Stepped magnetic field dependence of Faraday effect in semimagnetic semiconductors

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A stepped magnetic field dependence of the Faraday rotation of the semimagnetic semiconductors $Cd_{1-x}Mn_xTe$ and $Pb_{1-x}Mn_xI_2$, in fields up to 250 kOe, is reported for the first time. The observed anomalies are shown to be related to a stepped change in the magnetization of the magnetic subsystem of these semiconductors.

Many studies of the Faraday effect in semimagnetic semiconductors have revealed the numerous anomalies characteristic of these substances.[1-5] In this letter we are reporting the observation of a stepped change in the Faraday effect upon an increase in the magnetic field.

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Experiments were carried out on two semimagnetic semiconductors, $Cd_{1-x}Mn_xTe$, which is fairly well known, and $Pb_{1-x}Mn_xI_2$, which is a new type, at a temperature $T=4.2$ K in pulsed magnetic fields up to $H=250$ kOe. The samples were prepared by cleaving single-crystal wafers with a thickness $d \approx 100$ μm.

Figure 1 shows the Faraday rotation angle θ as a function of the field for the composition $Cd_{0.95}Mn_{0.05}Te$. It follows from Fig. 1 that at $H > 50$ kOe the Faraday effect begins to reach saturation, while at $H_1 \approx 100$ kOe and $H_2 \approx 180$ kOe there is a stepped change in the angle θ.

In a semimagnetic semiconductor with a low concentration of the magnetic component, such that the ion–ion interaction can be ignored, the magnetic field dependence of the Faraday effect should be described by a curve with saturation. This behavior corresponds to a complete alignment of the spins of the isolated Mn^{2+} ions in strong fields.[1-4] When the antiferromagnetic interaction between nearest ions, bound in Mn^{2+}–Mn^{2+} pairs, is taken into account, however, the curve of $\theta(H)$ becomes more complicated: As the magnetic field is increased further, an additional and abrupt alignment of the spins of pairs occurs. Correspondingly, there is a stepped change in the magnetization $\langle S_M \rangle$ of the magnetic subsystem of the semiconductor. The simple model of Refs. 6 and 7, which describes an interacting pair of ions as a set of energy levels which cross each other as the field is increased, predicts five equidistant steps on the plot of $\langle S_M \rangle (H)$. Using the expression for $\langle S_M \rangle$ calculated from that model, using its relationship with the exciton component of the Faraday effect according to Ref. 4, and restricting the discussion to only the two steps observed experimentally, at H_1 and H_2, we find

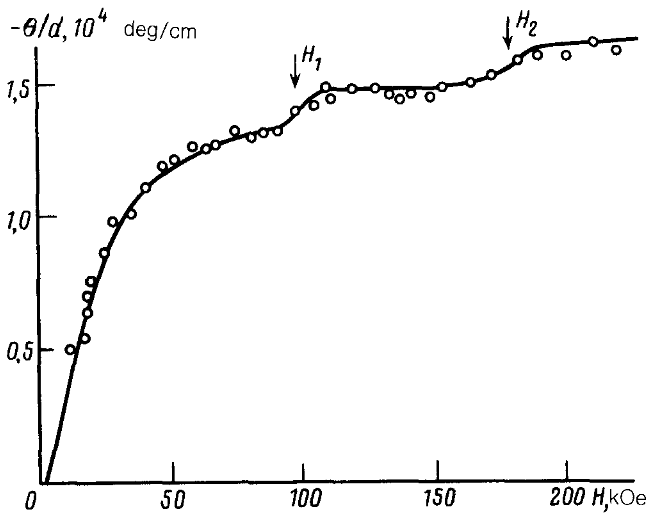

FIG. 1. Faraday effect in $Cd_{1-x}Mn_xTe$ versus the magnetic field at $T=4.2$ K for $E=1.35$ eV and $x=0.05$. Points—Experimental; line—calculated from the expression (1).

$$\frac{\theta}{d} = \frac{\sqrt{F_0}}{2\hbar c}\frac{E^2}{(E_0^2 - E^2)^{3/2}}[xN_0(J_e - J_h)]\left\{\frac{5}{2}\frac{x^*}{x}B_{5/2}\left[\frac{5\mu_B H}{k_B(T+T_0)}\right]\right.$$
$$\left.-\frac{1}{2}P_p\left[1+\exp\left[\frac{2\mu_B H}{k_B T}(H_1 - H)\right]\right]^{-1} - \frac{1}{2}P_p\left[1+\exp\left[\frac{2\mu_B H}{k_B T}(H_2 - H)\right]\right]^{-1}\right\} \quad (1)$$

Here F_0 is a constant which is proportional to the oscillator strength of the exciton transition, E is the photon energy, E_0 is the energy of an exciton transition, N_0 is the number of cation states per unit volume, $J_{e,h}$ are the integrals of the exchange interaction of electrons (holes) with Mn^{2+} ions, x^* is the mole fraction of isolated Mn^{2+} ions, $B_{5/2}(a)$ is the Brillouin function, T_0 is the correction to the temperature T for the ion–ion exchange interaction, and P_p is the probability for the existence of a pair of Mn^{2+} ions.

