Angular dependence of resistivity in the superconducting state of NdFeAsO$_{0.82}$F$_{0.18}$ single crystals

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Abstract
We report the results of angle dependent resistivity of NdFeAsO$_{0.82}$F$_{0.18}$ single crystals in the superconducting state. By doing the scaling of resistivity within the frame of the anisotropic Ginzburg–Landau theory, it is found that the angle dependent resistivity measured under different magnetic fields at a certain temperature can be collapsed onto one curve. As a scaling parameter, the anisotropy $\Gamma_1$ can be determined for different temperatures. It is found that $\Gamma_1(T)$ increases slowly with decreasing temperature, varying from $\Gamma_1 \approx 5.48$ at $T = 50$ K to $\Gamma_1 \approx 6.24$ at $T = 44$ K. This temperature dependence can be understood within the picture of multi-band superconductivity.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Since the discovery of superconductivity at 26 K in LaFeAsO$_1-x$F$_x$ [1], great interests have been stimulated in the community of superconductivity. The superconducting transition temperature was quickly raised to about $T_c = 55$ K in SmFeAsO$_{0.9}$F$_{0.1}$ [2], and in other fluorine-doped or oxygen-deficient samples. Moreover, hole-doped superconductors were also successfully synthesized in the La$_{1-x}$Sr$_x$FeAsO [3] and Ba$_{1-x}$K$_x$(FeAs)$_2$ systems [4]. Many experiments have revealed that the iron-based superconductors belong to a family with an unconventional pairing mechanism. These include point contact tunneling spectroscopy [5, 6], NMR [7], specific heat [8], lower critical field [9], etc. Meanwhile, so far many theoretical models have been proposed in order to have a basic understanding of the mechanism of superconductivity. As one of the basic parameters, the anisotropy $\Gamma$ is crucial for both understanding the superconducting mechanism and the application, because it reflects directly the coupling strength between the ‘charge reservoir’ LnO (Ln = La, Ce, Pr, Nd, Gd, etc) layers and the conducting FeAs layers.

An estimation of $\Gamma \geq 30$ was made on (Nd, Sm)FeAs$_{0.82}$F$_{0.18}$ polycrystals from the c-axis infrared plasma frequency [10]. Due to the successful growth of (Nd, Sm)FeAs$_{0.82}$F$_{0.18}$ single crystals [11, 12], precise determination of $\Gamma$ becomes possible. A recent study on SmFeAsO$_{0.8}$F$_{0.2}$ ($T_c \approx 45$ K) single crystals revealed that the magnetic anisotropy was temperature dependent, ranging from $\Gamma \sim 8$ at $T = 50$ K to $\Gamma \sim 23$ at $T \approx 0.4T_c$ [13]. Moreover, in our previous work on NdFeAsO$_{0.82}$F$_{0.18}$ single crystals [14, 15], $\Gamma$ was calculated from the upper critical fields parallel and perpendicular to the ab-plane, and was found to be below 5 near $T_c$. As a further study on the superconductivity of NdFeAsO$_{1-x}$F$_x$ single crystals, here we report the angular dependence of resistivity in the superconducting state of NdFeAsO$_{0.82}$F$_{0.18}$ single crystals. By doing the scaling of the resistivity based on the anisotropic Ginzburg–Landau (GL) theory, the angle dependent resistivity measured under different magnetic fields at a certain temperature collapse onto one curve. Thus the anisotropy was determined for different temperatures.

2. Experiment
The single crystals of NdFeAsO$_{0.82}$F$_{0.18}$ were grown by the flux method at ambient pressures, as described in [14, 12].
Figure 1. The resistive superconducting transition at zero magnetic field with $T_c(\text{onset}) \simeq 51.5$ K and $\Delta T \simeq 2$ K. The upper inset shows a scanning electron microscope image of a NdFeAsO$_{0.82}$F$_{0.18}$ single crystal with Pt leads. The lower inset illustrates schematically the definition of angle $\theta$.

