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2003 J. Phys.: Condens. Matter 15 S2039

(http://iopscience.iop.org/0953-8984/15/28/322)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **15** (2003) S2039–S2042 PII: S0953-8984(03)62573-7

Anomalous pressure dependence of the electrical resistance and thermal expansion of UGe_2 in the paramagnetic state

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Received 12 November 2002
Published 4 July 2003
Online at stacks.iop.org/JPhysCM/15/S2039

Abstract
The electrical resistivity of single-crystalline UGe_2 has been measured under high pressure. It is found that the pressure dependence of the electrical resistivity shows an anomaly around 1 GPa even in the paramagnetic temperature range above $T_C = 52$ K. But the anomaly disappears above 200 K. The thermal expansion of UGe_2 was also measured at high pressure to clarify the lattice properties. The thermal expansion coefficients show a peak near 1 GPa below T_C but a similar peak is also found near 1 GPa at 80 K, i.e., in the paramagnetic region. The compressibility shows an anomalous increase with decreasing temperature even in the paramagnetic region. These facts suggest that the paramagnetic state of UGe_2 is not only in the anomalous electronic state but also in the anomalous lattice state.

1. Introduction

Recently UGe_2 has been investigated extensively by many authors because it shows a lot of anomalous properties under high pressure: it shows a ferromagnetism around 50 K ($=T_C$), which disappears at moderately high pressures of 1.6–1.8 GPa [1, 2], and the most striking fact is the existence of superconductivity in the ferromagnetic phase at high pressure [3, 4]. The details of the anomalous properties of UGe_2 have not been well understood until now. It seems to be important to clarify the electronic properties over wide pressure (P) and temperature (T) ranges, to obtain a deep understanding of the electronic state of this material. In the present work, we attempted to observe the electrical resistance and thermal expansion not only in

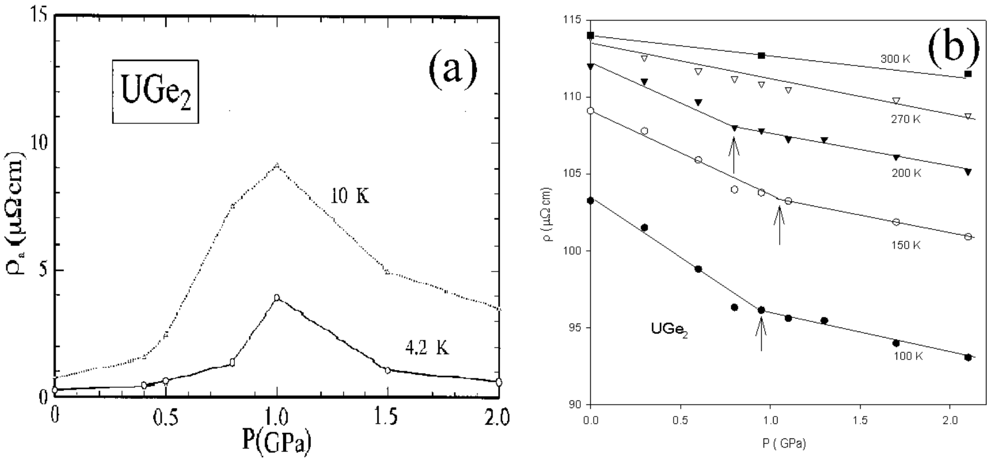

Figure 1. The pressure dependence of the electrical resistivity along the *a*-axis ρ_a (a) below and (b) above T_C.

the ferromagnetic region but also in the paramagnetic one. The results will be discussed in connection with recent experimental results. The extended P–T phase diagram of UGe_2 will be presented.

2. Experimental procedure

The details of the sample preparation and characterization have been reported elsewhere [5]. The electrical resistance was measured by using a standard dc four-probe method. The thermal expansion was measured by means of strain gauge [6]. High pressure was generated by using a piston and Cu–Be cylinder. Details of the present high-pressure apparatus have been reported previously [7]. The lattice constants were extracted from the thermal expansion data at high pressure.

3. Results and discussion

3.1. Electrical resistivity at high pressure

Figure 1(a) indicates the values of ρ_a at fixed temperatures, $T = 4.2$ and 10 K (below T_C), as a function of pressure. A peak in the pressure dependence of ρ_a is found around 1 GPa, which suggests a large electronic and magnetic fluctuation near 1 GPa and may correspond to some kind of phase transition [8, 9]. The details of this phase are not known at present, but it is well established that this phase is closely related to the occurrence of pressure-induced superconductivity. Recently, Miyake and Watanabe [10] suggested the existence of charge- or spin-density waves below T_C. Figure 1(b) shows ρ_a above T_C as a function of pressure. We found some anomalies in the pressure dependence of ρ_a. For example, ρ_a at 100 K decreases with pressure in an almost linear fashion up to 1 GPa but the decrease becomes sluggish above 1 GPa. This phenomenon is also observed at 150 K, but the anomalous behaviour is less prominent than that at 100 K. On the other hand, ρ_a above 200 K is found to show a smooth decrease with pressure and no anomalous pressure dependence is found above 200 K.

