# Singularities of the Faraday effect on EuO films in megagauss fields

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Measurements of the Faraday effect (FE) in pulsed magnetic fields on EuO films with oxygen vacancies has revealed two singularities: an abrupt increase of the FE in fields ~0.45 MOe, and an increase of the specific rotation to a value $3.7 \times 10^7$ deg/cm in fields ~ 0.8 MOe. The results are discussed.

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The Faraday effect was measured on EuO films of thickness $l = 1500 \pm 50$ Å, containing 4% oxygen vacancies, with activation energy 0.12 eV and with Curie temperature $T_c = 148$ °K, in magnetic fields up to 1.5 MOe, produced in a magnetocumulation generator. The procedure used to measure the Faraday effect was described in preceding papers[1,2] and consisted in the following. The beam from a helium-neon laser ($\lambda = 6328$ Å) passed in succession through a sample of heavy flint TF-5 with a Verdet constant $V = 0.046$ min/cmOe and a EuO film on a glass substrate ($l = 1.27$ mm $V = 0.01$—$0.02$ min/cmOe). The plane of the analyzer was rotated 45° relative to the initial polarization, and this made it possible to determine the sign of the FE. In the case of a positive effect, the plot of the intensity of the light has a maximum (the largest downward deviation from the null line), and the angle of rotation to the first maximum is 45°. Each succeeding spike on the oscillogram corresponds to rotation through 180°.

Figure 1 shows oscillograms of two experiments with one and the same EuO plane but with different length of the flint. In the first experiment the measurements were carried out up to $H \sim 0.8$ MOe, and resulted in a summary angle $\theta = 945°$. Although the field reached 1.5 MOe, the resolution of the apparatus and the incidence of extraneous light on the photomultiplier (large maximum at the end of the oscillogram) did not make it possible to carry out measurements to this value. In the second experiment the field was ~ 0.64 MOe, and the total angle was 470 deg. Subtracting the contributions of the flint and the substrate, we obtain from the EuO film rotation angles 550 and 310°, corresponding to respective per-unit rotation $\alpha = 3.66 \times 10^7$ deg/cm and $\alpha = 2.06 \times 10^7$ deg/cm. This is larger by one order of magnitude than the previously published data for $\alpha$. Thus, in[3] measurements on an EuS film yielded $\alpha = 2 \times 10^6$ deg/cm. The FE for the investigated EuO films at 20 °K, $H = 200$ Oe, and $\lambda = 6328$ Å is characterized by $\alpha = 1.85 \times 10^5$ deg/cm. It is seen from the oscillogram of Fig. 1 that the amplitude of the spikes decreases with increasing field. This indicates the onset of ellipticity, due to the dichroism. On the other hand, the increase of the ellipticity with increasing field, which is revealed on the oscillogram by the increase of the deviation of the minimum from the null line, is due to the red shift of the absorption line which was previously observed in[4]. Figure 2 shows a plot of $\theta = f(H)$. It is seen that in the field region 0.45—0.5 MOe there

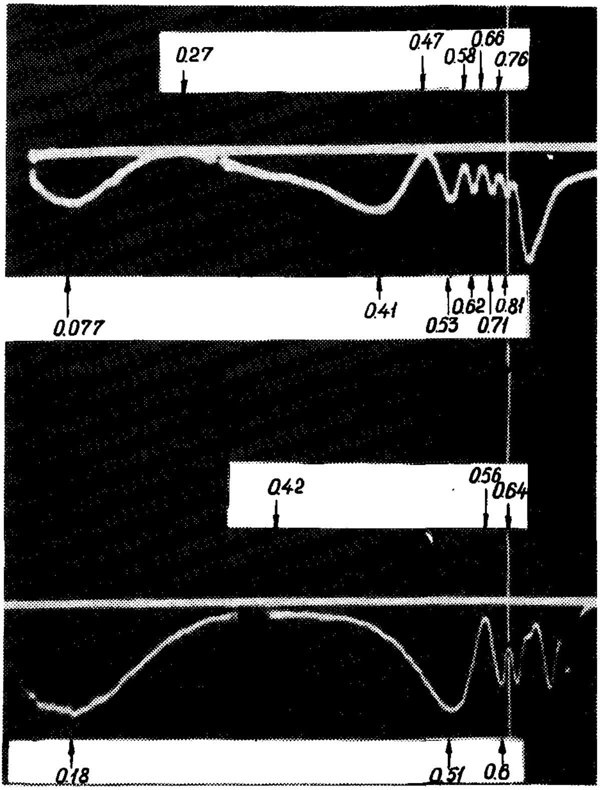

FIG. 1. Oscillograms of Faraday effect on composite samples TF-5+EuO. Top—first experiments with TF-5 ($l = 6$ mm), bottom—second with TF-5 ($l = 3$ mm). The arrows indicate the fields in MOe, and the vertical line marks the end of the Faraday-effect registration. $T = 293$ °K.

is an abrupt increase of $\theta$. An experiment was performed also on another EuO film ($l = 1900$ Å) with oxygen vacancies (activation energy 0.08 eV) without flint in a field reaching 0.9 MOe. The total angle $\theta$ was 270°, which is equivalent to $\alpha = 1.4 \times 10^7$ deg/cm.

