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Single crystal growth of the metallic triangular-lattice antiferromagnet PdCrO$_2$

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Abstract

We report details of single crystal growth of the metallic triangular-lattice antiferromagnet PdCrO$_2$ consisting of layers of Pd triangles and Cr triangles stacking along the $c$ axis. We used the NaCl flux method and obtained the crystals with the size as large as $2 	imes 3.5 	imes 0.3$ mm$^3$. We confirmed that single crystals have the delafossite structure with the $R\bar{3}m$ symmetry. The electrical resistivity along the $c$ axis and that in the $ab$ plane exhibit metallic temperature dependence with the anisotropic ratio $\rho_c/\rho_{ab}$ of over 300 at low temperatures. The residual resistivity of as small as $\rho_{0,ab} = 45$ n$\Omega$ cm and the residual resistivity ratio of over 100 indicate high quality of the crystals investigated. Nevertheless, there is no sign of superconductivity down to 0.3 K. These crystals are useful for the investigation of anisotropic magnetic and transport properties including the unconventional anomalous Hall effect (AHE).


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1. Introduction

Delafossites $A$BO$_2$ ($A$: noble-metal elements; $B$: transition-metal and rare-earth elements) crystallize in a layered structure consisting of alternating stacks of triangular lattices (TL) of monovalent $A^{1+}$ ions and trivalent $B^{3+}$ ions along the $c$ axis (Fig. 1). Because of the simple TL structure, members with the magnetic ions at the $B$ site are useful for the clarification of the unresolved issues of ideal TL magnets [1, 2, 3, 4]. In addition, by the choice of $A$ site ions, the metallicity can be controlled. Insulating delafossites are actively investigated as the typical multiferroic materials. For examples, CuFeO$_2$ [5] and CuCrO$_2$ [6, 7] are known to exhibit strong coupling between the spiral magnetic ordering with the proper-screw type spin structure and the ferroelectric polarization. Metallic delafossites with frustrated spin structure are promising for the investigation of the unconventional anomalous Hall effect (UAHE), which emerges not from the conventional order parameter magnetization $M$ but possibly from the multi-spin quantity “scalar spin chirality” [8].

Although most delafossites are insulators or semiconductors, there are several members of metallic delafossites, such as AgNiO$_2$ [9, 10], PdCoO$_2$ [11, 12], PtCoO$_2$ [13, 14], and PdCrO$_2$ [15]. Among them, only AgNiO$_2$ and PdCrO$_2$ are magnetic metals. In particular, since metallic and magnetic origins are well sepa-
sary. For these measurements, availability of the high-quality single crystals is crucial. Here, we present the details of the growth of high-quality PdCrO$_2$ single crystals. To the best of our knowledge, this is the first report of the details of the single crystal growth of PdCrO$_2$.

Previous studies on powder samples of PdCrO$_2$ have revealed that it exhibits an antiferromagnetic transition at $T_N = 37.5$ K forming a 120$^\circ$ spin structure [18, 15]. This Neel temperature is an order of magnitude lower than the Weiss temperature $\theta_W \approx -500$ K; the frustration parameter $f = |\theta_W|/T_N$ is about 13, indicating a strong frustration among spins. Single crystals obtained in this study revealed isotropic magnetization above $T_N$, consistent with the Heisenberg spins, while they clarified the emergence of anisotropy below $T_N$, indicating that the 120$^\circ$ spin structure is easy-axis type.

