RF skin-depth measurement of UIrGe in high magnetic fields

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Abstract. UIrGe crystallizes in the orthorhombic TiNiSi structure and it orders antiferromagnetically at low temperatures. Previous magnetoresistance and magnetization studies had revealed multiple metamagnetic transitions between ~ 12 T and ~ 19T. Our present studies show that RF skin depth measurement offers an alternative magnetotransport probe. A proximity detector oscillator (PDO) is used to perform the contactless RF skin-depth measurements of UIrGe in pulsed magnetic fields up to 47 T in temperature range 0.57–12 K. The frequency and amplitude shifts reflect the changes in both the real and imaginary components of the conductivity. Our results confirm that the measured frequency shifts can be related to the magnetoresistance effects.

1. Introduction

Correlated $5f$ electron compounds, such as uranium intermetallics, may exhibit a wide variety of exotic phenomena due to the competing localized and itinerant features of the $5f$ electrons. The delicate balance between itinerancy and localization can be altered by doping, pressure and magnetic field. The magnetism in uranium intermetallics is believed to be determined by two delocalization mechanisms, one is the direct overlap of the $5f$ wavefunctions, and the other is the hybridization of $5f$ states with the $p$ and $d$ states of the ligands. Isostructural UTX (U: Uranium, T: transition element, X: p-electron element) compounds have been studied for quite some time in order to disentangle the effects of $5f$-$5f$ hybridization and $5f$–ligand hybridization onto the formation of a magnetic ground state. UTX compounds crystallizing in the orthorhombic TiNiSi structure have attracted particular attention since they show a wide variety of moment configurations, whereas hexagonal ZrNiAl-type UTX compounds exhibit strong uniaxial c-axis magnetism [1].

UIrGe is one of the compounds that crystallize in the orthorhombic TiNiSi-type structure. Bulk magnetic studies revealed that the $a$-axis is the hard-magnetization direction or hard axis [2]. Temperature studies of bulk properties on powders indicated a single antiferromagnetic (AF) transition around 16.4 K, whereas in-depth single-crystal studies shows the AF order below 14.1 K and a second transition at ~ 15. 8 K [2]. Single-crystal neutron diffraction studies resulted in a non-collinear, antiferromagnetic magnetic structure at low temperatures [3, 4]. The $5f$ magnetic moment in UIrGe ($\sim 0.36\mu_B$ at 1.8 K) was found to be strongly reduced compared to the U$^{3+}$ free-ion moment, more so than that of most other TiNiSi-type UTX compounds.
Measurements of field-induced transitions in small-moment systems using magnetization or magnetoresistance probes can be a challenge. Recently, we have shown that one can utilize RF skin-depth measurements for the determination of transition fields for several UTX compounds [5]. Here, we report on RF skin-depth measurements of UIrGe in high magnetic fields.

2. Experimental

A single crystal of UIrGe was grown by the modified Czochralski method using stoichiometric amounts of the constituents with a purity of at least 99.95%. Previous electrical and magnetic transport measurements [6] utilized a small bar-shaped sample of $1 \times 2 \times 1 \text{mm}^3$ that had been cut from a larger single-crystalline ingot. The longest dimension is parallel to the $b$-axis. We used the same sample in order to perform the present radio-frequency (RF) measurements at high magnetic fields. The sample was placed in the sensor inductor coil in sample probe such that the $b$-axis is parallel to the coil axis, and then the probe was placed in a $^3\text{He}$ cryostat. The whole assembly was placed at the centre of 50-T mid-pulse magnet at the Pulse Field Facility, NHMFL, Los Alamos National Laboratory. The axis of the sensor coil and the magnetic field were aligned parallel, and thus the field was parallel to the $b$-axis of UIrGe. A proximity detector oscillator (PDO) circuit is placed at the top of the probe (almost a meter away from the centre of the magnet) and it is kept at room temperature. The main part of the PDO circuit is a commercially available integrated circuit (TDA0161), which is widely used in metal detectors. This circuit allows compensating for losses in the effective LC circuit using a principle that is very similar to a tunnel diode oscillator (TDO). The modified circuit oscillates at the resonance frequency given by

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where $L$ is the effective inductance and $C$ is the capacitance of the circuit. A careful design of the PDO circuit leads to a stable resonance frequency with a phase noise of less than 50 Hz over 2 hours. The PDO used in this study is optimized to produce a resonance frequency at 10 MHz, but the stable resonance frequencies up to 28 MHz are possible [7]. A more detailed description of RF skin-depth measurements in pulse field using this PDO circuit and a comparison with RF techniques using TDOs is given in reference 7.

