# Applicability of the two-current model for systems with strongly spin-dependent disorder

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The resistivities of the ferromagnetic alloy systems Fe-Ni and Co-Ni were studied in detail by application of first-principles techniques. For that purpose the Kubo-Greenwood formalism was applied on the basis of electronic structure data obtained using the spin-polarized Korringa-Kohn-Rostoker coherent potential approximation method of band-structure calculation for randomly disordered ferromagnetic alloys. One set of calculations was carried out fully relativistically, while for a second one the well-known and often applied two-current model was used. We compare the results of the two approaches as well as the difference between the calculated two-current resistivities and the resistivities obtained experimentally by the usual decomposition based on the two-current model. We discuss the validity of the two-current model for the systems investigated and the reason for the apparent success of this model. [S0163-1829(97)09140-6]

## I. INTRODUCTION

Many interesting and technologically important effects in ferromagnetic alloys have their origin in the symmetry reduction due to the presence of spin-orbit interaction. Corresponding examples are the anisotropy energy,[1] magneto-optical properties,[2] and galvano-magnetic effects such as the spontaneous magnetoresistance anisotropy and the anomalous Hall effect.[3,4] In addition to these spin-orbit induced phenomena, spin-orbit coupling also influences conventional physical properties as could be demonstrated recently for the isotropic residual electrical resistivity.[5]

For the discussion of electronic transport properties of ferromagnets usually the *two-current model*[6] is used. This model assumes that the majority and minority electron spin systems contribute independently to electronic conduction. Electrons that are part of one of the two spin subbands are scattered by chemical disorder, lattice imperfections, or phonons in a different way, giving rise to two spin-dependent partial resistivities $\rho^{\uparrow}$ and $\rho^{\downarrow}$, respectively. Mechanisms that change the spin direction of an electron are assumed to either vanish or be weak.[7] In the latter case one introduces correction terms that describe the effect of spin mixing (see below). Possible spin mixing mechanisms are scattering by magnons, electron-electron interaction, and spin-orbit interaction. Magnon scattering vanishes for $T=0\,\mathrm{K}$ and the effect of electron-electron scattering is negligible,[8] thus concerning residual resistivity one can concentrate on spin-orbit interaction, which is of course always present.

In the past there have been several indications that spin-orbit effects are by no means of minor importance for electronic conduction at zero temperature. Mertig *et al.* have pointed out that the abnormally small values for the residual resistivities of $3d$ impurities in nickel that they obtained using the Boltzmann equation in connection with the two-current model might originate from the absence of spin mixing in their model.[9] In a similar way Butler *et al.* interpreted their results for magnetic multilayer systems.[10]

Recently it became possible to investigate these questions in great detail by calculating the resistivity of ferromagnetic alloys using the first-principles Kubo-Greenwood formalism based on solutions of the Dirac equation.[11] Thus all relativistic effects including spin-orbit interaction could be taken into account and the spontaneous magnetoresistance anisotropy could be calculated in satisfying agreement with experiment without having to treat spin-orbit effects as a perturbation or use simple parametrizations.[11] By manipulating the Dirac equation, it could be shown explicitly that spin-orbit interactions cause the magnetoresistance anisotropy.[4] This rigorous, relativistic approach is used in the present work to supply proper theoretical reference data for calculations of the isotropic residual resistivity for the binary alloy systems Fe-Ni and Co-Ni based on the two-current model. In both alloys it was found that the two-current model strongly underestimates the isotropic resistivity. Reasons for this shortcoming will be given.

The Kubo-Greenwood formalism has recently been extended to be able to deal with layered systems.[10,12] It is expected that calculations of the electrical conductivity of magnetic multilayer systems will reveal that spin-orbit effects are at least as important in these complex systems as they are in ''normal'' bulk ferromagnetic alloys.

The alloy systems Fe-Ni and Co-Ni were chosen because they exhibit the strongest spontaneous galvanomagnetic effects of all alloys known, comparable to the giant anisotropies observed in certain amorphous ferromagnets.[13] Therefore, the importance of spin-orbit-induced effects was expected to be more pronounced in these alloys than in alloys with smaller effects such as, e.g., Co-Pd and Co-Pt.[5]

## II. THEORETICAL FRAMEWORK

### A. Simple and extended two-current model

As mentioned above, the basic idea of the two-current model is that the two spin-subsystems of a ferromagnet con-

