Magnetic transport properties of superconducting Nd$_{1-x}$Sr$_x$NiO$_2$ thin films

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Temperature and angle dependence of resistivity under different magnetic fields have been measured in Nd$_{1-x}$Sr$_x$NiO$_2$ thin films synthesized by the molecular-beam-epitaxy technique followed by the topotactic soft-chemistry reduction procedure. The onset superconducting transition occurs at about 16.2 K and zero resistivity appears below 9.3 K at 0 T. Temperature dependent upper critical fields $H^c_2(T)$ and $H^c_4(T)$ have been determined by using criterions of 98% $\rho_0(T)$ and 95% $\rho_0(T)$ with $\rho_0(T)$ the normal state resistivity. A temperature dependent anisotropy ratio is thus obtained by $\Gamma(T) = (H^c_2(T)/H^c_4(T))$, which yields a value in the range of 1.2 to 3 near $T_c$. In addition, the temperature dependent upper critical fields show a clear negative curvature near the onset transition temperature, which usually appears in a paramagnetically limited superconductor. The angle dependence of resistivity at a fixed temperature and different magnetic fields cannot be scaled to a curve expected by the anisotropic Ginzburg-Landau theory. However at low temperatures, the resistance difference can be scaled by the parameter $H^c_2(0)\cos \theta$ ($\beta = 6 ~ \sim 1$) with $\theta$ the angle enclosed between the $c$ axis and the applied magnetic field. We interpret these results as the consequence of a dominated contribution from the paramagnetic limit or the inhomogeneity of films. Our results clearly indicate small anisotropy and unconventional superconductivity in Nd$_{1-x}$Sr$_x$NiO$_2$.

INTRODUCTION

Superconductivity was successfully detected in Nd$_{1-x}$Sr$_x$NiO$_2$ [1] and Pr$_{1-x}$Sr$_x$NiO$_2$ [2] thin films recently, and the observation of superconductivity in the nickelate superconductor family is very important because it shares probably the similar electronic structure as that of high-$T_c$ cuprate superconductors. Until now, superconductivity has only been observed in thin films grown on SrTiO$_3$ substrates [1–5], but has not been observed in Nd$_{1-x}$Sr$_x$NiO$_2$ bulk samples [6, 7]. The superconducting transition exhibits in a narrow doping range of Sr, namely 0.125 $< x <$ 0.25 in Nd$_{1-x}$Sr$_x$NiO$_2$ films. Meanwhile, the underdoped and overdoped samples seem to show a weak insulating property [4, 8]. The multiband nature of the material is proved experimentally by the temperature dependent Hall coefficient [1, 3] and electron energy loss spectroscopy results [8]. Such observation is supported by several theoretical calculations of electronic structures [9–16] from which there are three sets of Fermi surfaces mainly contributed by Nd 5d and Ni 3d electrons. In this point of view, it is very interesting to investigate the superconducting anisotropy and its critical behavior in the infinite-layer nickelate superconductors with the multiband effect.

As a newly found superconductor, the possible origin of the superconductivity is discussed in several related works [3, 13, 16–20], and the possible gap symmetry is discussed based on theoretical calculations [11, 14, 21, 22]. A recent scanning tunneling microscopy (STM) work shows that there are two superconducting gaps in the system [23], i.e., a $d$-wave gap with a gap maximum of about 3.9 meV and a slightly anisotropic $s$-wave gap with a gap maximum of about 2.35 meV. The presence of a $d$-wave gap further strengthens the belief of similarity between nickelate superconductors and cuprates. In a superconductor, the superconducting gap ($\Delta$) and the pairing strength may be linked to the upper critical field $\mu_0H_{c2}$ via the Pippard relation $\xi = h v_F / \pi \Delta$ and $\mu_0H_{c2} = \Phi_0 / 2\pi\xi^2$ [24]. Here, $\xi$ is the coherence length, $v_F$ is the Fermi velocity, and $\Phi_0$ is the flux quantum. Therefore, it is worthy measuring the upper critical field to obtain the information of the pairing strength for this new superconducting system.

Here we report our experimental results of the temperature and angle dependent resistivity measured at different magnetic fields in superconducting Nd$_{1-x}$Sr$_x$NiO$_2$ thin films. We observe a negative curvature near $T_c$ on $\mu_0H_{c2}(T)$ curves measured when $H \parallel ab$ plane or $H \parallel c$ axis. The angle-dependent resistivity cannot be scaled by the anisotropic Ginzburg-Landau (GL) theory. These results suggest exotic properties of superconductivity in Nd$_{1-x}$Sr$_x$NiO$_2$ thin films.

