Anisotropic magnetoresistance of Co-Pd alloys

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The anisotropic magnetoresistance $\Delta\rho/\rho_0$ and electrical resistivity ρ_0 of $Co_{100-x}Pd_x$ alloys were measured at $T=4$, 77, and 300 K. The temperature dependence of $\Delta\rho/\rho_0$ is used to yield $(\Delta\rho/\rho_0)_{imp}$ and $(\Delta\rho/\rho_0)_{ph}$ data for Co-Pd alloys as a function of x. A two-current model and theories based on extended versions of it are used to explain the spin-down resistivity $\rho^{\downarrow}$ and spin-up resistivity $\rho^{\uparrow}$. There exists a maximum in $\rho^{\downarrow}$ at $x=65$ at. % Pd. For $x\geq 50$–75 at. % Pd, $\rho_{sd}^{\uparrow}\neq 0$ due to the magnetic weakness for the spin-up d band. ρ_{ss} follows Nordheim's rule, and ρ_{ss} increases, going from the Co-Ni to the Co-Pd case.

I. INTRODUCTION

The two-current model of Campbell, Fert, and Jaoul[1,2] has been successful in accounting for the anisotropic magnetoresistance $\Delta\rho/\rho_0$ in most nickel-rich crystalline alloys. In short, this model states that, at $T\simeq 0$,

$$\Delta\rho/\rho_0=\gamma(\rho^{\downarrow}/\rho^{\uparrow}-1)\ , \tag{1}$$

where $\rho^{\downarrow}$ and $\rho^{\uparrow}$ are the resistivities for the spin-down and -up bands, respectively, and $\gamma\simeq 0.01$. The condition $\rho^{\downarrow}/\rho^{\uparrow}\gg 1$ is assumed. In order to extend the theory to structurally disordered or weakly ferromagnetic materials, Malozemoff has given a more general formula,[3] which may be given as follows:

$$\Delta\rho/\rho_0=\gamma\frac{(\rho_{sd}^{\downarrow}-\rho_{sd}^{\uparrow})(\rho_{sd}^{\downarrow}+\rho_{ss}^{\downarrow}-\rho_{sd}^{\uparrow}-\rho_{ss}^{\uparrow})}{(\rho_{sd}^{\downarrow}+\rho_{ss}^{\downarrow})(\rho_{sd}^{\uparrow}+\rho_{ss}^{\uparrow})}\ , \tag{2}$$

where $\rho_{ss}^{\downarrow}$ and $\rho_{sd}^{\downarrow}$ are the resistivities arising from the s-s and s-d scatterings, respectively, in spin-down bands. $\rho_{ss}^{\uparrow}$ and $\rho_{sd}^{\uparrow}$ are the resistivities from the corresponding scatterings in spin-up bands. Finally, to extend the theory to the region of concentrated alloys, Berger has discussed the case in which the scattering potential with alloy disorder is strong.[4] The limitation of his approach is that both γ and r_F are assumed to be independent of the alloy composition x. $r_F\equiv|C_A(\varepsilon=\varepsilon_F)/C_B(\varepsilon=\varepsilon_F)|^2$, where $A=$Co and $B=$Pd. C_A or C_B is the average of the coefficient $C_{ln}(\varepsilon)$, used in the tight-binding approximation, over the atom A (Co) or B (Pd).

In this paper we will mainly discuss the anisotropic magnetoresistance of $Co_{100-x}Pd_x$ alloys. The magnetic and electrical resistivity properties for this same series of Co-Pd alloys have been studied previously.[5] In Ref. 5 we find that, for Co_5Pd_{95}, $\alpha\equiv\rho^{\downarrow}/\rho^{\uparrow}\simeq 2$. Although, as discussed in Ref. 5, the localized picture is expected to be applicable, we nonetheless choose a band picture to explain our results. The main reason is that as x decreases from 95 at. %, the band model becomes increasingly more appropriate. Here we just use the $\Delta\rho/\rho_0$ and α data of Co_5Pd_{95} to extract the value of γ, which is usually a parameter known only to an order of magnitude. In addition, we will show that even if we use a different γ, our main conclusion in this paper will be unaffected.

