The planar Hall effect of Ni, Fe, Co and Ni-Fe films with thicknesses between 100 and 1500 Å is investigated in the temperature range 77 to 293 °K. It is shown that the experimental data obtained may be explained by assuming that the mechanism of scattering and reflection on film surfaces does not give an appreciable contribution to the planar Hall effect.

Es wird der ebene Halleffekt von Ni-, Fe-, Co- und Ni-Fe-Schichten mit Schichtdicken zwischen 100 und 1500 Å im Temperaturbereich 77 bis 293 °K untersucht. Die experimentellen Ergebnisse können unter der Annahme erklärt werden, daß der Streumechanismus und die Reflexion an der Schichtoberfläche keinen merklichen Anteil zum ebener Hall-effekt liefern.

1. Introduction

The kinetic coefficients of thin metal films depend on thickness. On the one hand, scattering and reflection of electrons on film surfaces limit the mean free path. On the other hand, from Born-Karman's principle of periodicity the electron states are not distributed over the whole Brillouin zone, but only in some of its sections [1, 2]. Then the state density in the conduction band will depend on film thickness.

For ferromagnetic films the experiment shows that the resistivity $\rho$ and the ferromagnetic Hall constant increase essentially with decreasing thickness [3]. Because of scattering and reflection of electrons on film surfaces causing the increase of $\rho$, one may expect that these both effects give an essential contribution to the Hall effect. However, in [3] high temperatures were used and, therefore, the scattering by phonons gives the main contribution to the effect. But, the thickness dependence of the Hall constant was not yet explained.

For the resistivity anisotropy $\Delta\rho_a$ of Ni–Fe films at room temperature it was found [4] that $\Delta\rho_a$ does not change with thickness. Whether the observed independence of thickness is only a special property of the investigated alloy or a general one for all ferromagnetic films, and whether it is existing for all temperatures was not cleared up till now. There is no theory on galvanomagnetic effects in ferromagnetic films till now. Therefore, the experimental investigation of this problem is of great interest.

In this paper the thickness dependence of the planar Hall effect is considered [5, 6], for which the magnetization is always oriented parallel to the film plane. As it is shown in [5, 6], the transversal tension $V_y$ due to the planar Hall effect is given by

$$V_y = P \sin \varphi \cos \varphi \frac{I}{t},$$

(1)
where $P$ is the coefficient of this effect, $\varphi$ is the angle between the direction of magnetization vector and current density one, $I$ is the value of the current, $t$ is the film thickness.

As it was shown in [7], the coefficient $P$ in polycrystalline films is equal to the resistivity anisotropy $\Delta \rho_a$. Using (1) one can get the value of $P$ and, consequently, $\Delta \rho_a$ for different film thicknesses and different temperatures. The method of defining $\Delta \rho_a$ using the planar Hall effect is more precise than measuring the resistivity in two mutually perpendicular directions — parallel and perpendicular to the field direction.

2. Experimental Results and Discussion

Films of Ni, Fe, Co, and Ni–Fe alloys were investigated having thicknesses between 100 and 1500 Å. The film preparation and the measuring method are described in [8]. The temperature range from liquid nitrogen to room temperature was investigated. The film temperature measured by a copper-constantan thermocouple is assumed to coincide with that of the substrate.

2.1 Thickness dependence of $P$

In Fig. 1a the values of $P$ at room temperature for Ni, Fe, and Ni–Fe alloys are given in dependence on film thickness. As it was shown for resistivity in [4] we found that there is no thickness dependence of $P$ at room temperature for Ni, Fe, and Ni–Fe films.

For the thickness range investigated we may assume that the phonon spectrum does not depend on thickness. Moreover, in bulk samples of pure Ni and Fe the main contribution at room temperature is due to phonon scattering, but in Ni–Fe alloy samples the main contribution to the effect comes from scattering on ferromagnetic ions in the whole temperature range investigated [7]. Taking into account this we may explain the observed independence of $P$ of film thickness at room temperature by assuming that the mechanism of scattering and reflection on film surfaces does not give an appreciable contribution to planar Hall effect. There were not enough data till now which permit to test the above assumption. But as we shall see in the following a number of experimental facts are in agreement with it.