EXPERIMENTAL METHODS

The Nd$_{1-x}$Sr$_x$NiO$_3$ thin films were grown on SrTiO$_3$ substrates by using the reactive molecular beam epitaxy technique with a nominal composition of $x = 0.2$. The thickness of the film is about 6 nm. We then use the soft-chemistry topotactic reduction method [1, 6] to remove the apical oxygen and obtain the superconducting...
Nd\textsubscript{1-x}Sr\textsubscript{x}NiO\textsubscript{2} phase. In the beginning of the topotactic hydrogen procedure, a precursor Nd\textsubscript{1-x}Sr\textsubscript{x}NiO\textsubscript{3} thin film was placed in a quartz tube together with a pellet of CaH\textsubscript{2} weighted about 0.5 g. The tube was evacuated and sealed, then it was annealed at 340°C for 100 min. There is no direct contact between the samples and CaH\textsubscript{2} during the treatment process. The structure of the resultant Nd\textsubscript{1-x}Sr\textsubscript{x}NiO\textsubscript{2} film is characterized by the appearance of the (001) peaks in x-ray diffraction data measured by a Bruker D8 Advanced diffractometer. The resistivity was measured by using a standard four-electrode method in a physical property measurement system (PPMS, Quantum Design) with magnetic fields up to 9 T.

**RESULTS**

**Upper critical field**

Figure 1 shows the temperature dependent resistivity measured at different magnetic fields when the field is parallel or perpendicular to the c axis of the film. One can see that the normal-state \(\rho-T\) curve shows an almost linear behavior with a positive slope when \(T>20\) K. The normal state resistivity \(\rho(T=20\text{ K})=0.38\) mΩ cm, and the corresponding residual resistance ratio \(\rho(T=300\text{ K})/\rho(T=20\text{ K})=2.8\) determined from the wide-temperature-range \(\rho-T\) curve (not shown here). The normal-state resistivity in Fig. 1 shows a very small magnetoresistance in the presence of a magnetic field. The magnetoresistance value is only +0.16\% at \(T=20\text{ K}\) and \(\mu_0H=5\) T which is similar to the value reported previously [4]. A negative Hall coefficient \(R_H=-(2.7\pm0.3)\times10^{-3}\text{ cm}^3/C\) is obtained from the transverse resistance measurement by using a standard six-electrode method at \(T=20\text{ K}\) and with the maximum field of 5 T. The negative Hall coefficient is different from positive values reported previously [4, 5]. The difference may be due to slightly different oxygen contents in different films, and the sign of the Hall coefficient can be easily changed in this material with almost balanced charge densities of holes and electrons. The onset superconducting transition temperature \(T_{\text{c}}\text{onset}\) at 0 T is about 16.2 K determined by the criterion of 95\%\(\rho_n(T)\), and \(\rho_n(T)\) is the linear extrapolation of the normal state resistivity in the Nd\textsubscript{0.8}Sr\textsubscript{0.2}NiO\textsubscript{2} thin film. The zero-resistance transition temperature \(T_{\text{c}}\) is about 9.3 K determined with the criterion of 1\%\(\rho_n(T)\). The slightly large transition width may be originated from the inhomogeneity in the film.

In Fig. 1 one can see that the transition temperature decreases and the transition width widens when the magnetic field is applied in two perpendicular directions. In order to have a quantitative analysis on the field dependent critical temperatures, we try to obtain the values of irreversibility fields \(\mu_0H_{\text{irr}}\) and \(\mu_0H_{\text{c}2}\) from the \(\rho-T\) curves by using different criterions. Figure 2(a) shows temperature dependent characteristic fields. Obviously, slopes of \(\mu_0H_{\text{c}2}-T\) curves are huge near \(T_{\text{c}}\). We try to calculate the slope by using the \(\mu_0H_{\text{c}2}(T)\) data obtained at fields of 0 and 1 T, and obtained values are given in Table 1. The upper critical field in the zero-temperature limit \(\mu_0H_{\text{c}2}(0)\) can be derived based on the conventional Werthamer, Helfand, and Hohenberg (WHH) theory [25] via

\[
H_{\text{c}2}^{\text{orb}}(0) = -0.697T_c\frac{dH_{\text{c}2}}{dT}.
\]

