagnetic materials

Light can excite in magnets Frenkel excitons, which are excited states of the partially filled d or f shells. They can be excited by themselves or with the participation of magnons.⁹⁷ If the excitation of an exciton is accompanied by a change in the magnetic moment of the ion, then the magnetization of the crystal as a whole changes. In an antiferromagnetic material consisting of two equivalent sublattices excitons are normally excited in equal numbers in both sublattices, and therefore magnetization does not appear in the crystal. Modern experimental techniques, however, enable exciting excitons in one sublattice only and thereby achieving photoinduced magnetization in the crystal. This was done in MnF₂ in Ref. 6.

The MnF₂ crystal has a tetragonal structure, and the magnetic moments are collinear with the c axis, i.e., [001]. In this crystal there exist at 18418 cm⁻¹ magnetic dipole excitons, corresponding to the transition ${}^6A_1 - {}^4T_1$ in the Mn²⁺ ion. It corresponds to a moment of $2.11 \mu_B$ on the ion, parallel to [001]. In order to excite excitons in one sublattice only, a uniaxial stress is applied to the crystal in the [110] direction, which removes the degeneracy of the sublattices. As a result a difference of 5 cm⁻¹, exceeding by an order of magnitude the line width of the laser, appears between the frequencies of the excitons in the sublattice. The time of a transition of the exciton from one sublattice to the other, however, is very long, and for this reason the excited sublattice is magnetized. The power of the laser enabled the excitation of 0.005% of the Mn²⁺ ions in the illuminated region (Fig. 3).

The band of an electric exciton, associated with the magnon, lies next to the band of the magnetic exciton at 18476 cm⁻¹: the exciton is excited in one sublattice and the magnon is excited in the other sublattice. The magnetic moment of such a complex elementary excitation is small ($0.02 \mu_B$ per ion), so that the excitation for all practical purposes does not give rise to the appearance of magnetization. If, however, the magnon relaxes over a time shorter than the duration of the laser pulse, while the exciton is long-lived, then magnetization appears some time after the laser is switched on. It was recorded based on the emf induced in a coil containing the sample (see Fig. 3). The system was excited by linearly polarized light with an electric vector oriented either along [110] or along $[1\bar{1}0]$, which enabled selecting the sublattices in which the exciton and the magnon are excited. In this case the crystal need not be strained.

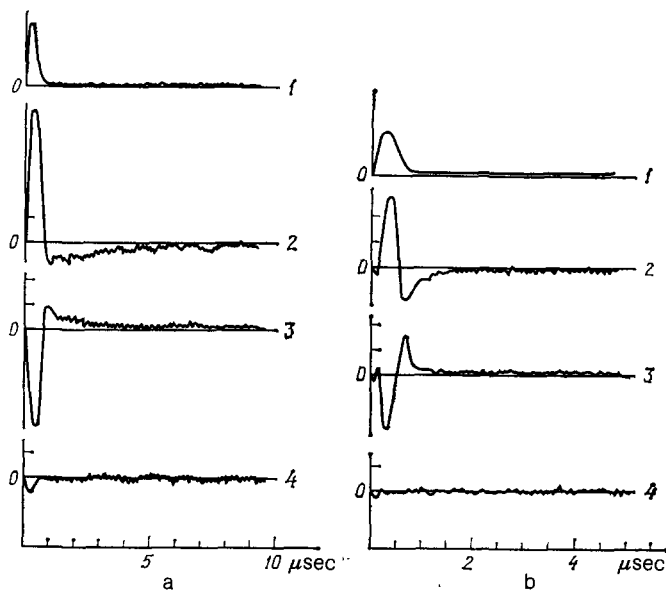


FIG. 3. Signals of the magnetic induction in MnF_2 , generated by optical pumping of excitons in one of the sublattices.⁶ a: 1) Laser pulse, 2) pumping of excitons in sublattice I, 3) pumping of excitons in sublattice II, 4) absence of a resonance. b: Magnetic induction signals generated by optical pumping of excitons in one sublattice and magnons in the other; 1) laser pulse, 2) pumping of excitons in sublattice I and magnons in sublattice II, 3) pumping of magnons in sublattice I and excitons in sublattice II, 4) pumping light, being in resonance, creates equal concentrations of magnons and excitons in each sublattice.

3.4. Exciton mechanism for the change in the type of antiferromagnetic order

Excitation of Frenkel excitons on magnetic ions by light alters not only the moments of the ions but also the exchange interaction of the ions with their neighbors as well as the magnetic anisotropy. As a result, the type of magnetic ordering can change. This is precisely what was observed in EuCrO_3 ^{14,15,98,99} under conditions of optical pumping with laser pulses at a wavelength of 532 nm with a pulse power of 280 kW.

At temperatures $T < 50$ K, at some threshold pumping power and for quite long pumping durations, a new resonance absorption signal, shifted relative to the starting AFM resonance (AFMR), was observed. After the pump was switched on the intensity of the old AFMR signal either decreased substantially or the signal vanished completely, depending on the pump power. The picture of the AFMR as a function of time is as follows. In the first minutes after the laser was switched off a rapid increase in the intensity of the new signal and a shift of the signal with respect to the field were observed (Fig. 4). Then the intensity of the signal remained virtually constant, and the shift of the resonance field slowed down and then also stopped changing. The new signal remained unchanged for more than a day.

In Refs. 14 and 15 Golovenchits *et al.* assume that prior to illumination the crystal was not in a state of thermodynamic equilibrium and that such a state is realized only as a result of the illumination. The excitons produced by the light are normal in the sense that their frequency is positive. When the excitons combine into quite large complexes, however, the energy of these complexes turns out to be lower than the energy of the starting state. If there are not enough excitons, then there is not enough time for them to combine into complexes and they are annihilated. This explains the threshold nature of the effect. The aforementioned delay in the appearance of the new signal is determined by the fact that in order for a new phase to form sufficient time is required for the

excitons to diffuse toward one another. It is thought that the light gives rise to a transition of the Eu^{3+} ion from a non-magnetic state into a magnetic state. The stabilization of the excitation is determined by the exchange interaction between Eu^{3+} ions, consisting of superexchange via the Cr^{3+} ions.

It is more likely, however, that the formation of exciton complexes leads not to the appearance of a true stable phase, but rather to the appearance of a long-lived exciton phase, discussed in Sec. 3.5. Indeed, if the exciton phase were a true ground state, then it could be reached not only by optical excitation of the crystal, but also by other paths, for exam-

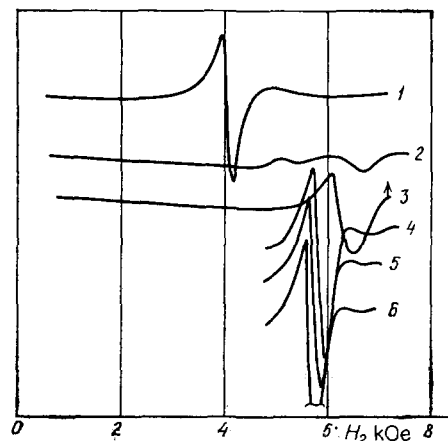


FIG. 4. Tracings of the AFMR lines (ω_{xy}) in EuCrO_3 .¹⁵ The signal intensity is plotted along the ordinate axis. The dimensions of the sample are $2 \times 1.5 \times 0.15$ mm³, $T = 25$ K, $f = 210$ GHz. 1) AFMR lines before pumping; 2, 3) during pumping (the arrow marks the moment at which the laser is switched off); 4-6) tracing of lines every 2 min after the laser is switched off. Pumping parameters: pulse power $P_p = 250$ kW, pulse duration $\tau_p = 15$ ns, repetition frequency $\Omega = 25$ Hz, pumping duration $t_p = 2$ min.

ple, by very slow cooling, which has not yet been achieved experimentally.

In ErCrO₃ a photoinduced phase transition of a different nature is realized.¹⁰⁰ This transition is linked to the fact that at $T_r = 9.4$ K this material exhibits a thermodynamically equilibrium spin-reorientational first-order transition from the high-temperature Γ_4 phase into the low-temperature Γ_1 phase. Below T_r in a magnetic field both phases can coexist.

The observation of one of the absorption lines in the spectrum of Er³⁺ showed that at this transition it is shifted from the position of Γ_4 to that of Γ_1 . When the phases coexist, both Γ_1 and Γ_4 lines are observed.¹⁰⁰ Illumination with a laser with a pulse duration of 20 ns at temperatures $T < T_r$ gives rise to a complete transition of the crystal into the Γ_4 state. Immediately after irradiation the Γ_4 line is substantially broadened and is shifted. Both these effects significantly exceed those determined by heating. They are explained by the fact that at first the Γ_4 phase arises from the Γ_1 phase in the form of clusters, which later coagulate. Although the thermal and photomagnetic effects were not clearly separated in Ref. 100, judging from the characteristic times of the processes, the second process should be the determining one. The effect is explained naturally by the change in the magnetic anisotropy accompanying the excitation of excitons.

3.5. Long-lived exciton phase

In order for exciton excitation to change the exchange interaction, the exciton density must be very high. If exchange between only nearest neighbors is important, then the number of excited atoms must be $\sim 100\%$.

Such high exciton densities can in principle be created. This possibility is determined by the fact that because of the coalescence of excitons into the exciton phase the probability of their annihilation under certain conditions decreases exponentially with increasing dimensions of the phase. As a result a long-lived exciton phase, which at low temperatures can exist for a very long time after the illumination is switched off, appears.^{184,205}

Excitons can be annihilated by means of both radiative and nonradiative transitions. The latter channel is most intense. We shall assume that high-frequency excitons are initially produced by the light in the crystal. By means of nonradiative transitions they transform into low-frequency excitons, for which radiative transitions are forbidden. Let us assume that such low-frequency excitons in the starting state are excited on all L atoms in some singly connected region G ,³⁾ while in the final state one of them is annihilated. As a result, an exciton hole is formed in the G region and moves over the entire region. Its motion inhibits the interaction with phonons. We shall be interested in the case when this interaction is not so strong as to give rise to self-trapping of the hole, and for this reason its motion along the atoms is coherent.

The electronic transition is accompanied by a change in the equilibrium position of the lattice atoms. In accordance with the theory of nonradiative multiphonon transitions¹⁰¹⁻¹⁰³ the probability of a transition is proportional to

$$\left. \begin{aligned} W_{if} &\sim \exp \left[-\frac{(\varepsilon - E_r)^2}{2\sigma^2} \right], \\ E_r &= M \sum_s \omega_{qs}^2 |\delta \tilde{Q}_{qs}|^2, \quad \delta \tilde{Q}_{qs} = \tilde{Q}_{qs}^i - \tilde{Q}_{qs}^f, \\ \sigma^2 &= \hbar M \sum_s \omega_{qs}^2 |\delta \tilde{Q}_{qs}|^2 (2n_{qs} + 1), \end{aligned} \right\} \quad (3.5)$$

where $\varepsilon \gg E_p$ is the frequency of the exciton, ω_{qs} and n_{qs} are the frequency and Bose distribution function for phonons with the wave vector \mathbf{q} from the branch s , \tilde{Q}_{qs}^i and \tilde{Q}_{qs}^f are the equilibrium positions of the phonons in the starting and final states, and M is the mass of the atom. Taking into account the fact that \tilde{Q}_{qs} is proportional to the Fourier component of the exciton density $\rho_{-\mathbf{q}}$, with the appearance of the exciton hole it changes by

$$\delta \tilde{Q}_{qs} \sim \frac{1}{L} \sum_{g \in G} e^{i\mathbf{g}\mathbf{q}} \equiv \delta \rho_{-\mathbf{q}} = \rho_{-\mathbf{q}}^i - \rho_{-\mathbf{q}}^f. \quad (3.6)$$

As follows from (3.6), for phonons, whose wavelength is less than the dimensions of the region, $\delta \tilde{Q}_{qs}$ is small. The number of such phonon modes increases with L , and therefore σ^2 and together with it the probability of the transition decrease. A detailed calculation shows that at high temperatures when the transition is of an activated character the activation energy in (3.5) is linear in L , i.e., the transition probability decreases exponentially with increasing L . At low temperatures the rearrangement of the lattice, induced by the annihilation of the exciton, occurs by means of quantum tunneling of its atoms from the old to the new positions of equilibrium. The probability of annihilation is therefore virtually independent of the temperature. In this limit the probability can decrease even more rapidly with increasing L .

The conditions for annihilation of the exciton on the surface of the exciton region are more favorable. If the spectrum of the exciton hole contains a surface band, then the activation energy for annihilation of the surface exciton is proportional to $L^{2/3}$. Thus in the limit $L \rightarrow \infty$ the most effective method of annihilation of the excitons is evaporation of the excitons from the excitonic phase. Because of this process the activation energy of annihilation is higher than the corresponding value for a separate exciton by an amount of the order of the binding energy of the excitons in the excitonic phase, remaining finite in the limit $L \rightarrow \infty$.

3.6. Singlet magnetic materials

There exists a class of materials—the so-called singlet magnetic materials—in which unpolarized light can not only alter the magnitude of the moments of the atoms, but it can also cause them to appear, when in the dark they were absent. By singlet magnetic materials, we mean rare-earth metals and their compounds in which the total moment of the ions J is different from 0, but, because of the removal of the degeneracy with respect to the directions of J by the crystal field, the average value of all three projections of J in

the ground state vanishes, i.e., the ion behaves as if it were nonmagnetic.

Such an ion acquires a moment in a magnetic field, but a moment can also appear owing to the exchange interaction with neighbors. For this the exchange J must exceed some critical value J_c of the order of the distance Δ from the singlet to the next level. In very many singlet magnetic materials J is close to J_c , and they therefore must be sensitive to external effects which alter the exchange.

The mechanisms responsible for the effect of light on singlet magnetic materials inducing magnetic moments in them, can be very diverse. In particular, the magnetization can appear because of the indirect exchange through the photoelectrons, described in Sec. 2.1. For characteristic parameters of the system (s-f exchange energy of ~ 0.5 eV, $\Delta \sim 10^{-3}$ eV), if J is assumed to be equal to 0, this requires a photoelectron density of $\sim 10^{18}$ cm $^{-3}$.⁷ If, on the other hand, the direct exchange integral J is ferromagnetic and is close in magnitude to J_c , then the conditions for the appearance of photoinduced moments must be much more favorable.

If the frequency of the light is close to the absorption edge, then the phase transition can be of first order. At a second order phase transition the rate of production of entropy has singularities, as described in Sec. 3.2.

Another possible mechanism for the action of light on singlet magnetic materials is by means of virtual transitions of electrons from the valence band into the conduction band, when the light frequency lies in the transmission band of the crystal¹⁸⁹ (a situation similar to that studied in Sec. 2.4).

