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Magnetoresistance behaviour of UNiGa and UNiAl

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The anisotropy of the transport properties of the antiferromagnets UNiGa and UNiAl is connected with the huge uniaxial magnetic anisotropy and the specific magnetic structures of these materials. The low temperature resistivity values are dramatically reduced in magnetic fields which produce a metamagnetic transition. The large magnetoresistance is typical for materials characterized by a strong coupling of conduction electrons with highly correlated f-electrons.

1. Introduction

UNiGa and UNiAl belong to the group of UTX (T = transition metal, X = p-metal) compounds with the hexagonal ZrNiAl-type structure [1]. Magnetization measurements of UNiGa and UNiAl single crystals point to antiferromagnetic ordering at low temperatures [2, 3]. The magnetic moments residing on the U atoms are locked in the *c*-direction by an enormous magnetic anisotropy which is caused primarily by the participation of the 5f electrons in the bonding. The collinear magnetic structures are, however, complex. In UNiGa, the magnetic moments ($\mu_U \simeq 1.4\mu_B$) are ferromagnetically ordered within basal-plane sheets (containing U and Ni atoms). These sheets are antiferromagnetically coupled along the *c*-axis in a sequence $+--++-$ [4]. The basal-plane sheets in UNiAl are modulated with a wave vector $\boldsymbol{k} = (0.1, 0.1, 0)$ and coupled along the *c*-axis in a simple AF sequence $+-+-$ [5]. By applying a magnetic field along the *c*-axis, a metamagnetic transition to a ferromagnetically aligned phase is found in UNiGa for $B \simeq 0.8$ T [2] and in UNiAl for $B \simeq 11$ T [3]. A dramatic reduction of the electrical resistivity connected with such a transition was observed in UNiGa [6]. In this paper, we discuss the magnetoresistance measured on UNiGa and UNiAl single crystals in the context of the magnetic behaviour of these compounds.

2. Experimental

Single crystals of UNiGa and UNiAl were grown by means of the tri-arc Czochralski technique. Bar-shaped samples (typically $0.5 \times 0.5 \times 4$ mm) cut parallel and perpendicular to the *c*-axis were used for electrical resistivity measurements with the electrical current $i \parallel c$ and $i \perp c$, respectively. UNiGa was measured by a standard DC four-probe technique. A magnetic field $B \leqslant 1.6$ T was applied $\parallel c$ and $\perp c$-axis in a conventional electromagnet. The resistance of UNiAl in zero magnetic field was measured by a standard AC four-probe method. Studies in magnetic fields up to 24 T were done in the High Field Installation of the University of Amsterdam. The resistance was measured by a DC technique in this case.

3. Results and discussion

The electrical resistivities of UNiGa and UNiAl are anisotropic and exhibit anomalous temperature dependence (figs. 1 and 2). The high temperature parts (paramagnetic range) are nearly temperature independent with large absolute values of the resistivity (hundreds of μΩ cm) which is characteristic of light-actinide intermetallics where conduction electrons are strongly coupled with 5f electrons.

For $i \parallel c$ in UNiGa, a gradual upturn in the $\rho(T)$ curve is observed on lowering the temperature. The upturn is suppressed by a magnetic field of 14 T applied along c [7] and can be tentatively attributed to AF spin fluctuations with $\boldsymbol{q} \parallel c$, which become gradually enhanced when approaching the magnetic ordering temperature. The two sharp peaks and the additional structure of the $\rho(T)$ curve between 38 and 28 K are connected with four successive magnetic phase transitions that take place in this narrow temperature range. The transitions separate the paramagnetic phase ($T > 38$ K) and four AF phases which differ from one another by the stacking sequence of the basal-plane (ab) ferromagnetic sheets [8]. For $i \perp c$, the drop of the resistivity, which sets in at 38 K, reflects the suddenly reduced scattering of the conduction electrons due to the ferromagnetic ordering within the ab sheets. At lower temperatures ($T < 20$ K), the resistivity follows a $\rho_0 + AT^2$ dependence. The values of ρ_0 and A are approximately four times larger for $i \parallel c$ than for $i \perp c$. The ratio $\rho_0^{\parallel}/\rho_{300}^{\parallel} \simeq 0.66$ is also much larger than for $\rho^{\perp}$ ($\simeq 0.21$).

