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GMR effects in actinide intermetallics

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Abstract

The resistance of antiferromagnets is usually enhanced due to Fermi-surface gapping and/or spin-dependent scattering even in the low-temperature limit. In magnetic fields sufficient to suppress the AF coupling, ‘ferromagnetic’ alignment of moments is achieved and the resistance is reduced to values typical for ferromagnets. We demonstrate on selected UTX compounds that in actinide intermetallics this can lead to giant magnetoresistance (GMR) effects ($\Delta\rho/\rho_{\text{H}} > 100\%$). This huge effect is presumably due to a strong hybridization of the 5f and conduction-electron states. GMR effects, observed in compounds like UNiGe and UPdSn, show that this phenomenon is not strictly limited to cases of layered AF structures. As a rule, the maximal magnetoresistance is observed for the current along the AF propagation of the magnetic structure. The size of the GMR is closely connected to the change of magnetic periodicity induced by the applied magnetic field.

1. Introduction

Transport properties in actinide intermetallics are not clearly understood [1] and a systematic experimental and theoretical effort is needed. The 5f states in materials with magnetic moments on actinide sites can be described in terms of a narrow band of strongly correlated electron states. The interaction between the 5f and conduction electron states, which is due to their hybridization, can be described as a resonant scattering, which strongly affects the transport properties. Compared to transition-metal and rare-earth compounds, the resistivity values in 5f intermetallics are often much higher (sometimes exceeding 500 $\mu\Omega\text{-cm}$) and a rather flat $\rho(T)$ dependence is observed, as a rule, in the paramagnetic range. This is presumably due to the enormous values of the spin-disorder resistivity ρ_{spd} , the dominating contribution to the total resistivity (the electron–phonon scattering contribution is much weaker even at high temperatures).

Below the magnetic ordering temperature, the resis-

tivity often decreases steeply and the residual resistivity in ferromagnets is usually small (of the order of 10 $\mu\Omega\text{-cm}$), which is expected as the spin-disorder resistivity ρ_{spd} is removed due to the ideal periodicity of magnetic moments in the low-temperature limit. In the AF state, however, much larger resistivity values are observed even in the low-temperature limit. Moreover, the anisotropic magnetism in actinide compounds is presumably responsible for the pronounced anisotropy of the electrical resistivity.

Magnetic field-induced (metamagnetic) transitions in antiferromagnets take place in a magnetic field sufficient to overcome the AF interactions and to modify the magnetic structure. The modification of the magnetic structure is frequently connected with a change of the translational symmetry, and is usually accompanied by a noticeable change in the resistivity.

The magnetoresistance is usually defined by

$$\Delta\rho/\rho_0 = (\rho_B - \rho_0)/\rho_0 \quad (1)$$

where ρ_B and ρ_0 are the resistivities in the actual and zero magnetic field, respectively.

This paper addresses the main features of electrical transport connected with magnetism in light-actinide

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intermetallics. Some recent results of systematic investigations of UTX compounds (T = transition metal, X = p-electron metal) are discussed. The results reported in this paper were obtained on bulk single crystals grown by the Czochralski technique in a tri-arc furnace at the center FOM-ALMOS at the University of Amsterdam. In the case of UPdIn the resistance measurements were performed on a single-crystalline whisker grown along c from a rapidly cooled melt.

2. Experimental results

The UTX compounds, crystallising in the hexagonal ZrNiAl structure, have been studied thoroughly [2–5]. This structure consists of U–T and T–X basal-plane layers alternating along the c -axis. The strong bonding of the 5f wave functions within the basal planes and the considerable 5f orbital moments lead to a huge magnetic anisotropy confining the U moments to the c -direction. Another consequence of the bonding in the basal plane is a ferromagnetic coupling of moments; thus magnetic structures consisting of ferromagnetic basal-plane layers are observed below the ordering temperature. The magnetic interactions along the c -axis are much weaker and in some cases antiferromagnetic with various propagation vectors. The electrical resistivity in AF compounds shows qualitatively different behaviour for the current along the plane and along the c -axis. The $\rho(T)$ dependence for the current in the plane resembles the behaviour of a ferromagnet, whereas for the current along the c -axis, the resistance is strongly influenced by AF correlations in the paramagnetic range. Below T_N , AF coupling of basal-plane ferromagnetic sheets along c is involved.

In Figs. 1 and 2, some resistivity results obtained on UPdIn are shown. UPdIn orders antiferromagnetically below 21 K with a sinusoidal modulation along c with a magnetic periodicity of $5c$. Below 8.5 K, the modulation is squaring up and because the size of the magnetic unit cell remains unchanged, the layers of the U-moments of $1.5\mu_B$, which are stacked along c in the sequence $(+ + - + -)$, yield a net ground-state magnetization of $0.3\mu_B$. While the basal-plane resistance is more ‘ferromagnetic’-like and decreases rapidly below the ordering temperature, an increase of the resistivity was found below 50 K for current along the c -axis [7]. Below the inflection point in $\rho(T)$ at T_N , a gradual saturation was observed. In a magnetic field along the c -axis, the upturn of the resistivity becomes gradually suppressed (see Fig. 1). This becomes more pronounced in the magnetic fields in which a magnetic

Fig. 1. Temperature dependence of the electrical resistivity of UPdIn for $i||c$ -axis in magnetic fields of 2, 3 and 10 T applied along the c -axis.

structure with $(+ + -)$ stacking is observed (>2.5 T). This drop in resistivity above 2.5 T is well documented by the field dependence of the resistivity at 4.2 K (Fig. 2). Two metamagnetic transitions can be seen in the magnetization curve. Now at the first transition the

Fig. 2. Magnetization (after Ref. [6]) and relative electrical resistivity for $i||c$ -axis of UPdIn at 4.2 K in magnetic fields applied along the c -axis.