Calculations have shown that when $J = 0$ and for excitation frequencies below 5 K the light gives rise to the appearance of magnetization if its frequency Δ is offset from the absorption edge by 0.01 eV, when the intensity in the field of the wave is $\sim 10^6$ V/cm.

An energetically more favorable process than the uniform distribution of photoelectrons over the crystal could be the formation of states of the ferron type (see Sec. 3.1), when the electron is self-trapped in some part of the crystal, giving rise to the appearance of a local magnetic moment in it. For $J < J_c$ in the rest of the crystal outside the region of localization of the electrons the moments J of the atoms vanish.^{104,105} At very high carrier densities they can combine into electron-hole drops of the type described in Sec. 2.5. The conditions for the formation of individual and collective ferrons with FM exchange are especially favorable when J is close to J_c : when $J \rightarrow J_c$ the moment created by each electron approaches infinity.

If the density of free photoelectrons is low, then the effect of illumination on the magnetic moments is manifested primarily through the photoelectrons trapped in attachment levels. Even in this case the effect is largest when $J \rightarrow J_c$.

In addition to the fact that the moment appears in the region of trapping of the electron, it also extends beyond the region. The radius of the magnetized region diverges as $|J_c - J|^{-1/2}$.¹⁰⁵ It has been observed experimentally that phosphorus vacancies in PrP induce magnetic moments in it.^{106,107} This leads to the expectation that moments induced by photoinduced effects can also appear in such materials.

4. PHOTOINDUCED CHANGE IN THE DOMAIN STRUCTURE AND ANISOTROPY

4.1. Change in the domain structure in circularly polarized light

It is evident that if light changes the exchange interaction and anisotropy, then it must also change the domain structure of a crystal. The effect of unpolarized light on domains is not large, since it is equivalent to a change in the exchange or renormalization of the anisotropy. This can change the dimensions of the domain wall. According to Refs. 63 and 108, a 10% increase in the thickness of a domain wall in a FM semiconductor requires a photocarrier density of $\sim 10^{19}$ cm $^{-3}$. Circularly polarized light has a much stronger effect on the domain structure. In this case its effect is similar to that of a magnetic field, i.e., it affects not only the thickness of the domain walls, but, much more importantly, it also affects the dimensions of the domains themselves.

The idea that circularly polarized light can alter the domain structure was apparently first stated in Ref. 17 in a discussion of optically induced dichroism in EuS.¹⁰⁹ Normally, owing to the domain structure, a ferromagnetic material in the absence of an external field has a zero total magnetization, since the number and dimensions of the domains with oppositely oriented moments coincide with one another. However, illumination with circularly polarized light directed along the magnetization increases the size of the domains with one of the orientations of the moment at the expense of domains with the opposite moment. This is explained by circular dichroism, determined by the difference in the coefficients of absorption k_+ and k_- for different circular polarizations. For this reason, when a magnetic semiconductor is illuminated with light with a definite circular polarization, different numbers of photoelectrons appear in domains with different orientations of the magnetization. Correspondingly, the intensity of indirect exchange is different in different domains. The same thing should occur in materials in which the light excites magnetic excitons: the number of excited excitons is different in different domains, and the exchange in domains changes differently. The possibility of the excitation of excitons owing to photoinduced transitions between levels of the Fe $^{3+}$ ion in IYG was pointed out in Ref. 110.

A detailed calculation of this effect was performed in Refs. 111–114. The domain structure was found directly from the minimum of the energy under the assumption that the domains differ from one another only by the value of the exchange integrals J_1 or J_2 . Strictly speaking, the use of the condition of minimum energy in systems with dissipation requires justification. It seems to us, based on (2.1), that the approach employed in Refs. 111–114 is correct, when the state of the magnetic subsystem depends only on the total number of photoelectrons and not on their momentum distribution. The simplest geometry, that of a plate whose easy axis is perpendicular to the plane of the plate, was examined in Ref. 114. The domains were regarded as strips. If the difference in the widths of the domains of two types is equal to α , then the reduction in the exchange energy owing to the

increase in the volume of the domains with the stronger exchange J_1 is evidently proportional to $\alpha(J_1 - J_2)$. On the other hand, there then arises an uncompensated magnetic moment $\sim \alpha$, creating magnetostatic energy proportional to its square, i.e., α^2 . The equilibrium value of α is found from the minimum of these two energies. This gives a relative change in the magnetization of

$$\frac{\Delta M}{M_0} = \frac{(J_1 - J_2) S^2}{4\pi M_0^2 \alpha^3}. \quad (4.1)$$

The relative change in the magnetization $\Delta M/M_0$ can be expressed in terms of the photoelectron densities in the domains and they, in their turn, can be expressed in terms of the circular dichroism $\Delta k = k_+ - k_-$:

$$\frac{\Delta M}{M_0} \approx 0,1 \frac{P \Delta k \tau (AS)^{1/2}}{\omega a m^{1/2} M_0^2}, \quad (4.2)$$

where P is the power flux of light with frequency ω , and τ is the lifetime of the photocarriers. For CdCr_2Se_4 with $\Delta k \sim 10^2 \text{ cm}^{-1}$, $P \sim 10 \text{ W/cm}^2$ and $\tau \sim 10^{-6} \text{ s}$ we obtain $\Delta M/M_0 \sim 10^{-2}$.

An analogous investigation was carried out in Ref. 112 for IYG, where the change in the volume is associated with the excitation of excitons on Fe^{3+} . In this case, since the exciton density is low, the excitons have a greater effect on the short-range order than on the long-range order. This, however, is not important for the domain energy in the limit $T \rightarrow 0$, and the calculation can be performed employing the same scheme as in Ref. 114. In Ref. 111 the Landau-Lifshitz domain structure with closing domains along the surface was studied on the basis of the same approximations, while in Ref. 113 cylindrical domains were studied. The dimensions of the latter are determined by the external magnetic field H_0 , and the effect of circularly polarized light on such a domain can be described in terms of some effective magnetic field H_{eff} . If it has the same sign as H_0 , then the light reduces the radius of the domain and the domain can even collapse. When H_0 and H_{eff} have opposite signs, the cylindrical domains transform into strip domains.

A different approach to the problem is proposed in Ref. 115. The effective magnetic field describing the action of the light was calculated in Ref. 115 by means of a generalization of the phenomenological calculation for uniaxial magnetic materials¹¹⁶ to the case of nonuniform structures. The generalization consisted of the fact that the coefficient of exchange rigidity α in front of the term $(\nabla M)^2$ in the expression for the energy density $E(x)$ was assumed to be coordinate-dependent. Leaving aside the standard question of the possibility of using the condition of minimum energy in the nonequilibrium case, we merely wanted to point out that for very narrow walls it is not self-evident that the contribution of terms containing $\nabla \alpha$ to $E(x)$ can be neglected. In Ref. 115 $\alpha(x)$ is evaluated under the assumption that α is determined by the photoelectron density. It was found that the effective field is proportional to the anisotropy factor β , i.e., the effect of the light on the domain structure increases with the anisotropy of the crystal.

As the authors of Ref. 115 themselves point out, in their calculation they did not take into account the possibility of electron diffusion along the crystal, determined by the non-

uniformity of the magnetization of the crystal (and, incidentally, it was also ignored in Refs. 111 and 114). Diffusion should decrease the effect, by reducing the degree of spin polarization of the electrons at any point in the crystal. Therefore localized photoelectrons must be more effective for restructuring the domain structure than free electrons. Since we agree with this conclusion¹¹⁵ we would also like to add that in Ref. 115 as well as in Refs. 111 and 114 the effect would have been larger if both the conduction photoelectrons and the photoelectrons transferred to attachment levels were taken into account there.

The direct observation of the photomagnetization of a many-domain sample of CdCr_2Se_4 by circularly polarized light was carried out in Ref. 22. A single-crystal sample of $\text{Cd}_{1-x}\text{Ag}_x\text{Cr}_2\text{Se}_4$ ($x = 0.02\%$) at 77 K was employed in the experiment. (In Ag-doped samples of CdCr_2Se_4 owing to the transfer of photoelectrons to local levels there is no increase in the local magnetization.⁸⁴) A laser with $\lambda = 1.06 \mu\text{m}$ and continuous radiation with power $P < 10 \text{ W/cm}^2$ was used. When the direction of rotation of the polarization is changed, the sign of the photomagnetization ΔM changes. For linearly polarized radiation $\Delta M = 0$. In an external magnetic field, close to saturation, $\Delta M = 0$, i.e., photomagnetization occurs only when the ferromagnetic material is in a demagnetized (multidomain) state. Photomagnetization is characterized by a short photoresponse time ($\tau < 10^{-4} \text{ s}$).

A detailed investigation of the effect for cases when the magnetization vector is both normal and parallel to the surface of the sample (Faraday or Cotton geometry, respectively) was carried out in Ref. 117. Since the demagnetizing field is higher for Faraday geometry, in this case the effect decreases more slowly with the field. The effect has a sharp maximum at 75 K. In the work the polarization and thermal effects of photomagnetization were carefully separated experimentally. Changing the wavelength of the irradiating light from $1.06 \mu\text{m}$ to $0.53 \mu\text{m}$, with the power remaining constant, reduces the polarization photomagnetization approximately by an order of magnitude, which is in agreement with the decrease in the magnitude of the dichroism with λ .

4.2. Effects induced by linearly polarized light

Linearly polarized light, in contrast to circularly polarized light, cannot give rise to the appearance of magnetization in the crystal by means of optical orientation of its spins. It can, however, substantially alter many properties of highly symmetrical crystals, including their domain structure. The physics here is entirely different from that studied in Sec. 4.1: the linearly polarized light removes the degeneracy with respect to the directions of the equivalent axes and thereby creates an easy axis of magnetization. Thus in the case of circularly polarized light the light has the greatest effect on the exchange, whereas in the case of linearly polarized light has the greatest effect on the anisotropy.

The mechanisms responsible for the change in the anisotropy could be of two types. First, the effect of photoinduced anisotropy is manifested only in doped crystals. It can therefore be assumed that the local change in anisotropy occurs as a result of transitions of electrons near the defect.

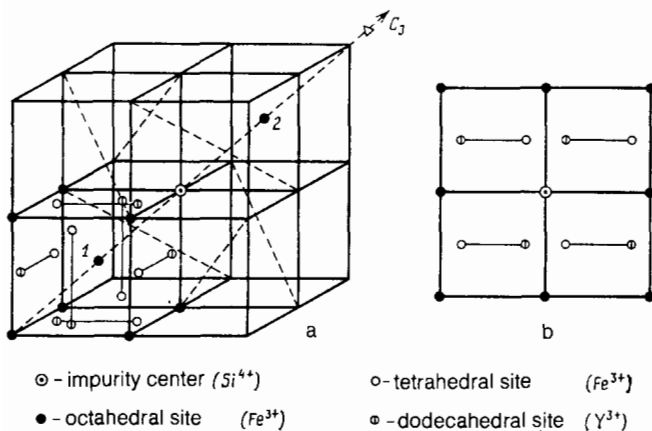


FIG. 5. a) The unit cell of $Y_3Fe_5O_{12}:Si$; the symmetry axis of the point group C_3 , characterizing the local environment of the octahedral impurity center, is indicated; the indices 1 and 2 mark the octahedral sites closest to the impurity center, for which the low-symmetry crystal field is equal to zero. b) Mutual arrangement of the cations in the (001) plane.

Such a transition is very often interpreted in a simplified manner as a redistribution of strongly anisotropic Fe^{2+} ions, coexisting in the IYG crystal with the normal (weakly anisotropic) Fe^{3+} ions, or Cr^{2+} ions with a high anisotropy amongst the Cr^{3+} ions in $CdCr_2Se_4$ (see, for example, Refs. 1 and 118). As already explained in detail in Sec. 2.2, this picture of fixed M^{2+} and M^{3+} ions is not consistent with either the theoretical or the experimental data. For this reason even those investigators who initially adhered to it now are beginning to reject it.⁷⁵

In reality, there is no need for such a model and the photoinduced change in the anisotropy can be explained on the basis of a more realistic model. We shall discuss this model for the example of IYG. In this model the charge of the Si ion is one unit higher than that of Fe^{3+} , and for this reason an extra electron appears near Si in order to compensate for this extra charge. If it is assumed that the electron is divided between the Fe ions in the vicinity of Si, then the wave function of the ground state of the complex formed will have the symmetry of the environment of the Si ion (see Sec. 2.2). A detailed analysis showed²⁰⁰ (Fig. 5) that the local symmetry on the impurity Si center is lower than cubic. In reality it corresponds to the point group C_3 or C_4 for octahedral or tetrahedral impurity centers. Octahedral centers are characterized by the predominant polarization of the electronic wave functions along one of the four equivalent axes $\langle 111 \rangle$. In the dark the numbers of centers of each type are the same, and there is no uniaxial anisotropy.

Under the action of the light the electron is transferred from the donor Si centers into the conduction band. If the light is linearly polarized, then centers with electronic polarization along one of the $\langle 111 \rangle$ axes are predominantly excited. Let us assume that the crystal is partially compensated: because of the presence of an acceptor impurity some of the donors are empty. Then an electron from the conduction band can be transferred into such an empty donor, and its axis of polarization can be different from that of the donor from which the electron is excited. This thereby reduces the population of donors of one of the four types owing to the

increase in the populations of other types, and uniaxial anisotropy appears.

Another possible mechanism for the appearance of anisotropy is the excitation of Frenkel excitons on magnetic ions in the neighborhood of a defect. In other words an extra electron does not appear in the neighborhood of a defect and its state does not change, while, for example, the d-shell of one of the Fe ions is excited. The Frenkel excitons, unlike electrons, as a rule, may be regarded as localized on definite atoms. (Because of the narrowness of the exciton band their polaron self-trapping is possible; see Secs. 2.2 and 3.3.) For this reason the polarization of light can have the effect of exciting those ions the anisotropy of whose excitonic states corresponds to the polarization of the light. The role of the effect in this case consists of the fact that by lowering the local symmetry it enables optical transitions which are forbidden in a perfect lattice. This mechanism can be realized if the Frenkel exciton is long-lived.

An extensive literature devoted to the experimental observation of the changes, primarily in the magnetic properties, brought about by linearly polarized light has accumulated. All these effects are caused by the same physical processes that give rise to the appearance of uniaxial anisotropy. They are unified by the common property that the magnitude of the photoinduced changes increases with the concentration of photoactive centers right up to the maximum possible value for injection into the crystal. These effects are observed only in IYG. In $CdCr_2Se_4$ and other photomagnetic materials the photo-induced effects, which depend on the orientation of the polarization vector of the irradiating light, are not observed.