One problem in this approach has already been encountered in Ref. 5: In the treatment of the temperature dependence of the resistivity Co_5Pd_{95}, there is a complication resulting from paramagnon scattering;[6] i.e., for $T<T_{sf}$, the ideal resistivity ρ_T of the alloy is proportional to T^2, but for $T>T_{sf}$, the behavior $\rho_T\propto T$ may result. For Pd-rich alloys, $T_{sf}\equiv 0.25T_s\simeq 20$ K. Perhaps the paramagnon theory can explain why in Ref. 5 we observed an anomalously large coefficient for the T^2 term in ρ_T for $T\leq 20$ K. But more significant is the fact that in Ref. 5 we took another temperature range, $20<T<50$ K, for the fitting, in which only the T^2 and T^3 dependences are evident, to obtain α. In the $20<T<50$ K region, there is little or no T dependence as predicted from paramagnon-scattering theory. Moreover, since, in Ref. 5, $\alpha\simeq 2$ is also obtained by another method, independent of the temperature effect, the same α value is used here for purposes of discussion.

II. EXPERIMENTS

The details of $Co_{100-x}Pd_x$ sample preparation were described before.[5] The anisotropic-magnetoresistance measurements are performed with standard techniques. We used a CF1200 liquid-helium cryostat and an ITC4 temperature controller, both made by Oxford Instrument, to maintain the sample temperature. We made measurements at three fixed temperatures $T=4$, 77, and 300 K. The temperature stability was good to within ± 0.2 K. A 7-in. electromagnet produced external fields up to 1 T. The sample is aligned either parallel or perpendicular to the field to measure $\rho_{\parallel}$ or $\rho_{\perp}$. Characteristic $\rho_{\parallel}$ and $\rho_{\perp}$ at 4 K for $Co_{45}Pd_{55}$ crystalline alloys are shown in Fig. 1. The anisotropic magnetoresistance is defined as

$$\Delta\rho/\rho_0=(\rho_{\parallel}^s-\rho_{\perp}^s)/(\tfrac{2}{3}\rho_{\perp}^s+\tfrac{1}{3}\rho_{\parallel}^s)\ ,$$

where $\rho_{\parallel}^s$ and $\rho_{\perp}^s$ are the saturated resistivities of $\rho_{\parallel}$ and $\rho_{\perp}$.

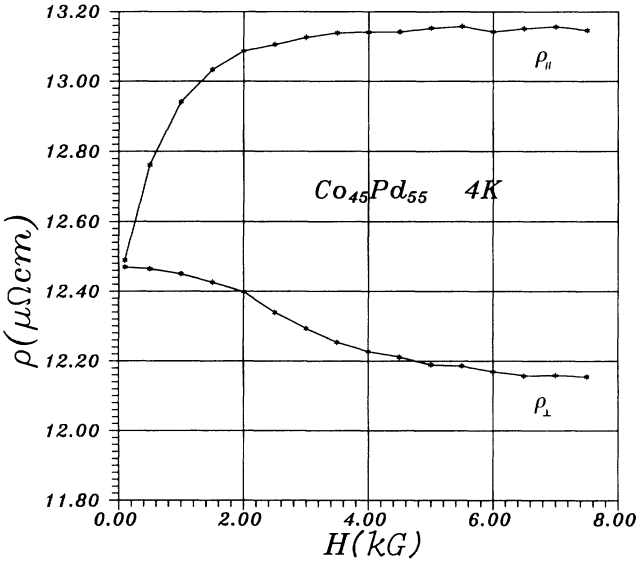

FIG. 1. Anisotropic resistivities $\rho_{\parallel}$ in parallel fields and $\rho_{\perp}$ in perpendicular fields of $Co_{45}Pd_{55}$ at $T=4$ K.

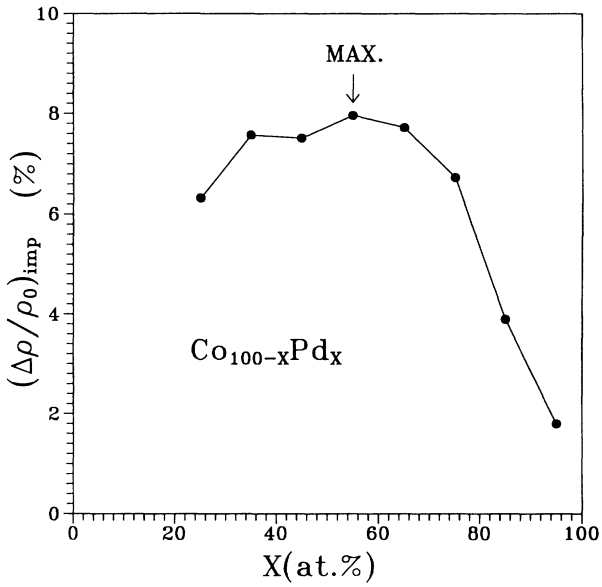

FIG. 3. $(\Delta\rho/\rho_0)_{imp}$ is defined as $(\Delta\rho/\rho_0)$ at $T=4$ K; $(\Delta\rho/\rho_0)_{imp}$ is plotted for each Pd concentration x.