 

tribute independently to the total conductivity or resistivity, respectively.[6] Accordingly, without any spin-flip processes the two subband resistivities add like those of two parallel resistors and the resulting average isotropic resistivity is simply given by

$$\overline{\rho}=\left(\frac{1}{\rho^{\downarrow}}+\frac{1}{\rho^{\uparrow}}\right)^{-1}. \tag{1}$$

If spin mixing is considered, the expression for the total resistivity can be modified to account for this effect by introducing a parameter $\rho^{\uparrow\downarrow}$ describing the rate of spin-flip transitions.[8,14,15] This leads to the expression

$$\overline{\rho}=\frac{\rho^{\downarrow}\rho^{\uparrow}+\rho^{\uparrow\downarrow}(\rho^{\downarrow}+\rho^{\uparrow})}{\rho^{\downarrow}+\rho^{\uparrow}+4\rho^{\uparrow\downarrow}}. \tag{2}$$

Slightly different expressions have been obtained by Malozemoff.[16]

The hypothetical subband resistivities $\rho^{\uparrow}$ and $\rho^{\downarrow}$ cannot be measured directly. Usually they are derived by measuring deviations from Matthiessen's rule for ternary alloys or the temperature dependence of the resistivity of binary alloys.[17] In both cases one assumes the validity of the two-current model and neglects spin mixing, hoping that this will not affect the results too much. It will be shown below that this assumption is often by no means justified and that the resistivities obtained in this way cannot be interpreted as partial subband resistivities $\rho^{\uparrow}$ and $\rho^{\downarrow}$ in a strict sense.

Assuming the validity of the two-current model, the ratio $\alpha=\rho^{\downarrow}/\rho^{\uparrow}$ of the partial resistivities can be determined in an alternative way by measuring the difference $\Delta\rho$ between the resistivities parallel and perpendicular to the spontaneous magnetization. If again spin-mixing effects are neglected one can write[15]

$$\frac{\Delta\rho}{\overline{\rho}}=\gamma\left(\frac{\rho^{\downarrow}}{\rho^{\uparrow}}-1\right)=\gamma(\alpha-1), \tag{3}$$

where $\Delta\rho/\overline{\rho}$ is the so-called spontaneous magnetoresistance anisotropy (SMA) ratio. The parameter $\gamma$ is introduced as a measure for the momentum transfer between the two spin systems due to spin-orbit coupling.

For the case that spin mixing has to be considered, the relation is more complicated and the spin-flip parameter $\rho^{\uparrow\downarrow}$ can be used again:[15]

$$\frac{\Delta\rho}{\overline{\rho}}=\gamma\frac{(\rho^{\downarrow}-\rho^{\uparrow})\rho^{\downarrow}}{\rho^{\uparrow}\rho^{\downarrow}+\rho^{\uparrow\downarrow}(\rho^{\uparrow}+\rho^{\downarrow})}. \tag{4}$$

In the following, Eqs. (1) and (3) will denote the simple two-current model, while Eqs. (2) and (4) specify the extended one. Concerning both models one should note that no clear, comprehensive definition or interpretation is given in the existing literature neither for $\gamma$ nor for the parameter $\rho^{\uparrow\downarrow}$. The parameter $\gamma$ has been determined, e.g., for nickel-based alloys by measuring the SMA and $\alpha$ for various alloying elements and plotting $\Delta\rho/\overline{\rho}$ versus $(\alpha-1)$ using Eq. (3). Values for $\gamma$ obtained this way[15,18] range from 0.0075 to 0.010 for nickel alloys. Equation (1) has also been used within theoretical investigations in connection with the Boltzmann equation,[9] as well as the more rigorous Kubo-Greenwood linear response formalism[10] to calculate the isotropic resistivity $\overline{\rho}$ of spin-polarized materials.

### B. Kubo-Greenwood formalism

A very sophisticated way to deal with transport properties of randomly disordered alloys has been introduced by Butler[19] by combining the Kubo-Greenwood formalism with the Korringa-Kohn-Rostoker coherent potential approximation (KKR-CPA) method of band-structure calculation for alloys. The CPA is the most reliable so-called single-site alloy theory that makes use of a hypothetical medium meant to represent the configurationally averaged electronic structure of a disordered alloy. Using the multiple scattering or KKR formalism, respectively, this medium is determined by demanding that substitutionally embedding one of the components of the alloy system should not cause any additional scattering on the average.[20] Accordingly, performing self-consistent KKR-CPA calculations for binary alloys, there is just one potential well connected to each of the components. Moreover, mostly the potential wells are assumed to be spherically symmetric, i.e., the muffin-tin or the atomic-sphere approximation is made.

