Transport Properties of the Iron-Oxypnictide Superconductor PrFeAsO$_{1-y}$ in High Magnetic Fields

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Abstract. We report the resistively determined upper critical field $\mu_0 H_{c2}$ of the iron-oxypnictide superconductor PrFeAsO$_{1-y}$ ($y \sim 0.15$), which exhibits superconductivity at $T_c = 44$ K. The resistivity $\rho(H,T)$ was measured with a typical four-probe method in static magnetic fields of up to 14 T and in pulsed high magnetic fields of up to 52 T. With increasing magnetic fields, the superconducting transition width of the $\rho(T)$ curve for $H \parallel c$ becomes broader than that for $H \parallel ab$. This behavior is likely to be due to dissipation associated with thermally activated vortex motion. The $\mu_0 H_{c2}(T)$ curves for both $H \parallel ab$ and $H \parallel c$ exhibit a pronounced upward curvature below $T_c$, and are very different from the conventional one-band Werthamer-Helfand-Hohenberg behavior. This result suggests that the iron-oxypnictide superconductor is a multiband system. We demonstrate the results of the two-band analysis for $\mu_0 H_{c2}(T)$ and discuss the anisotropy of $\mu_0 H_{c2}$ on some kinds of iron-based superconductors.

1. Introduction

The discovery of high-temperature superconductivity in the iron-pnictide LaFeAsO$_{1-x}$F$_x$ [1] (abbreviated as the 1111-system) and related compounds has generated great interest in understanding the interplay of magnetism, superconductivity, and electrical structure. So far, several other groups of iron-based superconductors have been discovered, such as $AeFe_2As_2$ (abbreviated as the 122-system, $Ae$ = alkali earth metals), LiFeAs (abbreviated as the 111-system), FeCh (abbreviated as the 11-system, $Ch$ = chalcogen), and the perovskite-type Fe-based superconductors. These iron-based compounds display a phase transition from antiferromagnetic to superconducting ground states tuned by chemical doping or external pressure, suggesting that the antiferromagnetic spin fluctuations of Fe play an important role in developing the superconducting ground states [2].

For a thorough understanding of the mechanism of superconductivity in iron-based superconductors, it is important to study the upper critical field ($\mu_0 H_{c2}$) because the $\mu_0 H_{c2}$ provides information on anisotropy, coherent length, effective electron mass, and the pair-breaking mechanism. In general, high $T_c$ superconductors show extremely high $\mu_0 H_{c2}$ values.
The temperature dependence of $\mu_0 H_{c2}(T)$ in low magnetic fields is often a very poor guide to its intrinsic features at low temperatures. Therefore, transport measurements in very high magnetic fields and at low temperatures close to $T$ have provided useful information not only on $\mu_0 H_{c2}(0)$ but also on the nature of the phase in the vicinity of a quantum phase transition point.

In this report, we present electrical resistivity measurements and its anisotropy on a single crystal of PrFeAsO$_{1-y}$ in high magnetic fields of up to 52 T, and demonstrate the results of the two-band analysis for $\mu_0 H_{c2}(T)$.

2. Experimental

Single crystals of PrFeAsO$_{1-y}$ ($y \sim 0.15$) were synthesized with a high-pressure method as described in Ref. [3]. We prepared a sample with typical dimensions of $900 \times 100 \times 20$ $\mu$m$^3$ for electrical resistivity measurements. The sample was mounted on a sapphire substrate ($4 \times 0.5 \times 20$ mm$^3$), which was a good thermal anchor. The electrical current direction was parallel to the $ab$-plane of the sample, and the magnetic field was applied along the $ab$-plane or the $c$-axis. The temperature dependence of $\rho(H)$ was measured by a dc four-probe technique in static magnetic fields of up to 14 T with a commercial superconducting magnet system (Oxford Instruments Ltd.). The $\rho(H)$ measurements in high magnetic fields of up to 52 T were performed with a non-destructive pulsed magnet at the High Magnetic Field Laboratory, KYOKUGEN, Osaka University. The duration of the pulsed high magnetic field was about 35 msec. The data traces were recorded on a digitizer using a custom digital lock-in amplifier operating at 100 kHz.