Values of \(\mu_0H_{\text{c}2}(0)\) derived from Eq. 1 are given in Table 1 and they are extremely large. Here one should note that the slope of \(\mu_0H_{\text{c}2}-T\) curve should be a constant near \(T_{\text{c}}\) (at least when \(T>95\%T_{\text{c}}\)) in the framework of WHH theory. However, the slope \(\mu_0dH_{\text{c}2}/dT\) increases with the increase of the temperature, even when the temperature is very near \(T_{\text{c}}\), showing a clear negative curvature of \(H_{\text{c}2}(T)\). It is known that in a two-dimensional (2D) superconducting system, \(\mu_0H_{\text{c}2} \propto (1-T/T_{\text{c}})^{1/2}\) may appear when the magnetic field is parallel to the film plane [26], which certainly leads to a negative curvature. However, the WHH theory should still work when the field is perpendicular to the film [26]. This means that we

![Figure 1](image-url)

**FIG. 1.** Temperature dependence of in-plane (the current \(I \parallel ab\) plane) resistivity measured in the Nd\textsubscript{0.8}Sr\textsubscript{0.2}NiO\textsubscript{2} thin film at different magnetic fields (\(H \perp I\)) with (a) \(H \parallel c\) axis and (b) \(H \parallel ab\) plane, respectively.
TABLE I. $\mu_0 H_{c2}(0)$ and $\Gamma$ of the Nd$_{0.8}$Sr$_{0.2}$NiO$_3$ thin film calculated based on different theoretical models.

| Criterion | $T_{c}^{\text{onset}}$ | Field direction | WHH model | BCS theory with $H_P$ and $H_{\text{orb}}$ |
|-----------|---------------------|----------------|-----------|------------------------------------------|
| $98\% \rho_n(T)$ | 17.14 K | $H \parallel c$ axis | $\mu_0 H_{c2}^{ab}(0)$ | $\mu_0 H_{c2}^{ab}(0)$ | $\Gamma_{\text{WHH}}(0)$ | $\alpha_{\text{M}}$ | $\mu_0 H_{\text{orb}}(0)$ | $\Gamma_{\text{orb}}(0)$ | $\mu_0 H_{P}(0)$ | $\Gamma_{P}(0)$ |
| 19.9 T/K | 235 T | 2.63 | $20 \pm 3$ | $240 \pm 32$ T | $4.79 \pm 0.98$ | $17.0 \pm 3.4$ T | $20.3 \pm 4.1$ T | $1.19 \pm 0.34$ |
| 52.4 T | 619 T | | |
| $H \parallel ab$ plane | 13.4 T/K | 149 T | 2.97 | $11 \pm 2$ | $128 \pm 20$ T | $6.42 \pm 1.40$ | $16.4 \pm 3.9$ T | $1.18 \pm 0.37$ |
| 39.7 T/K | 443 T | | |
| $95\% \rho_n(T)$ | 16.17 K | $H \parallel c$ axis | $\mu_0 H_{c2}^{ab}(0)$ | $\mu_0 H_{c2}^{ab}(0)$ | $\Gamma_{\text{WHH}}(0)$ | $\alpha_{\text{M}}$ | $\mu_0 H_{\text{orb}}(0)$ | $\Gamma_{\text{orb}}(0)$ | $\mu_0 H_{P}(0)$ | $\Gamma_{P}(0)$ |
| 12.8 T/K | 225 T | 3.97 | $4.44 \pm 0.73$ | $10 \pm 2$ | $128 \pm 20$ T | $6.42 \pm 1.40$ | $16.4 \pm 3.9$ T | $1.18 \pm 0.37$ |
| 39.7 T/K | 443 T | | |

TABLE II. Values are determined by using criterions of $0\% \rho_n(T)$ and $1\% \rho_n(T)$, which excludes the possibility of the 2D superconductivity. It should be noted that the transition near irreversibility field is wide as seen from Fig. 1, which suggests an inhomogeneity in the film. Although the onset transition should be dominated by the high-$T_c$ phases, the possible reason of the negative curvature in the $\mu_0 H_{c2}$ curve can also due to the inhomogeneous phases with different $T_c$ in the film. When we try to treat the experimental data from previous reports and treatment not shown here). In these previous works, thicknesses of the films are 11 nm and 35 nm, respectively, which means that the negative curvature seems to be a common feature in the material even when the magnetic field is along $c$ axis of the sample.

