SINGLE CRYSTAL GROWTH AND MAGNETIC PROPERTIES OF FERROMAGNETIC URhGe$_2$*

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We have successfully grown a single crystal of uranium intermetallic compound URhGe$_2$. The temperature dependence of electrical resistivity shows highly anisotropic behavior. Two anomalies, which correspond to the magnetic ordering temperatures, were observed in the resistivity, magnetic susceptibility and specific heat measurements at $T_{\rm M1}$= 30 K and $T_{\rm M2}$=25 K. The magnetic susceptibility also shows a large uniaxial anisotropy with a magnetic easy-axis along the [010] direction.

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Cerium and uranium compounds indicate a variety of magnetic and superconductivity properties such as magnetic and quadrupolar orderings, heavy fermions and unconventional superconductivity. Recently, a new aspect of cerium and uranium compounds with magnetic ordering have been discovered. When pressure P is applied to these compounds such as CeIn$_3$ [1], CeRhIn$_5$ [2] and UGe$_2$ [3], the ordering temperature $T_{\rm ord}$ decreases, and a quantum critical point corresponding to the extrapolation $T_{\rm ord} \to 0$ K is reached at $P = P_{\rm c}$. Surprisingly, superconductivity appears around $P_{\rm c}$

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even in the ferromagnetic state of UGe_2 [3]. More recent report indicated that ferromagnetic URhGe with Curie temperature $T_C = 9.5$ K and a saturated moment $\mu_s = 0.42\mu_B$/U becomes superconducting below 0.25 K [4]. Ferromagnetic moment-mediated superconductivity is realized in UGe_2 and URhGe. In order to clarify the superconducting properties, we searched for another uranium compounds. One of the candidates is $URhGe_2$ with the orthorhombic crystal structure ($a = 4.294$ Å, $b = 15.98$ Å and $c = 8.726$ Å) [5]. The previous data for the polycrystalline sample indicate that it orders ferromagnetically below $T_C = 31$ K and a saturated moment μ_s is about 0.2 μ_B/U.

We succeeded in growing a single crystal by the Czochralski-pulling method in a tetra-arc furnace under argon gas atmosphere. The starting material were 99.975%-pure U, 99.99%-Rh and 99.999%-Ge. The size of an ingot was about 2-3 mm in diameter and 65 mm in length, as shown in Fig. 1.

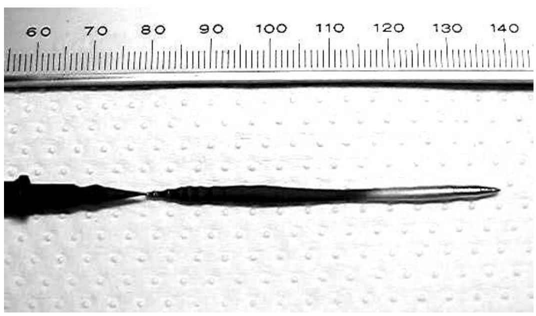

Fig. 1. Single crystal ingot of $URhGe_2$.

The electrical resistivity was measured by the ordinary four-probe dc method. The magnetic susceptibility and magnetization were measured by a commercial SQUID magnetometer. The specific heat was measured by the quasi-adiabatic heat-pulse method.

Figure 2 (a) shows the temperature dependence of the electrical resistivity ρ_{100}, ρ_{010} and ρ_{001} for the current J along [100], [010] and [001], respectively. For currents along [010] and [001], the resistivity increases slightly with decreasing temperature. We found two anomalies at $T_{M1} = 30$ K and $T_{M2} = 25$ K, as shown in Fig. 2(b). The upturn of ρ_{010} just below T_{M1} might be connected with magnetic super-zone gap formation, suggesting the possibility of modulated magnetic structure. On the other hand, the resistivity ρ_{100} is almost flat and slightly decreases with decreasing temperature down to about 50 K. Below T_{M1}, ρ_{100} decreases steeply, and small kinks are observed at T_{M1} and T_{M2}. The residual resistivity is, however, large, being 117 $\mu\Omega$cm in the current J along [100], 327 $\mu\Omega$cm in J//[010] and 389 $\mu\Omega$cm in J//[001].

