# *HALL EFFECT IN NICKEL ALLOYS*

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Submitted to JETP editor July 18, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 65-68 (January, 1965)

The temperature dependence of the spontaneous Hall constant ($R_s$), electric resistance ($\rho$) and spontaneous magnetization ($I_s$) in Ni-Mo (up to 5 at.% Mo) and Ni-Si (up to 8 at.% Si) alloys is investigated. The theoretical relations between the Hall constant and the electric resistance $\rho$ and magnetic part of the electric resistance $\rho_m$ are confirmed experimentally. The experimental dependence of $R_s$ on the temperature is found in the following explicit form $R_s = b_0 + b_1T + b_2T^2$. It is concluded that the impurity-phonon mechanism of conduction-electron scattering as well as the mechanism of scattering on magnetic inhomogenieties both contribute to the anomalous Hall effect.

RECENTLY a large amount of theoretical work has been done on the Hall effect in ferromagnetic metals, based on consideration of the spin-orbit interaction.[1-4] The scattering mechanisms considered in this work are due to impurities, phonons or simultaneously to phonons and lattice defects. The calculations lead, in general, to a linear-quadratic relation between the spontaneous hall constant $R_s$ and the electrical resistivity $\rho$:

$$R_s = a\rho + b\rho^2. \tag{1}$$

The case of scattering from spin inhomogeneities was not considered at all in the above work. This case has been treated only most recently by Irkhin and Abel'skiĭ[5]; it was pointed out that in scattering from spin waves $R_s \sim \rho_m$ ($\rho_m$ is the magnetoresistance) and $R_s \sim I_s^2$ ($I_s$ is the spontaneous magnetization).

In the majority of experimental investigations of the Hall effect, what is determined as a rule is the dependence of the constant $R_s$ on either $\rho$ or on its magnetic part $\rho_m$[6]. In the present paper, in contrast to the work done up to now, we report on an investigation of the simultaneous dependence of the Hall constant $R_s$ on the total electrical resistance $\rho$, on the magnetoresistance $\rho_m$, and also on the spontaneous magnetization $I_s$; this permits an estimate of the limits of validity of the theoretical expressions given above.

We carried out the investigation on the alloys Ni-Mo (up to 5 at.% Mo) and Ni-Si (up to 8 at.% Si) in a range from room temperature to significantly above the Curie point.

In Fig. 1 is shown the dependence of $R_s$ on $I_s^2$ for nickel alloys containing 1.2 at.% Mo and 2.0 at.% Si. Analysis of the experimental data shows that the relation

$$R_s - R_{s0} = K(I_0^2 - I_s^2) \tag{2}$$

holds between the Hall constant $R_s$ and the spontaneous magnetization $I_s$ over a wide temperature range (up to $T \approx 0.93\Theta$, where $\Theta$ is the Curie temperature); $R_{s0}$ and $I_0$ are the Hall constant and spontaneous magnetization at T = 0°K. The dependence of $R_s$ on $I_s^2$ given by (2) is also well satisfied for all the other Ni-Mo and Ni-Si alloys investigated and is possibly a universal relationship for ferromagnetic metals and alloys.

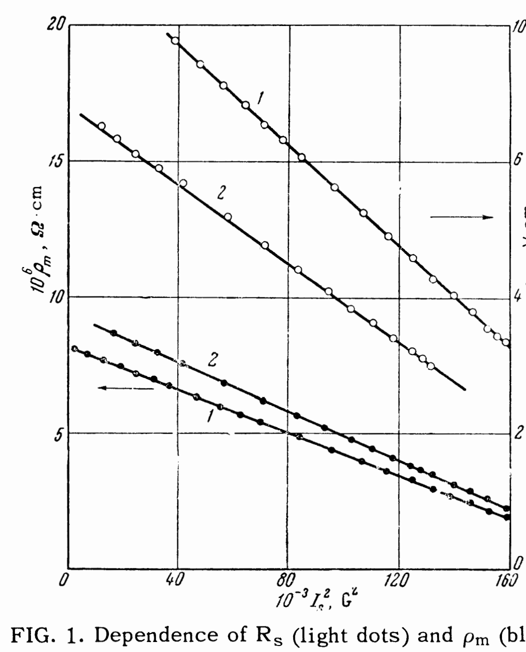


FIG. 1. Dependence of $R_s$ (light dots) and $\rho_m$ (black dots) on $I_s^2$: Curve 1 for an alloy of 1.2% Mo in Ni. Curve 2 for an alloy of 2.0% Si in Ni.

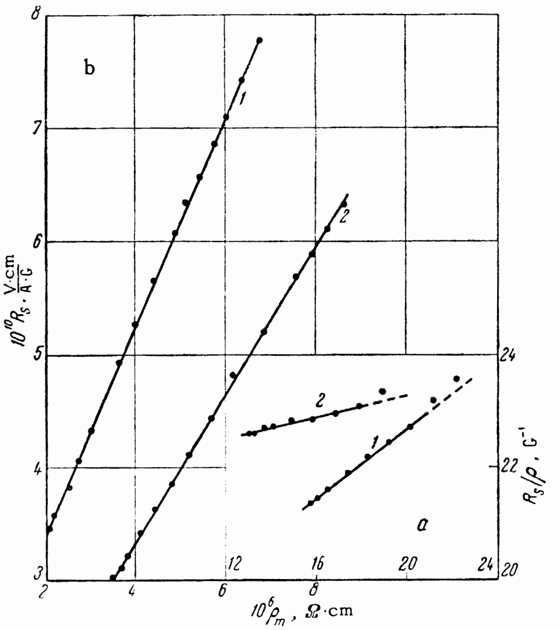


FIG. 2. Dependence of $R_s$: a-on the total electrical resistivity $\rho$. b-on the magnetoresistance $\rho_m$ for alloys of 1.2% Mo in Ni (curve 1) and 2.0% Si in Ni (curve 2).