(+ + - -) structure is transformed into the (+ + -) one and the full parallel alignment of moments is achieved in 16 T above the second transition. Both metamagnetic transitions are accompanied by a drop in the resistivity [3]. The major part of the magneto-resistance effect is concentrated in the latter transition.

Another typical example is UNiGa [2], which becomes antiferromagnetic below 40 K. The ground state can be characterised by the (+ + - + -) sequence polarisation of equal U magnetic moments of $1.4\mu_B$. The ferromagnetic configuration was reached in approximately 0.8–1 T (at 4.2 K). The first-order metamagnetic transition was accompanied by a drastic decrease in the resistivity ($\Delta\rho/\rho_0 = -86\%$).

From these two examples with $|\Delta\rho| \gg \rho_B$ (in the high-field state), it is evident that the magnitude of $\Delta\rho/\rho_0$ at low temperatures is strongly dependent on the residual resistivity in the ‘ferromagnetic’ state, which is essentially related to crystal imperfections. At elevated temperatures, the value of $\Delta\rho/\rho_0$ becomes reduced in most cases, because ρ_0 is enhanced due to electron scattering on phonons and magnetic excitations.

UNiGe [8,9] crystallises in the orthorhombic TiNiSi-structure type in which the strong bonding of the 5f wave functions is found not in planes but in chains along the *a*-axis. Below 41.5 K, this compound orders antiferromagnetically with a propagation vector (0, 1/2, 1/2). Applying the magnetic field along the *c*-axis, one first induces (in approximately 4 T) another magnetic structure with the propagation vector (0, 1/3, 1/3) and a net magnetic moment corresponding to the stacking (+ + -) is observed. Parallel alignment of U moments is achieved above 10 T. In the longitudinal geometry (*i*||*c*, *B*||*c*), we find that ρ is reduced by a similarly large relative value as in the compounds mentioned above. However, in contrast to the previous cases, by the transition from the ground state phase (+ -) to the one with the (+ + -) stacking a positive magnetoresistance step is observed.

Another case with strong coupling along chains is UPdSn which crystallises in the hexagonal GaGeLi-type structure [10]. In fields applied along the basal plane, the ground state antiferromagnetic structure gradually becomes suppressed towards parallel alignment of U magnetic moments. This transition is accompanied by a gradual reduction of the electrical resistivity with an increasing magnetic field also yielding a large negative magnetoresistance (>30%) in fields where the magnetization tends to saturate (see Fig. 3).

Fig. 3. Magnetization curve and the relative electrical resistivity for *i*||*b*-axis in UPdSn at 4.2 K in the magnetic field applied along the *b*-axis.

3. Discussion and conclusions

The examples of antiferromagnetic compounds presented above show unambiguously an additional contribution to the electrical resistivity due to the antiferromagnetic coupling of magnetic moments, which can be removed by forcing the moments to orient parallel to each other. This contribution does not vanish in the low-temperature limit, and at low temperatures it can represent a substantial part of the total resistivity.

Concerning possible mechanisms, by which the antiferromagnetic ordering influences the electrical resistivity, we should consider spin-dependent scattering, which can play an important role besides the Fermi-surface gapping, and which is often considered in the context of multilayers. In this concept, electrons with different spin orientation are supposed to experience different potentials and have a different *k*-space distribution. The origin of the spin-dependent scattering can be understood if different scattering amplitudes are considered for electrons with spin parallel or antiparallel to the ionic magnetic moments in the case of local moments. In band magnetism, the asymmetry of the scattering can be due to significantly different partial densities of states at E_F for each sub-band (spin-up or spin-down). In both cases, the increment of the resistivity in the AF state is expected

to be dependent on concentration of $+-$ interfaces. Systematic experimental effort is needed to verify this, i.e. whether the larger resistivity in the AF state is due to an additional scattering mechanism, or whether the explicit parameter is the modification of the effective conduction-electron concentration. In the former case, the value of $\Delta\rho$ should not be dependent on the purity of the sample. In the later case, the enhancement of the resistance in the AF state should be proportional to the total resistance in the 'ferromagnetic' state with the proportionality coefficient given by the effective Fermi-surface truncation factor. The unique proportionality constant given by the truncation factor should be observed at least in the low-temperature limit, where the different nature of the excitations in the antiferromagnetic and 'ferromagnetic' states can be neglected. Then, the size of the magnetoresistance effect should scale more with the size of the AF unit cell.

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