Superconducting gap of the single crystal $\beta$-PdBi$_2$

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Abstract. We investigate superconducting and normal properties of the single crystal of $\beta$-PdBi$_2$. The electrical resistivity $\rho(T)$ shows superconductivity at $T_c = 5.0$ K. Residual resistivity ratio (RRR) is estimated to be 2.9 obtained from $\rho(300$ K)/$\rho(5.0$ K). The $H_{c2}$ curve obtained from $\rho(T)$ in magnetic fields shows clear enhancement from the Werthamer-Helfand-Hohenberg theory in dirty limit. Specific heat $C(T)$ measurement shows that clear jump is observed at $T_c = 4.8$ K. $T$-dependence of the electronic specific heat $C_e(T)$ suggests full-gap symmetry with a single gap and strong coupling with $\Delta C_e/\gamma T_c = 1.8$.

1. Introduction

Several superconductors developed by utilizing topological insulators are reported, such as Cu-intercalated Bi$_2$Se$_3$[1, 2], In-doped SnTe$_{1.3}$[3] and M$_2$Te$_3$ (M = Bi, Sb) under pressure[4, 5]. The recent discovery of the topologically protected surface states in $\beta$-PdBi$_2$ has reignited the research interest in this class of superconductors[6]. $\beta$-PdBi$_2$ is reported to be a superconductor with superconducting transition temperature ($T_c$) = 5.2 K. Interestingly, specific heat measurement shows clear hump below $T_c$, suggesting that $\beta$-PdBi$_2$ is a multiple-band/multiple-gap superconductor[7]. On the other hand, $\mu$SR measurement suggests that superconductivity is full-gap symmetry with a single gap[8]. Thus, superconducting gap symmetry of $\beta$-PdBi$_2$ remains to be clarified at this stage.

In this article, we discuss the superconducting gap symmetry of the single-crystalline $\beta$-PdBi$_2$. To reveal superconducting gap symmetry of $\beta$-PdBi$_2$, we performed specific heat measurement down to 0.28 K with a quasi-adiabatic method.

2. Experimental Details

Single crystals of $\beta$-PdBi$_2$ were grown by a melt growth method[7]. The stoichiometric mixture of Pd (powder, 99.9%) and Bi (grain, 99.999%) was sealed in an evacuated quartz tube (total mass: 2 g). The ampule was heated at 800 °C maintained for 24 h, and then cooling down to 450 °C at a down rate of 4 °C/h before being quenched in ice water. The obtained single crystals had good cleavage, producing flat surfaces as large as $1 \times 1$ cm$^2$.

The crystal structure of the synthesized single-crystalline sample was examined by the powder X-ray diffraction (XRD) technique using a conventional X-ray spectrometer equipped with Cu-Kα radiation and a monochromator (RAD-2X, Rigaku). The intensity data were collected over a 2θ range of 10°–80° with a step width of 0.01° and a counting rate of 4°/minutes.

Electrical resistivity $\rho(T)$ was measured by a dc-four-probe method with a current source (Model 6221, Keithley) and a nano voltmeter (Model 2182A, Keithley), down to 0.3 K in zero
and various applied magnetic fields. Specific heat $C(T)$ was measured by an adiabatic heat-pulse and relaxation method down to 0.3 K using a commercial $^3$He refrigerator (Heliox-VL, Oxford Instruments).

3. Experimental Results

3.1. X-ray diffraction pattern

Figure 1 shows X-ray diffraction patterns of the single-crystalline $\beta$-PdBi$_2$ along $c$-axis at room temperature. These peaks can be indexed with a tetragonal unit cell with the space group of $I4/mmm$. The lattice constants estimated from all indexes are $a = 0.3620$ nm, $c = 1.2984$ nm for $\beta$-PdBi$_2$. These values are almost consistent with those of the previous report[7].

![X-ray diffraction patterns](image)

**Figure 1.** X-ray diffraction patterns of the single crystal $\beta$-PdBi$_2$ along $c$-axis at room temperature.

3.2. Electrical resistivity

Figure 2 shows the $T$-dependence of the electrical resistivity $\rho(T)$ of $\beta$-PdBi$_2$. The $\rho(T)$ shows typical metallic behavior with a residual resistivity $\rho_0$ of 22 $\mu\Omega$cm. The residual resistivity ratio (RRR) is estimated to be 2.9 obtained from $\rho(300 \text{ K})/\rho(5.0 \text{ K})$, as shown in the inset of Fig. 2. This value is smaller than that of the previous report[7]. The $\rho(T)$ of $\beta$-PdBi$_2$ shows superconductivity at $T_c = 5.1$ K. Zero resistivity was observed at around 5.0 K in $\rho(T)$ with the superconducting transition width $\Delta T$ of about 0.02 K. The sharp transition suggests good quality of sample.