4.2.1. Photoinduced uniaxial magnetic anisotropy. Linearly polarized light at constant temperature of the IYG:Si sample can induce reversibly in the sample a uniaxial magnetic anisotropy whose orientation and magnitude depend on the orientation of the polarization vector E relative to the crystallographic axes of the sample. An experiment was carried out in Ref. 27 on measuring the angular moment for the sample $Y_3Fe_{5-x}Si_xO_{12}$ ($x = 0.028$), cut out in the (001) plane. The sample was located in a saturating magnetic field $H \parallel [100]$ at a temperature of 4.2 K. The torque of the sample was equal to zero, since the $[100]$ direction, along which the field is applied, forms the same angles with all four directions of easy magnetization of the type $\langle 111 \rangle$. When the sample is illuminated with light with $E \parallel [110]$ the torque increases. After E turns into the new $[1\bar{1}0]$ direction the torque decreases, passes through zero, and changes sign (Fig. 6).

4.2.2. Photoinduced magnetic linear dichroism. The changes in the magnetic anisotropy of the crystal, of course, should also manifest themselves in the magneto-optics of the crystal. This was recorded in Ref. 27 in measurements of the magnitude of the dichroism $\Delta = I^{-1}(I_{110} - I_{1\bar{1}0}) \cdot 100\%$, where I_{110} and $I_{1\bar{1}0}$ are the intensities of the probing beam with polarization plane oriented along $[110]$ and $[1\bar{1}0]$, respectively, passing through the sample and I is the intensity of the unpolarized probing beam passing through the sample. The latter consisted of monochromatic light of low intensity with $\lambda = 1.2 \mu m$, for which the coefficient of optical absorption $k = 43 \text{ cm}^{-1}$. An external magnetic field of 8000

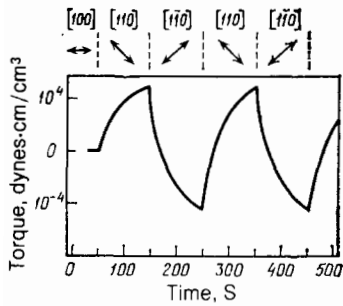


FIG. 6. Photoinduced torque of the sample $Y_3Fe_{4.972}Si_{0.028}O_{12}$ at 4.2 K.²⁷ The direction of the polarization vector is indicated at the top along the horizontal axis.

O_e was applied along the $[100]$ direction. The dichroism in this case is equal to zero because of the geometry chosen. However, because of the illumination, for which an intense source of white linearly polarized light was used, the quantity Δ varied, as shown in Fig. 7. During the illumination the photodetector was covered in order to prevent it from being saturated.

The two effects studied above were also studied experimentally and theoretically in Refs. 29 and 114–135.

4.2.3. *Photoinduced mechanical stress* was recorded in Ref. 30 in IYG:Si samples ($x = 0.028$ and 0.042) at temperatures of 4.2 K and 1.5 K. An external magnetic field $H = 8$ kOe was applied along the $[111]$ direction of the sample cut out in the (110) plane. When the crystal was irradiated with white light with $E \parallel [111]$ and $E \perp [111]$ a mechanical stress striving to stretch the crystal along the $[111]$ direction in the first case or compress it along the same direction in the second case was induced.

The photoinduced uniaxial anisotropy can be manifested in a most interesting manner in the change in the domain structure. The first indications of this possibility were obtained in Ref. 136 in the form of the possibility of photoinduced switching of magnetization. However, a clear and unequivocal proof of restructuring of the domain structure induced by linearly polarized light was first given in Refs. 23 and 24.

4.2.4. *Photoinduced switching of magnetization* was observed in Ref. 136 in a single-crystal $Y_3Fe_{4.98}Si_{0.02}O_{12}$ sample, cut out in the form of a disk with a (110) plane. The disk, magnetized up to 5 kG along $[1\bar{1}1]$, was cooled to 1.9 K. The magnitude of the linear dichroism induced by thermomagnetic annealing (see Sec. 4.3) was equal to 9.6% with the dichroism axis (direction of maximum transmission) ori-

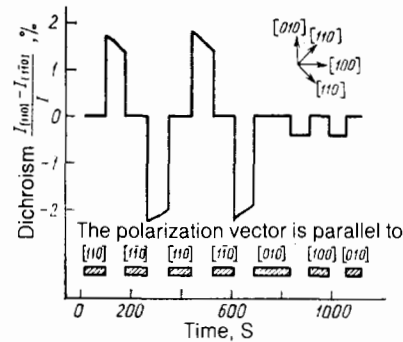


FIG. 7. Photoinduced optical dichroism in a sample of $Y_3Fe_{5-x}Si_xO_{12}$ ($x = 0.028$).²⁷ The sample is 0.05 cm thick. The (001) surface is illuminated. The temperature is equal to 1.5 K. For $\lambda = 1/2 \mu m$ the dichroism is $k_{[110]} - k_{[1\bar{1}0]} = 0.8 \text{ cm}^{-1}$.

ented along $[\bar{1}11]$. After the field was switched off, this value of the dichroism remained unchanged. This can happen if a domain structure with M along the $[\bar{1}11]$ and $[1\bar{1}\bar{1}]$ directions (180° domain boundaries) formed. The sample was then illuminated by intense (0.5 W/cm^2) white light with $E \parallel [\bar{1}11]$, which changed the magnitude of the dichroism (Fig. 8). If the polarization vector of the irradiating light is once again oriented along $[\bar{1}11]$, then the dichroism axis again returns to the old orientation $[\bar{1}11]$. The effects described above were not observed when the magnetic field was switched on. The authors explained their results in terms of photoinduced switching of the direction of magnetization $[111] \rightleftharpoons [\bar{1}\bar{1}\bar{1}]$.

4.2.5. *Photoinduced restructuring of the domain structure* was observed in Refs. 23 and 25 in a $Y_3Fe_{4.96}Si_{0.04}O_{12}$ plate cut out in the form of a disk in the (110) plane. The domain structure was visualized magneto-optically based on the Faraday effect with the help of a wide beam of light, probing the entire surface of the sample. This beam must have at least one of three properties: low intensity, photo-magnetically inactive wavelength (for example, $3.39 \mu m$), and the polarization vector E parallel to the axis of difficult magnetization of the plate. Then it can have no effect on the domain structure. The latter, in the absence of active illumination, at 77 K consists of labyrinthine domains with the vector M oriented perpendicular to the surface of the plate (a structure of the Faraday type). We note that in a plate the demagnetizing field strives to establish a different type of structure—the Cotton structure, in which the magnetization vector lies in the plane of the plate. The appearance of a

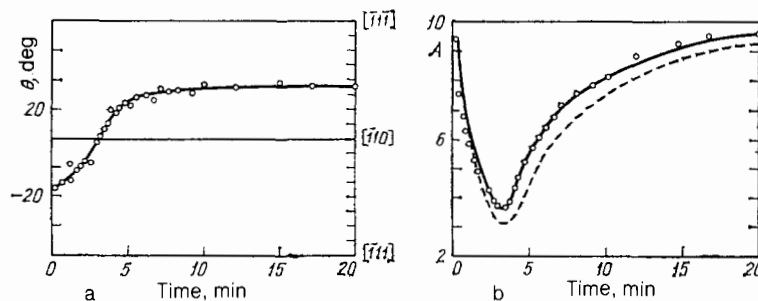


FIG. 8. The dependence of the angle θ between the axis of dichroism and the $[1\bar{1}0]$ direction (a) and the amplitude of the linear dichroism A (b) as a function of the illumination time of the sample of $Y_3Fe_{4.98}Si_{0.02}O_{12}$.¹³⁶

domain structure of the Faraday type in the demagnetized plate is caused by the presence of uniaxial magnetic anisotropy perpendicular to the surface of the plate. This anisotropy probably appears as a result of mechanical working of the plate and, as was verified, is removed by thermal annealing and etching of the surface with acid.

When the plate is illuminated by active light with a wavelength of $1.15 \mu\text{m}$ the domain structure changes: the initial structure of the Faraday type transforms into band-like 180° domain boundaries of the Cotton type. This change depends on the orientation of the polarization vector of the active light relative to the crystallographic axes of the plate (Fig. 9a). It is evident that light with \mathbf{E} oriented parallel to the axis of difficult magnetization, has no effect on the domain structure. (This property is used for the probing beam.) The orientation of the vector \mathbf{M} changes when the axis of easy magnetization, lying in the plane of the sample, is reoriented. Its role is played by the spatial diagonal with which the vector \mathbf{E} forms the lowest angle.

By changing the orientation of the polarization vector it is possible to change the axis of easy magnetization, giving rise at the same time to a corresponding restructuring of the

domain structure of the Cotton type (Fig. 9b). This process is reversible.

After the active light is switched off the nonequilibrium domain structure remains as long as the nitrogen temperature is maintained—for at least 24 hours.^{196,201}

The wavelength of the active light lies at the edge of the absorption band of IYG, where the sample is transparent to a large degree (for $\lambda = 1.15 \mu\text{m}$ the absorption coefficient $\alpha \sim 40 \text{ cm}^{-1}$). This fact can be employed in practical applications of the effect.^{201,202}

4.3. Effect of unpolarized light on magnetic anisotropy

This effect is observed primarily in the presence of an external magnetic field or residual magnetization in after-effects. It has a number of specific manifestations.

4.3.1. Photomagnetic annealing and change of the cubic anisotropy. The induction of uniaxial magnetic anisotropy in ferrites with a cubic structure by means of their thermomagnetic annealing is well known.¹³⁷⁻¹⁴⁰ The annealing regime consists of cooling the ferrite (often, but not necessarily, with a transition through the temperature of magnetic ordering) in an external magnetic field, as a result of which a uniaxial magnetic anisotropy is induced in it. It was observed in Ref. 33 that light increases the rate of relaxation of the uniaxial magnetic anisotropy induced by annealing in IYG:Si. Unpolarized light, in addition to changing the rate of relaxation of the anisotropy induced by annealing, can by itself give rise to the appearance of uniaxial magnetic anisotropy in magnetized IYG:Si samples.³¹ For this at the moment that the sample is illuminated by unpolarized light an external magnetic field is applied to it. This phenomenon, in analogy to thermomagnetic annealing, is called photomagnetic annealing. The effect of photomagnetic annealing in an FMR field³¹ is equivalent to further cooling of the sample. Photomagnetic annealing must be carried out at low temperatures (4.2, 20, 66 K³³ and 77 K³¹) in order to eliminate thermoactivated relaxation.

As later experiments¹⁹⁵ showed, however, unpolarized light can affect the magnetic anisotropy of IYG:Si even in the case when both cooling of the sample and subsequent action of light on it occur in the absence of a magnetic field. The experiment was performed at 77 K on single-crystal samples in the form of plates and epitaxial films of IYG:Si. The saturation time of the effect with an active light intensity of $6 \cdot 10^{-2} \text{ W/cm}^2$ was equal to ~ 10 min. The quantity δH_r relaxed over the same period of time after the light was switched off. The effect occurred for both white and monochromatic ($\lambda = 0.63$ and $1.15 \mu\text{m}$) light. The geometry of the sample is such that one of the local symmetry axes $\langle 111 \rangle$ is perpendicular to the surface of the sample cut out in the $\langle 111 \rangle$ plane. The axes of the three other states emerge at the same angle of 19.5° from the surface of the sample. Thus these three axes are not equivalent to the fourth axis. This effect has a simple explanation.

The sample contains complexes which themselves contain Si ions. In each such complex the electronic wave function is elongated along one of the axes $\langle 111 \rangle$. Since the orientation of the propagation vector of the light is fixed, the plane

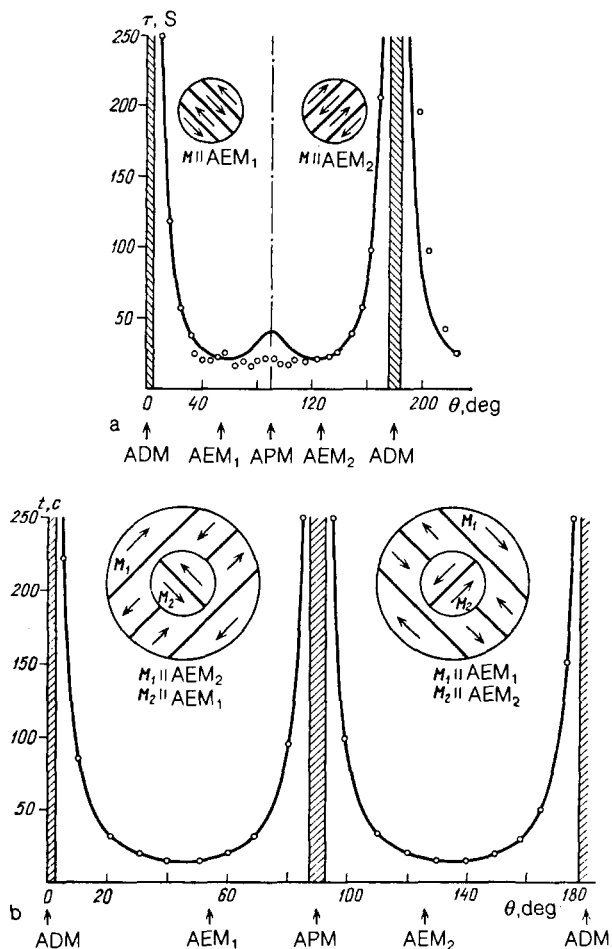


FIG. 9. The time for photoinduced destruction of the domain structure of the Faraday type (a) and restructuring of the domain structure of the Cotton type (b) in a $\text{Y}_3\text{Fe}_{4.96}\text{Si}_{0.04}\text{O}_{12}$ plate in the $\langle 110 \rangle$ plane as a function of the angle of orientation of the polarization vector of the irradiating light.²⁴

in which the electric vector of the light lies is also fixed. In this plane all its directions are equivalent and therefore it excites with equal probability the three states of the complexes in which the projection of the $\langle 111 \rangle$ axis on this plane is the same. The probability for exciting the fourth state, polarized perpendicular to the electric vector, is, however, much lower.¹⁹⁴

It was recently observed that unpolarized light affects the magnetic aftereffect in spin glass.¹⁴¹ Nonconducting cobalt aluminosilicate glass at $T \sim 1.3$ K was subjected to unpolarized light in the near-IR region with a maximum power density of $3 \cdot 10^{-4}$ W/cm². The effect was manifested as a change in the relaxation of the magnetization, occurring after the magnetic field was switched off. The rotation of the plane of polarization of the probing beam (according to the Faraday effect) was measured.

