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Temperature and magnetic-field dependences of the resistivity of Ga-doped $CdCr_2Se_4$ single crystals

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The electrical resistivity ρ of $Cd_{1-x}Ga_xCr_2Se_4$ single crystals ($x = 0.017$, 0.019, 0.037, 0.048, and 0.091) was investigated in the temperature range 4.2–300°K in magnetic fields 0–50 kOe. The dependence $\rho(T)$ was found to be nonmonotonic with a minimum below the Curie point T_c and a maximum in the region of T_c. The position of the maximum of the $\rho(T)$ curve shifted toward higher temperatures on increase of the magnetic field. In the region of the minimum, and particularly near the maximum, the behavior of $\rho(T)$ indicated a giant negative magnetoresistance: ρ in $H = 50$ kOe near T_c was one or two orders of magnitude less than ρ in $H = 0$. The observed anomalies were attributed to the presence of ferrons in this compound.

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An investigation was made of the resistivity of $Cd_{1-x}Ga_xCr_2Se_4$ single crystals ($x = 0.017$, 0.019, 0.037, 0.048, and 0.091) in a wide temperature range from 4.2 to 220°K, applying magnetic fields up to 50 kOe. The samples, application of ohmic contacts, and the method used to measure ρ were all described earlier.[1,2]

The magnetic field was produced in a superconducting solenoid. During measurements a sample was placed in an enclosure with double walls where vacuum down to 10^{-3} Torr was maintained. The necessary temperature was produced by an electric heater wound bifilarly on a single-crystal quartz rod and the sample was bonded to the end of this rod. The temperature was measured with a copper–copper-iron thermocouple.

Figure 1 shows the temperature and magnetic-field dependences of ρ obtained for a sample of $Cd_{0.983}Ga_{0.017}Cr_2Se_4$. It is clear from Fig. 1a that the temperature dependence of ρ is complex; when the temperature is increased from 4.2°K, the value of ρ first falls, passes through a minimum, and then rises steeply by about four orders of magnitude reaching a maximum in the region of the Curie point, and then falls again.

The resistivity depends strongly on the magnetic field H at temperatures beginning from the minimum and ending in the region of the maximum; the dependence

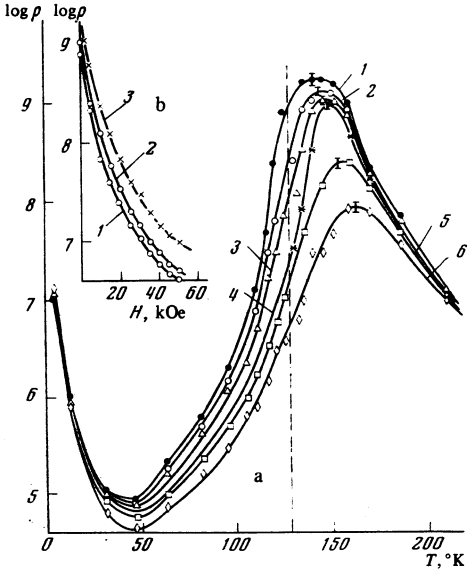

FIG. 1. Properties of $Cd_{0.983}Ga_{0.017}Cr_2Se_4$. a) Temperature dependence of the logarithm of the resistivity in various magnetic fields: 1) $H = 0$; 2) 5 kOe; 3) 10 kOe; 4) 20 kOe; 5) 30 kOe; 6) 50 kOe. The dashed line represents the temperature at which α has its maximum value. b) Dependence of log ρ on the magnetic field at various temperatures: 1) $T = 124.5$°K; 2) 128°K; 3) 132°K.

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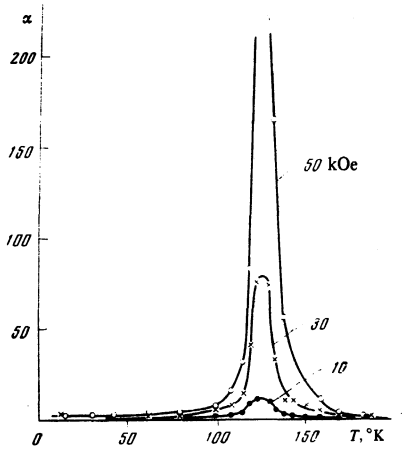

FIG. 2. Temperature dependence of $\alpha = \rho_{H=0}/\rho_H$ in various magnetic fields.