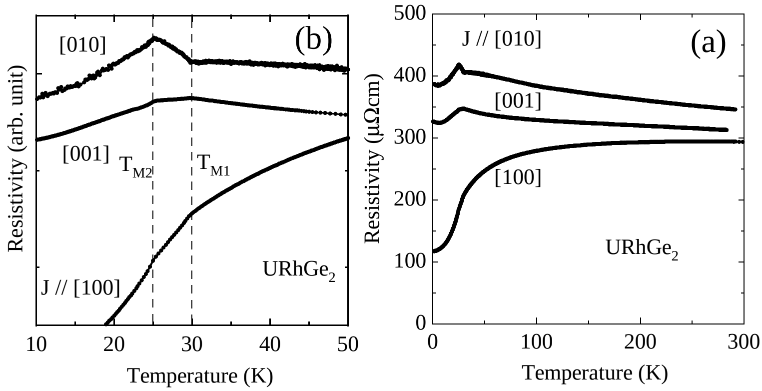

Fig. 2. Temperature dependence of electrical resistivity in $URhGe_2$.

Figure 3 shows the temperature dependence of the specific heat C in the form of C/T. With decreasing temperature, two λ-type anomalies are observed at $T_{\rm M1}$ and $T_{\rm M2}$. The electronic specific heat coefficient γ is estimated as γ =98 mJ/K^{2}mol. This value is relatively large for the uranium compounds.

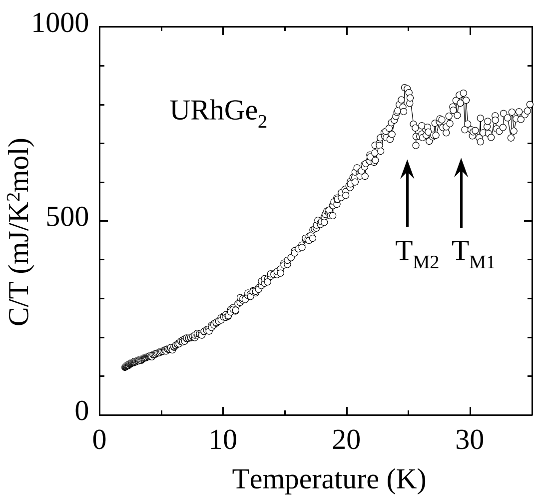

Fig. 3. Temperature dependence of specific heat in $URhGe_2$.

Figure 4 (a) shows the temperature dependence of magnetization. At low temperature, a steep increase of magnetization indicates ferromagnetic ordering. We note that the magnetic susceptibility is almost temperature-independent above 50 K, indicating $5f$-itinerant band magnetism.The easy magnetization direction is [010] axis, as shown in Fig. 4(b), while [100] and

[001] are hard-axes. The saturated moment for $H//[010]$ is 0.7 μ_B/U, which is larger than 0.2 μ_B/U for the polycrystalline sample. There exists a large magnetic anisotropic energy in $URhGe_2$.

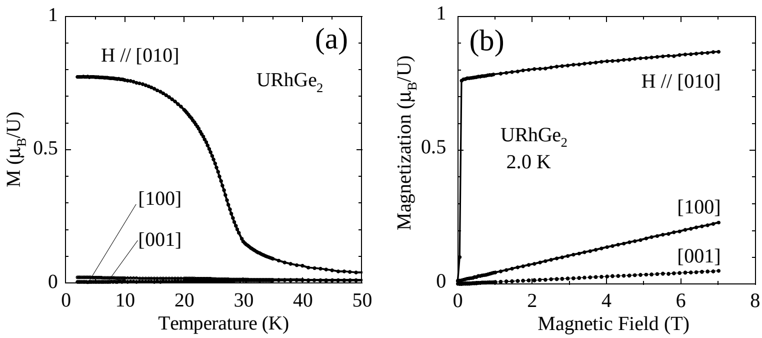

Fig. 4. (a) Temperature dependence of magnetization and (b) magnetization curve in $URhGe_2$.

The superconductivity is not observed down to 0.5 K for the present sample. It is important to reduce the residual resistivity, which is left to the future study.

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