The effect of unpolarized light on the anisotropy of CdCr₂Se₄:Ga in a magnetic field was studied in Refs. 84, 85, and 144. For this, the change in the components of the magnetization parallel to the field (M_{\parallel}) and perpendicular to the field (M_{\perp}), induced by the laser radiation (energy density $3 \cdot 10^{-2}$ J/cm², $\tau_p = 20$ ns, repetition frequency = 12.5 Hz, and $\lambda = 1.06$ μ m) was measured. It was found that in fields less than the field at which the domain structure vanishes H_s , both M_{\parallel} and M_{\perp} are increased by the light. In fields exceeding H_s the "light-induced" correction to M_{\parallel} changes sign, while the correction to M_{\perp} remains positive, though it decreases as the field increases. The effect is very sensitive to the Ga concentration in the samples. The possibility of photomagnetic annealing was not studied in Refs. 84, 85, and 144. The authors believe that the symmetry of the anisotropy Hamiltonian is not changed by the unpolarized light and only the cubic anisotropy constant changes. However, the microscopic model which they proposed reduces to the appearance of Cr²⁺ ions, exhibiting large anisotropy, under the action of the light. The inadequacy of this model was already pointed out in Secs. 2.2, 2.5, and 4.2.

4.3.2. Photoinduced magnetic birefringence in FeBO₃ was measured in Ref. 32 based on the ellipticity of the polarization of the probing light ($\lambda = 0.51$ μ m) at the outlet from the crystal (Cotton-Mouton effect). In this material the natural magnetic birefringence in fields $H \geq 100$ Oe, applied in the basal plane, is equal to $\Delta n = 1.5 \cdot 10^{-4}$. The change in the latter induced by additional illumination of the sample by intense white light by an amount $\pm \delta n = 10^{-6}$ depends on, in addition to the exposure time, the direction and intensity of the magnetic field in which the sample is illuminated. The sign of the photoinduced magnetic birefringence changes under continuing illumination and when the orientation of the magnetic field is changed to the perpendicular orientation. As the intensity of the field is raised, δn increases, and saturates in fields $H \geq 100$ Oe. The saturation is attained under illumination with an intensity of 1 W/cm² for ~ 1.5 min. The photoinduced state remains after the illumination is switched off with the temperature maintained at 78 K without appreciable relaxation for quite a long time, but is removed when the sample is heated up to 130 K. The spectral dependence of the effect in the wavelength range from 0.5 to

0.7 μ m is virtually free of dispersion. The study of this effect continued in Ref. 142 but carried out not on the basis of the measurement of the ellipticity of the light wave, but rather the measurement of the photoinduced rotation of the plane of orientation owing to the Cotton-Mouton effect, demonstrated the complicated nature of the spectral dependence of the effect in the near-IR region of the spectrum.

The determination of the orientation of the anisotropy axis induced in iron borate showed¹⁴³ that the easy axis of anisotropy is oriented perpendicularly to the magnetic moment, whose orientation is fixed by the external field at the time of illumination.

Based on the effects observed in FeBO₃, photoinduced formation of optical and local magnetic nonuniformities with different optical gradation in contrast is possible.¹⁴²

4.3.3. Photoinduced instability of the domain structure. A new manifestation of photomagnetism, previously not observed in any other material, was observed in FeBO₃:Ni.^{62,187} The effect consists of the fact that under illumination with light in the spectral region 0.8–1 μ m, in addition to jumps and displacements of separate domain boundaries over some appreciable distance observed in the sample at 78 K (see Sec. 5.1), the substructure appearing in the sample in the form of thin bands of three types, differing by their orientation relative to one another at an angle of 60° or 120°, executes a collective displacement. The rate of this displacement is equal to tens of microns per second and increases with the intensity of the exciting light. The direction of motion is perpendicular to the direction of the bands of the substructure and can for no apparent reason be oriented in one of three directions. The sources and sinks of the moving bands are domain boundaries and surface defects in the crystals. The period of the moving lattice is equal to several tens of microns. When a filter is inserted into the exciting light flux, cutting off the active near-IR region, the motion of the band substructure and the jumps of the domain boundaries disappear.

The phenomenon described above occurs in the absence of an external magnetizing field. The effect of a magnetic field on the parameters of the dynamic substructure is manifested as a change in the period of the substructure and also as a predominant separation from the three existing types of substructures of the particular substructure whose direction of motion is close to the direction of the magnetic field.

As also other photoinduced effects in FeBO₃, the observed effect exists only up to a temperature of ~ 130 K.

The following mechanism for the photoinduced motion of the domain walls in FeBO₃:Ni is proposed in Ref. 192. It is assumed that the values of the anisotropy constants are close to those at which the reorientational first-order phase transition between states with mutually perpendicular moments occurs. The light exciting the ions changes the anisotropy constants. Since the absorption of the light depends on the direction of the moments, a nonuniform distribution of the excited ions appears along the crystal. Because of this there appear pressure forces which act on the domain walls and force them to move. This process can be classified as an autowave process.

4.4. Effect of light on resonance phenomena

4.4.1. *The effect of light on FMR in CdCr₂Se₄* was first observed in Refs. 145 and 146; the effect was studied in greater detail in Ref. 147. The effect of light on FMR was manifested as an increase in the FMR field in the temperature range from 77 K up to the Curie temperature (~ 130 K) when the samples were illuminated by pulses of white light with a duration of $\lesssim 1$ ms and an intensity of $\sim 10^{-1}$ W/cm². At the same time the line width and the amplitude of the absorption signal changed insignificantly. The relaxation time for relaxation to the starting field was equal to $\sim 10^{-1}$ s. The magnitude of the effect and the relaxation time depend substantially on the intensity and duration of the light pulse, the temperature, and the wavelength of the incident radiation. It was established that the spectral region of maximum sensitivity in this case lies in the region of $1 \mu\text{m}$.

For tangential magnetization of diskotic samples the change in the FMR field ($\delta H_r = H_r^c - H_r^T$) is positive, i.e., the illumination with light increases the resonance field. When the sample is magnetized perpendicular to its surface, the sign of δH_r becomes positive, and the magnitude of the change is two times higher than in the case of parallel magnetization. For $\varphi = 45^\circ$ no change is observed (Fig. 10). The observed effect is isotropic relative to the crystallographic directions.

4.4.2. *The effect of an electric field* on the photoinduced change in the FMR parameters consists of the fact that when the electric-field intensity exceeds some threshold value ($E > E_{\text{th}}$) the quantity δH_r increases severalfold compared with the case when there is no electric field (up to 50 Oe instead of 5–10 Oe). Under illumination intensities of $I > I_0 \sim 10^{-2}$ W/cm² in fields of $E \sim 1$ kV an instability associated with the spontaneous change in δH_r is observed. Turning on the electric field in the dark does not change H_r .

Combined studies¹⁴⁷ of the electric, photoelectric, and photomagnetic properties of CdCr₂Se₄ showed that they are definitely interrelated. Thus, for example, illumination of a sample of CdCr₂Se₄ with monochromatic light ($\lambda = 0.88 \mu\text{m}$) gives rise to an instability in the electric subsystem also: self-excited oscillations of the photocurrent, whose amplitude and frequency depend on the intensity of the light and the magnitude of the electric field, appear in the current-

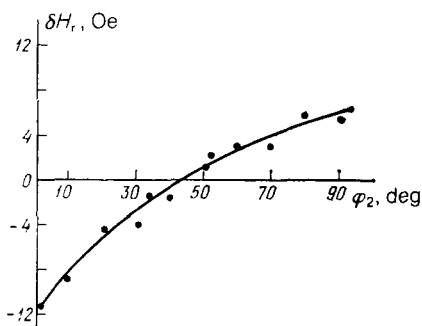


FIG. 10. The photoinduced change in the FMR field as a function of the angle φ between the external magnetic field and the normal to the surface of a CdCr₂Se₄ sample.¹⁴⁶

voltage characteristic. In addition, the observed “quenching” of photoconductivity in CdCr₂Se₄ has an analog in the photoinduced shift of the FMR field.¹⁴⁷ This phenomenon consists of the fact that when the CdCr₂Se₄ sample is simultaneously irradiated by two independent light sources (constant illumination with $\lambda = 0.88 \mu\text{m}$, giving rise to a photocurrent and δH_r , and additional “extinction” illumination with white light or with light with $\lambda = 0.94 \mu\text{m}$) the strength of the photocurrent and the value of δH_r decrease.

4.4.3. *Photoinduced broadening of the FMR absorption line* was observed in Ref. 148 in polycrystalline samples of IYG:Si at 77 K. Since the FMR line width is associated with relaxation processes, it may be assumed that the centers newly formed by the action of the light create a more intense relaxation channel. The nature of this channel, however, requires further study.

The effect of optical excitation of Ho³⁺ impurity ions on FMR in IYG¹⁴⁹ is manifested as a change in the line width and shift of the resonant field. The relaxation time of ~ 5 ms is associated with the lifetime of the Ho³⁺ ion in the excited state followed by a radiative transition with energy $\sim 400 \text{ cm}^{-1}$. Lasing at $\lambda = 2.1 \mu\text{m}$ was achieved on this transition.¹⁵⁰ The effect of pulsed laser radiation with $\lambda = 1.06 \mu\text{m}$ on FMR in IYG:Ho vanishes at a temperature of ~ 25 K.

4.4.4. Light also affects the *parameters of the resonance line of the domain boundaries* in epitaxial films with the composition (YBi)₃(FeGa)₅O₁₅,¹⁵¹ increases the resonance frequency, and broadens the absorption curve. This change in the resonance curve of domain boundaries indicates that the parameters characterizing the boundary change, namely, k/m and β/m increase, where k is the coefficient of elasticity, β is the damping factor, and m is the effective mass.

4.4.5. *A photoinduced change of the spin-wave resonance spectrum (SWR)*^{152–154} was observed in epitaxial Y₃Fe₅O₁₂ films, specially doped with silicon or annealed in an oxygen atmosphere. The critical angles between the external magnetic field and the normal to the surface of the film, at which the SWR modes are excited, depend on irradiation with unpolarized light.

Photoinduced uniaxial magnetic anisotropy was also observed in FeBO₃,⁴⁷ when the field of the magnetoacoustic resonance at a frequency of 1.25–2.5 MHz was measured at 77 K. This field changed after the sample was illuminated for 60 sec with white light with an intensity of 10^{-4} W/cm².

5. EFFECT OF LIGHT ON THE MOTION OF DOMAIN WALLS, MAGNETIC SUSCEPTIBILITY, AND COERCIVE FORCE

5.1. Experimental data

We mention at the outset that the effects studied in this section are not polarization sensitive, i.e., they are observed under the action of unpolarized light. We also point out the well-known fact that defects in crystals (point and linear) affect the kinetics much more strongly than the thermodynamic properties of the crystal. This is also observed when magnets are illuminated with light: photoinduced defects affect much more strongly the kinetics of magnetization than

its stationary value, which results in the fact that the effects studied in this section are, as a rule, produced by low-power sources of light (incandescent lamps), although, as we saw in Sec. 4, for other effects laser sources are required. Finally, the effects studied in this section are also unified by their concentration dependence: they all pass through a maximum as a function of the concentration.

We shall indicate the materials in which the effects studied in this section are observed.

1. $\text{Y}_3\text{Fe}_5\text{O}_{12}$ with Si,^{33,34} Co,³⁶ Ca,³⁷ Mn,³⁸ Cu,³⁹ Pb,⁴⁰ Ni,⁴¹ Ti,^{42,43} Zr,⁴³ and Sr⁴⁴ as impurities.
2. CdCr_2Se_4 with Ga²⁸ and Zn⁴⁵ as impurities.
3. FeBO_3 with the impurity Mg, Cu, and Ni.⁴⁶⁻⁴⁸
4. Li-ferrite, doped with Ru⁴⁹ and Li-ferrite with the composition $\text{Li}_{0.5}\text{Fe}_{2.5}\text{O}_{4.0}$.⁵⁰
5. Mn-Mg-ferrite,⁵¹ Mg-ferrite with Co impurity,⁵² and Mn-ferrite.⁵³
6. Li-Mn ferrite.⁵⁴
7. Ni-Zn-Ferrite with Co impurity.^{55,56}
8. Fe_3O_4 (magnetite).⁵⁷

5.1.1. Photoinduced change in the magnetic permeability was first observed³⁴ in a single-crystal sample of IYG:Si; the dynamic magnetic permeability $\mu(\omega)$, measured at a frequency of 10 kHz of a field of extremely low amplitude, decreased under the action of white light.

The spectral characteristic of the effect in IYG:Si was measured in Ref. 157 in a series of epitaxial films. This enabled excluding the strong absorption of optical radiation with short wavelengths, observed in massive samples.³⁴ The spectral dependence of the effect is characterized by the same features as is the optical absorption spectrum. The effect is observed, beginning at the edge of the optical absorption band ($\lambda \sim 1.2 \mu\text{m}$) and right up to $\lambda \sim 0.3 \mu\text{m}$. For another photomagnetic material— FeBO_3 —the spectral characteristic of this effect is just as wide: from $0.4 \mu\text{m}$ to $1.0 \mu\text{m}$.⁴⁶ In CdCr_2Se_4 the active part of the spectrum for the photomagnetic effect ranges from 0.6 to $1.2 \mu\text{m}$.¹⁶⁸

The photoinduced change $\Delta\mu(\omega)$ in the high-frequency susceptibility $\mu(\omega)$ was also observed in CdCr_2Se_4 .²⁸ The spectral characteristic of the effect was then studied in Ref. 206 (Fig. 11). Its comparison with the spectral characteristic of photoconductivity, presented in the same figure, shows that the maximum of $\Delta\mu$ lies in the same spectral region II as does the maximum in the photoconductivity spectrum at 77 K. This maximum is absent at 300 K.

The effect of photoinduced change in μ can also be observed in polycrystalline samples of photomagnetic materials.¹⁵⁸ It turned out that the magnitude and rate of change in this case is even higher than that of the analogous parameters in single-crystal samples. The main difficulty in carrying out experiments with polycrystalline samples of photomagnetic materials is that they have poor optical characteristics compared with single crystals. For this reason, special methods, which reduce the porosity of the samples, are employed to prepare the polycrystals, and the thicknesses of the light-transmitting samples are selected.