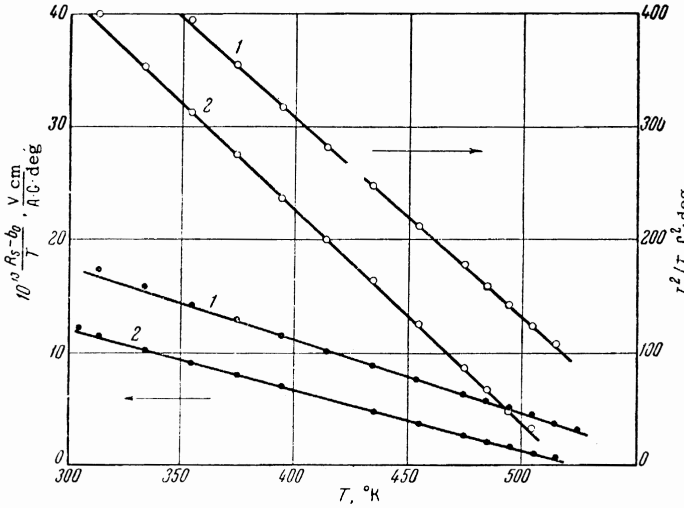


FIG. 3. Dependence of $I_s^2$ (light dots) and $R_s$ (black dots) on temperature for alloys of 1.2% Mo in Ni (curve 1) and 2.0% Si in Ni (curve 2).

For comparison we now consider the connection between $R_s$ and the total resistivity of the sample, shown in Fig. 2,a. These data demonstrate that the dependence of $R_s$ on $\rho$ can be described approximately by the linear-quadratic expression (1). However the temperature range for this appears to be much smaller than for the dependence of $R_s$ on $I_s^2$ (Fig. 1). It is typical that deviations from (1) are found on approaching the Curie point (from $T \approx 0.7\Theta$), precisely where the ferromagnetic anomalies in the Hall effect and electrical conductivity also show up most clearly.

With a view towards further clarification of which of the regularities is decisive in the Hall effect, an attempt was made to determine directly the temperature dependence of the Hall constant. It appears that the spontaneous magnetization of the alloys investigated can be described (Fig. 3) empirically over a broad range of temperatures by an expression of the form

$$I_s^2 = a_1 T - a_2 T^2. \quad (3)$$

Inserting (3) in (2) we find

$$R_s = b_0 + b_1 T + b_2 T^2. \quad (4)$$

The coefficients $b_0$, $b_1$, and $b_2$ are determined by the values of $a_1$, $a_2$, and K. The solid lines in Fig. 3 were calculated in this way and the experimentally determined values of $R_s$ for specified T are designated by points. From these data it follows also that the temperature dependence of the spontaneous Hall constant behaves in a way determined by the temperature dependence of $I_s^2$.

It is well known that a change in spontaneous magnetization leads also to an anomalous temperature behavior of the electrical resistivity in ferromagnetic metals, showing up particularly sharply in the region of the Curie point. From this it is possible to establish a relation between the anomalous Hall effect and the anomalous part of the electrical resistivity $\rho_m$.

The magnetoresistance $\rho_m$ was determined graphically from the temperature dependence of the resistivity by eliminating the phonon resistivity $r_{ph}$ graphically, and also analytically by the method of equal temperature intervals. As is clear from Fig. 1,

$$\rho_m = \alpha (I_0^2 - I_s^2), \quad (5)$$

which agrees with the conclusions of others [6-8] and, consequently, taking (2) into account, we have

$$R_s = R_{s0} + c\rho_m, \quad (6)$$

where c is a numerical coefficient. Actually, the dependence of $R_s$ on $\rho_m$ displayed in Fig. 2b shows that (6) is valid and is satisfied over a wider range of temperatures than is relation (1) for $R_s(\rho)$.

Thus, both (6) and (1) are satisfied far from the Curie point. This shows that both mechanisms for electron scattering—scattering from magnetic inhomogeneities as well as impurity-phonon scattering—give contributions to the anomalous Hall effect; the former mechanism shows up particularly strongly near the Curie temperature. However investigation of the effect in the region of technical magnetization does not yield an estimate of the contributions due to both scattering mechanisms. As was shown most recently in Kondorskiĭ's theoretical work [9] and in our experimental investigations [10], it is possible to obtain such an estimate by studying the Hall effect in the region of the paraprocesses (in the region of the onset of magnetic saturation).

In conclusion we express our sincere thanks to Prof. E. I. Kondorskiĭ for his interest and for discussions of the results.

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Translated by M. L. Glasser
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