High-pressure electrical resistivity measurement on heavy fermion superconductor URu$_2$Si$_2$ using super clean crystal

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Abstract. We have measured the electrical resistivity of URu$_2$Si$_2$ under high pressure using a high quality single crystal sample. The pressure phase diagram was re-investigated. With increasing pressure, the transition temperature $T_0$ from the paramagnetic to the “hidden order” states increases and the superconducting transition temperature $T_{sc}$ decreases simply. The superconducting transition temperature shows the applied electrical current dependence and the width of the transition temperature $\Delta T_{sc}/T_{sc}$ strongly increases above 0.94 GPa, suggesting the filamentary superconducting state above the pressure. It is suggested that the first order phase boundary of $P_x$ lies between 0.75 and 0.94 GPa. We analyzed the temperature dependence of the electrical resistivity $\rho_a$ for the current along the $a$-axis with a generalized power law $\rho = \rho_0 + AT^n$ in the low temperature regions from $T_{sc}$ to 2.75, 3.0, and 3.4 K. Below $P_x$, a power law exponent $n$ smaller than 2 is required to represent the data and the values of $n$ are generally about $1.5 \pm 0.1$. Above $P_x$, $n$ increases with increasing pressure and the value is about 2.0 at 1.51 GPa. It is suggested that the derivation of the exponent $n$ from the Fermi liquid theory is intrinsic to the hidden order state.

1. Introduction

URu$_2$Si$_2$ is a heavy-fermion superconductor with a superconducting transition temperature $T_{sc} \sim 1.5$ K at ambient pressure [1]. Furthermore, the compound undergoes a successive phase transition at $T_0 \sim 17.5$ K, and the ordered state coexists with the superconductivity. Only a tiny staggered moment of about $\sim 0.03 \mu_B/U$ was observed in the neutron diffraction experiments below $T_0$ and there were strong sample dependences on the value of the magnetic moment. Although intensive theoretical and experimental studies have been carried out, the nature of the ordered state has not been still explained consistently and the state is known as “hidden order” (HO) [2]. The applying pressure on the compound induces a first order phase transition from the HO to a large moment antiferromagnetic (LAFM) state at $P_x = 0.5$ GPa [2, 3, 4, 5, 6].

Recently, Zhu et al. reported that the resistivity along the $a$-axis $\rho_a$ exhibits a non-Fermi liquid behavior ($\rho_a \propto T$) in the low temperature limit, while that along the $c$-axis $\rho_c$ shows a typical Fermi liquid behavior ($\rho_c \propto T^2$) [7]. This behavior was interpreted theoretically based on a model assuming the quadrupolar ordering of the HO state [8, 9]. We succeeded in growing...
high-quality single crystals of URu$_2$Si$_2$ and investigated the sample dependence of the electrical resistivity [10, 11]. The $T$-linear dependence of $\rho$ was confirmed in a sample with a middle-class quality when $\rho$ between $T_{sc} < T < 2.8$ K was fitted with a relation $\rho = \rho_0 + AT^n$. With increasing sample quality, the value of $n$ increases and finally approaches to about 1.5. There have been several studies on the electrical properties of URu$_2$Si$_2$ under high pressure [2, 12, 13]. Since the electric state of this compound depends the sample quality, it is needed to investigate the electrical properties using a high quality single crystal. In this paper, we show the result of the electrical resistivity measurement on URu$_2$Si$_2$ using the high quality single crystal.

### 2. Experimental

We have grown the high quality single crystal of URu$_2$Si$_2$ by the Czochralski pulling method. The details of the sample preparation is given in the ref. 10. The electrical resistivity under high pressure was measured by the ac four terminal method in a $^3$He cryostat. The pressure was generated by a hybrid CuBe/MP35 piston cylinder-type high-pressure cell. The Daphne 7474 oil was used as a pressure-transmitting medium [14, 15]. It is very difficult to estimate the residual resistivity ratio RRR ($ = \rho_{RT}/\rho_{0K}$) because the residual resistivity $\rho_{0K}$ becomes a negative value if the resistivity just above $T_{sc}$ is simply extrapolated to 0 K. The value of RRR was estimated as about 300 using the resistivity just above $T_{sc}$ (RRR = $\rho_{RT}/\rho_{T_{sc}}$). It seems that the residual resistivity is very small and the real RRR value exceeds 1000 [11].

![Figure 1. Temperature dependence of the electrical resistivity in URu$_2$Si$_2$ at 1 bar, 0.24, 0.38, 0.65, 0.75, 0.94 and 1.51 GPa](image1.png)

**Figure 1.** Temperature dependence of the electrical resistivity in URu$_2$Si$_2$ at 1 bar, 0.24, 0.38, 0.65, 0.75, 0.94 and 1.51 GPa

![Figure 2. (upper panel) Pressure phase diagram in URu$_2$Si$_2$ determined the present resistivity measurement. (lower panel) Pressure dependence of the width on the superconducting transition temperature $\Delta T_{sc}/T_{sc}$](image2.png)

**Figure 2.** (upper panel) Pressure phase diagram in URu$_2$Si$_2$ determined the present resistivity measurement. (lower panel) Pressure dependence of the width on the superconducting transition temperature $\Delta T_{sc}/T_{sc}$
3. Results and discussions

Figure 1 (a) shows the temperature dependence of the electrical resistivity $\rho_a$ for the current along the $a$-axis at 1 bar, 0.24, 0.38, 0.65 and 0.75 GPa. At 1 bar, a clear superconducting transition temperature was observed at $T_{sc} = 1.43$ K. The transition temperature decreases with increasing pressure. Figure 1 (b) and (c) show the temperature dependence of $\rho_a$ at 0.94 and 1.51 GPa, respectively. Above 0.94 GPa, the superconducting transition temperature depends on the applied electrical current. The zero resistivity was not observed at 1.35 and 1.51 GPa. These results suggest that the superconducting state in the sample is not the bulk-type but filamentary above 0.91 GPa.