Figure 2. Main panels: the resistivity as a function of $\tilde{H}$ (see text) for (a) $T = 44$ K and (b) $T = 46$ K. Insets: the angular dependence of magnetoresistivity at (a) $\mu_0 H = 0.5, 2, 5, 6, 7, 8, 9$ T and (b) $\mu_0 H = 0.5, 2, 5, 7, 9$ T. The anisotropy parameters are found to be $\Gamma = 6.24 \pm 0.09$ for $T = 44$ K and $\Gamma = 5.92 \pm 0.09$ for $T = 46$ K.

The typical lateral sizes of the crystals are about 20–70 $\mu$m, while the thickness is about 1–5 $\mu$m. Electrical contacts were made using the Pt deposition technology of a focused-ion-beam (FIB) system. The upper inset of figure 1 presents an image of a single crystal with Pt leads.

The angle-resolved resistivity measurements were carried out on a Physical Property Measurement System (PPMS, Quantum Design) with magnetic fields up to 9 T. The angle $\theta$ was varied from $-10^\circ$ to $190^\circ$, where $\theta = 0^\circ$ corresponded to the configuration of $H \parallel c$-axis and $\theta = 90^\circ$ to $H \parallel ab$-plane, respectively (as shown in the lower inset of figure 1). The veracity of the angle was ensured by the good $c$-axis orientation of the crystals, which was demonstrated by x-ray diffraction (XRD) analysis [12]. In our measurement, the current density was 150 A cm$^{-2}$ and the current was always perpendicular to the magnetic field. The sample exhibited a sharp resistive superconducting transition at $T_c(\text{onset}) \simeq 51.5$ K with $\Delta T \simeq 2$ K (1–90% $\rho$, $\rho(0)$ K = 0.13 m$\Omega$ cm and $\text{RRR} = \rho(400)$ K$/\rho(0)$ K = 6.5 (shown in figure 1), demonstrating good quality of the single crystal.

3. Results and discussion

The insets in figures 2 and 3 present four sets of data for the angle dependence of resistivity at temperatures of 44, 46, 48 and 50 K. Taking the $\rho(\theta)$ data at $T = 44$ K (the inset of figure 2(a)) as an example, all the curves show a dip-like structure with the minimum at $\theta = 90^\circ$ and maximum at $\theta = 0^\circ$ and $180^\circ$. The angular dependence of resistivity is not very steep; this suggests the moderate anisotropy of the NdFeAsO$_{0.82}$F$_{0.18}$ single crystal.

In a layered superconductor, when the superconducting order parameter is quasi-continuous across the neighboring layers, the variation of the order parameter is smooth enough to be described by $\partial \psi/\partial z$; we thus have the Ginzburg–Landau equation in the anisotropic case. Assuming that the upper
critical fields in the two extreme cases are $H_{c2}^{ab}$ (for $H \parallel ab$) and $H_{c2}^c$ (for $H \parallel c$) respectively, the anisotropy $\Gamma$ can be defined as

$$\Gamma = H_{c2}^{ab}(\theta = 90^\circ)/H_{c2}^c(\theta = 0^\circ) = (m_c/m_{ab})^{1/2} = \xi_{ab}/\xi_c,$$

where $m_c$ and $m_{ab}$ are the effective masses when the electrons move along the $c$-axis and the $ab$-plane respectively, and $\xi_c$ and $\xi_{ab}$ are the coherence lengths along the $c$-axis and the $ab$-plane, respectively. In this anisotropic GL approximation, the interpolating upper critical field can be obtained as

$$H_{c2}^{ab}(\theta) = H_{c2}^c/\sqrt{\sin^2(\theta) + \Gamma^2 \cos^2(\theta)}.$$

Since the resistivity is a general function of $H/H_{c2}^{GL}$, Blatter et al. developed a general scaling approach for the angular dependence of resistivity [16] as $\rho = \rho(0) f(H/H_{c2}^{GL})$. Therefore the resistivity measured under different magnetic fields at a certain temperature should collapse on one curve if the $x$-coordinate is properly scaled. The rescaled function for the $x$-coordinate is