Originally, the Kubo-Greenwood formalism was combined with the nonrelativistic KKR-CPA for paramagnetic alloys.[19] However, this approach could be straightforwardly applied also to ferromagnetic alloys by using it to calculate the spin-projected resistivities $\rho^{\uparrow(\downarrow)}$ separately in the spirit of the two-current model. Accordingly, the total resistivity is obtained by use of Eq. (1). Apart from the questionable use of the two-current model, this approach obviously does not give access to the spin-orbit-induced galvanomagnetic effects such as the spontaneous magnetoresistance anisotropy and anomalous Hall resistivity. In contrast to this, these phenomena are accounted for if the Kubo-Greenwood formalism is combined with the spin-polarized relativistic (SPR) version of the KKR-CPA.[11,21] Inclusion of spin-orbit coupling within the description of the underlying electronic structure properly accounts for the reduced symmetry compared to the paramagnetic state, leading automatically to the proper nondiagonal form of the conductivity tensor.[2] Furthermore, the influence of spin-orbit coupling on the isotropic resistivity is included from the very beginning without making use of the two-current model.

## III. RESULTS AND DISCUSSION

### A. Spin-dependent disorder within the two-current model

Both theoretical approaches sketched above were used to investigate the residual resistivity of the ferromagnetic alloy systems Fe-Ni and Co-Ni. fcc structures were assumed for the two alloy systems, although this does not reflect the true situation in Fe-Ni, where fcc alloys can only be prepared up to around 60% Fe.[22] Iron rich Fe-Ni alloys are expected to be composed of a bcc/fcc mixture and eventually the $Fe_3Ni$ phase.

In a first set of calculations the Kubo-Greenwood formalism was used in combination with the two-current model. This means that conductivity calculations were performed separately for the minority and the majority subbands of each alloy. For this purpose, the potentials for each spin direction

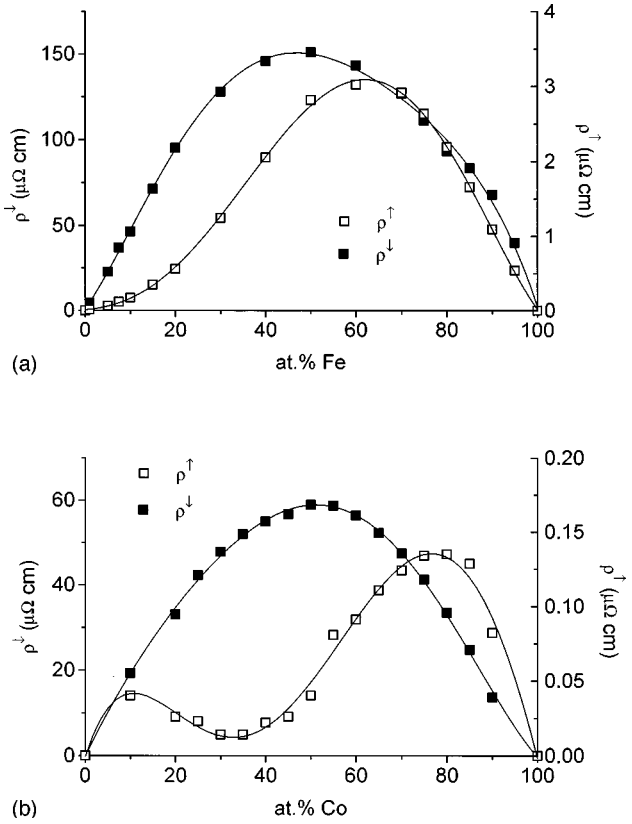


FIG. 1. Subband resistivities for the alloy systems Fe-Ni (a) and Co-Ni (b) calculated assuming the two current model. Open symbols: majority resistivity $\rho^{\uparrow}$, full symbols: minority resistivity $\rho^{\downarrow}$.

were treated as if they represented a paramagnetic alloy. Accordingly, the two subbands possess a different electronic structure having only the Fermi energy in common. Consequently, the corresponding partial resistivities $\rho^{\uparrow}$ and $\rho^{\downarrow}$ obtained this way can be expected to be quite different. This can indeed be seen in Fig. 1, where these quantities are shown for Fe-Ni and Co-Ni. While $\rho^{\uparrow}$ takes very low values, especially for Co-Ni, $\rho^{\downarrow}$ is found to be quite large. Consequently, the corresponding ratio $\alpha=\rho^{\downarrow}/\rho^{\uparrow}$ is also rather high, reaching values of up to 370 for Fe-Ni and 3800 for Co-Ni in contrast to values $\alpha\approx 20-30$ determined experimentally.

