Complex conductivity of UTX compounds in high magnetic fields

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We have performed rf-skin depth (complex-conductivity) and magnetoresistance measurements of antiferromagnetic UTX compounds (T=Ni and X=Al, Ga, Ge) in applied magnetic fields up to 60 T applied parallel to the easy directions. The rf penetration depth was measured by coupling the sample to the inductive element of a resonant tank circuit and then, measuring the shifts in the resonant frequency Δf of the circuit. Shifts in the resonant frequency Δf are known to be proportional to the skin depth of the sample and we find a direct correspondence between the features in Δf and magnetoresistance. Several first-order metamagnetic transitions, which are accompanied by a drastic change in Δf, were observed in these compounds. In general, the complex-conductivity results are consistent with magnetoresistance data. © 2009 American Institute of Physics. [DOI: 10.1063/1.3063068]

I. INTRODUCTION

Compounds containing 5f-electron states have been the subject of intense experimental and theoretical studies over past decades due to numerous different ground states. The magnetic properties of UTX intermetallic compounds (T =transition metal and X=p-electron element) vary from Pauli paramagnetism to different types of (sometimes unusual) long-range magnetic ordering, depending on the degree of the 5f-ligand hybridization.1,2 Magnetic-field-induced transitions in antiferromagnetic UTX compounds have attracted substantial attention.1,2 These transitions are called metamagnetic in analogy to the metastable (magnetic) state that sets in above the critical field. They take place in a magnetic field sufficient to overcome the antiferromagnetic interactions and to modify the magnetic structure. The modification of the magnetic structure is usually connected with a change in the translation symmetry, and subsequently accompanied by a noticeable change of the electrical resistivity.1,3 Here, we present measurements of the magnetoresistance and radio frequency (rf) skin depth of antiferromagnetic UTX (T=Ni, and X=Al, Ga, Ge) in magnetic field up to 60 T, applied along the easy magnetization directions. All three samples are best described as metallic. The experiments were performed on high purity single crystals using the 60 T short-pulse magnet at the Pulsed Field Facility, NHMFL, Los Alamos National Laboratory.

The rf penetration depth was measured by coupling the sample to the inductive element of a resonant tank circuit. Shifts in the resonant frequency (Δf) of the circuit are found to be proportional to the skin depth.4,5 rf-skin depth measurements are commonly referred to as complex conductivity in literature. The frequency (and amplitude) shifts reflect a change in both the real and imaginary components of conductivity. This technique is sensitive to both the dielectric εr and magnetic μr material properties.

II. EXPERIMENTAL RESULTS AND DISCUSSION

A. UNiAl

UNiAl crystallizes in the hexagonal ZrNiAl-type structure, and it was described as an itinerant 5f-electron antiferromagnet (AF) with Tr=19.3 K.1 Huge magnetic anisotropy with the easy magnetization direction along the hexagonal c-axis was found in studies of the bulk properties of single-crystalline UNiAl.6 At low temperature, this compound undergoes a metamagnetic transition for the magnetic field along c-axis, and the critical field was found to be equal to Bec=11.35 T at 1.7 K.7

Figure 1 compares the measured relative frequency shift in the tank circuit $\Delta f/f(B=0)$ as a function of applied magnetic fields along the crystallographic c axis of UNiAl to the magnetoresistance data, $\Delta \rho/\rho(B=0)$, measured previously.8 We find a direct correspondence between the features in $\Delta f/f(B=0)$ and magnetoresistance, $\Delta \rho/\rho(B=0)$. At 5 K, both properties exhibit a step related to the metamagnetic transition at about Bec=11.3 T in the field upswipe. At the critical field at 5 K, there is a sudden drop in the electrical resistivity (to about 45% of its zero-field value), which coincides with a sharp reduction in the relative frequency shift (to about 6% of its zero-field value). In addition, very narrow hysteresis around the transition fields (about 0.07 T) were observed in both $\Delta f/f(B=0)$ and $\Delta \rho/\rho(B=0)$ (not shown in...
the figure). The large magnetoresistance effects in uranium compounds is attributed to the suppression of AF fluctuation and to the disappearance of the magnetic superzones when the AF ordering is suppressed by magnetic field.\(^\text{8,9}\)

**B. UNiGa**

UNiGa is another compound that crystallizes in the hexagonal ZrNiAl-type structure. It undergoes several antiferromagnetic transitions below 40 K.\(^\text{1,10-12}\) At low temperatures (4.2 K), a magnetic field of 0.8 T applied along the \(c\)-axis yields a metamagnetic transition from the antiferromagnetic phase to a ferromagnetic phase.\(^\text{1}\) Again the transition is accompanied by a reduction of the electrical resistivity at the transition field. For the current along \(c\)-axis, \(\Delta \rho/\rho(B=0T) = 86\%\).\(^\text{13}\)

Figure 2 shows the measured relative frequency shift \(\Delta f/f(B=0)\) in the tank circuit for UNiGa as a function of applied magnetic fields along the crystallographic \(c\)-axis. As in the case of UNiAl, we find a direct correspondence between the features in \(\Delta f/f(B=0)\) and \(\Delta \rho/\rho(B=0)\). At 4 K, a metamagnetic transition at 0.8 T was observed in the skin depth measurements. The transition observed in \(\Delta f/f(B=0)\) corresponds directly to a change in the electrical resistivity.