III. TEMPERATURE DEPENDENCE OF $\Delta\rho/\rho_0$ IN Co-Pd

According to theory,[7,8] if $\alpha \gg 1$, Matthiessen's rule can be used to derive the temperature dependence of $\Delta\rho/\rho_0$:

$$\frac{\Delta\rho}{\rho_0}(T)=\left[\frac{\Delta\rho}{\rho_0}\right]_{ph}+\left[\left[\frac{\Delta\rho}{\rho_0}\right]_{imp}-\left[\frac{\Delta\rho}{\rho_0}\right]_{ph}\right]\frac{\rho_0(4.2\text{ K})}{\rho_0(T)}, \quad (3)$$

where $\rho_{\parallel}(T)=(\rho_{imp}+\rho_{ph})_{\parallel}$, $\rho_{\perp}(T)=(\rho_{imp}+\rho_{ph})_{\perp}$, and $\rho(4.2\text{ K})\simeq\rho_{imp}$. For Co-Pd alloys, the condition $\alpha \gg 1$ is not as strictly satisfied as for Co-Ni, Ni-Fe, and Ni-Mn alloys. As will be discussed later, the α of concentrated Co-Pd is about 5. Hence Eq. (3) is considered here as an empirical formula for obtaining $(\Delta\rho/\rho_0)_{imp}$ and $(\Delta\rho/\rho_0)_{ph}$ for Co-Pd alloys. Figure 2 shows the fitting of $\Delta\rho/\rho_0$ of Co_5Pd_{95}, $Co_{25}Pd_{75}$, and $Co_{65}Pd_{35}$ versus $\rho_0(4.2\text{ K})/\rho_0(T)$ at three temperatures $T=4$, 77, and 300 K. From the diagram the linear fit of Eq. (3) seems pretty good. By extrapolating each line to the vertical axis where $\rho_0(4.2\text{ K})/\rho_0(T)=0$, we can determine $(\Delta\rho/\rho_0)_{ph}$. On the lowest-temperature side, we use $(\Delta\rho/\rho_0)(4.2\text{ K})=(\Delta\rho/\rho_0)_{imp}$.

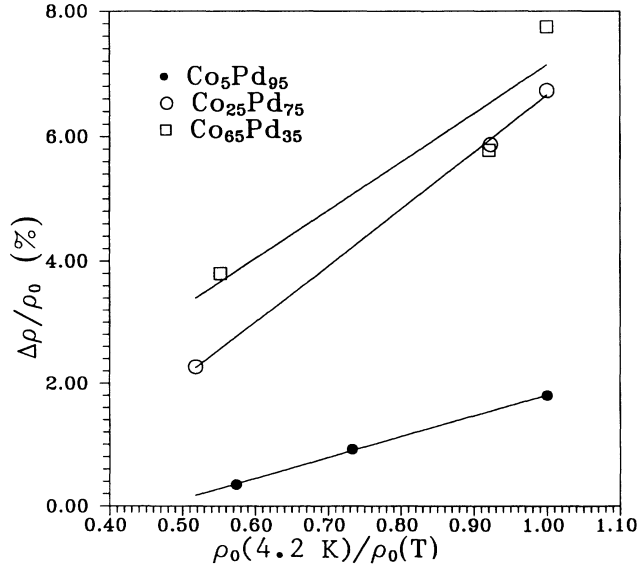

FIG. 2. Fittings of $\Delta\rho/\rho_0$ as a function of $\rho_0(4.2\text{ K})/\rho_0(T)$ with Eq. (3) for Co_5Pd_{95}, $Co_{25}Pd_{75}$, and $Co_{65}Pd_{35}$ alloys.

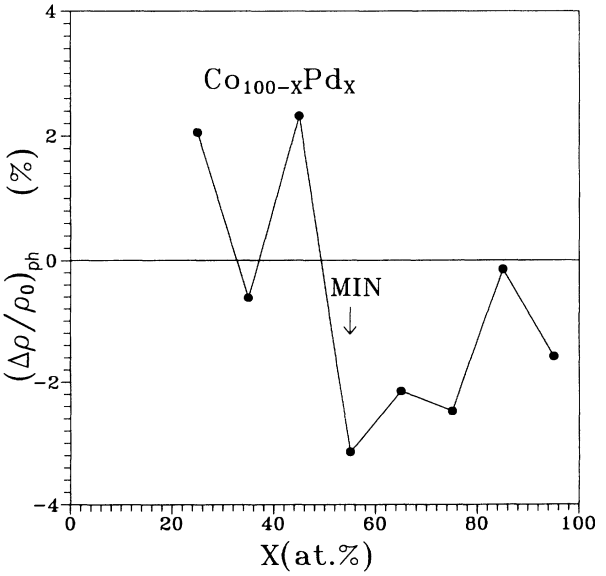

FIG. 4. $(\Delta\rho/\rho_0)_{ph}$ vs Pd concentration x.