The reason for these very different partial resistivities is that, depending on their spin character, the conduction electrons effectively seem to see a strongly different degree of disorder, i.e., loosely spoken, there is a strongly spin-dependent disorder present. This is because for both alloy systems the majority potentials of the two components are rather similar, while for the minority spin the potentials are shifted against one another in a pronounced way. To illustrate this point, we plot in Fig. 2 the resonance positions of the $d$-electron phase shift for $Fe_{20}Ni_{80}$ in the paramagnetic and ferromagnetic state. These quantities correspond to the atomic level positions of a tight-binding description and reflect for the paramagnetic state the more attractive potential of Ni compared to Fe. The additional exchange splitting that is quite different for Fe and Ni has the effect that the resonance positions for the majority channel get quite close to one another, while those for the minority spin channel drift further apart. As a consequence, the majority spin system behaves more or less like a virtual crystal system[20] with its

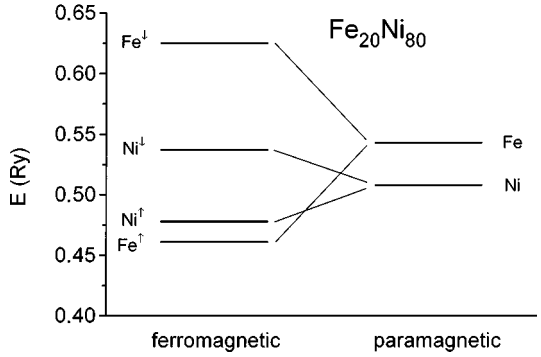


FIG. 2. Resonance positions of the $d$-electron phase shifts of Fe and Ni in $Fe_{20}Ni_{80}$ in the para- and ferromagnetic state.

density of states (DOS) curve sharply structured. The electronic structure of the minority spin system, on the other hand, is much more influenced by the disorder leading to a DOS curve that is strongly smeared out. Using spin-resolved Bloch spectral functions $A_{\mathbf{k}\sigma}(E)$ (Ref. 20) (for Fe-Ni these curves can be found in Refs. 23 and 24) to represent the electronic structure of these alloys in a most detailed way, one would get, according to the behavior described above, very different relaxation times $\tau^{\sigma}$ for the two spin systems.[10] This means that determining the partial resistivities $\rho^{\sigma}$ by means of the Boltzmann equation would lead to results in accordance with those obtained using the Kubo-Greenwood formalism and shown in Fig. 1.

As $\rho^{\uparrow}$ is extremely small especially for Co-Ni, the results depend to some extent on the details of the potential construction. This might explain the lower values for $\rho^{\uparrow}$ found for Permalloy by other authors[10] who used the muffin-tin construction, while the atomic sphere approximation (ASA) has been used here. To illustrate this somewhat technical point, model calculations have been performed for $Fe_{0.2}Ni_{0.8}$ with the potentials of two components shifted against one another. As Fig. 3 shows, there are only minor changes for $\rho^{\downarrow}$ with the potential shift, while $\rho^{\uparrow}$ reacts in a very pronounced way on this artificial distortion.

The CPA approximation used here assumes perfect periodicity and neglects any correlation concerning the occupa-

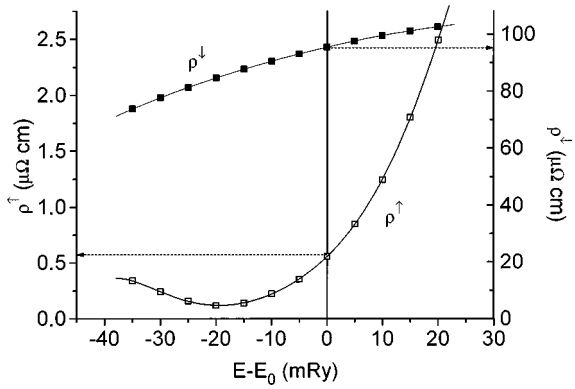


FIG. 3. Subband resistivities for the alloy $Fe_{20}Ni_{80}$. The energy of the muffin-tin zero for the iron potential $E$ was shifted with respect to the original zero $E_0$. The resistivities for $E-E_0=0$ correspond to the ones given in Fig. 1(a).

tion of neighboring sites. In line with that the configurationally averaged Green's function can be written as the concentration weighted sum of the component-projected Green's function, of which there is only one per component. Accordingly, there is a common and unique potential connected with each component within the CPA. However, even for a lattice, where the components are distributed randomly the neighborhoods of equal kinds of atoms show some fluctuations. Therefore, the potential of a given type of atom may be slightly different on different lattice sites. Normally the difference between atom type $A$ and type $B$ is much larger than the small fluctuations of each potential type, but in situations such as in the majority spin bands of Fe-Ni and Co-Ni, where the components $A$ and $B$ behave virtually in the same way concerning the scattering of electrons, the difference might be important. Moreover, the slight positional disorder due to the different atom radii of the components and short-range order effects, both omitted in the CPA, might contribute to the resistivity.