**C. UNiGe**

Unlike UNiAl and UNiGa, UNiGe crystallizes in the orthorhombic TiNiSi-type structure.\(^\text{1,14}\) The compound undergoes two antiferromagnetic transitions at 42 and 50 K.\(^\text{15}\) Previous magnetic measurements revealed several metamagnetic transitions for magnetic fields applied along the \(c\)-axis (at 3 and 10 T) or \(b\)-axis (at 17 and 25 T),\(^\text{16,17}\) while the \(a\)-axis, magnetization curve at 4.2 K is linear up to 38 T, with a small magnetic moment of 0.23 \(\mu_B/U\) at 35 T.

Figure 3 compares the measured relative frequency shift in the tank circuit \(\Delta f/f(B=0)\) as a function of applied magnetic fields along the crystallographic \(c\)-axis of UNiGe to the previously published magnetoresistance data \(\Delta \rho/\rho(B=0)\).\(^\text{18}\) The rf-skin depth data are in good agreement with Ref. 19. We again find a direct correspondence between the features in \(\Delta f/f(B=0)\) and \(\Delta \rho/\rho(B=0)\). At 1.4 K, a sudden increase in \(\Delta f/f(B=0)\) at about \(B_{C1}=5\ T\) was followed by a large decrease in \(\Delta f/f(B=0)\) at about \(B_{C2}=10\ T\), marking critical fields that are quite similar to the magnetoresistance data. The slight differences in the lower critical field can be attributed to either a slight misalignment or different \(dB/dt\).

For the complex-conductivity measurements discussed thus far the frequency shift mirrors the magnetoresistance, indicating that the change in conductivity is the dominant contribution. For UNiGe with the \(B||b\)-axis, however there is a marked deviation from this behavior. Figure 4 compares the measured relative frequency shift in the tank circuit \(\Delta f/f(B=0)\) as a function of applied magnetic fields along the crystallographic \(b\)-axis of UNiGe to magnetoresistance data, \(\Delta \rho/\rho(B=0)\). Both skin depth and magnetoresistance measurements were done on the same sample. At 5 K, we observed a sharp reduction in \(\Delta f/f(B=0)\) at \(B_{C1}=18\ T\), an increase in the slope of \(\Delta f/f(B=0)\) at \(B_{C2}=24\ T\), and a dra-

![FIG. 1. Comparison of rf-skin depth measurements and magnetoresistance for UNiAl at 5 K, with the magnetic field applied along the \(c\) axis. Data shown are taken during the field sweep up from zero to maximum field. Errors of \(\pm \sigma\) are smaller than the symbol size.](image1)

![FIG. 2. Comparison of rf-skin depth measurements and magnetoresistance for UNiGa at 4.2 K, with the magnetic field applied along the \(c\) axis. Data shown are taken during the field sweep up from zero to maximum field. The magnetoresistance data were taken from Ref. 13.](image2)
matics in corrections. We find a direct correspondence between the features observed an increase in sensitivity to both the dielectric and magnetic properties such that for some magnetic field orientations the effective is additive and others of opposite sign. The amplitude shifts (data are not shown) show exact similar behavior as the frequency shifts but with opposite sign.

III. CONCLUSION

In conclusion, we have performed magnetoresistance and rf-skin depth measurements of antiferromagnetic UTX compounds (\(T\)=Ni, and \(X\)=Al, Ga, Ge) in applied magnetic fields up to 60 T, applied along the easy magnetization directions. We find a direct correspondence between the features in \(\Delta f/f(B=0)\) and \(\Delta \rho/\rho(B=0)\). In particular, first-order metamagnetic transitions in these compounds are accompanied by a drastic change in both \(\Delta f/f(B=0)\) and \(\Delta \rho/\rho(B=0)\), where the frequency shift mirrors the magnetoresistance. For UNiGe with the \(B||b\)-axis, however, we find a marked deviation from this behavior.

FIG. 3. Comparison of rf-skin depth measurements and magnetoresistance of UNiGe at 1.8 K, with the magnetic field applied along the c axis. Data shown are taken during the field sweep up from zero to maximum field. The rf-skin depth data are taken from Ref. 19.

FIG. 4. Comparison of rf-skin depth measurements and rf-magnetoresistance of UNiGe at 4 K, with the magnetic field applied along the b axis. Data shown are taken during the field sweep up from zero to maximum field.

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