$\rho(H)$ is nonlinear (Fig. 1b). In this range the material exhibits a giant negative magnetoresistance, the longitudinal and transverse components being of the same magnitude. For example, in the case of $Cd_{0.983}Ga_{0.017}Cr_2Se_4$ the application of 50 kOe reduces ρ by a factor of 220 ($T = 128$ °K). Such a strong dependence $\rho(H)$ cannot be represented easily by the usual magnetoresistance defined as $(\rho_H - \rho_{H=0})/\rho_{H=0}$ because its modulus cannot exceed unity; therefore, we shall use $\alpha = \rho_{H=0}/\rho_H$, whose temperature dependence for this sample is shown in Fig. 2. We can see that $\alpha(T)$ has a sharp maximum in the region of 130 °K, which is located at a somewhat lower temperature than the maximum of $\rho(T)$.

It is clear from Fig. 1a that the position of the maximum of $\rho(T)$ depends strongly on the magnetic field. An increase in the field from 0 to 50 kOe shifts the maximum by about 20 °K in the direction of higher temperatures. The magnitude of this shift is shown in Fig. 3 as a function of the field.

Similar dependences of ρ and α on T and H were observed by us for other $Cd_{1-x}Ga_xCr_2Se_4$ samples with $x = 0.019$, 0.037, 0.048, and 0.091, except that the minimum $\rho(T)$ was in these cases located at higher temperatures 60–90 °K and the maximum value of α was somewhat smaller (112–15).

The nonmonotonic dependence $\rho(T)$ shown in Fig. 1a is typical of nondegenerate ferromagnetic semiconductors. As shown theoretically by Nagaev,[3] such a temperature dependence $\rho(T)$ is mainly due to the nonmonotonic temperature dependence of the carrier density resulting from the temperature dependence of the activation energy $E(T)$. At a given temperature the degree of the local ferromagnetic order near a nonionized donor is higher than the average over a crystal because the maintenance of the ferromagnetic order around the donor by the donor electron is energetically favorable from the point of view of the $s-d$ exchange. Consequently, in the spin-wave region the temperature shift of the donor level is small compared with the shift of the bottom of the conduction band. Therefore, in the ferromagnetic region the activation energy E rises with increasing temperature. In the paramagnetic region the magnetic order in the crystal as a whole is destroyed but the local magnetic order near nonionized donors may still exist. (Magnetic clusters of this kind near donors are known as ferrons.) Therefore, in the paramagnetic range the activation energy decreases with rising temperature. However, even in the limit $T \to \infty$ the magnetic moment of a ferron remains finite so that the high-temperature activation energy is greater than the low-temperature value.

Hence, it follows that the activation energy E of a doped ferromagnetic semiconductor passes through a maximum in the region of the Curie point T_c. The calculation reported by Nagaev[3] shows that in the case of moderately deep local levels, separated from the bottom of the conduction band by a gap not exceeding $AS/4$, we may observe an activation energy minimum at $T_m < T_c$. The temperature T_m is found from the inequality

$$\frac{d}{dT}\left[\frac{E(T)}{T}\right]_{T=T_m} = 0$$

(A is the $s-d$ exchange integral and S is the spin of a magnetically active ion).