Evaluating the Kubo-Greenwood equation one calculates a configurational average of a pair of Green functions and expresses it by averages of a single Green function. This gives rise to vertex corrections that can be accounted for within the CPA formalism. They correspond to the scattering-in terms of the Boltzmann equation and are important whenever the scattering is not isotropic. In a previous investigation of the alloy system Cu-Pt it was seen that vertex corrections are large, when the Fermi energy level lies well above the $d$-band complex in the regime of $s$ and $p$ states, and low when the Fermi energy cuts the $d$ bands.[25] This is exactly the behavior of the nickel alloys investigated: the vertex corrections, expressed by $x_{\mathrm{VC}}=(\rho_{\mathrm{NVC}}/\rho_{\mathrm{VC}}-1)$, are very small for the minority spin band of Fe-Ni and Co-Ni (i.e., $x_{\mathrm{VC}}<1\%$) where the Fermi energy states have mostly $d$ character, and very important for the majority spin band (Fe-Ni: $x_{\mathrm{VC}}=-25\%$ to $-6\%$, Co-Ni: $x_{\mathrm{VC}}=-40\%$ to $+50\%$) where the states are predominantly of $s$ and $p$ character.

### B. Comparison with fully relativistic results

In the following the total resistivity calculated within the framework of the two-current model by means of Eq. (1) will be denoted by $\overline{\rho_{2c}}$. This has to be distinguished from the resistivity $\overline{\rho}=(2\rho_{\perp}+\rho_{\parallel})/3$, which is calculated fully relativistically without any assumption concerning spin mixing. The resulting two-current resistivity $\overline{\rho_{2c}}$ is compared to $\overline{\rho}$ in Fig. 4. Obviously, $\overline{\rho_{2c}}$ is far smaller than the resistivity $\overline{\rho}$ for both alloy systems. Comparison of the proper relativistic result with experiment is not done here, because the main interest is with the results of the two theoretical approaches. Nevertheless, one should note that the experimental resistivities[28] are much higher than the calculated ones.[11] This applies in particular to the invar regime of the system Fe-Ni where additional contributions to $\overline{\rho}$ such as scattering from magnetically ordered clusters might be important, which cannot be included straightforwardly within our approach based on the CPA. However, this does not affect the comparison of the two theoretical models, which both make use of the CPA. Note also that the present results for Fe-Ni

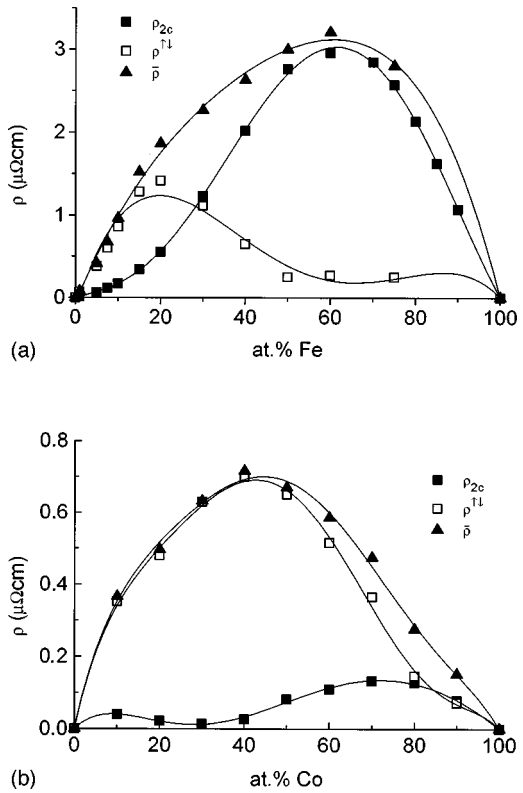


FIG. 4. Resistivities for the alloy systems (a) Fe-Ni and (b) Co-Ni: triangles, relativistic resistivities $\overline{\rho}$; full squares, two-current model resistivities $\rho_{2c}$; open squares, spin-mixing parameter $\rho^{\uparrow\downarrow}$.

are slightly smaller than the ones given in a previous calculation[11] due to a somewhat different potential construction.

