Effect of pressure on the anomalous magnetoresistance and antiferromagnetism of single crystal GdB$_4$

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Abstract. Electrical resistance of single-crystalline GdB$_4$ has been measured at high pressures and high magnetic fields. The antiferromagnetic ordering temperature $T_N$ increases with pressure at a rate 0.3 K/GPa, but the hidden transition temperature $T_a$ is almost pressure independent. The magnitude of magnetoresistance at 4.2 K (about 6000% at 8.5 T) is not affected by applying pressures below 3 GPa. This fact suggests similar origins of the hidden transition and of the extremely large magnetoresistance.

1. Introduction

Materials exhibiting extremely large magnetoresistance (MR) have been extensively studied because of the wide range of applications [1]. The origins of large MR (so-called giant magnetoresistance, GMR, or tunneling magnetoresistance, TMR) are studied both experimentally and theoretically. In these studies, high pressure is well known as an efficient tool because it significantly affects the transport properties [2]. Recently, we have reported that the GMRs of Fe/Cr magnetic multilayers and the TMR of Co-Al-O granular films are enhanced by pressure [3,4]. In order to understand GMR and TMR phenomena, it is worthwhile to document pressure effects on other large-MR materials.

The tetraborides RB$_4$ (R: rare earth elements) having tetragonal crystal structure have been investigated mainly because of potential applications, such as n-type thermionic emitter. These materials show magnetic ordering due to the RKKY interaction [5]. Recently, extraordinary large positive MR, as much as several thousand per cent, has been reported in antiferromagnetic GdB$_4$ ($T_N = 41$ K) [6], and its origin is yet unclear. The GMR or TMR in many systems, such as magnetic multilayers or granular materials, strongly depends on the spin-dependent scattering of conduction electrons. It is important to test whether or not this is true for GdB$_4$.

In this work, we measured electrical resistance of single-crystalline GdB$_4$ under high pressures and high magnetic fields in order to examine the relation between the large MR and the stability of antiferromagnetism at high pressure.

2. Experimental details

Single crystal of GdB$_4$ was prepared by solution growth method [6]. The residual resistivity ratio (RRR) was as high as 200. Pressures up to 3 GPa were generated using a piston-cylinder device. The pressure was automatically kept constant throughout the measurements. The details of the high-pressure apparatus were reported previously [7]. Electrical resistance was measured with a conventional four-probe method at constant pressure. The magnetoresistance was measured at 4.2 K by applying the magnetic fields up to 9 T in a superconducting magnet.
3. Results and discussion

Figure 1 shows the temperature dependence of electrical resistivity $\rho(T)$ at 3 GPa; $\rho$ decreases with decreasing temperature and shows a cusp-like anomaly around 41 K ($= T_N$) due to antiferromagnetic ordering. The shape of the $\rho(T)$ curve is not affected much by pressure. In the inset of figure 1, $\rho(T)$ at 0.1 and 3.0 GPa is shown in the narrow temperature range $35 < T < 50$ K. The sudden decrease at $T_N$ is clearly seen, and $T_N$ increases with pressure. In order to deduce the $T_N$ value, we differentiated $\rho(T)$ with respect to $T$ as shown in figure 2. There are two anomalies in the temperature dependence of $d\rho(T)/dT$ at $T_N$ and $T_a$ (~10 K). The anomaly at $T_N$ is sharper than that at $T_a$, which was also observed in the temperature dependence of the heat capacity, but less clear than that at $T_N$.

![Figure 1](image1.png)

Figure 1. Electrical resistivity of GdB$_4$ at 3 GPa. Inset zooms into $\rho(T)$ near $T_N$.

![Figure 2](image2.png)

Figure 2. First derivative of $\rho(T)$ as a function of temperature.

![Figure 3](image3.png)

Figure 3. Antiferromagnetic ordering temperature $T_N$ as a function of pressure.

![Figure 4](image4.png)

Figure 4. Hidden transition temperature $T_a$ as a function of pressure.
Below temperature $T_a$, $\rho(T)$ shows $T^2$ dependence with the coefficient of $47 \times 10^{-3} \ \mu\Omega cmK^{-2}$, which is moderately large compared with that of heavy fermions [8]. Figures 3 and 4 show pressure dependences of $T_N$ and $T_a$. Temperature $T_N$ slightly increases with pressure at a rate $dT_N/dP = 0.3$ K/GPa, which is an order of magnitude smaller than that of DyB$_6$ [9]. On the contrary, $T_a$ is pressure independent within the experimental error.

Figure 5 shows electrical resistivity at 4.2 K and at high pressures as a function of magnetic fields $H$. Resistivity increases smoothly with increasing $H$, indicating absence of metamagnetic transition below 9 T. This field dependence $\rho(H) \sim H^{1.5}$ is similar to the $\rho(H) \sim H^2$ behavior of normal metals at low fields and to the MR of $\alpha$-Ce [10]. It is different from those of magnetic multilayers [4] or layered antiferromagnetic compounds such as CeNiGe$_2$ [11], which shows a large negative MR of the order of several tens per cent. Therefore, the extremely large positive MR of GdB$_4$ below 9 T is not due to the spin-dependent scattering. It has been reported that MR of GdB$_4$ obeys the so-called Kohler rule [6]. According to this rule, a pure material with low resistivity at $H=0$ is required for large MR [12]. Such case was reported for $\alpha$-Ce, in which the MR was enhanced by decreasing the resistivity under applied pressure [13]. In this sense, our result implies that GdB$_4$ is a typical large-MR material because its RRR value exceeds 200.

MR curve is weakly affected by pressure as shown in figure 5. The magnitude of MR at 4.2 K is $R(8.5T)/R(H=0) = 6000 \%$ at ambient pressure. The inset of figure 5 reveals that MR is pressure independent below 3 GPa. If the origin of the large MR of GdB$_4$ is spin-dependent scattering of conduction electrons then the antiferromagnetic spin arrangement should be important. In order to examine this idea, we plot the temperature dependence of MR in figure 6. MR increases rapidly around $T_a$, but not at $T_N$, implying that the large MR of GdB$_4$ is related not only to the purity but also to the “hidden phase transition”. The details of this transition at $T=T_a$ are not clear and further studies are highly desired.

4. Conclusions
In this work, we have measured the electrical resistivity of single-crystalline antiferromagnetic tetraboride GdB$_4$ under high pressures and high magnetic fields. The main results are summarized as follows:

1) Electrical resistivity of GdB$_4$ is almost pressure-independent below 3 GPa.
2) The antiferromagnetic ordering temperature $T_N$ increases with pressure at a rate 0.3 K/GPa.
3) The hidden transition temperature $T_a$ is pressure independent and is related to the large MR.
4) The magnitude of MR is not affected by applying pressures below 3 GPa.
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