The anomalous negative curvature on the $\mu_0 H_{c2}$ curve near $T_c$ may suggest a dominant paramagnetic pair breaking effect in the present thin films, which have been actually observed in other superconductors. This occurs when the paramagnetic limit $H_P$ is smaller than the orbital limit $H_{\text{orb}}$ in some systems. The characteristic parameter is the Maki parameter $\alpha_{\text{M}} = \frac{\sqrt{2} H_{\text{orb}}}{H_P}$ which describes the contribution ratio between the pairing-breaking Zeeman energy and the orbital paring-breaking energy. The upper critical field in the zero-temperature limit $H_{c2}(0) = H_{\text{orb}}$ when $\alpha_{\text{M}} \rightarrow \infty$, while $H_{c2}(0) = H_P$ when $\alpha_{\text{M}} \rightarrow 0$. We try to fit our experimental $\mu_0 H_{c2}$ curves by using a weak-coupling Bardeen-Cooper-Schrieffer (BCS) model including both orbital and Pauli limitations for clean isotropic s-wave superconductors expressed as

$$\ln t = \int_0^\infty \frac{d\mu}{s_{\text{orb}}} \int_0^1 dx \left[ \cos \left( \frac{0.28 \alpha_{\text{M}} H_{\text{orb}}(0) x}{H_{\text{orb}}(0)} \right) \right] \cdot \exp \left[ -0.25 y^{2(1-x^2)} \frac{H_{\text{orb}}(0)}{H_{\text{orb}}(0)} - 1 \right],$$

where $t = \frac{T}{T_c}$.

![FIG. 2. (a) Temperature dependent $\mu_0 H_{c2}$ and $\mu_0 H_{c2}$ obtained from $\rho$-$T$ curves measured at different fields. $\mu_0 H_{c2}$ values are determined by using criterions of $0\% \rho_n(T)$ and $1\% \rho_n(T)$, while $\mu_0 H_{c2}$ values are determined by using criterions of $95\% \rho_n(T)$ and $98\% \rho_n(T)$. The solid lines are the fitting results to $\mu_0 H_{c2}$ data by using the BCS theory with $H_P$ and $H_{\text{orb}}$. (b) Temperature dependence of the anisotropy ratio $\Gamma = \frac{H_{c2}^{ab}}{H_{c2}^{ab}}$ (symbols) calculated based on the $\mu_0 H_{c2}$ data in (a), and solid lines present $\Gamma$ values derived from the fitting curves in (a).]

should not observe the negative curvature of $H_{c2}(T)$ near $T_{c0}$ when the field is along the $c$-axis. Here from our experimental data, however, the negative curvature appears on the $\mu_0 H_{c2}$ curves when magnetic fields along both directions, which excludes the possibility of the 2D superconductivity. It should be noted that the transition near irreversibility field is wide as seen from Fig. 1, which suggests an inhomogeneity in the film. Although the onset transition should be dominated by the high-$T_c$ phases, the possible reason of the negative curvature in the $\mu_0 H_{c2}$ curve can also due to the inhomogeneous phases with different $T_c$ in the film. When we try to treat the experimental data from previous reports and treatment not shown here). In these previous works, thicknesses of the films are 11 nm and 35 nm, respectively, which means that the negative curvature seems to be a common feature in the material even when the magnetic field is along $c$ axis of the sample.
angular dependent resistivity measured at different magnetic fields and temperatures in the Nd_{0.8}Sr_{0.2}NiO_{2} thin film. θ = 0° or 180° corresponds to the direction of $H \parallel c$ axis, while θ = 90° corresponds to that of $H \parallel ab$ plane. Magnetic fields are (a) from 2 to 9 T with an increment of 1 T, (b-d) 0.2, 0.5 T and from 1 to 9 T with an increment of 1 T.