The pronounced difference between the resistivities obtained by the two approaches is emphasized by plotting $\overline{\rho}/\overline{\rho_{2c}}$, which is given in Fig. 5 for the two alloy systems. One sees that $\overline{\rho}$ is larger than the two-current model resistivity $\overline{\rho_{2c}}$ by up to a factor of 8 for $Fe_{10}Ni_{90}$ and 55 for $Co_{20}Ni_{80}$. Thus, the simple two-current model is completely inadequate to deal with the resistivity of the two alloy systems investigated here. This is less pronounced for Fe-Ni than for Co-Ni, where it leads to an isotropic resistivity $\overline{\rho_{2c}}$ that is almost two orders of magnitude smaller than the proper relativistic result $\overline{\rho}$. This finding is completely in line with the corresponding importance of spin-dependent disorder. While for Fe-Ni the majority $d$ levels shown in Fig. 2 are still somewhat apart, they nearly coincide for Co-Ni, giving rise to an extremely low partial resistivity $\rho^{\uparrow}$ and a rather low $\overline{\rho_{2c}}$. This situation is drastically changed if spin-orbit coupling is taken into account. The effect of spin-orbit interaction is to allow electrons to be scattered from one spin subband to the other. Thus, some electrons in the majority subband having low resistivity are scattered into the minority subband where the scattering probability is very high. Although the fraction of electrons that flip their spins is probably quite low because the corresponding spin-orbit scattering cross section is rather small for light atoms such as Fe, Co, or Ni, this mechanism adds enormously to the resistivity of the majority subband.

There have been many successful applications of the two-current model to a large variety of alloy systems including

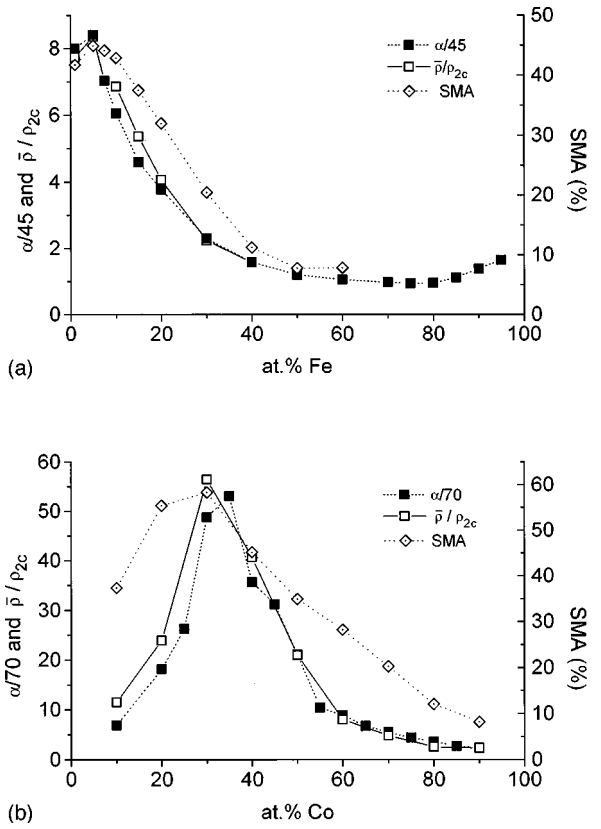


FIG. 5. Quantities related to deviations from two-current model for Fe-Ni (a) and Co-Ni (b). Squares: parameter $\alpha/C$, open squares: ratio $\overline{\rho}/\rho_{2c}$, diamonds: $\Delta\rho/\overline{\rho}$ [SMA (Ref. 11)]. For further details see text.

the systems studied in the present paper. This seems to be in contradiction to the results presented above and one might ask for the reason for this success. The reason the two-current model seems to work so well is the fact that the subband resistivities $\rho^{\uparrow}$ and $\rho^{\downarrow}$ that are used to interpret the experimental data are themselves deduced from experiments assuming the validity of this model. The success of such investigations therefore merely proves the consistency of the two-current model with its own assumptions.

Because spin-orbit interaction increases $\rho^{\uparrow}$ so effectively, one does not obtain a measure for scattering in the low resistance subband from the analysis of, e.g., the resistivity of ternary alloys but a sum of pure majority spin scattering and a contribution due to minority spin scattering weighted by some spin-flip matrix element. The partial resistivities deduced from experiment are therefore not subband resistivities in a strict sense, but at the most some kind of ''effective'' resistivities.