An investigation of the temperature dependence of the effect shows that, for example, in IYG:Si_{0.006} it persists up to

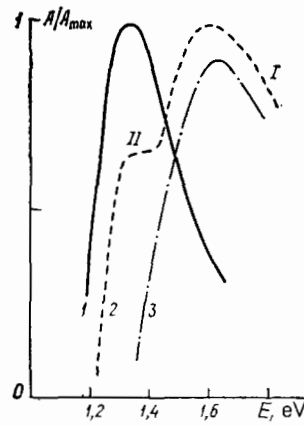


FIG. 11. The spectral dependence of the photoinduced magnetic permeability (1) and photoconductivity at 77 K (2) and 300 K (3) in CdCr_2Se_4 .²⁰⁶

temperatures of ~ 150 – 200 K (Fig. 12). The photoinduced part of μ can be partially restored during the magnetization of the photomagnetic material.^{46,159} The dependence of $\Delta\mu$ on the magnetic field indicates that it affects the state or the number of photosensitive centers.

We shall now discuss the case of arbitrary magnetic fields, with whose help $H_m \sin \omega t$ is measured. The permeability $\mu(\omega)$ is itself a function of H_m . As was first shown for IYG:Si,⁶¹ and then for CdCr_2Se_4 :Ga,¹⁶¹ the magnitude and nature of the change in the photoinduced permeability $\mu(\omega)$ depend on the amplitude of the remagnetizing field (Fig. 13). There exists an optimal value $(H_m)^{\text{opt}}$, at which the magnitude of the photoinduced change in the permeability $\Delta\mu$ is maximum and the photoresponse time is minimum. For an illuminated sample the curve $\mu(H_m)$ in the region of low values of H_m contains a section where $\mu(\omega)$ is constant. Even the saturating constant magnetic field does not transfer the sample out of the permeability-invariable (perminvar) state. A temperature analog of the permeability-invariable state was observed in CdCr_2Se_4 ¹⁶⁵: the curve $\mu(T)$ also contains a section with constant μ . Thus the light-stabilized domain boundaries can be stripped away from the pinning centers not only by an alternating magnetic field, but also by

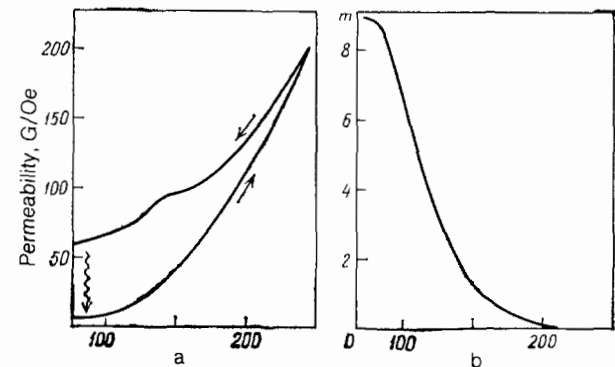


FIG. 12. The temperature dependence of the initial magnetic permeability of a single-crystal sample of IYG:Si_{0.006} (a) and the value of $m = 10^{-2} [(\mu^L)^{-1} - (\mu^D)^{-1}]$.¹⁵⁸

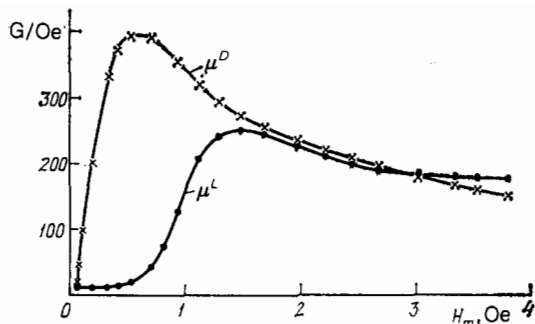


FIG. 13. The magnetic permeability of a sample of $Y_3Fe_{4.96}Si_{0.04}O_{12}$ at 77 K in the dark (μ^D) and after illumination (μ^L) as a function of the amplitude of the remagnetizing field ($H = H_m \sin \omega t$).⁶¹

heating. In both cases this effect is a threshold effect.

5.1.2. Photoinduced jumps in the susceptibility and magnetization. If the value of H_m is chosen near $(H_m)^{opt}$, then after the beginning of illumination $\mu(\omega)$ in IYG:Si drops as a function of time not continuously, but rather by jumps (Fig. 14).^{61,160,162} They are reminiscent of Barkhausen jumps on the curve of the magnetization as a function of the field in the region of domain restructuring. The magnitude of the jumps in $\mu(t)$ is, however, much higher. The regions of photoinduced jumps in $\mu(t)$ precedes the region of the unstable state (Fig. 14). This is manifested in the fact that if the light is switched off at the moment of the jump, then oscillations arise in the magnetic permeability with quite a long (~ 0.5 – 3 min) period of relaxation toward increasing μ . This manifestation of the instability of the domain structure on the screen of the spectrum analyzer is observed in the form of "white" noise in the region of higher-order harmonics of the magnetic permeability.

After the photoinduced jump the spectrum of the magnetic permeability contains only the first harmonic, i.e., $B(H)$ varies according to a linear law, which is confirmed by measurements of the magnetization curve and indicates a

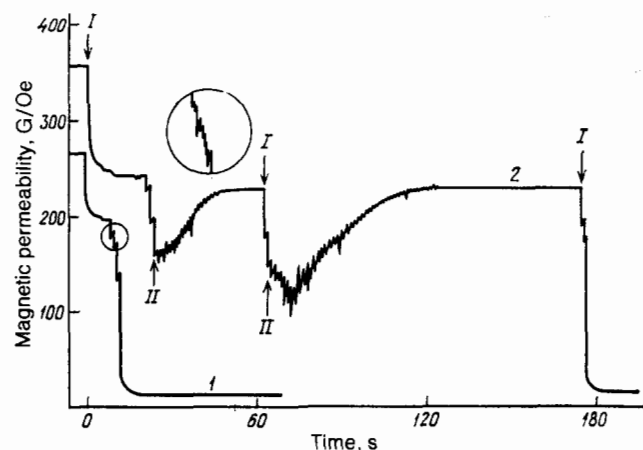


FIG. 14. The time dependence of the magnetic permeability of a single-crystal sample of $Y_3Fe_{4.96}Si_{0.04}O_{12}$ at 77 K.¹⁶⁰ I) Moment at which the light is switched on, II) moment at which the light is switched off. Curve 1: $H_m = 0.25$ Oe; 2) $H_m = 0.4$ Oe.

transition of the material into the permeability-invariable state. As a result of the photoinduced jump the amplitude of the third harmonic of the magnetic permeability decreases by more than a factor of 400. At the same time the first harmonic decreases approximately by a factor of 30.

The effect of light on field-induced Barkhausen jumps in IYG:Si was studied in Ref. 163. They were also observed in $CdCr_2Se_4$.¹⁶⁴ A visual investigation of the dependences of the amplitude of the oscillations of the domain boundary in this photomagnetic material as a function of the intensity of the alternating field H_m ⁶⁰ showed that large jumps occur in the magnitude of the displacement of the boundary. In the absence of illumination a jump is observed if the amplitude of the field H_m exceeds some field H_1 , while under illumination the jump is observed at a significantly higher field H_2 . A large photoinduced drop in the amplitude of the oscillations of the boundary occurs in the region of fields $H_1 < H_m < H_2$. Analogous results on the presence of an extremum as a function of the photoinduced change in μ as a function of H_m were obtained previously^{61,160} for IYG:Si, which indicates the generality of the details of the effect and its mechanism in different photomagnetic materials.

The direct observation of domain boundaries by the magneto-optical method first in IYG:Si⁵⁸ and then in $CdCr_2Se_4$ ^{59,60} enabled observing directly the stabilization of the motion of individual boundaries in an alternating magnetic field when the sample is illuminated by light right up to their complete stopping.

The effect of light on the magnetic permeability of $FeBO_3$ has the characteristic that μ can both decrease and increase depending on the dopant.^{46,47} For nominally pure (specially undoped, but, according to a chemical analysis, containing $\sim 0.5\%$ iron ions in the bivalent state) $FeBO_3$ at 77 K a photoinduced increase in $\mu(\omega)$ is observed. On one section of its growth μ exhibits low-amplitude oscillations as a function of the illumination time. Illumination of the $FeBO_3$ samples with a Cu or Mg impurity gives rise to a smooth decrease of $\mu(\omega)$.

Together with the optical quenching of photoconductivity and of the photoinduced shift in the FMR field in $CdCr_2Se_4$ ¹⁴⁷ (see Sec. 4.3), the photoinduced change in $\mu(\omega)$ is also quenched.¹⁶⁵ It is manifested as follows. At low temperatures of ~ 40 K for $CdCr_2Se_4$ after the illumination is switched off a residual amount $\Delta\mu$ is observed: only part of $\Delta\mu$ relaxes over a time of ~ 1 min. The change $\Delta\mu$ decays completely in several hours. (It should be noted, however, that a residual conductivity is not observed in this case.) If at the time t_3 (Fig. 15) the sample is illuminated by additional light with energy ~ 0.7 eV and an intensity up to 10^{-4} W/cm², then total decay of $\Delta\mu$ is observed over a time of ~ 2 min. The radiation giving rise to extinction of $\Delta\mu$ falls in the spectral range from 0.45 eV to 1 eV.

Definite information on the mechanism determining the dependence of μ on the intensity of the illumination could be obtained from data on the relaxation of $\mu(\omega)$ after the light is switched off. The change in $\Delta\mu$ persists for a long time after the light is switched off at low temperatures (77 K for IYG:Si and 4.2 K for $CdCr_2Se_4$), but vanishes rapidly at

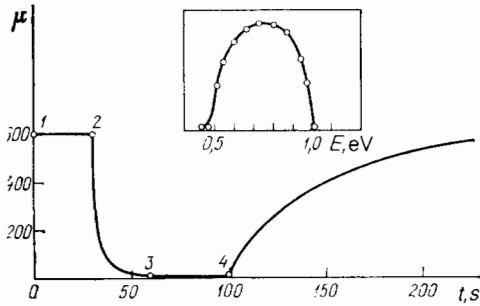


FIG. 15. Effect of light on the magnetic permeability at $T \sim 7$ K.¹⁶⁵ 1) CdCr_2Se_4 sample in the dark; 2) light with energy 1.1 eV is switched on; 3) light is switched off; 4) infrared illumination with an energy of ~ 0.7 eV is switched on.

higher temperatures (~ 175 K for IYG:Si and 77 K for CdCr_2Se_4). Unfortunately, the experimental data on this question do not yet permit constructing an unambiguous picture. According to Ref. 28, relaxation in CdCr_2Se_4 at $f = 10$ kHz and $T = 77$ K proceeds very slowly with $\tau \sim 10$ s. According to Ref. 166, where the frequency of the alternating field, unlike Ref. 28, was equal to 2.6 MHz, the relaxation time in this material is three orders of magnitude lower. On this basis it was proposed in Ref. 167 that a fundamentally new effect, determined by a different mechanism than that observed in Ref. 28, was observed in Ref. 166. However, in Ref. 161, which describes work carried out in the same laboratory, there is no mention of the results and conclusions of Refs. 166 and 167, and the results of Ref. 28 are in fact confirmed.

To resolve this contradiction the dependence of μ on the strength and frequency of the magnetic field, giving rise to the remagnetization, was studied in Ref. 169. It was found that τ decreases as these quantities are increased. In Ref. 169 Kuznetsov and Makhotkin stated that this dependence of the relaxation time indicates the existence of an entire spectrum of defects which retard the domain wall. The stronger is the field the less are the defects capable of effectively affecting the boundary, and the situation with increasing ω is analogous. The ideas regarding a new type of photomagnetism¹⁶⁷ are not used in Ref. 169. They also are not used in Refs. 168 and 170, where the dependence of τ on the dopant concentration and the concentration of point and extended defects (dislocations, pores, etc.) as well as on the wavelength of the irradiating light was observed.⁴⁾ The investigation of this question should be completed.⁵⁾

In this connection, we call attention to the opinion, which in our view is incorrect and which is encountered quite often in the literature (see, for example, Ref. 171) that the time constant of the photoinduced effects in IYG is much larger than in CdCr_2Se_4 . In reality the photoresponse time in IYG:Si was determined even in the pioneering works on photomagnetism to be $2 \cdot 10^{-2}$ s,³³ less than 10^{-4} s in Ref. 34, and less than $6.6 \cdot 10^{-7}$ s in Ref. 43.

We note that the magnetic permeability of IYG can vary not only under the action of light, but also under the action of x - and γ -rays on the sample, as well as under electronic bombardment.^{34,172-174}

5.1.3. *The effect of light on the magnetic hysteresis loop* was first observed³⁴ in a single-crystal sample of IYG:Si. At the same time the coercive force was observed to change from 0.8 Oe for the unilluminated sample to 2 Oe for the sample after illuminating the squareness factor of the loop also changed. The effect of light on the parameters of magnetic hysteresis has been observed in other materials also: polycrystalline IYG:Si,¹⁵⁸ lithium ferrite $\text{Li}_{0.5}\text{Fe}_{2.5}\text{O}_4$ doped with ruthenium,⁴⁹ nickel-zinc ferrite with cobalt impurity $\text{Co}_x^2 + \text{Co}_y^3 + \text{Fe}_{4-y}\text{O}_4$,¹⁵⁵ and the magnetic semiconductor CdCr_2Se_4 ³⁵ and FeBO_3 .⁴⁸

The magnitude and nature of the photoinduced changes in the parameters of the hysteresis loop as well as the time required to establish them depends, as it does also in the case of magnetic permeability, substantially on the amplitude of the remagnetizing field H_m . In the region of optimal values of H_m , in which the photoinduced jump of the magnetic susceptibility was observed, the hysteresis loop also undergoes a jump with increasing illumination time (Fig. 16). This jump occurs in the course of the illumination of the sample in the form of a collapse of the magnetic hysteresis loop and its transition into the hysteresis-free remagnetization cycle.¹⁶⁰

5.2. Nature of photopinning of domain walls

It is well known that in fields at which the domain structure exists the magnetic permeability is determined primarily by the restructuring of the domain structure: growth of domains with energetically favorable direction. In addition, the moments of the remaining domains rotate in space. It is also well known that the motion of the walls between domains and therefore $\mu(\omega)$ at finite frequencies are very sensitive to the degree of defectiveness of the crystal. In principle, the rotation of the moment should also be affected by defects as soon as they alter the anisotropy of the crystal, but this effect is much weaker, and for this reason will not be discussed here.

Many types of defects create a potential well for the domain wall: its energy decreases owing to the interaction with defects. It is qualitatively clear what properties the defects must have in order for this to happen from the fact that in a uniaxial magnet the specific energy of the domain wall is proportional to $(KJ)^{1/2}$, where K is the anisotropy constant and J is the exchange integral.^{116,177,178} For this reason it is energetically favorable for it to be situated in regions with low anisotropy and exchange intensity. In particular, it is actively trapped in nonmagnetic regions.