Angular dependent resistivity

The anisotropic upper critical field can usually be observed in angle resolved resistivity data. In Fig. 3 we show the angle dependence of resistivity measured at different temperatures and magnetic fields. Being different from the data measured in other systems, the resistivity dip near θ = 90° ($H \parallel ab$ plane) is very sharp. Based on the anisotropic GL theory [24], angle dependence of the orbital limiting upper critical field can be expressed as

$$H_{c2}(θ) = \frac{H_{c2}^{∥c}}{\sqrt{\cos^2 θ + Γ^{-2} \sin^2 θ}}, \quad (3)$$

where the anisotropic ratio $Γ = H_{c2}^{∥ab}/H_{c2}^{∥c}$ with $H_{c2}^{∥ab}$ and $H_{c2}^{∥c}$ representing the upper critical fields along $ab$ plane and $c$ axis, respectively. Then the angle resolved resistivity can be scaled with the effective field $\tilde{H} = H\sqrt{\cos^2 θ + Γ^{-2} \sin^2 θ}$ by adjusting the anisotropic ratio $Γ$ [48]. The theory successfully works in the iron-based [49, 50] and Bi$_2$Sr$_2$O$_{3+δ}$-based [51] superconductors of very different anisotropy ratios. We also try this scaling theory to our angle resolved resistivity data, but scalings are not successful with any values of $Γ$. One set of examples of failed fittings is shown in Fig. 4 with $Γ = 2$, and it is impossible to make all the curves scale together. In this point of view, our results obviously deviate from the standard anisotropic GL scaling theory. The failed scaling behavior has been found in repeated experiments measured in the other two films. One reason for the failed scaling may be inhomogeneous superconducting phases in the film. However, it should be noted that Eq. 8 is used to describe the anisotropic behavior of the orbital limiting upper critical field $μ_{0}H_{c2}^{∥b}(θ)$, therefore, it is not strange that the scaling does not work if the upper critical field is dominated by the paramagnetic limit $μ_{0}H_{F}$ here. It is difficult to obtain a simple function of $H_{c2}(θ)$ in the paramagnetically limited system [27], so we try to
scale the measured data in other ways. Here we use a new scaling parameter \((\mu_0 H)^\beta |\cos \theta|\) to scale the resistance difference \(\Delta \rho(H, \theta) = \rho(H, \theta) - \rho(H, \theta = \pi/2)\), and the scaling results are presented in Fig. 5. The new scaling law seems to work well for the data taken at 6 and 8 K, although \(\beta\) decreases with increase of temperature. While the scaling becomes worse at 10 K and fails again for data measured at higher temperatures. The applicability of the new scaling law confirms the failure of the scaling by the anisotropic GL theory, in the latter a zero resistance should appear and ramps gradually due to the dissipation of vortex motion near the angle \(\theta = \pi/2\). It seems that the c-axis component of the external magnetic field is more influential to enhance resistivity than that expected by the anisotropic GL theory. This discrepancy requires further studies with better quality samples, such as single crystals. Or it is intrinsic, as stated above, the upper critical field is determined by the paramagnetic pair-breaking effect.

DISCUSSIONS

In the superconducting Nd_{0.8}Sr_{0.2}NiO_{2} films, we observe a negative curvature in \(\mu_0 H_{c2}-T\) curves near \(T_c\) when the magnetic field is along the \(ab\) plane as well as the \(c\) axis, and the angular dependent resistivity measured at different fields can not be scaled according to the anisotropic GL theory. Since the negative curvature appears in \(\mu_0 H_{c2}-T\) curves when the magnetic field is along the \(c\) axis from our data and previous reported data \([\text{1, 5}]\) measured in films with different thicknesses from 6 to 35 nm, the possibility from the 2D superconductivity is excluded. Then there are two possible origins to interpret these experimental results. One possibility is the inhomogeneity of the film, and another is the dominant contribution from the Zeeman pair breaking effect which governs the upper critical field. The latter possibility can be checked by the estimated value of the paramagnetic limit from the binding energy of Cooper pairs, i.e., \(\mu_0 H_{p}^{\text{pair}} = \sqrt{2}\Delta/g\mu_B\). Here \(\mu_B\) is the Bohr magneton, and \(g\) is the electron \(g\) factor with the routinely assumed value of \(g = 2\) for free electrons. Based on our recent STM work \([\text{23}]\), two superconducting gaps may open in different Fermi surfaces, and the gap functions read \(\Delta_d = 3.9 \cos \phi \text{ meV}\) (a d-wave gap) and \(\Delta_s = 2.35(0.15 \cos 4\phi + 0.85) \text{ meV}\) (a slightly anisotropic s-wave gap). Averaged gap values determined by \(\Sigma = \frac{1}{2\pi} \int_0^{2\pi} \Delta^2(\phi) d\phi\) are \(\Sigma_d = 2.76 \text{ meV}\) and \(\Sigma_s = 2.01 \text{ meV}\). The corresponding \(\mu_0 H_{p}^{\text{pair}} = 21 \text{ T}\) and \(\mu_0 H_{p}^{\text{pair}} = 15 \text{ T}\), respectively. These estimated values of paramagnetic limits are very close to the fitting results given in Table 1. Accordingly, the fitting results especially \(\mu_0 H_p\) based on the single gap model seem to be reliable according to the consistency mentioned above.

