Transport properties of single-crystalline Ising magnet SmPt$_2$Si$_2$

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Abstract. The electronic transport properties of a SmPt$_2$Si$_2$ single crystal are measured, in which magnetically disordered (paramagnetic) Sm ions are expected to remain partially in the antiferromagnetically (AFM) ordered state occurring below $T_I = 5.1$ K. In the paramagnetic state, the resistivity exhibits a shallow minimum at $\sim 11$ K and a pronounced negative magnetoresistance, suggesting the occurrence of the Kondo effect and/or AFM short-range ordering. Below $T_I$, the resistivity increases sharply, indicating a decrease in the carrier density caused by a superzone gap formation associated with the AFM transition. As regards the Hall effect, the extraordinary component is negligibly smaller than the normal component. The positive sign of the normal Hall coefficient indicates that the hole Fermi surfaces dominate the electrical transport properties. The difference in the transport properties of the two ordered phases is discussed.

1. Introduction
Over the past decade, there has been increased interest in the strongly correlated electron behaviors appearing in Sm-based intermetallic compounds. Typical examples are the unusual magnetic-field-insensitive heavy-fermion behavior in SmOs$_4$Sb$_{12}$ [1, 2, 3], the magnetic-field-insensitive phase transitions and significantly enhanced Sommerfeld coefficients in Sm$T_2$Al$_{20}$ [4, 5, 6], the metal-insulator (MI) transition and magnetic-field-induced charge ordering in SmRu$_4$P$_{12}$ [7, 8, 9], and the MI transition under pressure in Sm$X$ ($X =$ S, Se, and Te) [10, 11, 12].

$RT_2X_2$ ($R$: rare earth; $T$: transition metal; $X$: Si and Ge) materials exhibit a variety of exotic strongly correlated electron behaviors. For $R =$ Sm, however, there are only a few reports concerning systematic physical property investigations using single crystals [13]. Recently, we succeeded in growing SmPt$_2$Si$_2$ single crystals, and determined that this material is a strong Ising magnet [14]. The magnetic field $H$ vs temperature $T$ phase diagram determined for $H \parallel c$ is shown in figure 1. Under zero-field conditions, an antiferromagnetic (AFM) ordering (named phase I) appears at $T_I = 5.1$ K. In phase I, a Curie term remains in the magnetic susceptibility $\chi(T)$, indicating the partial existence of magnetically disordered (paramagnetic) Sm ions [14]. The large electronic specific heat coefficient $\gamma = 350$ mJ/K$^2$mol in phase I indicates the existence of heavy quasiparticles, which may be formed on the sublattice of partially magnetically disordered Sm ions. A metamagnetic anomaly appears at the boundary between phases I and II. The magnetic structure of phase II is expected to be $\uparrow\uparrow\downarrow$ from the magnetization $M$ value. In this paper, we investigate the electronic transport properties of SmPt$_2$Si$_2$ using a single crystal.
Figure 1. $H$-vs-$T$ phase diagram of SmPt$_2$Si$_2$ for $H \parallel c$ (data below 7 T taken from Ref. [14] and data above 7 T determined from the present measurements).

2. Experimental
SmPt$_2$Si$_2$ single crystals were grown using the Sn-flux method and raw materials of 3N (99.9% pure) Sm, 4N Pt, 4N Si, and 5N Sn. These materials were inserted in an alumina crucible with an off-stoichiometric composition of Sm:Pt:Si:Sn = 1:3:1:40, and sealed in a quartz tube. The quartz tube was heated to 1150 $^\circ$C, maintained at this temperature for 1 day, and then cooled to 650 $^\circ$C at a rate of -2 $^\circ$C/h, which required approximately 10 days in total. Single crystals were obtained by spinning the ampoule in a centrifuge in order to remove excess Sn flux. The transport properties were measured using a standard AC four-probe technique in a commercial Physical Property Measurement System (Quantum Design Inc.).

3. Results and discussion
The temperature dependence of the electrical resistivity $\rho(T)$ of SmPt$_2$Si$_2$ measured for the current $j \parallel a$ under zero-field conditions is shown in figure 2 (a). The residual resistivity ratio $RRR$ ($\equiv \rho(300 \text{ K})/\rho(2 \text{ K})$) is 2.3. The overall temperature dependence of $\rho$ exhibits a metallic behavior with a slight downward curvature. There is no anomaly associated with a charge-density-wave transition, such as that observed in LaPt$_2$Si$_2$ at 112 K [15].

The low-temperature $\rho(T)$ data measured under various magnetic fields is shown in figure 2 (b). Under zero-field conditions, $\rho$ exhibits a steep increase below $T_1$, indicating a carrier-density decrease caused by a superzone gap formation associated with the AFM transition. The magnitude of the increase in $\rho$ is only approximately 1%. According to band-structure calculations [16, 17], SmPt$_2$Si$_2$ has five Fermi surfaces with strong two-dimensional characteristics. Considering the present $j \parallel a$ configuration, the observed small increase in $\rho$ may indicate that the magnetic ordering wave vector is parallel to the $c$ axis.