$$\tilde{H} = H/\sqrt{\sin^2(\theta) + \Gamma^2 \cos^2(\theta)}.$$

By adjusting $\Gamma$, excellent scaling curves are obtained for each set of data at different temperatures, as shown in the main panels of figures 2 and 3. In this analysis, only one variable $\Gamma$ is employed as the fitting parameter, so the value of $\Gamma$ is more reliable compared with that determined from the ratio of $H_{c2}^{ab}$ and $H_{c2}^c$, which might be affected by the criterion of $H_{c2}$ determination. The anisotropy parameter $\Gamma$ is 6.24±0.08 for $T = 44$ K, 5.92±0.08 for $T = 46$ K, 5.66±0.09 for $T = 48$ K and 5.48±0.09 for $T = 50$ K. Such values are consistent with what we estimated from $H_{c2}^{ab}/H_{c2}^c$ [14], but smaller than the values obtained on SmFeAsO$_6$F$_2$ single crystals using a torque technique [13]. This discrepancy may be understood as due to the different doping levels of the two samples. For example, the superconducting transition temperature is about 45 K for the SmFeAsO$_6$F$_2$ single crystals used in the torque measurements [13], which is about 10 K from the optimized temperature 55 K in this system [2]. Our sample has a $T_c$ of about 51 K, which is quite close to the highest transition temperature 53 K in the Nd-based system. And an higher anisotropy is anticipated for a more underdoped sample. It is further found that, as plotted in figure 4, the anisotropy increases slowly with decreasing temperature. The similar behavior of $\Gamma(T)$ was also observed in SmFeAsO$_6$F$_2$ single crystals [13], which was attributed to the two-gap scenario [17, 18]. For a single-band superconductor, the anisotropy is normally temperature independent. Interestingly, the resistive data measured in our experiment can be well described by the anisotropic GL theory; this is actually not the case in MgB$_2$. In MgB$_2$, a typical multi-band superconductor, clear deviations have been observed between the experimental $H_{c2}(\theta)$ and the anisotropy GL description [19, 20]. Such a phenomenon was attributed to the different anisotropy factors of the two bands [21]. However, no such deviation is found in our experiment on the iron-based NdFeAsO$_{6.83}$F$_{0.18}$, so we suggest that the multiple bands in the present system may have very similar anisotropic parameters.

In the following we present a further discussion to justify this conclusion. In MgB$_2$, there are two hole-type quasi-two-dimensional $\sigma$ bands ($\sigma_1$ and $\sigma_2$), and an electron-type ($\pi_1$) and a hole-type ($\pi_2$) three-dimensional $\pi$ band. These two different bands have very different anisotropy: $\Gamma_\sigma = (m_\sigma^2/m_\pi^2)^{1/2}$ is much larger than $\Gamma_{\pi_2} = (m_\pi^2/m_\pi^2)^{1/2}$. In this case the upper critical field $H_{c2}(\theta)$ cannot be described by the anisotropic GL theory. In the iron-based superconductors, according to the band structure calculation by Lebegue [22] and by Singh and Du [23], the Fermi surface consists of five sheets: two electron cylinders centered around the M–A line with high velocity, two hole cylinders around the $\Gamma$–Z line with lower velocity, and an additional heavy and small 3D hole pocket which is centered at $Z$. Since the 3d sub-bands have quite high degeneracy, the anisotropies from different bands are quite close to each other. The electron conduction is dominated by the two cylinder-like hole pockets and the two cylinder-like electron pockets. This is probably the reason why the anisotropic GL theory can still be applied in the iron-based system. However, we must mention that, regarding the magnitude of the anisotropy, there is a clear discrepancy between the values derived from the experiment and the theoretical predictions. The anisotropy $\Gamma = (m_c/m_{ab})^{1/2}$ was predicted to be about 15 for the parent phase, but from the experiment, we found a value of about 4–6 for the superconducting samples. Our data strongly suggest that the theoretical calculation needs to be reconsidered, especially for the superconducting samples which are doped away from the parent phase.

4. Summary

In conclusion, we have investigated the angle dependent resistivity in the superconducting state of NdFeAsO$_{6.83}$F$_{0.18}$ single crystals. It is found that the $\rho(\theta, H)$ data measured at a certain temperature can be described by a scaling law based on the anisotropic Ginzburg–Landau theory. Thus the values of anisotropy are extracted for different temperatures. It is found
that $\Gamma(T)$ increases with decreasing temperature, which was attributed to the multi-band effect.

Acknowledgments

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