![Scaling results of the resistivity difference](image)

**FIG. 5.** Scaling results of the resistivity difference \(\Delta \rho(H, \theta) = \rho(H, \theta) - \rho(H, \theta = \pi/2)\) versus \((\mu_0 H)^\beta |\cos \theta|\) at different temperatures.

Of course, the obtained \(\alpha_M\) values are incredibly large as obtained from the fittings. The reason of the large \(\alpha_M\) in heavy-fermion superconductors is due to the big effective mass. Based on the single-band model in the clean limit of BCS theory, the Maki parameter \(\alpha_M \propto m \Delta/E_F\) when \(H \parallel c\) axis \([\text{14, 49}]\). A very large value of \(\alpha_M\) corresponds to a very big effective mass \(m\) and/or a very small Fermi energy \(E_F\), however, both parameters are lacking for superconducting nickelate films at this moment. The situation in a multiband superconductor become more complex, and the related parameters are affected by the structure of the Fermi surface, the superconducting pairing symmetry, the crystalline anisotropy, etc \([\text{43}]\). Since there are many more fitting parameters in the multiband model than in the one-band model, a good fitting with...
these parameters requires more $\mu_0 H_c(0)$ data measured at much higher fields and low temperatures. In addition, upper critical field may be significantly enhanced at much higher fields and low temperatures. In addition, upper critical field may be significantly enhanced with the magnitude of more than $2.5 \mu_0 H_P(0)$ in a quasi two-dimensional superconductor with a mixed order parameter of an s wave and a d wave [33], and this is exactly the case of the superconducting nickelate films. Therefore it is highly desired to measure the upper critical field directly at low temperatures in future works.

Another observation from our experiments is that the anisotropy ratio is not big for both $\mu_0 H_P$ and $\mu_0 H_{orb}$ in these films. The obtained $\Gamma$ is in the range of 1.2 to 3.0 as derived from the experimental data in Fig. 2(b). This value is comparable to the ones in iron based superconductors [52] but much smaller than the ones in cuprates, like Bi-2212 system [24] and BiS$_2$-based [51] superconductors. It should be noted that the Nd$_{1-x}$Sr$_x$NiO$_2$ material is the infinite-layer phase, therefore, it is understandable for a small anisotropy value. Many theoretical calculations [13, 16–20] illustrate that the Ni-3d ($x^2 - y^2$) orbital constructs Fermi surfaces with a strong dispersion along $k_z$-axis, while the Nd-5d ($xy$, $3z^2 - r^2$) orbitals construct two 3D Fermi pockets, all these indicate a low anisotropy. Based on the picture of a paramagnetically dominated superconductivity, $\Gamma_P(0)$ is only about 1.2 from the fitting, which suggest a small anisotropy of Pauli susceptibilities or $g$ factors along the two perpendicular axes [27]. However, $\Gamma_{orb}(0)$ is about 4.5 to 6.5 from fittings. The increase of the anisotropy in Fig. 2(b) with temperature can be explained as the result of the continually increased contribution of the orbital limit term when it is approaching to $T_c$.

CONCLUSIONS
In conclusion, we have conducted the magnetic transport measurements in superconducting thin films of Nd$_{1-x}$Sr$_x$NiO$_2$ with the onset superconducting transition temperature of about 16.2 K. The anisotropy of the measured upper critical field is small, locating in the range of 1.2 to 3 near the transition temperature. We observe a negative curvature of the $\mu_0 H_c(0)$ curve near $T_c$, which is explained as the possible consequence of the paramagnetic limited superconductivity. The angle dependence of resistivity at a fixed temperature and different magnetic fields can not be scaled by using the anisotropic Ginzburg-Landau theory. It is observed that the $c$-axis component of magnetic field plays a more influential role. This may be induced by the paramagnetically limited superconductivity, or the inhomogeneity in the films. Our observations provide fruitful information for this newly discovered infinite-layer nickelate superconducting system.

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