3. Results and Discussion

The zero-field resistivity of the present sample exhibits a superconducting transition at $T_{c}^{\text{mid}}(0) \sim 44$ K (50% of the normal state resistivity), which is equal to the reported value of an optimally electron-doped PrFeAsO$_{1-y}$ [3]. With increasing magnetic fields, the superconducting transition width of the $\rho(T)$ curve for $H \parallel c$ becomes broader than that for $H \parallel ab$. This behavior is likely to be due to dissipation associated with thermally activated vortex motion. The slopes $(d\mu_0 H_{c2}/dT)$ for $H \parallel ab$ and $H \parallel c$ near $T_c$ were $-8.4$ and $-1.3$ T/K, respectively, which were estimated by fitting the $T_{c}^{\text{mid}}(H)$ data in the static magnetic fields up to 8 T to a linear function. On the basis of the conventional one-band Werthamer-Helfand-Hohenberg (WHH) theory [4], i.e., the dirty-limit Bardeen-Cooper-Schrieffer (BCS) relation of $\mu_0 H_{c2}(0) = -0.69T_c(d\mu_0 H_{c2}/dT)|_{T=T_c}$, we can obtain the orbital pair-breaking fields $(\mu_0 H_{c2}^{\text{orb}}(0))$, 255 T for $H \parallel ab$ and 39.5 T for $H \parallel c$.

Figures 1(a) and 1(b) show the magnetic field dependence of the in-plane electrical resistivities at designated temperatures for $H \parallel ab$ and $H \parallel c$, respectively. Upon heating from the lowest temperature, the transitions from superconducting to normal state shift to lower magnetic fields. The transition induced by applied magnetic fields is considerably broad. For $H \parallel c$, some $\rho(H)$ curves in the normal state exhibit a negative magnetoresistance behavior in high magnetic fields region. Although the origin of this behavior is not clear at this moment, it may be related to the thermally activated vortex motion.

Using the magnetic field dependence of the resistivity in pulsed high magnetic fields, we illustrate the field-temperature phase diagram of the present sample in Fig. 2. The mid-point values of $\mu_0 H_{c2}(T)$ in the superconducting transitions were plotted. The temperature is normalized against $T_c$. The broken curve represents the conventional one-band WHH prediction with only the orbital pair-breaking effect. The WHH curve is almost linear in temperature near $T_c$ and exhibits a saturation behavior at low temperatures. On the other hand, our experimental data, especially for $H \parallel c$, exhibit significant upward curvatures, and are very different from the WHH behavior. We consider that the upward curvature of $\mu_0 H_{c2}$ originates from two-band features recently shown by various experiments in 1111-system compounds [5, 6]. By the two-band theory in the dirty-limit, the equation for $H_{c2}(T)$ can be written in the following parametric
form [7]:

\[ a_0[\ln t + U(h)] + a_1[\ln t + \eta U(h)] + a_2[\ln t + U(\eta h)] = 0. \]  

(1)