3.2. Anomalous lattice properties of UGe_2

We have reported that the thermal expansion of UGe_2 also shows an anomalous temperature dependence, in which the lengths of each axis show anomalous expansion or shrinkage

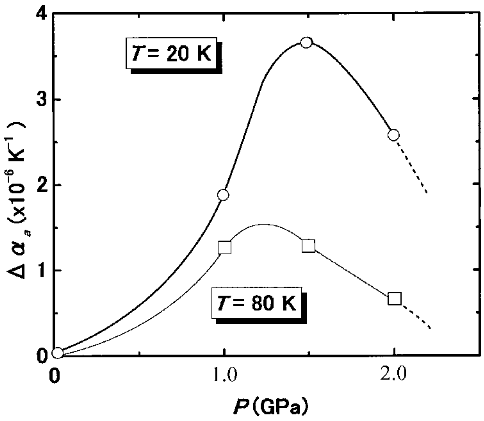

Figure 2. The thermal expansion coefficient along the a-axis below and above T_C, where $\Delta\alpha_a(T, P) = \alpha_a(T, P) - \alpha_a(T, 0)$.

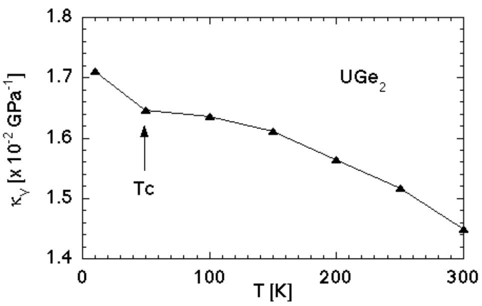

Figure 3. The temperature dependence of the compressibility of UGe_2.

depending on the direction of the crystal axis [11, 12]. In order to make clear the pressure dependence of the thermal expansion coefficients, we show the thermal expansion coefficients along the a-axis, $\Delta\alpha_a(T, P) = \alpha_a(T, P) - \alpha_a(T, 0)$, as a function of pressure at 20 K (below T_C) and 80 K (above T_C) in figure 2. $\Delta\alpha_a$ at 20 K increases with pressure and shows a peak around 1.5 GPa, which corresponds to the ferromagnetic–paramagnetic transition [8]. On the other hand, $\Delta\alpha_a$ at 80 K is found to show a similar peak around 1.2 GPa, although it is in the paramagnetic phase. The height of the peak in the paramagnetic phase is lower than that at 20 K (in the ferromagnetic phase). This finding is also very surprising because the magnetic state below 50 K is different from that above 50 K. This implies that the phase above 80 K may be not a 'pure' paramagnetic phase but also some kind of mixed phase including magnetic impurities or magnetic clusters such as a superparamagnetic phase. Recently Nishioka *et al* [13] suggested that the high-pressure phase at low temperature is regarded as an inhomogeneous phase containing magnetic domains of very small size. This seems to be compatible with our observations, although the temperature range is different.

From the pressure dependence of the volume [8], we calculate the isothermal compressibility, defined as $\kappa = -(1/V)(\partial V/\partial P)$, at several temperatures. The result is shown in figure 3 as a function of temperature. It is found that the value of κ increases with decreasing temperature and that the point at 10 K is higher than that extrapolated from the high-temperature range. This temperature dependence is in sharp contrast to the normal behaviour of metals and alloys, in which κ decreases with temperature; i.e., the materials

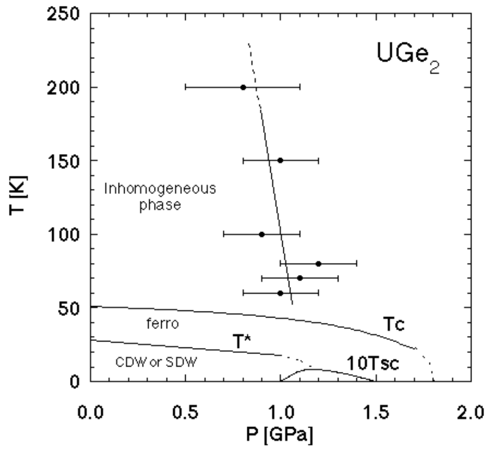

Figure 4. The extended P–T phase diagram of UGe_2, speculated from the present data.

should become hard at low temperature [14]. The softening below T_C is explained by a large magnetovolume effect, in which the volume is expanded by magnetic ordering [11, 12]. This result is considered to be due to a magnetic and structural inhomogeneities in the paramagnetic phase of UGe_2, which may give rise to a large compressibility.

Figure 4 summarizes the present data as an extended P–T phase diagram of UGe_2. This diagram includes the ferromagnetic phase, a kind of density wave phase, and the well known pressure-induced superconducting phase. The present work suggests that there may be an inhomogeneous phase above T_C, in which some persistent magnetic domains or clusters such as a superparamagnetic phase or a crystallographically disordered phase may exist. These inhomogeneities result in unstable magnetic and electronic states giving an anomalous pressure dependence of the electrical resistivity, thermal expansion, and the anomalous temperature dependence of the compressibility.

Acknowledgment

This work was financially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, Culture, and Technology of Japan.

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