Anomalous Hall effect in holmium single crystal in the region of helicoidal magnetic ordering

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The Hall resistivity ρ_H, magnetic susceptibility χ, and resistivity ρ of holmium single crystals are measured in the region of helicoidal magnetic ordering. The current density vector is directed along the $\langle 10\bar{1}0\rangle$ axis in the investigated crystals and the magnetic field strength vector along the $\langle 0001\rangle$ and $\langle 11\bar{2}0\rangle$ directions. It is shown that the helicoidal magnetic structure affects appreciably the temperature dependence of the helicoidal Hall coefficient R_h. The characteristic features of the temperature dependence of R_h are similar to those of the temperature dependence of the magnetic resistance ρ_m measured in the same direction as the Hall coefficient, and hence $R_h \sim \rho_m$ for both crystallographic directions. An extremum is observed in the temperature dependence of the Hall resistivity at ~ 93 °K. Its existence is ascribed to the possible existence of an intermediate phase transition at the same temperature.

The Hall effect in a number of single crystals of heavy rare-earth metals (Tb, Dy, Ho, and Er) was investigated in many studies[1-8]. They have led to the important qualitative conclusion that the complicated magnetic structure of the rare-earth metals (REM) is the cause of the complicated field dependence of the Hall resistivity ρ_H. Very little is known so far, however, concerning the influence exerted on the magnetic structure by the coefficients of the anomalous and classical Hall effects R_a and R_0, respectively. At the present time it is possible to determine quantitatively the coefficients R_a and R_0 only in the region of the paramagnetic state of the REM.

In the ferromagnetic ordering region we were able to determine the Hall coefficients R_a and R_0 only for Tb[4,6] and Dy[3], and only for the case when the magnetic field is directed along the easy-magnetization axis. The temperature interval in the immediate vicinity of the magnetic-transformation temperature is excluded in this case. In an earlier investigation of Ho[8], in contrast to the other studies, the magnetizing fields were increased to 56 kG. Unfortunately, even these fields were insufficient to produce ferromagnetic saturation and to determine the coefficients R_a and R_0, even in the case of magnetization along the easy axis.

Whereas some progress was made in the ferromagnetic-ordering region, there are no data whatever in the region of antiferromagnetic ordering. Yet the atomic noncollinear magnetic structure, as is well known, exerts a strong influence on the energy spectrum of the conduction electrons and on the character of the scattering of the conduction electrons in REM crystals. We wish to explain in the present article how this becomes manifest in the temperature dependence of the Hall coefficients. To be able to determine the Hall coefficients we measured in addition to the Hall resistivity ρH also the magnetic susceptibility κ.

The object of the investigation was chosen to be holmium, in which the antiferromagnetic ordering is observed in a sufficiently large magnetic-field interval (critical field $H_c \sim 18$ kG).

The holmium single crystals employed in the paper were grown by the recrystallization-annealing method in an atmosphere of spectrally pure helium. Measurements of the Hall resistance were carried out on samples in the form of plates measuring $10 \times 1 \times 0.2$ mm, which were placed in a gap between two halves of an ellipsoid made of permendur. We present the results of the measurements for two samples oriented in such a way that the current-density vector was directed along $\langle 10\bar{1}0\rangle$ and the magnetic field intensity H was directed along the crystallographic directions $\langle 0001\rangle$ and $\langle 11\bar{2}0\rangle$.

Figure 1 shows isotherms of the dependence of the Hall resistivity ρ_H on the magnetic field H in the cases when the magnetic field is directed along $\langle 0001\rangle$ and $\langle 11\bar{2}0\rangle$. It is seen from the figure that for a sample magnetized in the basal plane, in the paramagnetic region of temperatures ($T > \Theta_N$, $\Theta_N = 125$°K), ρ_H is a linear function of the field H in the entire range of values of the magnetic field. On going into the temperature region $T < \Theta_N$, the form of the isotherms changes significantly. In the region of helicoidal ordering, just as the paramagnetic region, there is the linear dependence $\rho H(H)$. Deviation from linearity sets in in magnetic fields stronger than the critical field H_c that destroys the helicoidal magnetic order.