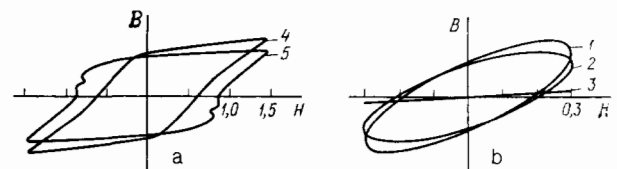


FIG. 16. Remagnetization curves $B(H)$ for different amplitudes of the remagnetizing field.¹⁶⁰ H_m (Oe) = 1.5 (a) and 0.3 (b). The curves 1 and 4 were measured for the sample of $\text{Y}_3\text{Fe}_{4.96}\text{Si}_{0.04}\text{O}_{12}$ at 77 K in the dark, 2) after 5 s, 3) after 20 s, 5) 100 s after illumination was switched on.

Naturally, potential wells for boundaries hinder their motion in magnetic fields, thereby decreasing $\mu(\omega)$. The trapping of domain walls by potential wells also explains the existence of a coercive force and Barkhausen jumps: in order to alter the magnetization of the sample an external magnetic field strong enough to tear the wall out of the potential well must be applied.

As discussed in Secs. 2 and 4 the action of light gives rise to the appearance of centers with elevated values of the anisotropy and exchange. Regions where there are anomalously few such centers could play the role of potential wells for walls. In this connection we call attention to the fact that the interpretation of the photostopping of domain walls given in Refs. 84, 144, and 180 is incorrect. It is assumed there that in CdCr_2Se_4 the photostopping is carried out by photoinduced Cr^{2+} ions, which trap the domain wall because of the fact that their magnetic anisotropy is higher than that of the regular Cr^{3+} ions. The fact that this model of the photoinduced defects is incorrect was already pointed out in Sec. 2.2. But the situation will still not change even if a more realistic model with an excess electron spread out over the Cr ions near the defect is studied. First of all, it is incorrect to say that the walls are stopped by the light as a result of being trapped by centers with high anisotropy. On the contrary, the walls strive to avoid these centers, and they are pushed away by them.

The physical meaning of this is obvious: the larger is J , the more difficult it is to tilt one spin away from the other. And the higher is the value of K , the stronger is the tendency of the spins to align themselves parallel to the same direction—the easy axis. Therefore, for small tilting angles the exchange, just as the anisotropy, strives to keep the spins parallel to one another. In other words, the local growth of J , just as the growth of K , increases the energy of the domain wall, creating for it not a potential well, but rather a potential hump.

Second, it is believed in Refs. 84 and 144 that a domain wall can be pinned by randomly distributed photoinduced point defects. In reality, in magnetically soft materials point defects cannot affect the motion of the domain walls because of their great thickness: such walls perceive the medium with point defects as a uniform medium. Indeed, even with a defect concentration of $\sim 1\%$ its relative fluctuation over the thickness of the wall is only 10^{-6} or less. An excellent confirmation of the small role of point defects is the well-known fact that the properties of permalloys are improved and not degraded by quenching, leading to a disordered state.¹⁹³

To stop a domain wall it is most likely necessary to have an inherent nonuniformity in the distribution of defects with a characteristic length comparable to the size of the wall, but small compared with the size of the domain. One- or two-dimensional defects of the dislocation type or twinning planes, whose state can vary under the action of the light, may be effective for trapping a wall. In particular, a change in the electronic states in the impurity atmosphere surrounding a dislocation⁶⁾ changes its stress field. The stresses, on the other hand, strongly affect the motion of the domain boundaries.^{177,178}

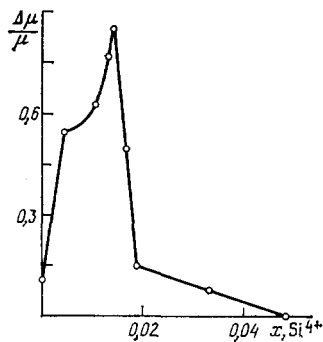


FIG. 17. The relative photoinduced change in the magnetic permeability of $\text{Y}_3\text{Fe}_{5-x}\text{Si}_x\text{O}_{12}$ as a function of silicon concentration.¹⁸³

The experimental data^{156,170} on $\text{CdCr}_2\text{Se}_4:\text{Ga}$ confirm our point of view regarding the role of dislocations. As regards IYG, on the subject of dislocations the only samples studied were those into which Si was not injected, but rather photoactive centers were created by gamma irradiation and electron bombardment. The effect of plastic deformation, creating dislocations, was not observed in them.¹⁷⁴ It is, however, possible that in CdCr_2Se_4 the dislocations are more important than in IYG, since in CdCr_2Se_4 the domain walls are thicker.

Pinning centers in CdCr_2Se_4 and IYG:Si were studied experimentally by the method of measurement of transient processes in magnetic^{179,180} or electric¹⁸¹ fields as well as under pressure.¹⁸² It was established that the pinning centers and potential wells for domain walls in illuminated and unilluminated samples are characterized by different parameters: the formation and relaxation times and the depth and configuration of potential wells.¹⁶⁹ Their number as well as the density distribution in the crystal are also different.

An important experimental result, playing a key role in determining the nature of the centers of photopinning of domain boundaries and the mechanism of their interaction, is the dependence of the magnitude of the photoinduced effect on the density of the dopant, which always passes through a maximum¹⁹⁷ (Fig. 17). In Ref. 195 photosensitive centers in $\text{Y}_3\text{Fe}_5\text{O}_{12}:\text{Si}$ are studied by a new, for photomagnets, method of thermostimulated depolarization.

6. CONCLUSIONS

Having listed in our review the achievements of research on photomagnetism, we would like to point out a number of problems which await solution. Although the photoinduced increase in the magnetization in FM semiconductors has been observed, the contributions of photoinduced long- and short-range order to it have still not been separated. The extent to which T_c increases and what singularities appear in the rate of generation of entropy have not been established. There are no experimental data which could be used to judge the relative role of different mechanisms for establishing photoinduced ordering. In particular, the concentrations of photocarriers and the photoinduced change in the volume of the crystal have not been measured. Such experiments would stimulate the further development of the theory of nonequilibrium order-disorder phase transi-

tions. As regards the photoinduced order-order transitions, it would be desirable to complete their study, in particular, in order to establish by neutron diffraction studies the magnetic structure of the photoinduced phase. It would also be desirable to expand the range of materials studied in order to observe in them photoinduced magnetism, in particular, by including singlet magnetic materials.

Many unsolved problems regarding the photomagnetism of domain boundaries remain. The time has come to reject the models in which the action of light on these boundaries is ascribed to the formation of Fe^{2+} and Cr^{3+} ions, and to take up seriously the study of the nature of these centers and the mechanism of their interaction with the domain boundaries. Furthermore, it is necessary to study theoretically and experimentally the magnetic structure of the region in IYG induced by linearly polarized light and the dynamics of its formation, to study in detail the nature and properties of the magnetic (domain) instability in FeBO_3 , and also to answer a number of other questions.

Among the problems which in our view should be attacked first and which are of fundamental importance for further progress in this area, the following should be singled out: 1) the search for new magnetic materials with photomagnetic properties and ways to change deliberately the parameters of known photomagnetic materials; 2) the start of an intensive study of photomagnetism in magnetic films; 3) the start of research on the possibility of practical utilization of photomagnetic materials and determination of the range of devices in which it is expedient to use such materials; 4) solution of the problem of raising the limiting temperature for the existence of photoinduced magnetism right up to room temperature, which is especially important for practical applications.¹⁹⁶

¹¹In Ref. 191 an attempt is made to prove numerically that ferrons cannot exist in EuTe. The results of this work, however, cannot be viewed as reliable for the following reasons. First, the model used in Ref. 91 is simplified compared with real EuTe, and it is not known how close the values of the parameters chosen there are to the true values. Second, the calculation of the ferron states, being based on a variational procedure, obviously gives overestimated values of the ferron energies. For this reason, the results of the calculation can be used only to prove uniquely the stability of ferrons, and not their instability. A reliable theoretical proof of the stability of ferrons can be given for materials of the type of metamagnetic EuSe, in which the conditions for the existence of ferrons are extremely favorable. As regards materials of the EuTe type, where these conditions are much less favorable, the question of the stability of ferrons can be resolved unequivocally only on the basis of experimental data, which contradict the results of Ref. 191. The general ideology of Ref. 191 indicates that the authors of that work were not adequately familiar with the fundamental works on ferrons.

²²To avoid misunderstandings it should be noted that here we are talking about the expansion of the energy of the ground state at $T = 0$, and not the free energy near T_c , where the term η^4 also occurs in the presence of Heisenberg exchange.

³³Excitons are pulled into a single region because of attractive forces existing between them.¹⁹⁰

⁴⁴The results of Refs. 168 and 170 are in agreement with the fact, pointed out by other workers in the same laboratory, that because of the deficiencies of the technology for growing the crystals in this laboratory the reproducibility of the photoferromagnetic effect in them is very poor.²⁰⁴

⁵¹In photoelectric materials a spread of the relaxation time of photocar-

riers by five to six orders of magnitude, depending on the degree of defectiveness of the crystals, is a standard phenomenon. It can be explained without invoking the existence of fundamentally new types of photoconductivity.

⁶⁹By an impurity atmosphere we mean an elevated impurity concentration near dislocations.

¹D. Diggle and R. Gehring, *J. Phys. C* **8**, 1423 (1975).

²B. Zakharchenya in: Proceedings of the XI International Conference on Physics of Semiconductors, Warsaw (1972), p. 1315.

³J. van der Ziel and N. Bloembergen, *Phys. Rev. A* **138**, 1287 (1965).

⁴J. van der Ziel, S. Pershan, and L. Malmstrom, *Phys. Rev. Lett.* **15**, 190 (1965).

⁵S. Pershan, J. van der Ziel, and L. Malmstrom, *Phys. Rev.* **143**, 574 (1966).

⁶J. Holzrichter, R. Macfarlane, and A. Schawlow, *Phys. Rev. Lett.* **26**, 652 (1971).

⁷E. L. Nagaev, *Zh. Eksp. Teor. Fiz.* **80**, 2346 (1981) [*Sov. Phys. JETP* **53**, 1227 (1981)].

⁸V. M. Matveev and E. L. Nagaev, *Fiz. Tverd. Tela* **17**, 2483 (1975) [*Sov. Phys. Solid State* **17**, 1653 (1975)].

⁹N. S. Lidorenko, V. M. Matveev, and E. L. Nagaev, *Dokl. Akad. Nauk SSSR* **230**, 1085 (1976) [*Sov. Phys. Dokl.* **21**, 585 (1976)].

¹⁰A. A. Berdyshev, *Fiz. Tverd. Tela* **8**, 1382 (1962) [*sic*].

¹¹B. V. Karpenko and A. A. Berdyshev, *Fiz. Tverd. Tela* **5**, 3397 (1963) [*Sov. Phys. Solid State* **5**, 2494 (1964)].

¹²E. L. Nagaev, *Usp. Fiz. Nauk* **117**, 437 (1975) [*Sov. Phys. Usp.* **18**, 863 (1975)].

¹³V. D. Lakhno and E. L. Nagaev, *Zh. Eksp. Teor. Fiz.* **74**, 2123 (1978) [*Sov. Phys. JETP* **47**, 1105 (1978)].

¹⁴E. I. Golovenchits, B. D. Laikhtman, and V. A. Sanina, *Pis'ma Zh. Eksp. Teor. Fiz.* **31**, 243 (1980) [*JETP Lett.* **31**, 223 (1980)].

¹⁵E. I. Golovenchits, V. A. Sanina, and T. A. Shaplytina, *Zh. Eksp. Teor. Fiz.* **80**, 1911 (1981) [*Sov. Phys. JETP* **53**, 992 (1981)].

¹⁶P. S. Kuts, V. F. Kovalenko, and V. A. Ruban, *Fiz. Tverd. Tela* **15**, 3707 (1973) [*sic*].

¹⁷M. M. Afanas'ev, M. E. Kompan, and I. A. Merkulov, *Zh. Eksp. Teor. Fiz.* **71**, 2068 (1976) [*Sov. Phys. JETP* **44**, 1086 (1976)].

¹⁸M. M. Afanas'ev, M. E. Kompan, and I. A. Merkulov, *Pis'ma Zh. Eksp. Teor. Fiz.* **23**, 621 (1976) [*JETP Lett.* **23**, 570 (1976)].

¹⁹M. M. Afanas'ev, M. E. Kompan, and I. A. Merkulov, *Pis'ma Zh. Tekh. Fiz.* **2**, 982 (1976) [*Sov. Tech. Phys. Lett.* **2**, 385 (1976)].

²⁰E. L. Nagaev, *Pis'ma Zh. Eksp. Teor. Fiz.* **6**, 484 (1967).

²¹P. Wachter, *CRC Crit. Rev. Sol. State Sci.* **3**, 189 (1972).

²²G. M. Genkin, Yu. N. Nozdrin, I. D. Tokman, and V. N. Shastin, *Pis'ma Zh. Eksp. Teor. Fiz.* **35**, 162 (1982) [*JETP Lett.* **35**, 199 (1982)].

²³V. F. Kovalenko, P. S. Kuts, and V. P. Sokhatskiĭ, *Fiz. Tverd. Tela* **24**, 145 (1982) [*Sov. Phys. Solid State* **24**, 80 (1982)].

²⁴V. F. Kovalenko, E. S. Kolezhuk, and P. S. Kuts, *Zh. Eksp. Teor. Fiz.* **81**, 1399 (1981) [*Sov. Phys. JETP* **54**, 742 (1981)].

²⁵V. F. Kovalenko, P. S. Kuts, and S. N. Lyakhimets, *Fiz. Tverd. Tela* **24**, 2428 (1982) [*Sov. Phys. Solid State* **24**, 1379 (1982)].

²⁶R. Pearson, A. Annis, and P. Kompfner, *Phys. Rev. Lett.* **21**, 1805 (1968).

²⁷J. Dillon, E. Gyorgy, and J. Remeika, *ibid.* **23**, 643 (1969).

²⁸W. Lems, P. Rijnierse, P. Bongers, and U. Enz, *ibid.* **21**, 1643 (1968).

²⁹J. Dillon, E. Gyorgy, and J. Remeika, *J. Appl. Phys.* **41**, 1211 (1970).

³⁰J. Dillon, E. Gyorgy, and J. Remeika, *Appl. Phys. Lett.* **15**, 221 (1969).

