THE EFFECT OF MAGNETOSTRICTIVE STRAINS ON ANISOTROPY OF TRANSFER PHENOMENA IN SINGLE-CRYSTAL NICKEL–PALLADIUM ALLOYS

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The anisotropy of the Hall effect, Nernst–Ettingshausen effect, transverse spontaneous magnetoresistance, and transverse magnetothermo-emf of single-crystal Ni–Pd alloys with a Pd content of 0 to 70 at. % has been studied in the temperature range from 300 K to Curie temperature. It has been shown that magnetostrictive strains do not produce any substantial influence on the anisotropy of the coefficients of anomalous Hall and Nernst–Ettingshausen effects, but they play a decisive part in the formation of magnetoresistance and magnetothermo-emf anisotropy.

In this work we report the results of investigating the anisotropy of the Hall effect, Nernst–Ettingshausen effect, transverse magnetoresistance, magnetothermo-emf, and magnetostriction in single-crystal Ni–Pd alloys with a Pd content of 0 to 70 at. %. These effects were measured on the same samples at temperatures ranging from 300 K to Curie temperatures in a field of $1.4 \times 10^6$ A/m, with the electric field or temperature gradient oriented along the [110] crystallographic axis. The methods of sample preparation and measuring procedures are described in [1, 2].

The anisotropy of the coefficients of anomalous Hall effect (AHE) $R_s$ and anomalous Nernst–Ettingshausen effect (ANEE) $Q_s$ was characterized by the parameters

$$
\xi = \frac{R_s^{[110]} - R_s^{[001]}}{|R_s^{[001]}|},
$$

$$
\eta = \frac{Q_s^{[110]} - Q_s^{[001]}}{|Q_s^{[001]}|},
$$

where the crystallographic indices indicate the direction of the magnetic moment vector. The anisotropy of AHE and ANEE is an even magnetization effect, and this justifies a comparison of the anisotropy of AHE and ANEE with another even effect: magnetic anisotropy. Figure 1a shows the temperature dependences of the parameters $\xi$ and $\eta$ for pure Ni; Fig. 1b shows the temperature dependences of the magnetic anisotropy constant $K_1$ and of the intrinsic magnetic anisotropy constant $K_{1\text{int}}$, which is derived by subtracting the contribution of magnetostrictive strains $\Delta K$ from the measured values of $K_1$ [3]. The data presented in Fig. 1 are also typical of Ni$_{1-x}$–Pd$_x$ alloys with $x \leq 50$ at. %. From comparison of these data one can make the following conclusions. First, as can be seen in Fig. 1a, the temperature dependences of the parameters $\xi$ and $\eta$ are completely similar, and the values of these parameters are close. Considering the general relation between $Q_s$ and $R_s$ [4]

$$
Q_s = \frac{SR_s}{\rho} = \frac{\pi^2 k_B^2}{3} |c| \left( \frac{\partial R_s}{\partial E} \right)_B R_s
$$

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(where $S$ is the thermo-emf force and $\rho$ is the electrical resistance) and the small anisotropy of $\rho$ and $S$ compared with the anisotropy of $R_s$, such behavior of the parameters $\xi$ and $\eta$ can be easily explained. Second, the temperature dependences of $\eta$ and $\xi$ are similar to the temperature dependences of the intrinsic magnetic anisotropy constant $K_1^{\text{int}}$, rather than of the total $K_1$ which comprises the magnetostrictive contribution. Consequently, the magnetostrictive properties of Ni–Pd alloys, which play a noticeable part in the formation of the magnetic anisotropy constant, do not exert any appreciable effect on the anisotropy of AHE and ANEE.

Figure 1

Figure 2 shows how the spontaneous transverse magnetoresistance (TMR) $\Delta \rho_\perp/\rho$ (Fig. 2a) and transverse magnetostriction $\lambda_\perp$ (Fig. 2b) depend on the orientation of the magnetic field in the (110) plane for the alloy Ni–25 at.% Pd at 300 K. The spontaneous TMR was determined by extrapolating the field dependence of $\Delta \rho_\perp/\rho$ to the zero magnetic induction. It should be pointed out that the TMR of the investigated single-crystal alloys on magnetization along [001] is positive, whereas for polycrystalline Ni and Ni–Pd alloys $\Delta \rho_\perp/\rho < 0$ [5]. Figure 2 shows that on magnetization along [001] the magnetostriction $\lambda_\perp$ is also maximum. Therefore, one can suppose that magnetostrictive strains play an essential part in the formation of TMR, i.e.,

$$\frac{\Delta \rho_\perp}{\rho} = \left(\frac{\Delta \rho_\perp}{\rho}\right)^\lambda + \left(\frac{\Delta \rho_\perp}{\rho}\right)^\text{int},$$

where the first term is proportional to $\lambda_\perp$ and positive while the second term describes the intrinsic contribution and is negative.