The $(\Delta\rho/\rho_0)_{imp}$ of $Co_{100-x}Pd_x$ alloys is displayed as a function of the Pd concentration x in Fig. 3. From this picture we can see that there exists a maximum of $(\Delta\rho/\rho_0)_{imp}$ at $x \simeq 55$ at. % Pd. A detailed discussion about $(\Delta\rho/\rho_0)_{imp}$ will be given in the next section. At present, we show that $(\Delta\rho/\rho_0)_{ph}$ data as a function of x in Fig. 4. Besides the irregular datum point at $x=40$ at. %, the general trend in Fig. 4 is clear: (i) For small x, $(\Delta/\rho/\rho_0)_{ph}$ is positive; (ii) as x increases, $(\Delta\rho/\rho_0)_{ph}$ becomes negative; and (iii) $(\Delta\rho/\rho_0)_{ph}$ has a minimum near $x=55$ at. % Pd, which looks like an inverted mirror image of $(\Delta\rho/\rho_0)_{imp}$ in Fig. 3. The theoretical explanation, based on the idea of resistivity saturation of $\rho^{\downarrow}$, is given in Ref. 7 to account for this phenomenon.

IV. $\rho^{\downarrow}$ AND $\rho^{\uparrow}$ OF Co-Pd ALLOYS

The idea of the two-current model can also be used to write the residual resistivity ρ_0 of the alloy as

$$\rho_0^{-1}=(\rho^{\downarrow})^{-1}+(\rho^{\uparrow})^{-1} . \tag{4}$$

Then, by combining Eqs. (1) and (4), it is easy to calculate $\rho^{\downarrow}$ and $\rho^{\uparrow}$, respectively, for each alloy, provided that γ is known.

As stated before, γ is determined experimentally, and it is difficult to compare it with theoretical values.[1] For example, it is estimated that $\gamma \simeq 0.01$ for Ni alloys and $\gamma \simeq 0.018$ for Fe alloys.[4] Here we can use only one set of known $\Delta\rho/\rho_0$ and α data of Co_5Pd_{95} to evaluate γ; i.e., we tentatively assume that Eq. (1) is applicable to Co_5Pd_{95}. Then, by substituting $\Delta\rho/\rho_0=1.80\%$ and $\alpha \simeq 2$ into Eq. (1), we find $\gamma \simeq 0.018$ for Co-Pd alloys. On the other hand, it is known from the magnetization data[5] of Co-Pd alloys that when $x \geq 75$ at. % Pd, a magnetic weakness occurs. Obviously, as x becomes large enough, $\rho_{sd}^{\uparrow}$ is finite and nonzero. Then it may not be correct to use Eq. (1). We may want to use Eq. (2) instead. Before employing Eq. (2) to extract γ from the Co_5Pd_{95} data, we make the following assumptions:

$$\begin{aligned} \rho^{\downarrow}&=\rho_{ss}^{\downarrow}+\rho_{sd}^{\downarrow} , \\ \rho^{\uparrow}&=\rho_{ss}^{\uparrow}+\rho_{sd}^{\uparrow} , \\ \rho_{ss}^{\uparrow}&=\rho_{ss}^{\downarrow}=\rho_{ss} . \end{aligned} \tag{5}$$

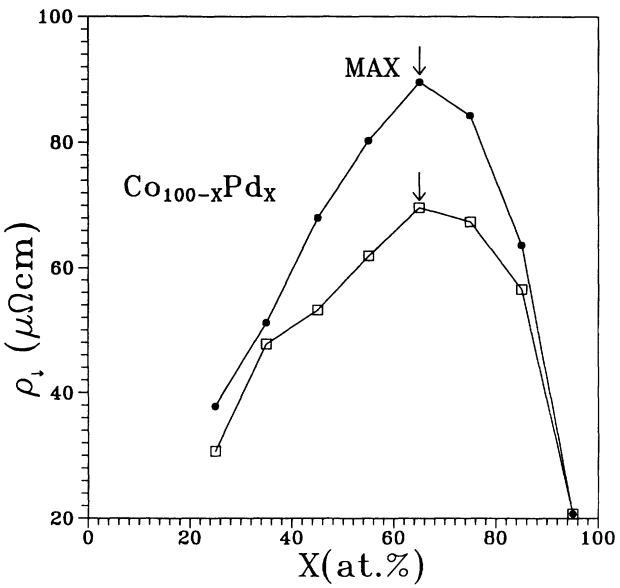

FIG. 5. Pd concentration x dependence of the spin-down resistivity $\rho^{\downarrow}$ of Co-Pd alloys. The solid circles are data obtained from Eqs. (1) and (4), and the open squares are from Eqs. (4) and (6).