2. Crystal growth

Single crystals of PdCrO$_2$ were grown by a NaCl flux method. Polycrystalline PdCrO$_2$ used for the single crystal growth were prepared in two steps. In the first step, LiCrO$_2$ was prepared as a precursor by the solid-state reaction of the stoichiometric mixture of Li$_2$CO$_3$ (99.99%, Aldrich Chemical Co.) and Cr$_2$O$_3$ (99.99%, Rare Metallic Co. Ltd.) at 850$^\circ$C in air in an alumina crucible for 24 hours. In the second step, PdCrO$_2$ powder was synthesized by the following metathetical reaction: Pd + PdCl$_2$ + 2LiCrO$_2$ $\rightarrow$ 2PdCrO$_2$ + 2LiCl [13, 15, 19]. For this step, Pd powder (99.99%, Furuuchi Chem. Co.) and PdCl$_2$ powder (99.999%, Aldrich Chemical Co.) were used. The mixture was ground in a mortar for 30–60 minutes, sealed in an evacuated quartz tube (100 mm $\times$ 10 mm), heated to 790$^\circ$C and kept at this temperature for 96 hours. The obtained product was washed with aqua regia and distilled water to remove LiCl, unreacted Pd, and other by-products. Single crystals were grown from the mixture of polycrystals of PdCrO$_2$ and NaCl (99.99%, Rare Metallic Co. Ltd.) with a mass ratio of typically 1 : 10. We note here that the minimum mass ratio in which single crystals were formed was 1 : 4. The mixture was sealed in an evacuated quartz tube (130 mm $\times$ 20 mm), heated to 880$^\circ$C in 3.5 hours, and kept at this temperature for 24 hours. It was then cooled down to 800$^\circ$C at the cooling rate of 0.25–0.5$^\circ$C/h and to 700$^\circ$C at 1$^\circ$C/h. We should note that the melting point of NaCl is 801$^\circ$C at ambient pressure. After the slow cooling processes, the quartz tube was furnace-cooled down to room temperature. Single crystals were obtained with by-products such as Cr$_2$O$_3$. In order to grow larger crystals, single crystals were added in the mixture as seeds. The largest crystal size obtained is about 2.0 $\times$ 3.5 $\times$ 0.3 mm$^3$ (see the microscope pictures in Fig. 2). We note here that single crystals of PdCrO$_2$ were not obtained either with PdCl$_2$ flux, Bi$_2$O$_3$ flux, or Bi$_2$O$_3$–B$_2$O$_3$ mixed flux. The starting PdCrO$_2$ polycrystals remained unreacted in PdCl$_2$ flux. They decomposed in Bi$_2$O$_3$ and Bi$_2$O$_3$–B$_2$O$_3$ fluxes but did not produce any crystals. We also note that attempts to grow the single crystals in air using Pt crucibles were not successful.

3. Characterization

Figure 3 represents the powder X-ray diffraction (XRD) spectra of polycrystalline and single-crystalline samples of PdCrO$_2$, with the CuK$_{\alpha1}$ radiation. These
two spectra exhibit the same patterns, yielding the lattice parameters of $a = b = 2.923$ Å, $c = 18.086$ Å for both single crystals and polycrystals.

The X-ray Laue patterns for the (001) plane and (100) plane are presented in Figs. 4(a) and (b). Calculated patterns for these conditions shown in Figs. 4(c) and (d) are consistent with the measured patterns. The clear Laue spots guarantee high crystallinity of the crystals. Scanning electron microscope (SEM) images with the energy dispersive X-ray (EDX) analysis mapping are presented in Fig. 5. The EDX analyses confirmed the homogeneity of the crystals with the composition ratio of Pd/Cr = 1.1 ± 0.1. Fig. 5 also indicates the Cr$_2$O$_3$ impurity phase localized on the left edge of the crystal.

Figure 6(a) represents the electrical resistivity along the $c$ axis ($\rho_c$) and in the $ab$ plane ($\rho_{ab}$) measured with both the ac and dc four-probe methods from 300 K to 0.32 K. Both $\rho_c$ and $\rho_{ab}$ exhibit metallic temperature dependence down to the lowest measurement temperatures with clear anomalies at $T_N$. The residual resistivities are $\rho_{0c} = 16.5$ μΩ cm and $\rho_{0ab} = 45$ nΩ cm (see the inset of Fig. 6). The residual resistivity ratio, $\text{RRR} \equiv \rho(295\text{K})/\rho(0.32\text{K})$, is estimated to be 104 for $\rho_c$ and 200 for $\rho_{ab}$. By using the value of the Fermi wave number $k_F = 0.93$ Å$^{-1}$ [20] and the carrier density $n = 1.62 \times 10^{22}$ cm$^{-3}$ [21], the mean free path $l = (\hbar k_F/e^2\rho_0)$ in the $ab$ plane is estimated to be as large as $l_{ab} \approx 30$ μm. These large RRR and $l$ guarantee high quality of the obtained crystals. The anisotropic ratio $\rho_c/\rho_{ab}$ is over 190 in the whole measurement temperature range. The large anisotropy of the resistivity is consistent with the expectation that the metallic conductivity mainly originates from the Pd layer.

