Evidence for two distinct scales of current flow in polycrystalline Sm and Nd iron oxypnictides

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Abstract
Early studies have found quasi-reversible magnetization curves in polycrystalline bulk rare-earth iron oxypnictides that suggest either widely spread obstacles to intergranular current or very weak vortex pinning. In the present study of polycrystalline samarium and neodymium iron oxypnictide samples made by high pressure synthesis, the hysteretic magnetization is significantly enhanced. Magneto-optical imaging and study of the field dependence of the remanent magnetization as a function of particle size both show that global currents over the whole sample do exist but that the intergranular and intragranular current densities have distinctly different temperature dependences and differ in magnitude by about 1000. If the highest current density loops lie only within grains, their magnitude is $\sim 5 \times 10^6 \text{ A cm}^{-2}$ at 5 K and self-field. Whole sample current densities, though two orders of magnitude lower at 1000–10 000 A cm$^{-2}$, are some two orders of magnitude higher than in random polycrystalline cuprates. We cannot yet be certain whether this large difference in global and intragrain current density is intrinsic to the oxypnictides or due to extrinsic barriers to current flow, because the samples contain a significant second phase, some of which wets the grain boundaries and may cause a superconducting–normal–superconducting proximity effect in the whole sample critical current.

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

1. Introduction
The recent discovery of superconductivity in the LaFeAsO$_{1-x}$F$_x$ compound [1] has stimulated a rapid exploration of superconductivity in the rare-earth iron oxypnictides [2–14]. It has now been established that the iron oxypnictides can be superconducting when doped to $x \sim 0.05$–0.2 and that they can have transition temperature $T_c$ above 40 K when La is replaced by Ce [5] and above 50 K by Pr, Nd, Sm and Gd [7–11]. In a recent paper [12] we addressed the issue of electromagnetic granularity in polycrystalline La iron oxypnictides, finding an asymmetric $M(H)$ loop that indicated an irreversible moment due to hysteretic bulk currents that was almost as small as the reversible magnetization of the superconducting state. In that case we were not able to distinguish definitively between a state where the intragrain pinning was very weak, leading to very low intragrain current densities or to the state where currents were largely confined to the intragrain regions and might have been rather high. Based on the rather high upper critical field $B_{c2}(0)$ values of
63–65 T observed by Hunte et al [6] on the same sample and the nanoscale coherence length $\xi (\xi_{ab}(0) = 5 \text{ nm}, \xi_c(0) = 1.2 \text{ nm})$, we would expect strong vortex pinning even from naturally occurring atomic-scale defects. By analogy to randomly oriented polycrystalline cuprates, which also show small hysteretic current loops and large intragrain current densities of $10^5$–$10^6 \text{ A cm}^{-2}$ at 4 K [15, 16], we proposed [12] that electromagnetic granularity was likely to be characteristic of polycrystalline oxypnictides too. By granularity we mean that two distinct scales of current flow would exist. The intragrain current would be dominated by vortex pinning, while the global current would be limited by connections across grain boundaries, some of which might be superconducting (S), some normal (N) or some even insulating (I). In the case of SNS or SIS connections, we would expect clear evidence that the global current density would be lower than the current circulating on scales where the whole path was superconducting. Evidence for electromagnetically granular behavior was indeed also presented in two subsequent studies of a Sm oxypnictide (Senatore et al [13]) and a Nd oxypnictide (Prozorov et al [14]), the latter of which also presented magneto-optical images of confined current flow within intragranular regions. In the present study, we extend our initial examination of the length scales of current flow in La oxypnictide by combining magneto-optical imaging, remanent magnetic field analysis and powdering of the sample to conclusively demonstrate the presence of two distinctly different length scales of current flow in our dense Nd and Sm oxypnictides and to show that the temperature dependence of the inter and intragranular current densities are quite different and that their ratio is strongly dependent on temperature.

2. Experimental details

The polycrystalline SmFeAsO$_{0.85}$ and NdFeAsO$_{0.94}$F$_{0.06}$ bulk samples were synthesized by solid state reaction under a high pressure [8, 10]. SmAs (or NdAs) pre-sintered powder and Fe, Fe$_2$O$_3$, and FeF$_2$ powders were mixed together according to the nominal stoichiometric ratio then ground thoroughly and pressed into small pellets. The pellets were sealed in boron nitride crucibles and sintered in a high pressure synthesis apparatus under a pressure of 6 GPa at 1250°C for 2 h.

Microstructural observations were performed using a field emission scanning electron microscope (Carl Zeiss 1540 ESB and XB) and a laser scanning confocal microscope (Olympus OLS3100). Resistivity measurements were performed by the conventional four-point-probe method using a Quantum Design PPMS. Magnetization of the samples was measured by a SQUID magnetometer (Quantum Design: MPMS-XL5s) and a 14 T vibrating sample magnetometer (Oxford) with field parallel to the broad face. Magneto-optical imaging with a 5 μm thick Bi-doped iron-garnet indicator film placed directly onto the sample surface was used to image the normal field component $B_z$, produced by magnetization currents induced by solenoidal fields of up to 0.12 T applied perpendicular to the imaged surface [17, 18].

