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SINGLE CRYSTAL GROWTH AND ANNEALING TEMPERATURE OF FERROMAGNETIC URhGe*

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We searched for an experimental condition of crystal growth for a ferromagnetic superconductor URhGe. Samples were prepared for both polycrystalline and single crystals, which were arc-melted and grown by the Czochralski-pulling method in a tetra-arc furnace, respectively. Annealing is an important process in order to increase sample-quality, namely the residual resistivity ratio. We tried to anneal the samples under various temperatures, which were wrapped by the Ta-foil and vacuum-sealed in the quartz ample, together with the solid state electrotransport (SSE) method in ultra-high vacuum.

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URhGe with the orthorhombic TiNiSi-type crystal structure is a ferromagnet with a Curie temperature $T_{\rm C} = 9.6$ K and its saturated moment is 0.35 $\mu_{\rm B}$/U [1]. Recently, superconductivity was reported below 0.3 K at ambient pressure for URhGe [2], which is compared to the pressure-induced

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superconductivity of UGe_2. The relation between ferromagnetism and superconductivity is an urgent problem to be clarified both experimentally and theoretically. To grow a high-quality sample, we studied the experimental condition of crystal growth for polycrystalline and single crystals of URhGe.

The polycrystalline ingot was obtained in a tetra-arc furnace under the Ar gas atmosphere. The single crystal was grown by the Czochralski pulling method in a tetra-arc furnace under the Ar gas atmosphere. A tetra-arc furnace is a furnace that heats up with 4 arc torches. The temperature of mother liquor in a tetra-arc furnace is more stable than the one in a conventional tri-arc furnace. The purity of Ar was 99.9999%. Starting materials were 99.95% U, 99.99% Rh and 99.999% Ge. The pulling speed was 10 mm/h in the Czochralski method. It was decided from our experience. The seed used to prepare the single crystal was the polycrystalline ingot. Neither the single crystal nor the crucible was rotated to avoid a mosaic crystal. The crucible was fixed during the pulling process. Figure 1 shows a single crystal ingot, which is 2–3 mm in diameter and 60 mm in length.

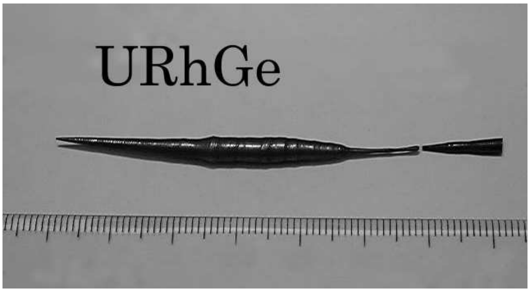

Fig. 1. Single crystal ingot of URhGe.

Annealing is important to get a high-quality sample. In order to determine the best annealing temperature, the polycrystalline samples were cut from the same polycrystalline ingot, then wrapped in a tantalum foil, sealed in a quartz tube under vacuum of 1×10^{-6} torr and annealed from 750 to 925°C for 50 hours.

To check the sample quality, we measured the temperature dependence of the electrical resistivity. The sample quality was determined by the residual resistivity ratio (RRR) value, $\rho_{\rm RT}/\rho_0$, where ρ_0 is the residual resistivity and $\rho_{\rm RT}$ is the resistivity at room temperature. The electrical resistivity was measured by the usual 4-probe DC method.

Figure 2 shows the temperature dependence of the resistivity for polycrystalline samples with several annealing temperature. The $\rho_{\rm RT}$ values ranged from 1000 to 1600 $\mu\Omega\,$cm. A steep decrease of the resistivity below 9.6 K in Fig. 3 is due to ferromagnetic ordering. The low temperature resistivity follows the equation of $\rho(T) = \rho_0 + aT^2$. By fitting the data to this equation, we got the ρ_0 value. Thus, obtained RRR value for each sample was plotted as a function of the annealing temperature, as shown in Fig. 2. The best RRR value was obtained for the annealing temperature of 875°C, where $\rho_0 = 38.9\ \mu\Omega\,\mathrm{cm}$.

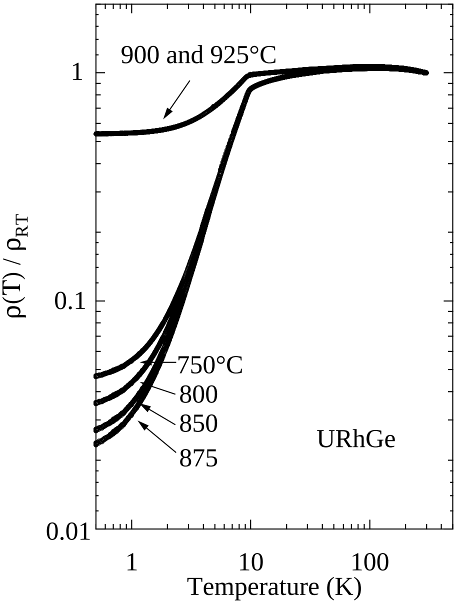

Fig. 2. Temperature dependence of the electrical resistivity for URhGe samples with different annealing temperatures.

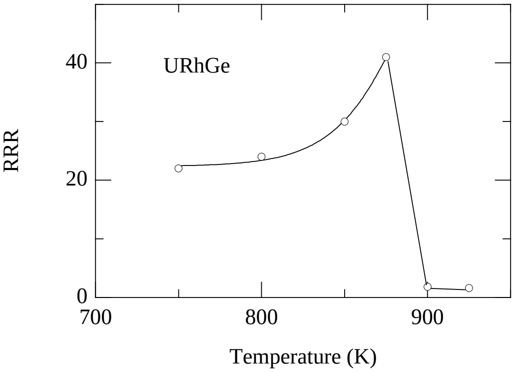

Fig. 3. Annealing temperature dependence of the residual resistivity ratio value.

In the polycrystalline sample in Ref. [2], which shows superconductivity at 0.3 K, ρ_0 was about 2 $\mu\Omega\,$cm. The present best sample is worse than the sample in Ref. [2]. This is mainly due to stacking faults in the present sample because the present sample is brittle. As shown in Fig. 3, the RRR value decreases steeply above 900°C. The main reason is that the annealing temperature is very close to the melting point of URhGe. The surface of the sample was colored brown and a small part of the sample was melted.

On the basis of this obtained appropriate annealing temperature, we annealed the single crystal ingot by the solid states electrotransport (SSE) method Ref. [3] at 870°C and 670°C for 1 week under vacuum of 8 $\times 10^{-10}$ torr. The present annealing temperatures 870°C means the highest temperature for a middle part of the ingot, which ranges from 800 to 870°C in location of the ingot. We measured the resistivity for four different single crystal samples from the same ingot with the annealing temperature of 870°C for the current along the [100] direction. All the samples showed RRR $\simeq$ 5 and $\rho_0 \simeq 45$ $\mu\Omega\,$cm, which is similar to the single crystal value with RRR $\simeq$ 4 and $\rho_0 = 86.3$ $\mu\Omega\,$cm [1]. For the single crystal ingot with the annealing temperature of 670°C, we got RRR = 10 and $\rho_0 = 31.5$ $\mu\Omega\,$cm. This is better than the single crystal sample with annealing temperature of 870°C. The appropriate annealing temperature, which was obtained for the polycrystalline samples, is not applicable for the single crystal ingot under another vacuum condition. In the SSE method, there might be another appropriate annealing temperature.

In conclusion we determine the 875°C for the sample of vacuum-sealed in the quartz sample.

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