³¹P. S. Kuts, V. F. Kovalenko, and V. A. Ruban, *Izv. Vyssh. Uchebn. Zaved., Ser. Fiz. No. 9*, 138 (1976) [*Sov. Phys. J.* **19**, 1222 (1976)].

³²Yu. M. Fedorov and A. A. Leksikov, *Pis'ma Zh. Eksp. Teor. Fiz.* **27**, 389 (1978) [*JETP Lett.* **27**, 365 (1978)].

³³R. Teale and D. Temple, *Phys. Rev. Lett.* **19**, 904 (1967).

³⁴H. van der Heide and U. Enz, *Solid State Commun.* **6**, 347 (1968).

³⁵L. V. Anzina, V. G. Veselago, and S. G. Rudov, *Pis'ma Zh. Eksp. Teor. Fiz.* **23**, 520 (1976) [*JETP Lett.* **23**, 476 (1976)].

³⁶F. Lotgering, *J. Phys. Chem. Sol.* **36**, 1183 (1975).

³⁷K. Hisatake, *Jpn. J. Appl. Phys.* **13**, 2069 (1974).

³⁸K. Hisatake and K. Kirasaki, *Phys. Status Solidi A* **27**, K61 (1975).

³⁹K. Hisatake and K. Hirasaki, *Trans. Inst. Electron. Commun. Eng. Japan. C* **58**, 160 (1975).

⁴⁰K. Hisatake *et al.*, *Phys. Status Solidi A* **26**, K75 (1974).

⁴¹K. Hisatake and K. Hirasaki, *Jpn. J. Appl. Phys.* **13**, 2065 (1974).

⁴²R. Teale *et al.*, *J. Appl. Phys.* **40**, 1435 (1969).

⁴³R. Metselaar and M. Huyberts, *Philips Res. Rept.* **29**, 453 (1974).

⁴⁴K. Hisatake and K. Ohta in: Proceedings of the International Confer-

- ence on Ferrites, Japan (1970), Vol. 1, p. 14.
- ⁴⁵V. E. Makhotkin *et al.*, *Fiz. Tverd. Tela* **16**, 3141 (1974) [*Sov. Phys. Solid State* **16**, 2034 (1975)].
- ⁴⁶D. Lacklison, J. Chadwick, and L. Page, *J. Phys. D* **5**, 810 (1972).
- ⁴⁷M. Seavey, *Solid State Commun.* **12**, 49 (1973).
- ⁴⁸N. M. Salanskii, Yu. M. Fedorov, and V. V. Rudenko, *Fiz. Tverd. Tela* **17**, 2471 (1975) [*Sov. Phys. Solid State* **17**, 1643 (1975)].
- ⁴⁹H. Jonker, *J. Sol. State Chem.* **10**, 116 (1974).
- ⁵⁰K. Hisatake *et al.*, *Jpn. J. Appl. Phys.* **15**, 1823 (1976).
- ⁵¹N. M. Salanskii and N. A. Drokina in: *Magnetic Films: Proceedings of the 6th International Colloquium, Minsk (1974)*, p. 290.
- ⁵²K. Hisatake and K. Ohta, *J. Phys. (Paris)* **38**, 219 (1977).
- ⁵³D. Luminata *et al.*, *Bull. Inst. politehn. Gh. Greorghiu-Dej (Bucuresti), Ser. chem.-metallurg.* **41**, 9 (1979).
- ⁵⁴P. Bernstein and T. Merceron, *J. Phys. (Paris)* **38**, 211 (1977).
- ⁵⁵T. Holtwijk *et al.*, *IEEE Trans. MAG-6*, 853 (1970).
- ⁵⁶T. Merceron and P. Bernstein, *Phys. Status Solidi A* **35**, 681 (1976).
- ⁵⁷N. A. Drokina and V. K. Chernov, *Fiz. Tverd. Tela* **21**, 1230 (1979) [*Sov. Phys. Solid State* **21**, 714 (1979)].
- ⁵⁸J. Haisma, J. Robertson, and U. Enz, *Solid State Commun.* **10**, 1021 (1972).
- ⁵⁹R. A. Doroshenko *et al.*, *Fiz. Tverd. Tela* **21**, 292 (1979) [*Sov. Phys. Solid State* **21**, 176 (1979)].
- ⁶⁰R. A. Doroshenko *et al.*, *ibid.* **21**, 2193; **22**, 2216 (1980) [*ibid.* **21**, 1262 (1979); **22**, 1293 (1980)].
- ⁶¹V. F. Kovalenko, *Fiz. Tverd. Tela* **19**, 1866 (1977) [*Sov. Phys. Solid State* **19**, 1092 (1977)].
- ⁶²Yu. M. Fedorov, A. A. Leksikov, and A. E. Aksenov, *Pis'ma Zh. Eksp. Teor. Fiz.* **37**, 134 (1983) [*JETP Lett.* **37**, 161 (1983)].
- ⁶³E. L. Nagaev, *Fizika magnitnykh poluprovodnikov (Physics of Magnetic Semiconductors)*, Nauka, Moscow (1979).
- ⁶⁴J. I. Pankov, *Optical Processes in Semiconductors*, Prentice-Hall, Englewood Cliffs, N. J., 1971 [Russ. Transl., Mir, M., 1973].
- ⁶⁵G. M. Genkin and I. D. Tokman, *Fiz. Nizk. Temp.* **7**, 1068 (1981) [*Sov. J. Low Temp. Phys.* **7**, 520 (1981)].
- ⁶⁶I. D. Tokman, *Fiz. Tekh. Poluprovodn.* **17**, 1160 (1983) [*Sov. Phys. Semicond.* **17**, 732 (1983)].
- ⁶⁷V. G. Baru, E. V. Grekov, and A. A. Sukhanov, *Fiz. Tverd. Tela* **17**, 948 (1975) [*Sov. Phys. Solid State* **17**, 610 (1975)].
- ⁶⁸A. I. Larkin and D. A. Khmel'nitskii, *Zh. Eksp. Teor. Fiz.* **55**, 2345 (1968) [*Sov. Phys. JETP* **28**, 1245 (1969)].
- ⁶⁹E. L. Nagaev, *Zh. Eksp. Teor. Fiz.* **56**, 1013 (1969) [*Sov. Phys. JETP* **29**, 545 (1969)].
- ⁷⁰E. L. Nagaev, *Fiz. Met. Metalloved.* **29**, 905 (1970) [*Phys. Met. Metallogr. (USSR)* **29**(5), 10 (1970)].
- ⁷¹Yu. A. Izyumov and M. V. Medvedev, *Zh. Eksp. Teor. Fiz.* **59**, 553 (1971) [*Sov. Phys. JETP* **32**, 302 (1971)].
- ⁷²S. Methfessel and D. C. Mattis, "Magnetic Semiconductors," in: *Handbuch der Physik* (ed. by H.P. J. Wijn), Vol. 18, Part 1, Springer Verlag, Berlin, 1968, pp. 389-562 [Russ. Trans., Mir, M., 1969].
- ⁷³B. Shastru and D. C. Mattis, *Phys. Rev. B* **24**, 5340 (1981).
- ⁷⁴E. L. Nagaev, *Physics of Magnetic Semiconductors*, M. Mir Publ. (1983).
- ⁷⁵P. Larsen and R. Metselaar, *Phys. Rev. B* **14**, 2520 (1976).
- ⁷⁶U. Enz, R. Metselaar, and P. Rijnierse, *J. Phys. (Paris) Suppl.* **32**, C1-703 (1971).
- ⁷⁷W. Lenz *et al.*, *J. Appl. Phys.* **41**, 1248 (1970).
- ⁷⁸A. Harris, *J. Phys. C* **7**, 1671 (1974).
- ⁷⁹A. Harris and T. Lubensky, *Phys. Rev. Lett.* **33**, 1540 (1974).
- ⁸⁰T. Lubensky, *Phys. Rev. B* **11**, 3573 (1975).
- ⁸¹D. E. Khmel'nitskii, *Zh. Eksp. Teor. Fiz.* **68**, 1960 (1975) [*Sov. Phys. JETP* **41**, 981 (1975)].
- ⁸²Yu. Shraiber and Yu. Khandrikh, *Pis'ma Zh. Eksp. Teor. Fiz.* **14**, 57 (1971) [*JETP Lett.* **14**, 37 (1971)].
- ⁸³D. Wagner and E. Wohlfarth, *J. Phys. F* **9**, 717 (1979).
- ⁸⁴S. G. Rudov and V. G. Veselago, *Fiz. Tverd. Tela* **21**, 3250 (1979) [*Sov. Phys. Solid State* **21**, 1875 (1979)].
- ⁸⁵S. G. Rudov, "Effect of photoinduced centers on the magnetic properties of the magnetic semiconductor CdCr₂Se₄," Author's Abstract of Candidate's Dissertation, Physics Institute of the USSR Academy of Sciences, Moscow (1983).
- ⁸⁶K. P. Belov, L. I. Koroleva *et al.*, *Pis'ma Zh. Eksp. Teor. Fiz.* **20**, 191 (1974) [*JETP Lett.* **20**, 82 (1974)].
- ⁸⁷N. Sanford *et al.*, *Phys. Rev. Lett.* **50**, 1803 (1983).
- ⁸⁸V. G. Veselago, S. G. Rudov, and M. A. Chernikov, *Pis'ma Zh. Eksp. Teor. Fiz.* **40**, 181 (1984) [*JETP Lett.* **40**, 940 (1984)].
- ⁸⁹K. Westerhold, A. Eiling, and H. Bach, *J. Magn. Magn. Mater.* **28**, 214 (1982).
- ⁹⁰H. Fujiwara *et al.*, *Solid State Commun.* **42**, 509 (1982).
- ⁹¹J. Kato, *J. Phys. Soc. Jpn.* **47**, 1367 (1979).
- ⁹²J. Shapira, S. Foner, and N. Oliveira, *Phys. Rev. B* **10**, 4765 (1974).
- ⁹³N. Oliveira, S. Foner, J. Shapira, and T. Read, *ibid.* **5**, 2634 (1972).
- ⁹⁴J. Shapira *et al.*, *ibid.*, p. 2647.
- ⁹⁵J. Vitins and P. Wachter, *Solid State Commun.* **13**, 1273 (1973).
- ⁹⁶J. Vitins and P. Wachter, *Phys. Rev. B* **12**, 3529 (1975).
- ⁹⁷E. G. Petrov, *Teoriya magnitnykh éksitonov (Theory of Magnetic Excitons)*, Naukova dumka, Kiev (1976).
- ⁹⁸E. I. Golovenchits and V. A. Sanina, *Fiz. Tverd. Tela* **26**, 1640 (1984) [*Sov. Phys. Solid State* **26**, 996 (1984)].
- ⁹⁹E. I. Golovenchits and V. A. Sanina, *Fiz. Tverd. Tela* **24**, 375 (1982) [*Sov. Phys. Solid State* **24**, 213 (1982)].
- ¹⁰⁰S. Kurita *et al.*, *Solid State Commun.* **38**, 235 (1981).
- ¹⁰¹R. Kubo and J. Tojozawa, *Prog. Theor. Phys.* **13**, 160 (1955).
- ¹⁰²M. Lax, *J. Chem. Phys.* **20**, 1752 (1952).
- ¹⁰³G. Rickayzen, *Proc. R. Soc. London Ser. A* **241**, 480 (1957).
- ¹⁰⁴O. I. Zatsarinnyi and E. L. Nagaev, *Pis'ma Zh. Eksp. Teor. Fiz.* **25**, 505 (1977) [*JETP Lett.* **25**, 475 (1977)].
- ¹⁰⁵E. L. Nagaev and A. I. Podel'shchikov, *Zh. Eksp. Teor. Fiz.* **86**, 1831 (1984) [*Sov. Phys. JETP* **59**, 1065 (1984)].
- ¹⁰⁶S. Hasanain *et al.*, *Phys. Rev. B* **24**, 5165 (1981).
- ¹⁰⁷H. Yoshizawa *et al.*, *ibid.* **27**, 448 (1983).
- ¹⁰⁸V. M. Matveev and E. L. Nagaev, *Zh. Eksp. Teor. Fiz.* **69**, 2151 (1975) [*Sov. Phys. JETP* **42**, 1094 (1975)].
- ¹⁰⁹M. M. Afanas'ev, B. P. Zakharchenya, M. E. Kompan, V. G. Fleisher, and S. G. Shul'man, *Pis'ma Zh. Eksp. Teor. Fiz.* **21**, 486 (1975) [*JETP Lett.* **21**, 224 (1975)].
- ¹¹⁰G. Scott *et al.*, *Phys. Rev. B* **12**, 2562 (1975).
- ¹¹¹G. M. Genkin and I. D. Tokman, *Zh. Eksp. Teor. Fiz.* **82**, 1532 (1982) [*Sov. Phys. JETP* **55**, 887 (1982)].
- ¹¹²G. Genkin, I. Tokman, and V. Zil'berberg, *Solid State Commun.* **44**, 631 (1982).
- ¹¹³G. M. Genkin and I. D. Tokman, *Fiz. Tverd. Tela* **25**, 2206 (1983) [*Sov. Phys. Solid State* **25**, 1271 (1983)].
- ¹¹⁴G. M. Genkin and I. D. Tokman, *Pis'ma Zh. Eksp. Teor. Fiz.* **33**, 119 (1981) [*JETP Lett.* **33**, 113 (1981)].
- ¹¹⁵I. A. Merkulov and G. G. Samsonidze, *Fiz. Tverd. Tela* **22**, 2437 (1980) [*Sov. Phys. Solid State* **22**, 1419 (1980)].
- ¹¹⁶L. Landau and E. M. Lifshitz, *Elektrodinamika sploshnykh sred, Nauka, M., 1982* [Engl. Transl. of 1957 edition (Electrodynamics of Continuous Media), Pergamon Press, Oxford, 1960].
- ¹¹⁷G. M. Genkin *et al.*, *Fiz. Tverd. Tela* **25**, 3706 (1983) [*Sov. Phys. Solid State* **25**, 2135 (1983)].
- ¹¹⁸H. Reik and R. Schirmer, *Solid State Commun.* **10**, 1209 (1972).
- ¹¹⁹R. Alben *et al.*, *Phys. Rev. B* **5**, 2560 (1972).
- ¹²⁰R. Teale, D. Temple, and D. Weatherley, *J. Phys. C* **3**, 1376 (1970).
- ¹²¹R. Pearson, A. Annis, and J. Page in: *Ref. 44*, Vol. 1, p. 8.
- ¹²²J. Dillon, E. Gyorgy, and J. Remeika, *ibid.*, p. 3.
- ¹²³P. Flanders *et al.*, *J. Appl. Phys.* **42**, 1443 (1971).
- ¹²⁴R. Churchill, P. Flanders, and C. Graham, *ibid.*, p. 1451.
- ¹²⁵R. Alben *et al.*, *ibid.*, p. 1447.
- ¹²⁶J. Hawkes and R. Teale, *J. Phys. C* **5**, 481 (1972).
- ¹²⁷A. Tucciarone, *Lett. Nuovo Cimento* **4**, 919 (1972).
- ¹²⁸F. Barreto, H. Reik, and R. Schirmer, *Solid State Commun.* **12**, 231 (1973).
- ¹²⁹A. Tucciarone, *Lett. Nuovo Cimento* **6**, 20 (1973).
- ¹³⁰R. Teale and D. Weatherley, *J. Phys. C* **6**, 750 (1973).
- ¹³¹B. Sharp and R. Teale, *ibid.* **7**, 965 (1974).
- ¹³²B. Antonini *et al.*, *Phys. Rev. B* **12**, 3840 (1975).
- ¹³³A. Tucciarone, *IEEE Trans. MAG-14*, 871 (1978).
- ¹³⁴B. Antonini *et al.*, *Phys. Rev. Lett.* **41**, 1556 (1978).
- ¹³⁵R. V. Pisarev and A. Tucciarone, *Fiz. Tverd. Tela* **23**, 2743 (1981) [*Sov. Phys. Solid State* **23**, 1606 (1981)].
- ¹³⁶J. Hawkes and R. Teale, *J. Phys. C* **5**, 2200 (1972).
- ¹³⁷L. Neel, *J. Phys. Radium* **15**, 225 (1954).
- ¹³⁸S. Taniguchi, *Sci. Rept. Res. Inst. Tohoku Univ. A* **8**, 173 (1956).
- ¹³⁹I. C. Slonczewski in: *Magnetism*, edited by G. T. Rado and H. Suhl, Academic Press, New York (1963), Vol. 1, p. 205.
- ¹⁴⁰R. P. Hunt, *J. Appl. Phys.* **38**, 2826 (1967).
- ¹⁴¹M. Ayadi and J. Ferre, *Phys. Rev. Lett.* **50**, 274 (1983).
- ¹⁴²A. A. Leksikov and Yu. M. Fedorov, *Pis'ma Zh. Eksp. Teor. Fiz.* **8**, 934 (1982) [*Sov. Tech. Phys. Lett.* **8**, 405 (1982)].
- ¹⁴³Yu. M. Fedorov, A. A. Leksikov, and A. E. Aksenov, *Fiz. Tverd. Tela* **25**, 2531 (1983) [*Sov. Phys. Solid State* **25**, 1457 (1983)].
- ¹⁴⁴V. G. Veselago, A. A. Minakov, and S. G. Rudov, *Zh. Eksp. Teor. Fiz.*