The dc magnetization $M$ was measured with a SQUID magnetometer (Quantum Design, MPMS) from 300 K to 1.8 K in magnetic fields $\mu_0H$ between 0.01 and 7 T in both field-cooled (FC) and zero field cooled (ZFC) conditions. Figure 6(b) shows the temperature dependence of the magnetic susceptibilities ($\chi = M/\mu_0H$) measured in the field $\mu_0H = 1$ T along the $c$ axis, and in the $ab$ plane. Above $T_N$, $\chi$ is isotropic, exhibiting the Curie–Weiss behavior above 200 K with the localized moment $\mu_{\text{eff}} = 4.0 \pm 0.2$ μB [15]. These results suggest that PdCrO$_2$ constitutes a Heisenberg spin system, consistent with the expectation of the localized spins of the Cr$^{3+}$ ion (3d$^3$, $S = 3/2$). In contrast, below $T_N$, at which the spins form a 120° structure [15, 18], $\chi$ becomes anisotropic with a sudden decrease at $T_N$; the value of $\chi_{ab}$ becomes larger than that of $\chi_c$. Such anisotropy is similar to the susceptibility of another delafossite CuCrO$_2$ [7], but is different from a similar layered TL magnet LiCrO$_2$ with $\chi_c$ larger than $\chi_{ab}$ [22]. Within the mean field approximation [23], $\chi$ should be isotropic even below $T_N$ if the inter-plane spin configuration is ferromagnetic. The observed anisotropy $\chi_{ab} > \chi_c$ is expected if the inter-plane configuration is
4. Conclusion

We have succeeded in growing single crystals of PdCrO$_2$ by a NaCl flux method. It was confirmed that the obtained crystals are in the delafossite structure with the $R3m$ symmetry. The large values of the residual resistivity ratio over 100 and the mean free path in the $ab$ plane as large as 30 $\mu$m guarantee the high quality of the crystals.

The metallic resistivity with a large anisotropy ($\rho_c/\rho_{ab} > 190$) supports the expectation that the conductivity in PdCrO$_2$ mainly originates from the Pd layers. The magnetic susceptibility above $T_N$ confirms that PdCrO$_2$ constitutes a Heisenberg spin system. Moreover, the emergence of the anisotropy at $T_N$ indicates an antiferromagnetic coupling between the layers with the easy-axis type 120° spin structure.

These crystals make possible further investigations of the details of both the actual spin configuration and the Fermi surface topology, as well as searches of other fascinating phenomena related to the frustrated magnetism.

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[20] T. Shishidou and T. Oguchi, (Personal communication). Here, the value of \( k_F \) is estimated from the band structure calculation.
[21] The carrier density \( n \) is estimated from the ordinary Hall coefficient \( R_0 \) with the single band approximation, \( R_0 = 1/\rho e \). It is however difficult to evaluate \( R_0 \) of PdCrO\(_2\) because the Hall resistivity in PdCrO\(_2\) contains the anomalous Hall resistivity in addition to the ordinary Hall resistivity. Thus, \( R_0 \) of PdCrO\(_2\) is approximated by \( R_0 \) of the isostructural nonmagnetic compound PdCoO\(_2\) [16]. This approximation is based on the expectation that one Pd 4d electron per formula unit dominantly contributes to the electric conductivity for both PdCrO\(_2\) and PdCoO\(_2\). Indeed, the electronic specific heat coefficient, related to the density of states of conduction carriers, is nearly the same between these two oxides.