Under applied magnetic fields of $\mu_0 H > 2$ T, phase II appears in the measured temperature range. At the $I \rightarrow II$ phase transition, $\rho$ exhibits a decrease. This change in $\rho$ is more clearly shown in the field dependence of $\rho$ (see figure 2 (c)). For $\mu_0 H > 7.5$ T, phase I does not exist.
At the paramagnetic (PM) → II transition, ρ exhibits a sharp increase, indicating the first-order character of the transition.

Under zero-field conditions, ρ(T) exhibits a shallow minimum at 11 K (≡ T_{min}). This feature indicates the existence of a contribution with dρ/dT<0, which can be attributed to the Kondo effect and/or a short-range ordering possibly present above T_{I}. This interpretation is supported by pronounced negative magnetoresistance (MR) appearing at T>T_{I}. Figure 2 (d) shows ∆ρ ≡ ρ(H) − ρ(0) vs T for various applied fields. It is apparent from this figure that the negative MR develops with decreasing temperature. As reported in Ref. [14], the 4f-electron contribution to the entropy S_{4f} at T_{I} is 4.6 J/mol·K, which is 80 % of R ln 2. This decrease in S_{4f} can be attributed to the Kondo effect and/or the short-range ordering. Comparison of S_{4f}(T_{I}) = 4.6 J/mol·K with a single-impurity Kondo model calculation [18] provides the upper bound of the Kondo temperature T_{K}, which is 2.3 K.

![Figure 2](image-url)

**Figure 2.** Temperature dependence of resistivity ρ for j || a (a), low-temperature part of ρ for various magnetic fields (b), H dependence of ρ at 2, 4.5, and 10 K (c), and transverse magnetoresistance ∆ρ ≡ ρ(H) − ρ(0) vs T (d).

The temperature dependence of the Hall coefficient R_{H} ≡ ρ_{H}/H, where ρ_{H} represents the Hall resistivity, and that of the Hall mobility μ_{H} = R_{H}/ρ are shown in figure 3 (a). Usually, the ρ_{H} of magnetic materials is expressed as ρ_{H} = R_{0}H + R_{S}M, i.e., the sum of the normal component originating from the cyclotron motion of the conduction electrons and the extraordinary component caused by the magnetic scattering of the conduction electrons from the magnetic ions [19]. Comparison of R_{H}(T) with χ(T), as shown in figure 3 (b), indicates that the extraordinary component is extremely weak in SmPt_{2}Si_{2}. R_{H}(T) gradually increases
with decreasing temperature and begins to saturate below $\sim 50$ K, while $\chi(T)$ exhibits a strong temperature dependence below $\sim 50$ K, corresponding to the Curie-Weiss behavior; note that the two components in $\rho_H$ cannot be distinguished based on the field dependence, because both $\rho_H$ and $M$ exhibit almost linear $H$ dependence (not shown). Therefore, we assume $R_H \simeq R_0$ in the following analysis.

SmPt$_2$Si$_2$ is a compensated metal, i.e., it has equal numbers of electrons and holes. Therefore, we use a two-carrier model. (Note that this is a simplified model, as SmPt$_2$Si$_2$ has five Fermi surfaces [16, 17].) In the measured temperature range, $R_H$ is always positive. This feature indicates that holes dominate the transport properties; the hole mobility is higher than that of the electrons (in the two-carrier model, $\mu_H = \mu_h - \mu_e > 0$, where $\mu_h$ and $\mu_e$ represent the hole and electron mobilities, respectively). At room temperature, $R_H = 1.22 \times 10^{-10}$ m$^3$/C (this value corresponds to a carrier density of $\sim 8.87$/f.u. in a single-carrier model). $R_H$ increases with decreasing temperature and almost saturates at a value of $2.3 \times 10^{-10}$ m$^3$/C below $\sim 20$ K in the PM state. As shown in figure 3 (c), $R_H$ exhibits an increase below $T_1$ and, at $T_{II}$, it exhibits a further increase. This feature is also apparent in the $\rho_H$-vs-$H$ curve measured at 2 K shown in figure 3 (d). This observation indicates that the dominance of the hole mobility increases in a stepwise manner at the PM$\rightarrow$I$\rightarrow$II phase transitions.

![Figure 3](image_url)

**Figure 3.** Temperature dependences of Hall coefficient $R_H$ and Hall mobility $\mu_H = R_H/\rho$ of SmPt$_2$Si$_2$ measured at 4.5 T (a), $\chi$ for $H \parallel a$ and $H \parallel c$ (data taken from Ref. [14]) (b), low-temperature part of $R_H(T)$ at 2, 4.5, and 9 T (c), and $H$ dependence of $\rho_H$ at 2, 4.5, and 6 K (d).

4. Summary

The electronic transport properties of a SmPt$_2$Si$_2$ single crystal have been measured. In the paramagnetic state, the resistivity $\rho$ exhibits a shallow minimum at $\sim 11$ K and a pronounced

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