By substituting Eq. (5) into Eq. (2), a simpler equation is obtained:

$$\Delta\rho/\rho_0=\gamma(\alpha-1)^2/\alpha . \tag{6}$$

Hence, if Eq. (6) is used instead of Eq. (1), γ would turn out to be 0.036.

Having found γ, we may calculate $\rho^{\downarrow}$ and $\rho^{\uparrow}$ from $\Delta\rho/\rho_0$ and ρ_0 with either Eqs. (4) and (6) or Eqs. (1) and (4). Table I summarizes all the $\rho^{\downarrow}$ and $\rho^{\uparrow}$ values for each $Co_{100-x}Pd_x$ sample. If we plot $\rho^{\downarrow}$ as a function of Pd concentration x, the result is shown in Fig. 5. There are two sets of data in Fig. 5: The solid circles are $\rho^{\downarrow}$ data with $\gamma=0.018$ and Eq. (1), and the open squares are that with $\gamma=0.036$ and Eq. (6). Two conclusions can be made from Fig. 5: (i) A maximum of $\rho^{\downarrow}$ is located at $\bar{x}=65$ at. % Pd. This is true, irrespective of which data plot is considered. (ii) The value of maximum $\rho^{\downarrow}$ is about 70 or

TABLE I. Magnetoresistance $\Delta\rho/\rho_0$ and residual resistivity ρ_0 at 4 K for the $Co_{100-x}Pd_x$ alloys and $\rho^{\downarrow}$ and $\rho^{\uparrow}$ calculated.

Sample	$\Delta\rho/\rho_0$ (%)	ρ_0 ($\mu\Omega$ cm)	$\rho^{\downarrow}$ ($\gamma=0.018$)[a] ($\mu\Omega$ cm)	$\rho^{\uparrow}$ ($\gamma=0.018$)[a] ($\mu\Omega$ cm)	$\rho^{\downarrow}$ ($\gamma=0.036$)[b] ($\mu\Omega$ cm)	$\rho^{\uparrow}$ ($\gamma=0.036$)[b] ($\mu\Omega$ cm)
Co_5Pd_{95}	1.80	6.91	20.73	10.37	20.73	10.37
$Co_{15}Pd_{85}$	3.90	15.28	63.67	20.11	56.54	20.94
$Co_{25}Pd_{75}$	6.73	14.68	84.25	17.78	67.38	18.77
$Co_{35}Pd_{65}$	7.72	14.25	89.62	16.94	69.64	17.92
$Co_{45}Pd_{55}$	7.96	12.49	80.21	14.79	61.95	15.64
$Co_{55}Pd_{45}$	7.51	11.02	68.02	13.17	53.23	13.90
$Co_{65}Pd_{35}$	7.52	9.89	51.21	12.26	47.77	12.47
$Co_{75}Pd_{25}$	6.32	6.78	37.86	8.39	30.69	8.85

[a] γ is defined from $\Delta\rho/\rho_0=\gamma(\alpha-1)$, where $\alpha=\rho^{\downarrow}/\rho^{\uparrow}$.
[b] γ is defined from $\Delta\rho/\rho_0=\gamma(\alpha-1)^2/\alpha$.

90 $\mu\Omega$ cm, depending on which set of data is used.

Discussions about the existence of a maximum for $\rho^{\downarrow}$ and the shifting of the maximum from $x=50$ at. % are the main subject in Ref. 4. In short, Ref. 4 stresses the fact that if the scattering potential associated with alloy disorder is strong enough to cause a variation of the $3d$ wave function between chemically different atoms, d-d scattering is strong and resonant. In turn, Nordheim's rule is not obeyed for $\rho^{\downarrow}$, and a shifted maximum is observed in $\rho^{\downarrow}$. To consider Co-Pd alloys, first, the valence difference $|Z|$ between Co and Pd is 1. Therefore the split-band limit[9] is as marginal for Co-Pd as for Co-Ni. Second, from neutron-diffraction data,[10] magnetic moments $\mu_{\rm Pd}=0.43\mu_B$ and $\mu_{\rm Co}=1.97\mu_B$, where μ_B is the Bohr magneton. Then, according to Ref. 4, $r_> \equiv \mu_{\rm Co}/\mu_{\rm Pd}=4.58$, which is pretty large and indicates a strong scattering potential. Hence the case of shifted maximum in $\rho^{\downarrow}$ is expected. Indeed, that is observed for Co-Pd. Another parameter of the theory is r_F, which is related to the $\bar{x}$ location of the maximum in $\rho^{\downarrow}$ by $(1-\bar{x})=(1+r_F)^{-1}$. From Fig. 5, obviously, $\bar{x}=0.65$. Then it is easy to show $r_F=1.9$ for Co-Pd. This value is the same as that for Co-Ni.