The problem becomes obvious from Table I where $\rho^{\uparrow}$, $\rho^{\downarrow}$, and $\alpha$ from an experimental analysis, a theoretical impurity calculation and the present results are compared. Clearly, the values for $\rho^{\downarrow}$ are similar for all three cases, but the values for $\rho^{\uparrow}$ and $\alpha$ are totally different. Note that even the calculated minority spin resistivities of the present work and of Ref. 9 differ considerably due to the problems with the potential construction mentioned in Sec. III A. Nevertheless both are obviously much lower than the experimental ''effective'' resistivities. The partial resistivities $\rho^{\uparrow}$ and $\rho^{\downarrow}$ have been deduced from experiment not only for diluted, but also

TABLE I. Resistivities for Fe and Co impurities in Ni (in $\mu\Omega$ cm/at. %), low concentration limit for Fe-Ni and Co-Ni (from present work, 1 at. % Fe or Co, given in $\mu\Omega$ cm). The letters *E* and *T* in the last column indicate experimental and theoretical work, respectively.

| Alloy | $\rho^{\downarrow}$ | $\rho^{\uparrow}$ | $\alpha=\rho^{\downarrow}/\rho^{\uparrow}$ | Ref. | |
|---|---|---|---|---|---|
| FeNi | 4.8 | 0.44 | 17.7 | 17 | *E* |
| | 3.26 | 0.45 | 7.35 | 27 | *E* |
| | 7.3 | 0.34 | 21.5 | 29 | *E* |
| | 6.50 | 0 | $\infty$ | 9 | *T* |
| $Fe_1Ni_{99}$ | 4.14 | 0.01 | 414 | Present | *T* |
| CoNi | 2.6 | 0.20 | 13 | 17 | *E* |
| | 2.0 | 0.15 | 13.2 | 27 | *E* |
| | 4.3 | 0.13 | 33 | 29 | *E* |
| | 6 | 0.2 | 30 | 14 | *E* |
| | 3.79 | 0.041 | 92.4 | 9 | *T* |
| $Co_1Ni_{99}$ | 2.1 | 0.0028 | 750 | Present | *T* |

for concentrated alloys. For Fe-Ni and Co-Ni Muth *et al.*[26] determined the subband resistivities using Eqs. (1) and (3) (see also a discussion by Berger on this[30]). These authors find pronounced maximum values of $\rho^{\downarrow}$ for $Fe_{15}Ni_{85}$ and $Co_{35}Ni_{65}$, respectively, which are not present in our theoretical curves obtained by using the two-current model calculations (see Fig. 1). This is understandable because a quantitative decomposition of $\rho$ into $\rho^{\uparrow}$ and $\rho^{\downarrow}$ based on the assumption of vanishing spin-orbit interaction must fail for Fe-Ni and Co-Ni because of the reason given above.

That the strongly spin-dependent disorder in the two alloy systems Fe-Ni and Co-Ni is responsible for the failure of the simple two-current model is obvious from the fact that $\overline{\rho_{2c}}$ deviates much stronger from $\overline{\rho}$ for Co-Ni than for Fe-Ni (see above). In addition this can also be seen by comparing the ratio $\overline{\rho}/\rho_{2c}$ and $\alpha$. One finds that the two quantities are almost proportional to one another

$$\frac{\rho}{\rho_{2c}} \approx C\frac{\rho^{\downarrow}}{\rho^{\uparrow}} = C\alpha. \tag{5}$$

This is demonstrated in Fig. 5 where $\rho/\rho_{2c}$ and $\alpha/C$ are compared with C set to 45 for Fe-Ni and to 70 for Co-Ni. One easily notes that the two-current model results deviate the more from the proper results the more the resistivity of the two subbands differs, i.e., the higher the ratio $\alpha$ is.

### C. Spin-orbit related parameters $\rho^{\uparrow\downarrow}$ and $\gamma$: SMA

Another way to demonstrate the importance of spin-orbit effects is to use Eq. (2) and to insert the calculated values for $\rho^{\uparrow}$ and $\rho^{\downarrow}$ together with the fully relativistic resistivity $\overline{\rho}$ to determine the spin mixing parameter $\rho^{\uparrow\downarrow}$. The result is included in Fig. 4 for the two alloys. One sees that for Fe-Ni very high values up to 1.3 $\mu\Omega$ cm are obtained. For low iron concentrations $\rho^{\uparrow\downarrow}$ is essentially the total resistivity, i.e., the most effective scattering for majority electrons is via spin-orbit interaction into the minority subband. For Co-Ni the situation is even more dramatic: the spin-orbit interaction induced scattering dominates over the entire composition range. There have been attempts in the literature to derive