The upper panel of Figure 2 shows the pressure phase diagram of URu$_2$Si$_2$ determined by the present resistivity measurement. There are three phase lines in URu$_2$Si$_2$: $T_0(P)$ of the transition from the paramagnetic (PM) to the HO, $T_x(P)$ from the HO to the LAFM state and $T_N(P)$ from the PM to HO states [2, 6]. It was almost established by the previous studies with the ac magnetic susceptibility and heat capacity that the bulk-superconducting state exists only below $P_x$ and the superconducting transition in the resistivity observed above $P_x$ is due to a filamentary superconducting state in a sample [2, 5, 6]. In this study, the superconducting transition temperature shows the applied electrical current dependence and the width of the transition temperature $\Delta T_{sc}/T_{sc}$ increases largely above 0.94 GPa as shown in the lower panel of Figure 2. It is supposed that the value of $P_x$ lies between 0.75 and 0.94 GPa in the present study.

Figure 3. Pressure dependences of the resistivity exponent $n$ obtained by fittings a generalized power low to the low temperature resistivity in the three temperature regions in URu$_2$Si$_2$

Figure 4. Pressure dependences of $A$ obtained by fittings a generalized power low to the low temperature resistivity in the three temperature regions in URu$_2$Si$_2$


Next we briefly discuss the phase boundary of \(T_x(P)\). There has been a controversy whether the line of \(T_x(P)\) ends in a critical end point or intersects with the other two lines of \(T_0(P)\) and \(T_N(P)\) at a tricritical point of \(P^*\) [2, 4, 6]. This is an important point concerning the symmetry of the order parameter of the HO [16]. Since the present study shows only the resistivity data, we make a rough speculation assuming that the tricritical point exists. The reference 13 reported a small anomaly appeared around the phase boundary of \(T_x(P)\) in the temperature derivative of the electrical resistivity \(\partial \rho_a/\partial T\). In our study, there is no anomaly in the temperature dependences of \(\partial \rho_a/\partial T\) from 0.94 to 1.51 GPa (data not shown). The ref. 2 pointed out that the width of the transition at \(T_0\) in the resistivity and ac heat capacity increases above \(P^*\). In our study, the width of the transition at \(T_0\), estimated from \(T_{\min} - T_0\) where \(T_{\min}\) is the temperature where the resistivity shows a minimum value just above \(T_0\), increases strongly above 0.94 GPa (data not shown). One speculation is that the phase boundary line of \(T_x(P)\) runs upward in a very steep gradient and \(P^*\) is located below 0.94 GPa as shown in dotted line. This should be checked by a future study with other type of measurements such as a thermal expansion or heat capacity.

We analyzed the temperature dependence of the electrical resistivity \(\rho_a\) with a generalized power law \(\rho = \rho_0 + AT^n\) in the temperature regions from \(T_{sc}\) to 2.75, 3.0, and 3.4 K. Below \(P_x\), a power law exponent \(n\) smaller than 2 is required to represent the data in the temperature ranges. The pressure dependences of \(n\) and \(A\) are shown in Figure 3 and 4, respectively. Below \(P_x\), \(n\) shows a very weak pressure dependence and the values of \(n\) are generally about 1.5 ± 0.1. Above \(P_x\), \(n\) increases with increasing pressure and the value of \(n\) is about 2.0 at 1.51 GPa. These results suggest that the derivation of the exponent \(n\) from the Fermi liquid theory is intrinsic to the hidden order state. The value of \(A\) simply decreases with increasing pressure. There is no anomalous behavior in the pressure dependences of \(A\).

Finally, we discuss the exponent \(n\) of the antiferromagnetic state above \(P_x\). As pointed out in the ref. 2, the appearance of the filament superconductivity above \(P_x\) suggests the residual HO phase, origin of the superconductivity, still exists in the antiferromagnetic phase as impurities. Generally, the behavior of the resistivity is strongly influenced by impurities. With increasing pressure above \(P_x\), the superconducting transition temperature becomes more sensitive to the applied electrical current and the zero resistivity was not observed at 1.3 and 1.5 GPa, suggesting the decrease of the residual HO phase in the sample at the higher pressure region. If we estimate the resistivity exponent \(n\) from those at 1.35 and 1.51 GPa, the value of \(n\) in the antiferromagnetic state is estimated as close to 2.

4. Acknowledgments

This work was financially supported by a Grant-in-Aid for Scientific Research on Innovative Areas “Heavy Electrons” (No. 20102002), Scientific Research S (No. 20224015), C (No. 21540373, 22234567), Specially Promoted Research (No. 20001004) and Osaka University Global COE program (G10) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society of the Promotion of Science (JSPS).

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