The \( a_0, a_1, \) and \( a_2 \) are determined from the BCS coupling constant tensor \( \lambda_{m'm'} = \chi^{EP}_{m'm'} - \mu_{m'm'} \), where \( \chi^{EP}_{m'm'} \) are electron-phonon constants, and \( \mu_{m'm'} \) is the Coulomb pseudopotential. Here, the diagonal terms \( \lambda_{11} \) and \( \lambda_{22} \) quantify the intraband superconducting coupling, and the off-diagonal terms \( \lambda_{12} \) and \( \lambda_{21} \) describe the interband coupling. The other parameters are defined by \( U(x) = \psi(1/2 + x) - \psi(x) \), \( t = T/T_c \), \( h = H_{ab}D_1/(2\phi_0 T) \), and \( \eta = D_2/D_1 \), where \( \psi(x) \) is the di-gamma function, \( \phi_0 \) is the magnetic flux quantum, and \( D_m \) are the electronic diffusivity for the \( m \)-th Fermi Surface sheet. Shown in Fig. 2 is an example of the fit of Eq. (1) to the data for \( \lambda_{11} = \lambda_{22} = 0.5 \) and \( \lambda_{12} = \lambda_{21} = 0.25 \). Here, we use the coupling parameters of NdFeAsO\(_{0.7}F\(_{0.3}\) in Ref. [6]. Although there are arbitrarines in the parameters of Eq. (1), we find that the diffusivity ratio \( \eta \) for \( H \parallel c \) is a small value (\( \sim 0.1 \)). This result suggests that the superconductivity in the present sample is explained by the two-band model. On the basis of the band calculations for iron-based superconductors [8], we assume that the superconductivity in these compounds results from two bands: a nearly two-dimensional electron-band with high diffusivity \( D_1 \) and a weak anisotropic heavy hole-band with smaller diffusivity \( D_2 \). For \( \eta < 1 \) (\( D_2 < D_1 \)), the upward curvature is pronounced, while for \( \eta = 1 \) (\( D_2 = D_1 \)), Eq. (1) reduces to the equation \( \ln t + U(h) = 0 \) for \( H_{c2} \) in one-band dirty-limit superconductors (the WHH prediction). For \( H \parallel ab \), we obtain a rather good fit for \( \eta \sim 1 \), suggested in Ref. [6]. However, the \( (-d\mu_0H_{c2}/dT)_{T-T_c} \) for \( H \parallel ab \) is larger than that for \( H \parallel c \) as described above. So, it is difficult to determine the \( \mu_0H_{c2}^{ab} \) at lower temperature in our high-field measurements up to 52 T.

Finally, we discuss the anisotropy of \( \mu_0H_{c2} \) for the present sample (the 1111-system). Near \( T_c \), the anisotropy coefficient \( \gamma \) defined by \( H_{ab}^{c2}/H_{c2}^{c2} \) is \( \sim 5 \), which is in agreement with reported values [3]. Previously, we have reported that the anisotropy of \( \mu_0H_{c2} \) for the 11-system \( Fe_{1+\delta}(Te,Se) \) decreases from \( \sim 2.4 \) near \( T_c \) to \( \sim 1 \) at \( T = 0 \), monotonically, and the small anisotropy at low temperatures is robust against the variation of the Te/Se ratio [9]. Similar isotropic behavior of \( \mu_0H_{c2} \) at low temperatures has also been observed in the 122-system of iron-based superconductors [10]. For both the 11- and the 122-system, the upward curvature in the \( \mu_0H_{c2}^{ab} \) below \( T_c \) is smaller than that for the 1111-system. It is expected that the in-plane superconducting coherence length \( \xi_{ab} = (\phi_0/2\pi\mu_0H_{c2}^{c2}) \) of the 1111-system is larger than that of

Figure 1. In-plane electrical resistivity of PrFeAsO\(_{1-y}\) measured in pulsed high magnetic fields at designated temperatures for (a) \( H \parallel ab \) and (b) \( H \parallel c \).
other iron-based superconductors, because the FeAs sheets are separated by the LnO blocking layers. We think that the upward curvature in the $\mu_0 H_{c2}$ for the 1111-system is related to the two-dimensional feature of the superconductivity.

4. Conclusions
In conclusion, we have investigated the resistive upper critical field $\mu_0 H_{c2}$ of the iron-oxypnictide superconductor PrFeAsO$_{1-y}$ ($y \sim 0.15$), which exhibits superconductivity at $T_c = 44$ K. The anisotropy of $\mu_0 H_{c2}$ for the present sample is $\gamma \sim 5$, which is larger than those for other iron-based superconductors. The $\mu_0 H_{c2}(T)$ curves for both $H \parallel ab$ and $H \parallel c$ exhibit a pronounced upward curvature below $T_c$, and are very different from the conventional one-band WHH prediction. This result suggests that the iron-oxypnictide superconductor PrFeAsO$_{1-y}$ is a multiband system, being consistent with many theoretical and experimental results.

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