V. ρ_{ss} OF Co-Pd ALLOYS

Since it is assumed that there is no exchange splitting between the spin-up and -down s bands, $\rho_{ss}^{\uparrow}=\rho_{ss}^{\downarrow}=\rho_{ss}$, as shown in Eq. (5). However, though we do not distinguish between $\rho_{ss}^{\uparrow}$ and $\rho_{ss}^{\downarrow}$, when ρ_{ss} is mentioned here, we take it to mean $\rho_{ss}^{\uparrow}$.

From Table I it is seen that $\rho^{\uparrow}$ is not very different from ρ_0. This is understood from Eq. (4), that since $\rho^{\downarrow}>\rho^{\uparrow}$, ρ_0 approximates $\rho^{\uparrow}$ more than $\rho^{\downarrow}$. If $\rho^{\downarrow}\gg\rho^{\uparrow}$, as in the case of Co-Ni, it is also certain that $\rho_0\simeq\rho^{\uparrow}$. In Fig. 6 we have plotted the ρ_0 (solid circles) data as a function of Ni concentration x for Co-Ni. Then it is known that

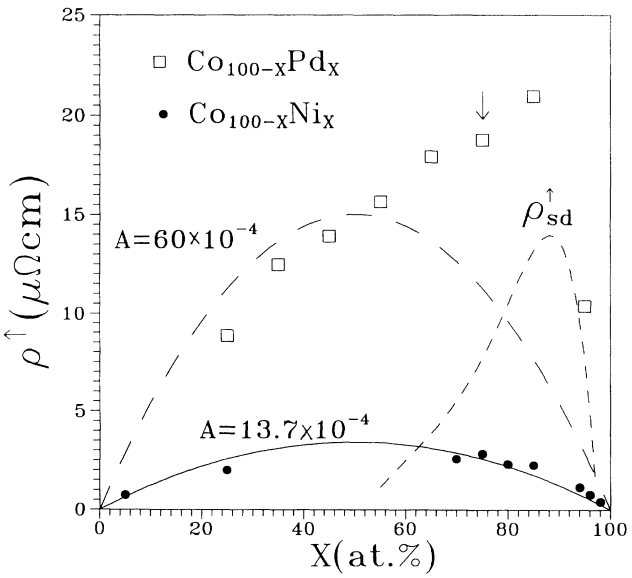

FIG. 6. Spin-up resistivity $\rho^{\uparrow}$ of Co-Pd and Co-Ni alloys plotted vs the Pd or Ni concentration x.

(i) Co-Ni is a strong ferromagnet for all x, and (ii) the ρ_{ss} of the $4s$ band follows Nordheim's rule[4,11] $\rho_{ss}\propto x(1-x)$. We use the equation

$$\rho_{ss}=Ax(1-x) \tag{7}$$

to fit all the Co-Ni data in Fig. 6. A in Eq. (7) is taken as a fitting parameter. For Co-Ni, $A=13.7\times10^{-4}$ $\mu\Omega$ cm.

For Co-Pd, we have used the $\rho^{\uparrow}$ data (open squares) in the fourth column of Table I to plot Fig. 6. It is to be noted that whether the third or the fourth column of Table I was used does not made much difference.

Since it is considered that (i) Co-Pd becomes weak ferromagnetic when $x\geq75$ at. % Pd and (ii) the ρ_{ss} of the $5s$ band still abides by the Nordheim's rule, we take the following steps to analyze our data.