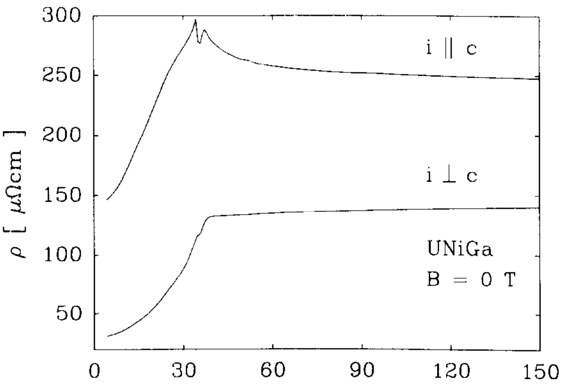

Fig. 1. Temperature dependence of the electrical resistivity of the UNiGa single crystal for $i \parallel c$ and $i \perp c$. It is noted that the intrinsic values of the resistivity for $i \parallel c$ can be much smaller than those presented. In some cases, suddenly and irreversibly, an enhanced resistivity was measured when passing the magnetic phase transitions (no such effects were found for $i \perp c$). After the last measurement, a value of $\rho_{300}^{\parallel} \cong 460$ μΩ cm was recorded. The presented results for $i \parallel c$ have therefore been normalized to the first recorded resistivity value. But this value may already be enhanced substantially because the same crystal was used before for a number of previous magnetization measurements [2]. These effects are probably connected with large magnetostriction effects along the c-axis, which can produce microcracks in the sample. Further investigation of a new crystal is desired to study these phenomena and to determine whether the anisotropy of the resistivity at high temperatures is an intrinsic property of UNiGa.

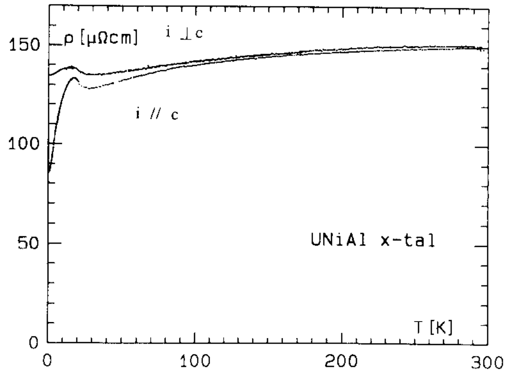

Fig. 2. Temperature dependence of the electrical resistivity of the UNiAl single crystal for $i \parallel c$ and $i \perp c$.

Magnetic fields applied within the basal plane have no influence on the resistivity values. When a magnetic field $B \parallel c$ is applied, sufficient to induce a metamagnetic transition (fig. 3), the resistivity is drastically reduced to approximately $0.1\rho_0^{\parallel}$ and $0.4\rho_0^{\perp}$ for $i \parallel c$ and $i \perp c$, respectively. Both residual resistivity values in a field above the metamagnetic transition are only about 8% of the corresponding room temperature values.

The resistivity of UNiAl (fig. 2) shows only small anisotropy above 100 K ($\rho_{300} \simeq$ 150 μΩ cm). With decreasing temperature, the $\rho^{\parallel}(T)$ and $\rho^{\perp}(T)$ curves gradually deviate from one another. In contrast to UNiGa, however, lower resistivity values are measured for $i \parallel c$.

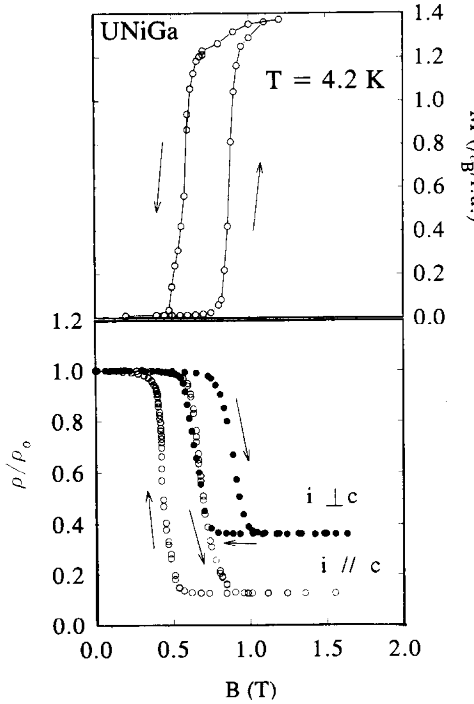

Fig. 3. (upper part) Magnetization curve of the UNiGa single crystal at 4.2 K for $B \parallel c$. (lower part) Magnetic field dependence of the relative electrical resistivity (ρ_0 = the value at $B = 0$ T) of the UNiGa single crystal at 4.2 K for $B \parallel c$, $i \parallel c$ and $i \perp c$. We note that the different fields of metamagnetic transition observed in the magnetization and resistivity measurements for $i \parallel c$ and $i \perp c$ are due to different demagnetization factors of the samples. In the case that the demagnetization factor is minimized (a bar-shaped sample with the longest dimension along c) the metamagnetic fields are close to the intrinsic values.