When the crystal is magnetized along $\langle 0001\rangle$, the effective magnetic field is weak in comparison with the effective magnetic-anisotropy field of the holmium, and therefore causes no noticeable changes in the character

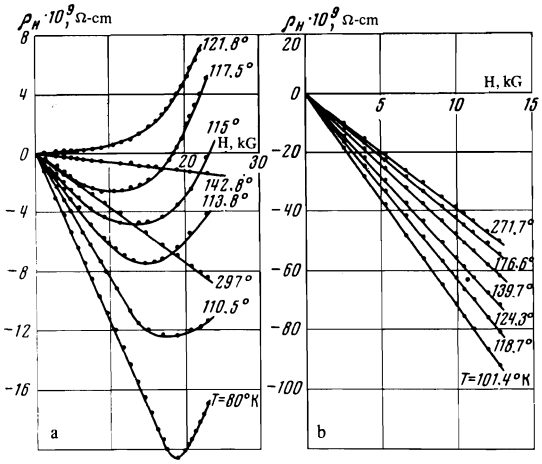

FIG. 1. Dependence of the Hall resistivity ρ_H on the magnetic field H for certain typical temperatures with the magnetic field directed along $\langle 11\bar{2}0\rangle$ (a) and $\langle 0001\rangle$ (b).

of the helicoidal magnetic structure. This is precisely why in this case the linear field dependence of ρ_H is observed in the entire range of values of H.

Thus, the linear $\rho_H(H)$ dependence is typical of both the paramagnetic and the helicoidal state of holmium.

The reason is that in the indicated cases, as shown by experiment, the magnetic susceptibility does not depend on the magnetic field, i.e., the magnetization is a linear function of the field. From the linear section of the $\rho_H(H)$ curve we determine the value of $R^* = \rho_H/H$, which is shown in Fig. 2 as a function of the temperature for the two investigated samples. The same figure shows the temperature dependence of the measured magnetic susceptibility κ of the same samples. Attention is called first to the correlation between the temperature dependences of the coefficient R^* and of the magnetic susceptibility κ, which is particularly obvious in the region of the Neel temperature. Thus, if the crystal is magnetized in the $\langle 11\bar{2}0\rangle$ direction, we observe a maximum of the susceptibility in the region of the Neel temperature; this maximum is due to the true magnetization process, which takes place in the basal planes of the holmium. At the same temperature, R^* has likewise an extremal value (Fig. 2). It is obvious that no such extremum should be observed in the case of magnetization in the $\langle 0001\rangle$ direction, owing to the absence of an influence of the true magnetization process on the $\kappa(T)$ curve. Experiment shows indeed (Fig. 2) that in this case there is no maximum on the $\kappa(T)$ curve in the region of the Neel temperature, and the curve exhibits an inflection corresponding to the maximum of the derivative $d\kappa/dT$. A similar inflection is observed also on the $R^*(T)$ curve.

A graphic analysis of the $R^*(\kappa)$ dependence, on the basis of the analytic form presently assumed for this dependence, is presented in our paper[9], and the resultant information on to the temperature dependence of the anomalous Hall coefficient in the region of helicoidal magnetic ordering is given in[10].

The helicoidal Hall coefficient R_h is essentially anisotropic in sign, in absolute magnitude, and in the character of the temperature dependence. In the case

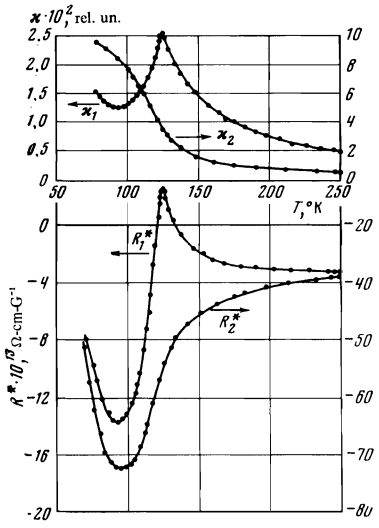

FIG. 2. Temperature dependence of $R^* = \rho_H/H$ and of the magnetic susceptibility κ of holmium single crystals: κ_1 and R_1^* are the plots obtained with H along $\langle 11\bar{2}0\rangle$, and κ_2 and R_2^* were obtained with H along $\langle 0001\rangle$.

of magnetization along $\langle 0001\rangle$, when the Hall emf is measured in the basal plane, R_h has a negative sign. R_h does not change in absolute magnitude as a function of the temperature, and decreases in proportion to the temperature below 125°K, in analogy with the temperature dependence of the magnetic component ρ_m of the electric resistivity measured in the basal plane. In the case of magnetization along $\langle 11\bar{2}0\rangle$, when the Hall emf is measured along the hexagonal axis of the crystal, we have $R_h > 0$. At $T > 180$°K, the coefficient R_h does not vary with temperature, and at $T < 180$°K it has a temperature dependence with singularities of the same character as ρ_m measured along the hexagonal axis (Fig. 3). This interpretation of the temperature dependence of R_h as being governed by a proportionality to ρ_m is valid in the entire investigated temperature interval. At the same time, in ferromagnetic d-metals, the correlation between the temperature dependence of the anomalous Hall coefficient and ρ_m is observed in a rather limited temperature interval[11]. The reason for this difference is that in the magnetically-ordered heavy rare-earth metals the main contribution to the Hall resistance is made only by scattering from magnetic inhomogeneities, whereas in d-metals scattering by phonons is also significant.