The long-dashed line in Fig. 6 represents the experimental fit to Eq. (7), using $x=25$, 35, 45, 55 at. % Pd data. A is found to be 60×10^{-4} $\mu\Omega$ cm. From our assumptions (i) and (ii) just mentioned and Eq. (5), $\rho_{sd}^{\uparrow}$ can be estimated and is shown by the short-dashed line in Fig. 6. Because there exists some degree of arbitrariness in the fitting procedure, the set point $x_{\rm set}$ for $\rho_{sd}^{\uparrow}$ not being equal to zero, $x_{\rm set}\simeq50$ at. % Pd, cannot be taken too seriously. The downward arrow in Fig. 6 indicates the set point of magnetic weakness x_w, as implied from the magnetization data. It is seen that x_w differs from $x_{\rm set}$. However, x_w lies in the region where $\rho_{sd}^{\uparrow}$ bends up considerably. The location of maximum $\rho_{sd}^{\uparrow}$ is near $x=85$ at. % Pd, which is the same maximum as viewed from $\rho^{\uparrow}$.[5]

From the previous discussions, we have $\rho_{sd}^{\uparrow}\simeq\rho_{ss}$ in Co-Pd. Therefore $\rho^{\downarrow}>\rho_{ss}$ or $\rho_{sd}^{\uparrow}$. From Eq. (5) we may further state that $\rho_{sd}^{\downarrow}>\rho_{sd}^{\uparrow}$, and $\rho_{ss}^{\downarrow}$ follows Nordheim's rule also. Therefore, even if we had subtracted the ρ_{ss} contribution from $\rho^{\downarrow}$, the discussions of Sec. IV would be expected to be $\rho_{sd}^{\downarrow}$, except when $\rho_{sd}^{\downarrow}$ is slightly smaller than $\rho^{\downarrow}$.

From fittings to Eq. (7), it is found that A for Co-Pd is 4.38 times larger than that for Co-Ni. Then we can make the following estimates. From theory[4] it is known that

$$\rho_{ss}^{\uparrow}=\frac{m_s}{n_s e^2}D_{\uparrow}^{s}(\varepsilon_F)x(1-x)\frac{1}{\tau_{ss}}\ , \tag{8}$$

where m_s is the electron effective mass, n_s is the number of carriers per unit volume, e is the electron's charge, $D_{\uparrow}^{s}(\varepsilon_F)$ is the density of states of the spin-up s band, and τ_{ss} is the electron's relaxation time for s-s scattering. τ_{ss} can be expressed as

$$\tau_{ss}^{-1}=2\pi\int_0^{\pi}(1-\cos\theta)P(\theta)\sin\theta\,d\theta\ , \tag{9}$$

where θ is the angle between the wave vectors $\mathbf{k}$ and $\mathbf{k}'$ of a free electron and $P(\theta)$ is the differential scattering cross section per unit solid angle. In the approach of Mott and Jones,[12] using the screened Coulomb potential

$$V_{\text{Co-Pd}}=V_{\rm Co}-V_{\rm Pd}=(\Delta Z\,e^2/r)e^{-qr}\ ,$$

where ΔZ is the nuclear-charge difference between Co and Pd and $1/q$ is the screening length, $P(\theta)$ is calculated to be

$$P(\theta)=\left[\frac{2m_s\,\Delta Z\,e}{\hbar^2}\right]^2\frac{1}{[q+4k^2\sin^2(\frac{1}{2}\theta)]^2}\ . \tag{10}$$

Then

$$\tau_{ss}^{-1}=\frac{\pi}{2}\frac{(\Delta Z)^2e^4}{\varepsilon_F^2}\left[\ln\left[1+\frac{4k_F^2}{q^2}\right]-\left[1+\frac{q^2}{4k_F^2}\right]^{-1}\right], \tag{11}$$

where ε_F is the Fermi energy and k_F is the Fermi wave vector. Alternatively, the approach of de Casteljau and Friedel[13] gives

$$\tau_{ss}^{-1}\propto\sum(L+1)\sin^2(\eta_L-\eta_{L+1})\ ,$$

where L is the angular momentum and η_L is the phase shift. If only one η_L dominates, $\tau_{ss}^{-1}\propto\sin^2(\Delta Z\,\pi/4L+2)$. Though the result of de Casteljau and Friedel agrees with the experimental data better, the determination of phase shifts is, in general, a more complicated problem. Here we take the $(\Delta Z)^2$ form of Eq. (11) of Mott and Jones for the purpose of discussion. First, n_s, ε_F, q, k_F, and $D_\uparrow^s(\varepsilon_F)$ are assumed to be roughly constants for both Co-Ni and Co-Pd. Combining Eqs. (7), (8), and (11), we obtain $A\propto(\Delta Z)^2$. For Co-Ni, $|\Delta Z|=1$. However, for Co-Pd, because the shielding of electrons on nuclear charges is less effective and the Born approximation is less valid, its effective $|\Delta Z|$ may not be equal to the valence difference $|Z|$ exactly and may become larger than 1. The experimental data of Sec. V show that $A(\text{Co-Pd})/A(\text{Co-Ni})\simeq4.38$. In turn, $|\Delta Z|$ for Co-Pd appears to be about 2.09.