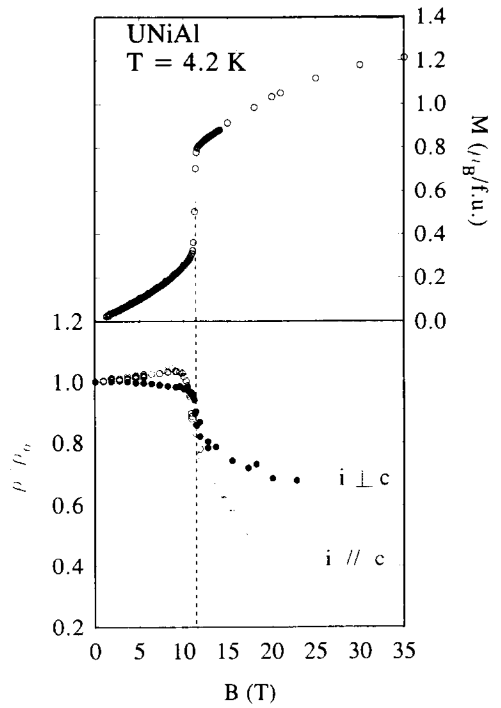

Fig. 4. (upper part) Magnetization curve of the UNiAl single crystal at 4.2 K for $B \parallel c$. (lower part) Magnetic field dependence of the relative electrical resistivity (ρ_0 = the value at $B = 0$ T) of the UNiAl single crystal at 4.2 K for $B \parallel c$, $i \parallel c$ and $i \perp c$.

Below 30 K, a minimum followed by a maximum are observed in both $\rho(T)$ curves at about 25 K (30 K) and 19 K (15 K), respectively. These features, connected with the magnetic ordering at 19 K, are more pronounced for $i \parallel c$. Moreover, at temperatures below the $\rho(T)$ maximum, $\rho^{\parallel}$ decreases steeply with decreasing T to a low temperature value of $\rho_0^{\parallel} = 85\ \mu\Omega$ cm ($\rho_0^{\parallel}/\rho_{300} \simeq 0.57$) whereas for $\rho^{\perp}$, only $\rho_0^{\perp} = 130\ \mu\Omega$ cm ($\rho_0^{\perp}/\rho_{300} \simeq 0.87$) is reached.

Application of magnetic field $B \parallel c$ larger than the critical value of the metamagnetic transition ($B > 11.3$ T) leads also in UNiAl to a considerable reduction of the resistivity (fig. 4), which in $B = 24$ T amounts to about $0.4\rho_0^{\parallel}$ and $0.66\rho_0^{\perp}$ for $i \parallel c$ and $i \perp c$, respectively.

The $\rho(B)$ curves of UNiGa and UNiAl at 4.2 K differ, however, in several aspects: In UNiGa (fig. 3), the precipitous drop in $\rho(B)$ marks the first order magnetic phase transition. The pronounced hysteresis of the transition found in the $M(B)$ curve also appears consistently in the $\rho(B)$ curves. The resistivity is field independent in fields below and above the transition.

In UNiAl (fig. 4), $\rho^{\parallel}$ increases with increasing field and reaches a maximum at 8 T. In higher fields it starts to decrease steeply with a maximum slope around $B = 10$ T. Then, the resistivity gradually but slowly saturates similar to the $M(B)$ behaviour. For $i \perp c$, a slow decrease of the resistivity is found in fields up to about 9 T. Then, $\rho^{\perp}$ drops through the transition by about 15% and, in larger fields, it behaves qualitatively similar to $\rho^{\parallel}(B)$.

The initial increase of $\rho^{\parallel}(B)$ in UNiAl can be attributed consistently with the theory for standard antiferromagnets [9], to the scattering of conduction electrons on gradually enhanced fluctuations when the metamagnetic transition is approached. This effect is absent in UNiGa for both directions of the electrical current which indicates absence of fluctuations in the magnetically ordered state. The resistance of UNiAl for $i \perp c$ in fields below the transition is decreasing with decreasing field. Whether this is connected with some gradual changes of the magnetic ordering within the *ab* planes or with suppression of a specific type of fluctuation remains an open question, which can be answered by neutron-scattering experiments.

Such enormous magnetoresistance changes associated with the metamagnetic transitions (90% in UNiGa) can be connected with the reconstruction of the Fermi surface due to the modified periodicity of the potential along *c* in the AF state. Whether this is combined with other phenomena, such as decoupling of conduction electrons from f electrons, cannot be answered at the present state of research. Further experiments (Hall effect, neutron scattering) are desired to shed more light on these problems.

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