The interpretation of the abrupt increase of $\theta$ is connected with the formation of tremendous ferromagnetic molecules—ferrons[5]—around the oxygen vacancies. The edge of the absorption edge is due to the excited states formed by electron transfer from the $Eu^{2+}$ to the $5d$ shell of the neighboring $Eu^{2+}$ ion (magnetic exciton).[6] Owing to the strong interatomic $d-f$ exchange interaction, the edge of the absorption band shifts by an amount $\Delta\omega = -2I_{d\text{-}f}\bar{J}\sigma = -I_{d\text{-}f}E$, where $J$ is the average value of the angular momentum of the ground state of $Eu^{2+}$. Using the molecular-field equation $\bar{J} = JB_J(x)$, at $T_c = 148$ °K, we obtain $J = 1.77$ in a field 0.5 MOe. Taking $I_{d\text{-}f} = 540$ cm$^{-1}$,[6,7] we obtain $\Delta\omega \approx 0.12$ eV, which is equal to the donor activation energy. The increase of the

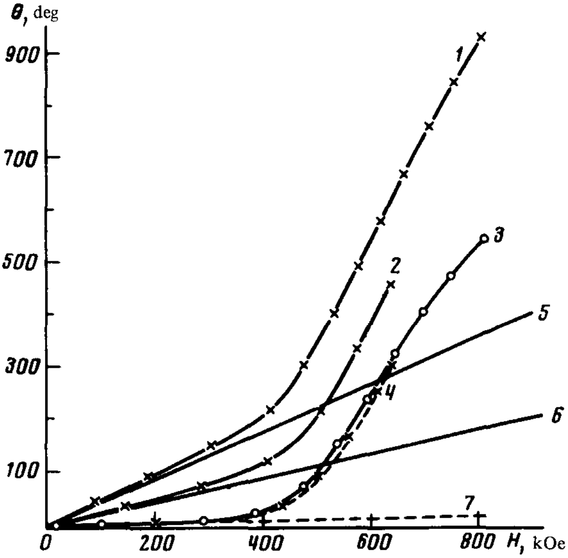

FIG. 2. Dependence of the polarization-plane rotation angle on the field for both composite samples in the first (1) and second (2) experiments, and separately for the samples TF-5 (5 and 6), the EuO film (3 and 4), and a glass substrate with $V=0.01$ min/cmOe (7).

concentration of the conduction leads to an increase of the exchange integral via the conduction electrons between the $Eu^{2+}$ surrounded by vacancies. As a result, ferrons are produced with an average value $J \sim 3.5$ per ion. The formation of ions is registered in various studies,[6,8] including Faraday-effect studies of antiferromagnetic EuTe.[9] Assuming that each ferron contains 12 $Eu^{2+}$ ions,[6] the value of $\bar{J}$ in the field 0.5 MOe reaches 2.6 jumpwise. Thus, the abrupt increase of $\theta$ in a field 0.45—0.5 MOe points to a semiconductor—metal transition under the influence of the external field, something not previously observed.

The per-unit rotation in the region of the absorption line is described by the following formula[1,10]

$$a = \frac{\omega_p^2 \omega^2}{4nc} \sum_{ab} \beta_a \left\{ \frac{(f_+ - f_-)[p^2(p - 2\Gamma^2) - k^2(p + 2\Gamma^2) + 8\Gamma^2\omega^2 p]}{\omega_{ba}[(p^2 - k^2)^2 + 16\Gamma^2\omega^2 p^2]} + \frac{2(f_+ + f_-)\omega_H(p^2 - k^2 - \Gamma^2 p)}{(p^2 - k^2)^2 + 16\Gamma^2\omega^2 p^2} \right\} \left( \frac{n^2 + 2}{3} \right)^2, \qquad (1$$

where $\omega_p^2 = 4\pi N e^2/m$, $\Gamma$ is the half-width of the absorption line at half amplitude, $f_\pm$ is the oscillator strength for right- and left-polarized light, $\beta_a$ is the probability of populating the level $a$, $p = \omega_{ab}^2 + \omega_H^2 + \Gamma^2 - \omega^2$, $k^2 = 4(\Gamma^2\omega^2 + \omega_{ba}^2\omega_H^2)$, and $\omega_H = g' H \mu_B/\hbar$.

The first term in the curly brackets (1) is the paramagnetic contribution, and the second is the diamagnetic contribution. The maximum value of the first contribution at $\omega = \omega_{ba} - \Gamma$ is estimated from the formula[10]

$$a = \frac{\omega_p^2 f_0}{16 n c \Gamma} \left( \frac{n^2 + 2}{3} \right)^2, \ \text{rad/cm} . \qquad (2)$$

At $N = 1.7 \times 10^{22}$ cm$^{-3}$, at the experimental values $f_0 = 0.1$ and $n = 2.3$,[10] and also at $\Gamma = 0.1$ eV, we get $\alpha = 1.2 \times 10^7$ deg/cm, which is of the same order of magnitude as obtained in our measurements. We note that according to (2) the theoretical limit of $\alpha$ is $10^8$ deg/cm at $f_0 = 1$. The value of $\Gamma$ is 0.9 eV at $T = 8$ °K and 0.4 eV at 300 °K.[11] It appears that an external ultrastrong field narrows down the transition line to 0.1 eV, as is indicated by the field dependence of the absorption coefficient, measured by us in the third experiment. If this is so, then at $\omega_{ba} = \omega_{ba}^0 - I_{d\text{-}f}\bar{J}$ and at $\omega_{ba}^0 = 3.36 \times 10^{15}$ sec$^{-5}$ (according to our measurements), the difference in a field $H = 0.8$ MOe is $\omega_{ba} - \omega \approx 0.1$ eV. so that Eq. (2) can be used. The narrowing of the line explains the lower temperatures and in relatively weak magnetic fields. According to the estimates, the diamagnetic term in (1) also makes a contribution that cannot be neglected.

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