In a number of theoretical papers[12,13] it was shown that the complicated nonmonotonic temperature dependence of the resistivity ρ along the hexagonal axis of REM near the magnetic-transition temperature is due to the appearance of a complex atomic antiferromagnetic structure.

On the basis of our results we can assume that the characteristic features in the temperature dependence of the helicoidal Hall coefficient R_h are also due to the influence of the noncollinear magnetic structure. First, when a helicoidal structure is produced, changes take place in the electronic structure of the holmium and these changes determine the number and mobility of the carriers. Second, the presence of a helicoid with a period that does not coincide with the period of the crystal structure leads to an additional "helicoidal" scattering of the conduction electrons, and this makes an additional contribution to the anomalous Hall effect in comparison with the paramagnetic and ferromagnetic ordering.

Figure 4 shows the dependence of the Hall resistivity ρ_H on the temperature at certain values of the magnetic field in the temperature interval 4.2–300°K for a crystal magnetized in the basal plane. Notice should be

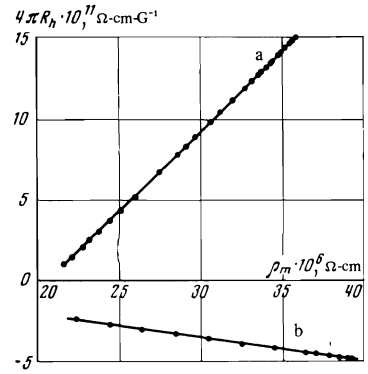

FIG. 3. Dependence of the anomalous Hall coefficient $4\pi R_h$ on the magnetic resistivity ρ_m for holmium single crystals: a) H along $\langle 11\bar{2}0\rangle$, b) H along $\langle 0001\rangle$.

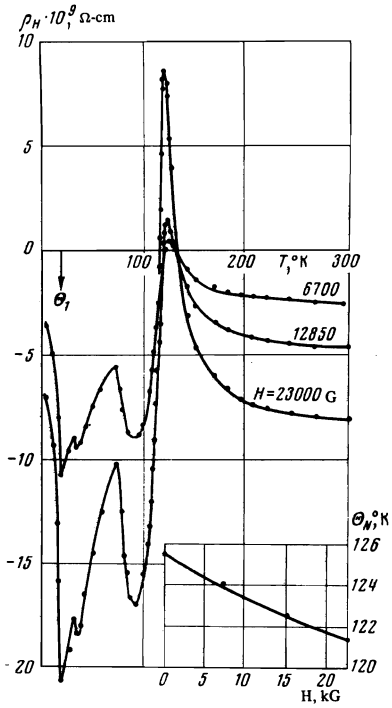

FIG. 4. Temperature dependence of the Hall resistivity ρ_H at certain values of the magnetic field in the case when H is directed along $\langle 11\bar{2}0 \rangle$.

taken first of the presence of extrema on the $\rho_H(T)$ curve at 20, 35, and 125°K. According to neutron-diffraction investigations[14], the temperature 20°K corresponds to the transition of the holmium from the ferromagnetic to the antiferromagnetic state, while 35°K is the temperature at which an abrupt change takes place in the angle of the helicoid, as well as a distortion of the helicoidal structure of the holmium. Above 35° the holmium has a simple spiral structure, and the angle of the spiral increases practically linearly with temperature up to the Neel temperature[15]. The position of the maximum in the region of Θ_N depends on the magnetic field intensity and decreases with temperature in proportion to H with increasing field (insert of Fig. 4). Extrapolation of the $\Theta_N(H)$ line to H = 0 yields the temperature 125°K, which was taken by us to be the Neel temperature. Neutron-diffraction investigations yield for the Neel temperature a value 133°K. Some of the difference is possibly due to the presence of the impurities in the investigated samples.

Special notice should be taken of the presence, observed by us for the first time, of a minimum on the $\rho_H(T)$ curves at ~93°K; the position of this minimum does not change when the magnetic field is varied. The presence of the minimum is observed also on the $\kappa(T)$ curve (see Fig. 2). In the region of the same temperature, a deep minimum is observed on the R*(T) curve for the crystal when the magnetic field is directed along $\langle 0001 \rangle$. We note in this connection that anomalies in the absorption of ultrasound in the region of the indicated temperature were recently also observed [16]. This seems to indicate that at this temperature there is an immediate phase transition, although it was not revealed by neutron diffraction.

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