Effect of longitudinal magnetic field on the conductivity in magnetic semiconducting *p*-type spinels

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The effect of a longitudinal magnetic field on the conductivity was investigated in the ferromagnetic semiconducting p-type spinels $Cd_{1-x}Ag_xCr_2Se_4$ and $Cu_yCr_2Se_{4-z}Br_x$. A positive magnetoresistance, linear in the magnetization and independent of the carrier drift velocity, was observed in the ferromagnetic region.

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Study of the kinetic properties of magnetically ordered crystals with high carrier mobility is of interest in view of the possibility of coherent interaction between the carriers and the plasma-spin waves.[1,2]

We have investigated the magnetoresistance of single-crystal ferromagnetic semiconducting spinels with p-type conductivity in a longitudinal magnetic field ($\mathbf{H}\|\mathbf{j}$, where **H** is the external magnetic field and **j** is the current density).[3] The objects of investigation were $CdCr_2Se_4$ doped with Ag (Curie temperature $T_C = 130$ K, carrier density $p = 2\times10^{16}$ cm^{-3}, mobility $\mu_h = 250$ cm^2/V sec at $T = 150$ K), henceforth labeled I, and also $Cu_yCr_2Se_{4-z}Br_x$ ($T_C = 310$ K, $p = 4\times10^{20}$ cm^{-3}, $\mu_h = 25$ cm^2/V sec at $T = 150$ K), designated II. The carrier parameters were determined by us from measurements of the Hall effect and of the resistance. The hole density and mobility in the high-resistance sample I were not measured at temperatures below T_C in view of the difficulty of determining the normal Hall coefficient.

The measurements were made on samples in the form of rectangular parallelepipeds measuring $0.3\times0.8\times3$ mm. The current direction coincided with the longest face of the sample. A detailed description of the experimental procedure is contained in[4].

Figure 1 shows a family of $\Delta\rho_{\|}/\rho_0 = (\rho_H - \rho_0)/\rho_0$ curves for sample I, plotted at various temperatures, as well as the corresponding family of magnetization curves obtained for the same sample with a vibration magnetometer.[5] As seen from Fig. 1,

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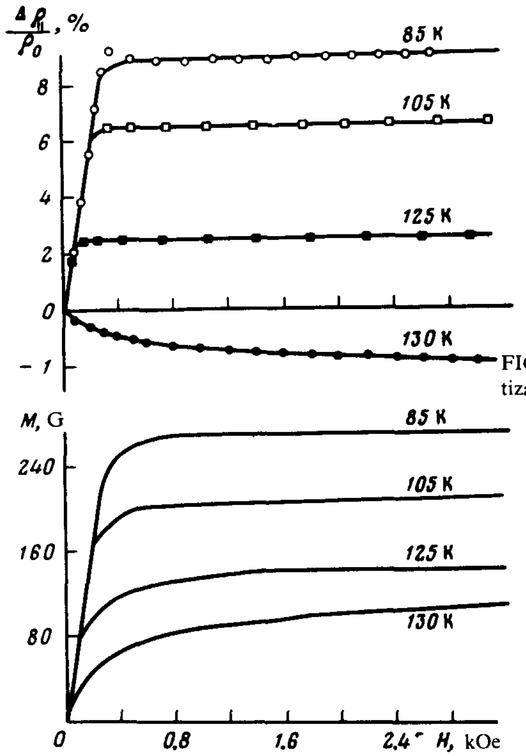

FIG. 1. Longitudinal magnetoresistance and magnetization curves of $Cd_{1-x}Ag_xCr_2Se_4$.

the growth of the resistance in the ferromagnetic temperature region is linear in the magnetization, an unusual occurrence for even galvanomagnetic phenomena. We note that an increase of the resistance of $CdCr_2Se_4$ of p-type in a longitudinal magnetic field was observed earlier in[6]. According to[6], however, the sample resistance increases in a magnetic field only in electric fields stronger than a certain threshold value ($E > 100$ V/cm at $T = 100$ K). Our measurements have shown that the function $\Delta\rho_{\parallel}/\rho_0(H)$ does not change within the limits of experimental error when the electric field is varied from 0.4 to 25 V/cm. The apparent reason for this discrepancy is the difference between the experimental procedure, since the two-probe method with pulsed excitation of the current in the sample, used in[6], does not exclude the influence of the non-ohmic behavior of the contacts on the results.

Figure 2 shows plots of the longitudinal magnetoresistance for sample II. It is seen that the difference from sample I reduces only to somewhat small values of $\Delta\rho_{\parallel}/\rho_0$ in the saturation region.

The foregoing experimental data indicate that the motion of the holes in these materials is subject to the influence of magnetic ordering, although at the phase-transition point itself this influence is much weaker than for samples with n-type conductivity.[7] The most interesting is here the linear dependence of $\Delta\rho_{\parallel}/\rho_0$ on the sample magnetization. The fact that the linear magnetoresistance duplicates the mag-

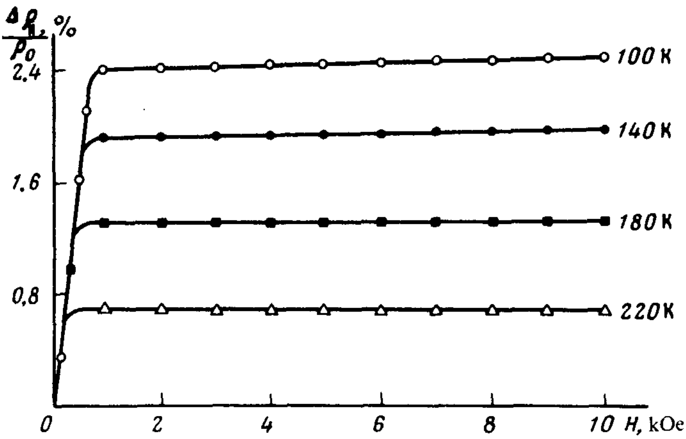

FIG. 2. Longitudinal magnetoresistance of $Cu_yCr_2Se_{4-z}Br_x$.

netization curves in the ferromagnetic temperature region, but is nonexistent at $T \geqslant T_c$, indicates that these phenomena are connected with a realignment of the domain structure by the magnetization. The domain walls in the sample are inhomogeneities that scatter effectively the long-wave magnons. It can therefore be assumed that the carrier motion in the domain walls is less subject to the influence of the electron-magnon scattering than in domains with homogeneous magnetization. When the sample is magnetized, the domain walls vanish and the total contribution of the electron-magnon scattering to the resistivity increases, and it is this which leads to a linear growth of the resistance in the magnetic field. With decreasing temperature, on the other hand, the average magnon wavelength increases, but on the other hand the number of domain walls in the sample is increased because of the increase in the anisotropy constant. Consequently the effect of the domain structure on the electron-magnon scattering becomes more appreciable at low temperatures, and leads to larger values of $\Delta\rho_{\parallel}/\rho_0$ in the saturation region (see Fig. 1).

It should be noted that the mechanism that leads to the increase of the resistance in the magnetic field cannot be the scattering of the carriers by the domain walls, since the mean free path of a carrier with mobility $\mu \sim 250$ cm^2/V sec is much less than the domain-wall thickness, and furthermore, the vanishing of the domain walls upon magnetization should lead in this case to a decrease of the resistance.

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