The theoretical curve calculated from expression (1) gives a generally satisfactory description of the experimental results (Fig. 1). Here are the main parameter values used in the calculations: $N_0(J_e - J_h) = 1.126$ eV (Ref. 6), $x^*/x = 0.604$, $T + T_0 = 5$ K, $P_p = 0.33$ (Ref. 6), $H_1 = 100$ kOe, and $H_2 = 180$ kOe. We wish to stress that these values make it possible to estimate the exchange-interaction constant of the Mn^{2+} ions in pairs:

$$J_{NN}/k_B = -\frac{1}{2}g_{Mn}\mu_B(H_2 - H_1) \approx -(5,4 \pm 0,5)\mathrm{K}. \quad (2)$$

This estimate agrees satisfactorily with a value found previously from direct measurements of the magnetization of $Cd_{1-x}Mn_xTe$ crystals.[7]

There is an interesting situation in the case of the $Pb_{1-x}Mn_xI_2$ crystals: In addition to the exchange component of the Faraday effect, one must also consider the linear component, which is opposite in sign and which reflects the direct Zeeman splitting of the exciton spin states. For $Cd_{1-x}Mn_xTe$, the latter component can be ignored, primarily because of the much larger value of $N_0(J_e - J_h)$. For $Pb_{1-x}Mn_xI_2$, this value is almost two orders of magnitude smaller,[8] so the linear component of θ is greater in absolute value than the exchange component in strong magnetic fields.

The experimental data on $Pb_{1-x}Mn_xI_2$ (Fig. 2) do indeed describe a dominant role of the direct Zeeman component, $\mu_B g_{e,h} H$, in strong fields. In addition, in the interval $H \approx 65$–85 kOe there is a plateau. As in the preceding case, this plateau can be interpreted on the basis of a stepped magnetic field dependence of the magnetization of the magnetic subsystem in these semimagnetic semiconductors. Because of the strong effect of the linear component of the Faraday effect, however, this step is transformed into a plateau. From the position of the midpoint of this plateau we find the value $H_1 \approx 75$ kOe, and we can estimate the constant:

$$J_{NN}/k_B = -\frac{1}{2}g_{Mn}\mu_B H_1 \approx (5,0 \pm 0,5)\mathrm{K}, \quad (3)$$

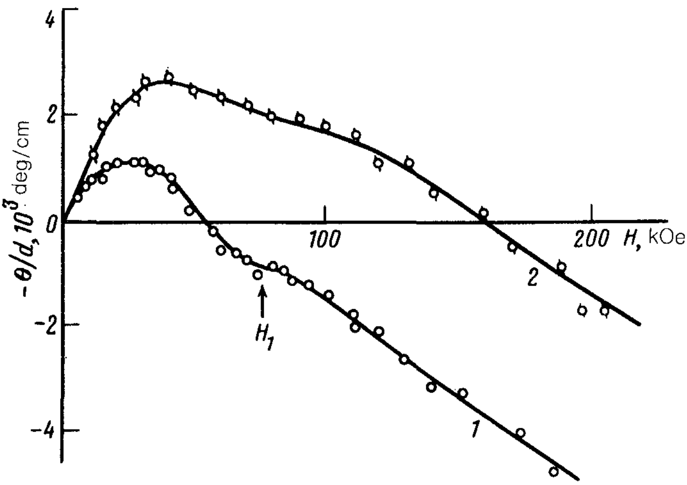

FIG. 2. Faraday effect in $Pb_{1-x}Mn_xI_2$ versus the magnetic field at $T = 4.2$ K for $E = 2.27$ eV. Points and line *1*—Experimental data for the composition $x = 0.01$; *2*—$x = 0.03$.

As the Mn content in the $Pb_{1-x}Mn_xI_2$ solid solutions is increased, the magnetic field dependence of the Faraday effect remains complicated, but the value of the field at which the decay of θ begins as x is increased shifts to a larger H. In addition, for compositions with $x \geqslant 0.03$ the plateau on the $\theta(H)$ curve is less obvious (curve *2* in Fig. 2).

We note in conclusion that the features of the magnetic field dependence of the Faraday effect which have been observed here and which are associated with a stepped variation of the magnetization of the subsystem of Mn^{2+} ions point to some new opportunities for using the Faraday effect to study the exchange interactions of magnetic ions with each other and with band carriers in the class of semimagnetic semiconductors.

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