We also observed a reduction in the activation energy in the low-temperature range, compared with the high-temperature value. In fact, as indicated by the results in Table I, the low-temperature values of E of all the investigated samples are lower than in the paramagnetic range. The nonmonotonic dependence $\rho(T)$ similar to that shown in Fig. 1a has been reported earlier for nondegenerate magnetic semiconductors EuO and EuS,[4,5] as well as for polycrystalline $Cd_{0.98}In_{0.02}Cr_2Se_4$.[6]

The maximum of ρ at T_c may also be due to the scattering of carriers by the magnetic moments of the ferrons[7] or the capture of carriers by nonionized donors.[8]

TABLE I. Activation energies of $Cd_{1-x}Ga_xCr_2Se_4$ samples.

x	E, 10^{-3} eV, spin-wave range	E, 10^{-1} eV, paramagnetic range
0.017	1.9	2.35
0.019	5.2	1.82
0.037	3.6	2.9
0.048	1.41	2.5
0.091	4.8	0.61

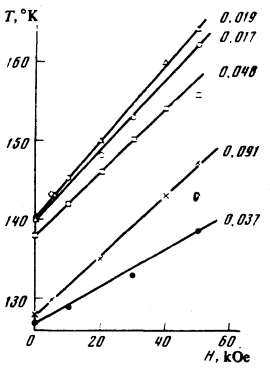

FIG. 3. Shift of the position of the maximum of the dependence $\rho(T)$ of the $Cd_{1-x}Ga_xCr_2Se_4$ system in a magnetic field. The numbers alongside the lines are the values of x.

The application of an external magnetic field increases the degree of the long-range order in a crystal and automatically reduces the activation energy in the region of T_c and weakens the scattering of carriers by the magnetic moments of the ferrons. Therefore, a giant negative magnetoresistance is observed in the region of T_c and the maximum of $\rho(T)$ is shifted toward higher temperatures, as observed in our study.

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The capture cross section for holes of a charged dislocation in a semiconductor

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The temperature dependence of the cross section for hole capture by a negatively charged dislocation in an n-type semiconductor has been found. It is shown that because of the special character of the filling of the dislocation with the electrons that saturate it, this dependence is stronger than in the case of point centers. The magnitude of the cross section is in agreement with the experimental data.

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According to the Shockley model[1] an edge dislocation in an n-type semiconductor behaves like an infinitely long negatively charged line of acceptors. As a result, dislocations act as recombination centers for excess carriers. In this situation the minority carriers, which are acted on by the electrostatic attraction, are the most effectively captured. To be captured by a dislocation it is necessary for a hole to reduce its energy by an amount sufficient for it to undergo transition to the bound state. One of the energy-removal mechanisms which ensure experimentally observable large cross sections[2] is interaction with acoustic phonons. Since at sufficiently high temperatures the scattering of holes by phonons has a quasielastic nature and the levels associated with a charged dislocation are quite deeply situated in the forbidden band, the most probable process is Lax's[3] cascade capture mechanism.

In a recent paper by Abakumov and Yassievich[4] a convenient method was proposed for calculating the cross section for capture by attracting centers in semiconductors. This method was first used by Pitaevskiĭ[5] to obtain the electron recombination coefficient in a weakly ionized plasma.

In the present paper we shall make use of the method developed in[4] to find the capture cross section for holes by a unit length of a negatively charged dislocation. Let us note that because of the special character of the electrostatic field of the dislocation as a linear imperfection in the crystal lattice, the temperature dependence of the capture cross section is stronger than in the case of point centers.[4]

1. THE ELECTROSTATIC POTENTIAL OF A DISLOCATION

It is well known that an edge dislocation can capture additional electrons on the broken bonds which arise at the edge of the extra half-plane, thereby building up a positively charged cylinder of ionized impurities around itself. In this situation the degree to which the dislocation is filled with the electrons that saturate it can be characterized by the ratio $\zeta = a/c$, where a and c are the distances between broken and saturated bonds respectively. However, in calculating the electrostatic potential we shall consider the dislocation as a uniformly charged filament of infinite length. It is evident that this idealized approximation is valid only at not too small distances from the dislocation axis, where the discrete nature of the filament charge becomes significant.

Let us introduce the cylindrical coordinates (r, θ, z) with the dislocation axis as the polar one. To find the potential $\varphi(r)$ of the charged dislocation with allowance for the screening of the electric field by free charges and by the ionized impurity we shall make use of the Poisson equation

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