3.3. Specific heat

Figure 3 shows the $T$-dependence of the specific heat $C(T)$ divided by temperature $T$ of $\beta$-PdBi$_2$ in 0 and 1 T. The normal state specific heat can be fitted by the equation $C/T = \gamma + \beta T^2 + \gamma T^4$, where $\gamma$ is the electronic specific heat coefficient (Sommerfeld constant), and $C_{\text{ph}} = \beta T^2 + \gamma T^4$ is the phonon contribution. The parameters were obtained as $\gamma = 7.56$ mJ/(mol-K$^2$), $\beta = 2.121$ mJ/(mol-K$^4$) for $\beta$-PdBi$_2$. In a simple Debye model of the phonon contribution, the $\beta$ coefficient is related to the Debye temperature $\Theta_D$ according to the equation $\Theta_D = (\frac{12\pi^4}{5}nR)^{1/3}$, where $R = 8.314$ J/(mol-K) and $n = 3$ for $\beta$-PdBi$_2$. From this relationship, we calculated $\Theta_D =$
Figure 2. $T$-dependence of the electrical resistivity $\rho(T)$ of $\beta$-PdBi$_2$. The inset shows $\rho(T)$ of $\beta$-PdBi$_2$ in several magnetic fields.

149 K, for $\beta$-PdBi$_2$. From specific heat measurement, clear jump was observed at $T_c = 4.8$ K. $T$-dependence of the electronic specific heat $C(T)$ suggests that full-gap symmetry with a single gap and strong coupling with $\Delta C_e/k_B T_c = 1.8$.

Figure 3. $T$-dependence of the specific heat $C(T)$ divided by $T$ of $\beta$-PdBi$_2$ in magnetic fields of 0 and 1 T. Solid line shows the fitted result of $C(T)/T = \gamma + \beta T^2 + \gamma T^3$. 
3.4. upper critical field

From $\rho(T)$ in several magnetic fields, the upper critical field $\mu_0 H_{c2}(T)$ is determined. $T_c$ of $\rho(T)$ is defined as the temperature at which the resistivity drops to 50% of $\rho_0$. The $H-T$ phase diagram is presented in Fig. 4. The $H_{c2}$ curve shows cleat enhancement from the Werthamer-Helfand-Hohenberg (WHH) theory in dirty limit ($h^* = 0.69$)$[^9, 10]$. Such a behavior is seen in a multi gap superconductor. However, our specific heat measurements show a single gap superconductor. The enhancement seems to be generated from strong electron-phonon coupling, and it is often observed in strong electron-phonon coupling superconductors$[^11]$.

To estimate $H_{c2}$, we fitted $\mu_0 H_{c2}(T)$ using polynomial function presented by solid line. From the analysis, $\mu_0 H_{c2}(0)$ is determined to be 1.07 ($ab$-plane) and 0.72 T ($c$-axis) for $\beta$-PdBi$_2$. From the relationship $\mu_0 H_{c2}(0) = \Phi_0 / 2\pi \xi(0)^2$, $\xi(0)$ was calculated to be 24.5 ($ab$-plane) and 30.7 nm ($c$-axis).

![Figure 4. $T$-dependence of the upper critical field $\mu_0 H_{c2}(T)$ of $\beta$-PdBi$_2$. The dotted lines are the WHH prediction with dirty limit. The solid lines show the polynomial function.](image)

4. Summary

We studied superconducting properties of the single crystal of $\beta$-PdBi$_2$ at $T_c = 4.9$ K. Electrical resistivity $\rho(T)$ shows metallic behavior with a residual resistivity $\rho_0$ of 22 $\mu\Omega\text{cm}$ and the residual resistivity ratio (RRR) is estimated to be 2.9. The upper critical field $\mu_0 H_{c2}(0)$ of $\beta$-PdBi$_2$ is estimated to be 1.07 ($ab$-plane) and 0.72 T ($c$-axis), which are good agreement with the previous report. Specific heat measurements show a single gap superconductor with strong electron-phonon coupling.

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