- 87, 629 (1984) [Sov. Phys. JETP **60**, 360 (1984)].
- ¹⁴⁵N. M. Salanskii and N. A. Drokin, *Fiz. Tverd. Tela* **17**, 331 (1975) [Sov. Phys. Solid State **17**, 205 (1975)].
- ¹⁴⁶N. M. Salanskii, N. A. Drokin, and V. K. Chernov, *ibid.*, p. 3705 [2409].
- ¹⁴⁷N. M. Salanskii, N. A. Drokin, V. K. Chernov, and A. N. Borisov, *Zh. Eksp. Teor. Fiz.* **70**, 1317 (1976) [Sov. Phys. JETP **43**, 686 (1976)].
- ¹⁴⁸K. Hisatake, *Jpn. J. Appl. Phys.* **13**, 2069 (1974).
- ¹⁴⁹G. A. Petrakovskii and G. S. Patrino, *Fiz. Tverd. Tela* **25**, 3147 (1983) [Sov. Phys. Solid State **25**, 1812; Solid State Commun. **48**, 25 (1983)].
- ¹⁵⁰L. F. Johnson, J. P. Remeika, and J. F. Dillon, *Phys. Lett.* **21**, 37 (1966).
- ¹⁵¹P. D. Kim, T. V. Drokina, A. M. Balbashov, and A. P. Cherkasov, *Zh. Tekh. Fiz.* **50**, 653 (1980) [Sov. Phys. Tech. Phys. **25**, 395 (1980)].
- ¹⁵²T. S. Stakelon, P. Yen, Puzskarski, and P. E. Wigen, *AIP Conf. Proc.* **29**, 660 (1975).
- ¹⁵³P. Yen, T. S. Stakelon, and P. E. Wigen, *Phys. Rev. B* **19**, 4575 (1979).
- ¹⁵⁴K. Uematsu, M. Deguchi, and Y. Kito, *J. Magn. Magn. Mater.* **35**, 65 (1983).
- ¹⁵⁵G. S. Krinchik, E. A. Gan'shina *et al.*, *Izv. Akad. Nauk SSSR, Ser. Fiz.* **42**, 1646 (1978) [Bull. Acad. Sci. USSR, Phys. Ser. **42**(8), 68 (1978)].
- ¹⁵⁶V. G. Veselago *et al.*, *Fiz. Tverd. Tela* **26**, 2203 (1984) [Sov. Phys. Solid State **26**, 1337 (1984)].
- ¹⁵⁷R. Metselaar, M. A. H. Huyberts, and H. Logmans, *J. Appl. Phys.* **46**, 3171 (1975).
- ¹⁵⁸U. Enz *et al.*, *IEEE Trans. MAG-5*, 467 (1969).
- ¹⁵⁹P. S. Kuts and V. F. Kovalenko, *Fiz. Tverd. Tela* **17**, 1481 (1975) [Sov. Phys. Solid State **17**, 960 (1975)].
- ¹⁶⁰V. F. Kovalenko, I. I. Kondilenko, and P. S. Puts, *Zh. Eksp. Teor. Fiz.* **74**, 734 (1978) [Sov. Phys. JETP **47**, 386 (1978)].
- ¹⁶¹L. V. Anzina, V. G. Veselago *et al.*, *Fiz. Tverd. Tela* **21**, 2947 (1979) [Sov. Phys. Solid State **21**, 1697 (1979)].
- ¹⁶²S. S. Dindun and E. A. Raftman, *Fiz. Tverd. Tela* **20**, 1914 (1978) [Sov. Phys. Solid State **20**, 1108 (1978)].
- ¹⁶³V. N. Kuznetsov *et al.*, *Fiz. Tverd. Tela* **26**, 926 (1984) [Sov. Phys. Solid State **26**, 565 (1984)].
- ¹⁶⁴V. G. Veselago, V. N. Kuznetsov, and V. E. Makhotkin, *Izv. Akad. Nauk SSSR, Ser. Fiz.* **45**, 1646 (1981) [Bull. Acad. Sci. USSR Phys. Ser. **45**(9), 56 (1981)].
- ¹⁶⁵L. V. Anzina *et al.*, *Fiz. Tverd. Tela* **19**, 3001 (1977) [Sov. Phys. Solid State **19**, 1757 (1977)].
- ¹⁶⁶V. G. Veselago *et al.*, *Pis'ma Zh. Eksp. Teor. Fiz.* **15**, 316 (1972) [JETP Lett. **15**, 223 (1972)].
- ¹⁶⁷V. G. Veselago and A. M. Prokhorov, Preprint No.30, Physics Institute of the USSR Academy of Sciences, Moscow (1977).
- ¹⁶⁸S. G. Rudov *et al.*, *Kr. soobshch. fiz. (FIAN SSSR)*, No. 4, 3 (1975).
- ¹⁶⁹V. N. Kuznetsov and V. E. Makhotkin, *Fiz. Tverd. Tela* **22**, 3700 (1980) [Sov. Phys. Solid State **22**, 2166 (1980)].
- ¹⁷⁰V. G. Veselago, V. N. Kuznetsov, and V. E. Makhotkin, *Fiz. Tverd. Tela* **24**, 1526 (1982) [Sov. Phys. Solid State **24**, 874 (1982)].
- ¹⁷¹N. A. Drokin, Author's Abstract of Candidate's Dissertation, Institute of Physics of the Siberian Branch of the USSR Academy of Sciences, Krasnoyarsk (1975).
- ¹⁷²K. Hisatake *et al.*, *Phys. Status Solidi A* **26**, K79 (1974).
- ¹⁷³L. M. Dedukh and A. A. Polyanskiĭ, *Fiz. Tverd. Tela* **18**, 899 (1976) [*sic*].
- ¹⁷⁴L. M. Dedukh, Yu. P. Kabanov, and A. A. Polyanskiĭ, *Fiz. Tverd. Tela* **22**, 383 (1980) [Sov. Phys. Solid State **22**, 225 (1980)].
- ¹⁷⁵J. F. Dillon *et al.*, *J. Phys. (Paris)* **31**, C1-794 (1971).
- ¹⁷⁶E. M. Gyorgy *et al.*, *J. Appl. Phys.* **42**, 1454 (1971).
- ¹⁷⁷C. Kittel and J. Galt, *Solid State Phys.* **3**, 437 (1956).
- ¹⁷⁸A. Hubert, *Theorie der Domänenwände in geordneten Medien*, Springer Verlag, Berlin, 1974 [Russ. Transl., Mir, M., 1977].
- ¹⁷⁹V. E. Makhotkin, G. I. Vinogradova, and V. G. Veselago, *Pis'ma Zh. Eksp. Teor. Fiz.* **28**, 84 (1978) [JETP Lett. **28**, 78 (1978)].
- ¹⁸⁰A. V. Myagkov, V. E. Makhotkin, and V. N. Kuznetsov, *Tr. Fiz. Inst. Akad. Nauk SSSR* **139**, 87 (1982).
- ¹⁸¹R. A. Doroshenko and V. G. Veselago, *Fiz. Tverd. Tela* **23**, 1170 (1981) [Sov. Phys. Solid State **23**, 681 (1981)].
- ¹⁸²V. G. Veselago and R. A. Doroshenko, *Tr. Fiz. Inst. Akad. Nauk SSSR* **139**, 67 (1982).
- ¹⁸³M. Wurlitzer and W. Schaller, *Phys. Status Solidi A* **28**, K41 (1975).
- ¹⁸⁴E. L. Nagaev, *Fiz. Tverd. Tela* **27**, 1870 (1985) [Sov. Phys. Solid State **27**, 1123 (1985)].
- ¹⁸⁵E. L. Nagaev and A. I. Podel'shchikov in: Abstracts of Reports at the 17th All-Union Conference of the Physics of Magnetic Phenomena, Donetsk (1985), p. 93.
- ¹⁸⁶E. Z. Katsnel'son and A. G. Karoza, *ibid.*, p. 278.
- ¹⁸⁷Yu. M. Fedorov, A. A. Leksikov, and O. V. Vorotynova, *ibid.*, p. 197.
- ¹⁸⁸J. D. Eshelby, *Continuum Theory of Lattice Defects*, *Solid State Phys.* **3**, 79 (1956) [Russ. Transl., IL, M., 1963].
- ¹⁸⁹E. L. Nagaev and E. B. Sokolova, *Pis'ma Zh. Eksp. Teor. Fiz.* **28**, 105 (1978) [JETP Lett. **28**, 97 (1978)].
- ¹⁹⁰R. S. Knox, *Theory of Excitons*, Suppl. No. 5 to *Solid State Phys.*, Academic Press, N. Y., 1963 [Russ. Transl., Mir, M., 1966].
- ¹⁹¹A. Mauger and D. Mills, *Phys. Rev. B* **31**, 8024 (1985).
- ¹⁹²A. K. Zvezdin and A. A. Mukhin, *Pis'ma Zh. Eksp. Teor. Fiz.* **42**, 129 (1985) [JETP Lett. **42**, 157 (1985)].
- ¹⁹³S. V. Vonsovskii, *Magnetizm*, Nauk, M., 1971 [Engl. Transl., Magnetism, Halsted, N. Y., 1975].
- ¹⁹⁴A. V. Zhukovskii, V. F. Kovalenko, P. S. Kuts, B. P. Nam, and A. S. Khe, *Fiz. Tverd. Tela* **27**, 2841 (1985) [Sov. Phys. Solid State **27**, 1713 (1985)].
- ¹⁹⁵N. G. Nakhodkin, V. V. Voznyuk, V. F. Kovalenko, and P. S. Kuts, *Fiz. Tverd. Tela* **26**, 918 (1984) [Sov. Phys. Solid State **26**, 560 (1984)].
- ¹⁹⁶V. F. Kovalenko and S. N. Lyakhimets, *ibid.*, p. 3014 [1817].
- ¹⁹⁷S. N. Lyakhimets, V. F. Kovalenko, and P. S. Kuts, *Ukr. Fiz. Zh. No.* **10**, 1522 (1985).
- ¹⁹⁸V. F. Kovalenko and A. Yu. Chekhovoi, *Fiz. Tverd. Tela* **27**, 2479 (1985) [Sov. Phys. Solid State **27**, 1483 (1985)].
- ¹⁹⁹P. S. Kuts, V. F. Kovalenko, and A. V. Zhukovskii in: *Fundamentalnye osnovy opticheskoi pamyati i sredy* (Fundamentals of Optical Memory and Media), Vishcha shkola, Kiev (1984), No. 15, p. 67.
- ²⁰⁰Zh. V. Gumenyuk-Sychevskaya, V. F. Kovalenko, and S. N. Lyakhimets, *Fiz. Tverd. Tela* **28**, 675 (1986).
- ²⁰¹V. F. Kovalenko, E. S. Kolezhuk, and P. S. Kuts, *Pis'ma Zh. Tekh. Fiz.* **7**, 1012 (1981) [Sov. Tech. Phys. Lett. **7**, 435 (1981)].
- ²⁰²V. F. Kovalenko and P. S. Kuts in: Ref. 199 (1985), No. 16.
- ²⁰³E. L. Nagaev, *Zh. Eksp. Teor. Fiz.* **90**, 652 (1986) [Sov. Phys. JETP **63**, No. 2 (1986)].
- ²⁰⁴A. V. Shakhanov and K. M. Golant, *Fiz. Tverd. Tela* **26**, 2639 (1984) [Sov. Phys. Solid State **26**, 1599 (1984)].
- ²⁰⁵E. L. Nagaev and A. I. Podel'shchikov, *Zh. Eksp. Teor. Fiz.* **90**, 1360 (1986) [Sov. Phys. JETP **63**, No. 4 (1986)].
- ²⁰⁶G. I. Vinogradova in: Ref. 180, p. 3.

Translated by M. E. Alferieff