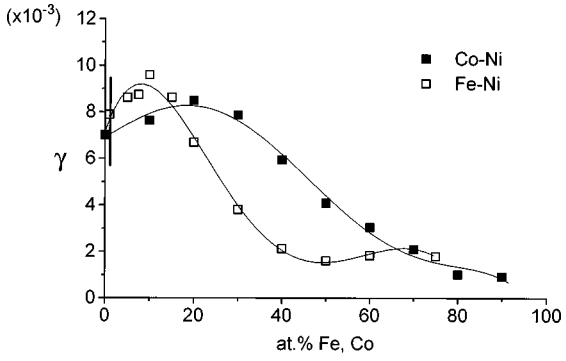


FIG. 6. Parameter $\gamma$ calculated from Eqs. (2) and (4). Vertical bar: experimental values for the dilute limit of both alloy systems (Refs. 15 and 18).

$\rho^{\uparrow\downarrow}$ from measured data. One such attempt starts from Eq. (4) using experimental values for $\Delta\rho/\overline{\rho}$ and values for $\gamma$ and $\alpha$ determined from measurements on ternary alloys.[31] But as this procedure implies use of the two-current model without spin mixing, the results have to be taken with care. For Ni diluted with Fe and Co, values for $\rho^{\uparrow\downarrow}$ at $T=0$ K between 0.2 and 0.35 $\mu\Omega$ cm were found. This is somewhat more than the calculated values for comparable Fe or Co contents but the same order of magnitude (see Fig. 4).

Another manifestation of spin-orbit interaction is the occurrence of spontaneous magnetoresistance anisotropy. The SMA ratio $\Delta\rho/\overline{\rho}$ calculated relativistically (for Fe-Ni see Ref. 11) is compared to the ratios $\overline{\rho}/\rho_{2c}$ and $\alpha/C$ in Fig. 5. Apparently there is a close correlation between SMA and $\alpha/C$, especially for Fe-Ni, as one would expect on the basis of Eq. (3). However, because in deriving this equation the assumptions of the simple two-current model are used, the coincidence cannot expected to be perfect.

Up to this point it has become clear that the use of Eqs. (1) and (3) leads to erroneous results for systems with a strong spin-dependent disorder. If one accepts Eqs. (2) and (4) as valid for situations with strong spin mixing one can determine the parameter $\gamma$ in Eq. (4) by using the calculated subband resistivities, the spin mixing parameter $\rho^{\uparrow\downarrow}$ shown in Fig. 4, and the calculated $\Delta\rho/\overline{\rho}$. The corresponding results are shown in Fig. 6. For both alloy systems we find maximum values for the composition where the maximum SMA value occurs and decreasing values for lower nickel contents. If one extrapolates the calculated values for $\gamma$ to the limit $x_{\mathrm{Ni}}=1$, one finds that they agree well with the parameters determined experimentally for dilute FeNi and CoNi alloys [0.0075–0.01 (Refs. 15 and 31)]. The reason for this is that these experimental values are obtained using consistently the expressions based on the simple two-current model. This procedure obviously leads to results similar to those based on Eq. (2), i.e., the extended two-current model together with our correctly calculated subband resistivities. This again illustrates how one can obtain apparently meaningful results by repeatedly neglecting the crucial spin mixing contribution.

## IV. SUMMARY

The electrical resistivity of the alloy systems Fe-Ni and Co-Ni was investigated in two different ways: by treating the alloy and transport problem fully relativistically and by separately calculating the resistivity of each spin system, thus assuming the validity of the simple two-current model. For the alloy systems studied here we found that the two-current calculations yield spin-subband resistivities that differ much greater than one would expect from experimental considerations and that lead to an average resistivity $\overline{\rho_{2c}}$ that is much too small compared to the proper relativistic result $\overline{\rho}$. This demonstrates that a coupling of the two spin subsystems by spin-orbit interaction can be of crucial importance in contrast to the basic assumption of the two-current model in its most simple form.

It is therefore concluded that an application of this model for deriving spin subband resistivities from experimental data leads to effective resistivities that might be quite different from values calculated directly. As it has been demonstrated, the use of the simple two-current model is the more problematic the more pronounced the spin-dependent disorder is for the system under investigation. This finding is completely in line with our recent work on Co-Pd and Co-Pt, where the two-current model works reasonably well and where spin-dependent disorder is much less pronounced than for Fe-Ni and Co-Ni.

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