Photomagnetization of multidomain ferromagnetic materials by circularly polarized light

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It is shown that photomagnetization can be produced as a result of absorption of circularly polarized light by multidomain magnetic materials with circular dichroism. Its occurrence in magnetic semiconductors is attributed to different densities of photocarriers arising from circular dichroism.

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1. Because of the domain structure in ferromagnetic materials, the crystal has a zero magnetization in the absence of external magnetic field. It is assumed that the exchange-interaction parameter J is the same in different domains. There are cases, however, in which the domains with oppositely directed magnetization vectors in the ferromagnetic material have different values of the parameter J. Thus, for example, circular dichroism, which is determined by different light absorption coefficients K_+ and K_- for different circular polarizations, exists in the chromium spinels[1] $CdCr_2Se_4$, in europium chalcogenides[2] EuC and EuS--magnetic semiconductors, and in YiG garnets. Therefore, when a magnetic semiconductor is illuminated by light with circular polarization,[1] different numbers of photoelectrons appear in domains with oppositely directed magnetization. Moreover, since the electrons take part in an indirect exchange (see, for example, Ref. 4), the effective exchange-interaction constant is different. Analogously, the adjacent domains in the YIG garnets, in which the illumination gives rise to transitions[3] between the levels of the Fe^{3+} ion, have different numbers of these ions in the excited state in which the parameter J generally is different.

We examine in this paper the changes in the equilibrium domain structure. As will be shown, in the absence of the external magnetic field the widths of the domains with different directions of the magnetization vectors are different, which results in a magnetization of the sample. The light with a circular polarization causes a photomagnetization of a multidomain ferromagnetic material. We note that the light absorption is determined by the electron transitions due to the electric field of the light; however, the effect is produced by circular dichroism that occurs because of relativistic interactions.

2. The equilibrium domain structure is determined form the condition of minimum total energy. For simplicity, we shall examine a crystal with a strip domain structure. We determine the magnetostatic energy of such a structure, where the width of domains with M_z $-M_z$ is equal to a and b. We choose a crystal in the shape of a plate of thickness 1 with the easy axis along the OZ axis and perpendicular to the plane of the plate. By solving the two-dimensional Laplace equation for the magnetostatic potential with known boundary conditions, we can easily see that the magnetostatic energy per unit volume--a unit area of the plate multiplied by the thickness l--is[2])

$$W_{ms} = \frac{2\pi M_0^2 (b-a)^2 l}{(a+b)^2} + \frac{8 M_0^2 (a+b)}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^3} \sin^2\left(\frac{\pi n a}{a+b}\right), \tag{1}$$

where M_0 is the magnetization.

The exchange energy in this volume is

$$W_{ex} = -\left\{J_1\left(\frac{a}{a+b}\right) + J_2\left(\frac{b}{a+b}\right)\right\}\frac{lS^2}{a_0^3} \equiv -\left\{(J_1 + J_2) + \frac{a-b}{a+b} \times (J_1 - J_2)\right\}\frac{lS^2}{a_0^3}, \tag{2}$$

where a_0 is the lattice constant, S is the spin, J_1 is the exchange constant in the domain a, and J_2 is the same for the domain b. The domain-wall energy of this volume is $W_{wall} = \frac{2\sigma 1}{a+b}$, where σ is the energy density of the wall. The equilibrium values α_0 and d_0 of the parameters $\alpha \equiv a-b$ and $d \neq a+b$ are determined by the minimizing conditions

$$\frac{\partial W}{\partial \alpha} = 0, \quad \frac{\partial W}{\partial d} = 0, \text{ where } W = W_{ms} + W_{ex} + W_{ms} \tag{3}$$

Equations (3) for $\alpha/d < 1$ give the relations

$$\frac{\alpha_0}{d_0} = \frac{(J_1 - J_2) S^2}{8\pi M_0^2 a_0^3}, \quad d_0 = d_0' \left[1 + \frac{(J_1 - J_2)^2}{32 M_0^4 a_0^6}\right]. \tag{4}$$

The terms of higher orders of smallness of the parameter $d/1 \ll 1$ have been dropped; here $d'_0/2$ is the equilibrium value of the domain in width for $J_1 = J_2$. It follows from Eq. (4) that the width of a domain with a large parameter J becomes large. Thus, in addition to the magnetostatic energy and the energy of the domain boundaries, the exchange energy takes part in the determination of the domain structure. At $\alpha \neq 0$ the additional magnetostatic energy, which is proportional to α^2, tends to returen α to zero; however, the addition due to the different exchange-interaction constants is proportional to $\alpha\sigma$ and, since the interaction is ferromagentic, it tends to increase α for $J_1 > J_2$ and $|\alpha|$ for $J_1 < J_2$; this indicates that the domain with the larger value of the J parameter increases. For α_0 an absolute minimum of the total energy exists and the total change in energy because of rearrangement of the domain structure is

$$\Delta W \approx - \frac{(J_1 - J_2)^2 l S^2}{4\pi M_0^2 a_0^6} . \tag{5}$$

3. The magnetization ΔM resulting from the rearrangement of the strip[3]) domain structure is

$$\frac{\Delta M}{M_0} \approx \frac{2\alpha_0}{d_0} = \frac{(J_1 - J_2) S^2}{4\pi M_0^2 a_0^3} . \tag{6}$$

We shall examine the magnetic semiconductors in which the carriers participate in the indirect exchange; according to Ref. 4, we have

$$\frac{\Delta J}{J} \approx \left(\frac{\pi}{6}\right)^{2/3} \frac{AS}{k_B T_C a_0 q_0} \frac{n_1 - n_2}{N} , \tag{7}$$

where $\hbar q_0 = (2\, mAS)^{1/2}$, T_C is the Curie temperature, N is the total number of states in the Brillouin zone, n_1 and n_2 are the carrier densities in the domains a and b, respectively[4]) A is the s-d exchange constant, and m is the electron mass. Thus, although the relative photomagnetization is proportional to the small parameters $(n_1 - n_2)/N$, it also contains a large parameter -- the ratio of the exchange-interaction energy to the magnetostatic relativistic energy. Therefore, the characteristic estimate of the effect is

$$\frac{\Delta M}{M_0} \sim \left(\frac{c}{v}\right)^2 \frac{n_1 - n_2}{N} . \tag{8}$$

Expressing the difference $(n_1 - n_2)$ in terms of $\Delta K = K_+ K_-$, we obtain the relative photomagnetization of a multidomain semiconductor

$$\frac{\Delta M}{M_0} \approx 0{,}1 \frac{P \Delta K \tau (AS)^{1/2}}{\omega a_0 m^{1/2} M_c^2} , \tag{9}$$

where P is the power flux of the light of frequency ω and τ is the lifetime of a photocarrier.

In conclusion, we estimate that $\Delta M / M_0 \sim 10^{-2}$ for $CdCr_2Se_4$, where[1] $\Delta K \sim 10^3$ cm^{-1}, for a light power flux $P \sim 1 W/cm^2$ if we assume that $\tau \sim 10^{-6}$ sec.

[1]The direction of light propagation is assumed to ba along the magnetization direction.
[2]At $a = b$ the known result for the magnetostatic energy of the domain structure is determined from Eq. (1), and at $a = 0$, the energy of a uniformly magnetized plate of thickness 1 is determined.
[3]The rearrangement of the structure with closing domains will be examined in a separate paper; a preliminary study shows that the effect in this case is greater by the parameter $1/d$.
[4]We assume that a and $b > L$, where L is the diffusion length; this condition is usually satisfied in magnetic semiconductors.

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