Figure 2

The above statement is supported by the following estimate. According to the data from [6], under tensile loads $P = 2.5 \times 10^5$ N/m$^2$ for Ni the quantity $\Delta \rho_\perp/\rho$ changes by $\Delta(\Delta \rho_\perp/\rho)P \approx 0.3 \times 10^{-3}$. Then,
taking into account that the relative elongation of the sample $\Delta l/l = P/E$, where for Ni the modulus of elasticity $E = 2 \times 10^{-11}$ N/m$^2$, and also the fact that by definition $\lambda_\perp = \Delta l/l$, it is easy to obtain:

$$
\left(\frac{\Delta \rho_\perp}{\rho}\right)^\lambda = \Delta \left(\frac{\Delta \rho_\perp}{\rho}\right)^P \frac{E}{P} \frac{1}{\lambda}.
$$

(4)

At $\lambda_{[001]} = 4.2 \times 10^{-5}$ this leads to $(\Delta \rho_\perp/\rho) \approx 10^{-2}$. Subtracting this positive contribution from the measured value of $\Delta \rho_{[001]}^\perp/\rho$, we find that the intrinsic TMR is negative and by order of magnitude it coincides with the data for polycrystalline alloys.

The data on the temperature dependence of TMR [7] can serve as an additional confirmation of the substantial contribution of magnetostrictive strains to TMR. In the neighborhood of the "compensation" temperature, i.e., when $K_1$ becomes zero, and, consequently, the band contribution to $K_1$ is small, it should be expected that $(\Delta \rho_\perp/\rho)^{\text{int}}$ is small too, and under this condition the TMR and $\lambda$ dependences must be the same, which was indeed recorded in the experiment. In particular, for pure Ni in the 460–510 K temperature range, TMR and $\lambda$ had two extrema at $H \parallel [110]$ and $H \parallel [001]$.

Figure 3 shows angular dependences of the transverse magnetothermo-emf (transverse thermomagnetic effect) for the Ni-25 at.% Pd alloy. A comparison with the data on the angular dependence of the magnetostriction $\lambda_\perp$ (see Fig. 2b) demonstrates that both effects have almost coinciding extrema at $M_\perp \parallel [001]$ and $M_\perp \parallel [110]$; at the same time, the magnetothermo-emf has a small maximum at $M_\perp \parallel [112]$. In the case of elastic scattering the thermo-emf is defined by the following expression:

$$
S = -\frac{\pi^2 k_B T}{3} \frac{1}{|e|} \sigma \left(\frac{\partial \sigma}{\partial E}\right)_{E_F} = A T \rho \left(\frac{\partial \sigma}{\partial E}\right)_{E_F},
$$

(5)

where $A$ is a constant and $\sigma = 1/\rho$ is the electrical conductivity. Consequently, in view of Eq. (3),

$$
\frac{\Delta S_\perp}{S} = \left(\frac{\Delta S_\perp}{S}\right)^\lambda + \left(\frac{\Delta S_\perp}{S}\right)^{\text{int}},
$$

(6)

where

$$
\left(\frac{\Delta S_\perp}{S}\right)^\lambda = \left(\frac{\Delta \rho_\perp}{\rho}\right)^\lambda, \quad \left(\frac{\Delta S_\perp}{S}\right)^{\text{int}} = \left(\frac{\Delta \rho_\perp}{\rho}\right)^{\text{int}} + \Delta \left(\frac{d \rho_\perp}{d E}\right)_{E_F}.
$$

(7)

The first contribution in Eq. (6) is connected with magnetostrictive strains, and the second contribution is intrinsic. According to the estimates presented above in the analysis of TMR, the contribution $(\Delta S_\perp/S)^\lambda$ is positive, on the order of $10^{-2}$, and proportional to $\lambda_\perp$, this being consistent with the experimental data, except for a small additional maximum of $\Delta S_\perp/S$ at $M_\perp \parallel [112]$. This suggests that the main mechanism leading to the magnetothermo-emf anisotropy is magnetostrictive extensional strain of the sample, although the band contribution due to the scattering anisotropy is far from being negligibly small.

Therefore, we can conclude that in single-crystal Ni-Pd alloys.
(1) magnetostrictive strains make a negligibly small contribution to the anisotropy of AHE and ANEE;
(2) the contribution of magnetostrictive strains to the anisotropy of magnetoresistance is commensurable in order of magnitude with the intrinsic effect caused by specific features of the band structure;
(3) the anisotropy of transverse magnetothermo-emf mainly depends on the contribution of magnetostrictive strains; the zonal contribution, though smaller in magnitude, also plays a part in the formation of the effect discussed.

REFERENCES


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