As the applied magnetic field or the temperature are changed for a magnetic sample, its magnetic permeability modifies the effective inductance of the whole circuit and that causes a shift in the resonance frequency, which is given by the following relation

$$\frac{\Delta f}{f_0} = -\frac{\Delta L}{2L}$$

The frequency shift can be directly related to the skin-depth and dynamic susceptibility of a material [8, 9]. The Drude model predicts that the skin-depth is related to complex conductivity [10], and thus a shift in resonant frequency is a measurement of magneto-transport. Here, we performed RF skin-depth studies on single-crystalline UIrGe at a frequency of 25 MHz, in temperature range from 0.57 K to 12 K and in pulsed magnetic fields from 0–47 T applied along the $b$-axis.

3. Results and discussion

Figure 1 shows the variation of frequency shift in UIrGe as a function of magnetic field applied along the $b$-axis at various fixed temperatures. The frequency strongly decreases as the field is increased. At 0.57 K, we find that the frequency at 47 T is less than 5 % of the frequency at 0 T. More
interestingly, at the lowest temperature (0.57 K), we can clearly distinguish two stronger metamagnetic transitions at ~ 14.5 T and ~ 18.9 T and a third weaker transition at ~19.4 T. One can extract the temperature dependence of those metamagnetic transitions by comparison with the experimental results at elevated temperatures. All three metamagnetic transitions exhibit some small hysteresis, which persists at higher temperatures. For clarity, except at 0.57 K and 12 K variation of frequency with only up sweeps of field are shown in figure 1. The features in \( f \) coincide reasonably well with similar anomalies in magnetoresistance data on the same sample [6]. However, previous \( b\)-axis magnetoresistance studies were limited to fields up to ~18 T, and the here observed transitions around 19 T were out to the field range.

**Figure 1.** The field dependence of the frequency shift (\( f \)) in the proximity detector oscillator (PDO) circuit coupled to UIrGe with applied field along the \( b \)-axis at different temperatures.

**Figure 2.** B-T phase diagram of UIrGe. The open circles are data points determined from RF skin-depth measurement. The solid circles are from resistivity and heat capacity [6]. The lines are guide to the eye. AF is for antiferromagnetic phase, FIP is for field induced phase, FIF is for field induced ferromagnetic phase and PARA is for paramagnetic phase.

We used the values determined from field-up sweeps in order to construct the phase diagram shown in figure 2. The B-T phase diagram obtained from our skin-depth studies is in reasonable agreement with the data proposed from previous bulk studies [6]. The first two metamagnetic transitions are in reasonable agreement with B-T phase diagram extracted from resistivity, magnetization and specific-heat measurements [6, 11]. However, the third weaker transition at 19.4 T at 570 mK had not been seen previously. That transition becomes weaker as the temperature is increased and starts fading at 6 K. It is possible that this third metamagnetic transition is not intrinsic, but it is due to a small misaligned UIrGe crystallite. This third weak transition contributes a very small phase as shown in figure 2. The metamagnetic transitions shift towards lower field with increasing temperature, which is consistent with an antiferromagnetic ground state. Results of Prokes et al group shows that the \( a \)-axis component survives for field applied along the \( b \)-axis [4] whereas it disappears for field applied along \( c \)-axis [12]. In our measurements upto 47 T field along \( b \)-axis, there is no sign of separate transition due to the alignment of this \( a \)-axis component of moment in UIrGe something that had been seen in RF skin-depth measurement in UNiGe [13].
4. Conclusion

We measured the RF skin-depth for UlrGe in pulsed fields applied along the $b$-axis using PDO technique. The features in frequency with the variation of magnetic field and temperature are in good agreement with magnetoresistance data. It seems reasonable to assume that the conductivity dominates the changes in the complex-conductivity measurements since similar changes were seen in magnetoresistance data. Our B-T phase diagram is consistent with previously published magnetisation, transport and heat-capacity data.

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