Fig. 1a. Coefficient of planar Hall effect $P$ at room temperature for Ni, Fe, Ni–Fe, and Co films
From this assumption it doesn't follow the necessity of independence of \( P \) of film thickness at all temperatures. So, at liquid nitrogen temperature, as we see in Fig. 1b, a weak increase for \( P \) with decreasing thickness is found in Ni and Fe films. According to the results obtained in [7] at low temperatures the coefficient \( P \) for ferromagnetic metals is proportional to the concentration of defects and impurities, so that the observed increase of \( P \) may be explained by a weak increase of the concentration of defects and impurities in films of small thickness.

Except this, the mean free path increases at low temperatures and because of scattering and reflection of electrons on the film surface the resistivity increases. If the scattering and reflection of electrons on the film surface at liquid nitrogen temperature gives no appreciable contribution to planar Hall effect, the value of \( P/\rho \) must be smaller for thinner films than for thicker ones. Indeed, the curves in Fig. 2 show an appreciable decrease of \( P/\rho \) with decreasing thickness for Ni films both at liquid nitrogen and at room temperature.

For Ni–Fe alloys it was shown previously [7] that the planar Hall effect was mainly caused by scattering on ferromagnetic ions. Therefore, the temperature dependence of \( P \) is determined by that of \( M^2 \) (\( M \) is the magnetization). For the investigated thickness range we may assume that the temperature dependence of \( M^2 \) is the same for all thicknesses. If the mechanism of scattering and reflection of electrons on the film surface gives no appreciable contribution to the planar Hall effect, the value of \( P_{77}/P_{293} \) will not depend on thickness (the indices 77 and 293 indicate the temperature in °K). In Fig. 3 the values of \( P_{77}/P_{293} \) and \( \Theta_{77}/\Theta_{293} \) are plotted versus film thickness for the alloy 90% Ni and 10% Fe. We see that \( P_{77}/P_{293} \) is constant for all thicknesses, but \( \Theta_{77}/\Theta_{293} \) increases with decreasing thickness.
In Fig. 1a the thickness dependence of $P$ is given for Co films. Contrary to Ni, Fe, or Ni-Fe films in Fig. 1a we see that at room temperature for Co films $P$ increases appreciably with decreasing thickness. This thickness dependence, as it will be shown in the following, may not be explained by the resistivity increase in thin films. Perhaps, it is related to the intrinsic structure of Co films. In Co films, obtained by conventional thermal evaporation in high vacuum, there is coexistence of the hexagonal and cubic phase. At room temperature the hexagonal phase is the predominating one. Crystals with hexagonal structure have two planar Hall coefficients: the one is related to the plane parallel to the hexagonal axis, the other one to that perpendicular to it. Therefore, if the phase concentrations and the distribution in space of the hexagonal axis depend on thickness the mean value of $P$ over the whole film volume depends also on thickness.

### 2.2 Temperature dependence of $P$

In Fig. 4a and b the temperature dependence of $P$ are given for Ni and Co films having different thicknesses. As we see in Fig. 4a and b, $P$ decreases monotonously from room temperature to liquid nitrogen one for all thicknesses. But the decrease of $P$ at low temperatures is slightly greater in thick films than in thin ones.

An analogous fact is observed for resistivity too. The slope of the curves $\rho/\rho_{220}(T)$ for Ni, Fe, and Co films is also slightly greater for thick films than for thin ones.

![Fig. 4a. Temperature dependence of $P$ for Ni films. (a) 220 and 300 Å thickness, (b) 730 and 1220 Å thickness](image)

![Fig. 4b. Temperature dependence of $P$ for Co films](image)
Planar Hall Effect in Ferromagnetic Films

Fig. 5a. Temperature dependence of $P_s/\rho$ for Ni.
(a) bulk metal, (b) film thickness 1220 Å,
(c) film thickness 300 Å

Fig. 5b. Temperature dependence of $P_s/\rho$ for Fe films.
$\bullet$ — 900 Å thickness, $\bigcirc$ — 350 Å thickness

thin ones. This behaviour of $\rho$ may be explained by the fact that in thin films the concentration of defects and impurities is greater and at low temperatures the scattering and reflection of electrons on the film surface becomes more important. Since this mechanism causes an appreciable increase of $\rho$, but according to the assumption gives no contribution to $P$, the value $P_s/\rho$ (where $P_s = P/M^2$) must be smaller at low temperatures, as it was indeed observed experimentally (cf. Fig. 5a and b). (The values of $M$ for the investigated thickness range were assumed to be equal to those of bulk material and they were taken from the experimental data of [9].) In Fig. 5a the curve $P_s/\rho$ for bulk Ni is also given. Contrary to films an increase of $P_s/\rho$ is found with decreasing temperature.

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References


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