Strictly speaking, n_s, ε_F, q, k_F, and $D_\uparrow^s(\varepsilon_F)$ may show different values and may be x dependent for $Co_{100-x}Ni_x$ and $Co_{100-x}Pd_x$. However, we are going to show that these variations are small. For example, considering the free-electron model $\varepsilon_F\propto n_s^{2/3}$, $D_\uparrow^s(\varepsilon_F)\propto n_s^{1/3}V$, and the term

$$[\ln(1+4k_F^2/q^2)-(1+q^2/4k_F^2)^{-1}]\simeq\tfrac{1}{2}\ ,$$

in Eq. (11). Then $A\propto V(n_s)^{-2}\propto a_0^3$, where a_0 is the lattice constant of the alloy. Here $N\equiv Vn_s=(0.54e/\text{atom})$ (4 atoms/cell) for the strong ferromagnets Co-Ni and Co-Pd. Since, in general, the a_o of Co-Pd is slightly larger than that of Co-Ni, the A of Co-Pd is larger. Using the data $a_0=3.86$ Å ($Co_{25}Pd_{75}$) and $a_0=3.55$ Å ($Co_{25}Ni_{75}$), we also find A to be increased by a factor of 1.28 going from Co-Ni to Co-Pd. However, this is only a minor reason to explain the change observed in A. We believe the main cause for the change still comes from the variation of $|\Delta Z|$, due to less effective shielding in Co-Pd. Hence, if the effect of a_0 has been taken into account, by setting the ratio $A(\text{Co-Pd})/A(\text{Co-Ni})\simeq4.38/1.28$, then $|\Delta Z|$ for Co-Pd becomes 1.85, which is a more reasonable value.

VI. CONCLUSIONS

Some magnetoresistance and electrical-resistivity data of Co-Pd alloys are reported in this study. Based on the two-current model and later extended theories, we are able to analyze $\rho^\downarrow$ and $\rho^\uparrow$ as a function of the Pd concentration x. For $x\geq50$–75 at. % Pd, the spin-up and d band is not full, and $\rho_{sd}^\uparrow\neq0$.

$(\Delta\rho/\rho_0)_{\text{imp}}$ and $(\Delta\rho/\rho_0)_{\text{ph}}$ are obtained by the application of Matthiessen's rule to $\Delta\rho/\rho_0$. The location in x of the maximum of $(\Delta\rho/\rho_0)_{\text{imp}}$ is the same as that of the minimum of $(\Delta\rho/\rho_0)_{\text{ph}}$.

ρ_{ss} is known to obey Nordheim's rule. ρ_{ss} increases considerably from Co-Ni to Co-Pd and then from Co-Pd to Co-Pt,[14] while $\rho^\downarrow$ or $\rho_{sd}^\downarrow$ does not increase as much in the corresponding case. Therefore the value of $\Delta\rho/\rho_0$ decreases substantially, going from Co-Ni to Co-Pt.

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[1]I. A. Campbell, A. Fert, and O. Jaoul, J. Phys. C. Suppl. **1**, S95 (1970).
[2]O. Jaoul, I. A. Campbell, and A. Fert, J. Magn. Magn. Mater. **5**, 23 (1977).
[3]A. P. Malozemoff, Phys. Rev. B **32**, 6080 (1985).
[4]L. Berger, J. Appl. Phys. **67**, 5549 (1990).
[5]S. U. Jen, T. P. Chen, and S. A. Chang, J. Appl. Phys. **70**, 5831 (1991).
[6]A. B. Kaiser and S. Doniach, Int. J. Magn. **1**, 11 (1970).
[7]L. Berger, P. P. Freitas, J. D. Warner, and J. E. Schmidt, J. Appl. Phys. **64**, 5459 (1988).
[8]R. Parker, Proc. Phys. Soc. London A **64**, 447 (1951).
[9]L. Berger, Physica **91B**, 31 (1977).
[10]J. W. Cable, E. O. Wallan, and W. C. Koeller, Phys. Rev. **138**, A755 (1965).
[11]L. Nordheim, Ann. Phys. (N.Y.) **9**, 607 (1931).
[12]N. F. Mott and H. Jones, *The Theory of the Properties of Metals and Alloys* (Oxford University Press, Oxford, 1936).
[13]P. de Faget de Casteljau and J. Friedel, J. Phys. Radiat. **17**, 27 (1956).
[14]S. U. Jen and T. P. Chen (unpublished).