![Figure 1](image1.png)  
**Figure 1.** Temperature dependence of resistivity for the SmFeAsO$_{0.85}$ and NdFeAsO$_{0.94}$F$_{0.06}$ bulk samples. Inset shows resistivity near $T_c$.

![Figure 2](image2.png)  
**Figure 2.** Temperature dependence of magnetization under zero-field-cooling (ZFC) and field-cooling (FC) conditions in an external field of 1 mT for bulk SmFeAsO$_{0.85}$ and NdFeAsO$_{0.94}$F$_{0.06}$.  

3. Results

The temperature dependences of resistivity for the SmFeAs O$_{0.85}$ and NdFeAsO$_{0.94}$F$_{0.06}$ bulk samples are shown in figure 1. Resistivity began to drop at 57 and 51 K and vanished below 51 and 44 K for the Sm and Nd samples, respectively. The calculated resistivities at 300 K for the Sm and Nd samples were 2.3 and 2.0 mΩ cm and the $RRR = \rho(300 \text{ K})/\rho(60 \text{ K})$ were 3.7 and 3.4, respectively. By contrast the $RRR$ value of 17 was observed for the earlier studied LaFeAsO$_{0.89}$F$_{0.11}$ bulk sample [4, 12], which might suggest that the Sm and Nd samples are less strongly doped and that the actual doping state may not be well represented by the nominal composition.
Figure 2 shows the temperature dependences of magnetization in zero-field-cooled (ZFC) and field-cooled (FC) states under an external field of 1 mT. Onset magnetic $T_c$ values were found to be 54 K for the Sm sample and 49 K for the Nd sample. Compared to the LaFeAsO$_{0.89}$F$_{0.11}$ sample [12] and other reported samples [13, 14], superconducting transitions are rather sharp ($\Delta T_c \sim 10$ K), indicative of bulk scale shielding currents flowing in both samples, even close to $T_c$. Within the uncertainty limits produced by the demagnetization fields of these imperfectly shaped samples, we conclude that the shielded volumes were 100%.

Figure 3(a) shows magnetic hysteresis loops at 4.2, 20, 30 and 40 K obtained by VSM for the SmFeAsO$_{0.85}$ bulk sample. So far very small hysteresis loops were reported for polycrystalline iron oxypnictides [12, 13]. However, this Sm sample shows quite large hysteresis loops, which implies either strong flux pinning and/or good intergranular coupling. Slightly smaller hysteresis loop widths were observed in the Nd sample. Similar to the previously studied LaFeAsO$_{0.89}$F$_{0.11}$ sample [12], a paramagnetic background was observed in all curves taken below $T_c$, which can be well fit by a Langevin expression [19].

Figure 3(b) shows the magnetic field dependence of the critical current density $J_c$ derived from the hysteresis loop width using the extended Bean model $J_c = 20 \Delta m / V a (1 - a/3b)$ for the Sm bulk sample taking the full sample dimensions of $2 \times 1 \times 0.6$ mm$^3$. This expression yields a $J_c$ of $10000$–$30000$ A cm$^{-2}$ at 4.2 K, which is nearly independent of field over the range of 4–14 T. $J_c$ for the Nd bulk sample is lower, as is shown in figure 3(b). Broad maximum in $J_c$ was observed at 20, 30 and 40 K, a result also noted in [13]. Since the contribution of currents circulating on smaller length scales to the hysteresis loop is large, as discussed later, the critical current density shown in figure 3(b) is likely to be overestimated, since our later, size-dependent studies allow us to deduce that the contribution of global currents to the hysteretic magnetization is less than that produced by the locally circulating currents. However, these $J_c$ values are distinctly lower than those produced by other reported samples [13, 14], superconducting transitions are rather sharp ($\Delta T_c \sim 10$ K), indicative of bulk scale shielding currents flowing in both samples, even close to $T_c$. Within the uncertainty limits produced by the demagnetization fields of these imperfectly shaped samples, we conclude that the shielded volumes were 100%.

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Figure 3(b) shows the magnetic field dependence of $J_c$ at 4.2, 20, 30 and 40 K for SmFeAsO$_{0.85}$ bulk. $J_c$ data for NdFeAsO$_{0.6}F_{0.06}$ bulk at 4.2 K (dashed line) is also shown for comparison.
measurement of the remanent moment, \( m_R \) [12, 20–22]. For a pure and homogeneous sample, we expect flux to penetrate when \( H_a/(1 - D) \) first exceeds the lower critical field \( B_{c1} \), where \( D \) is the relevant demagnetizing factor. For weakly coupled polycrystals, where the weakness could occur either at grain boundaries or at non-superconducting second phases, flux penetration is expected to occur locally at lower fields than into the grains. Therefore information about the size of current loops derived from \( m_R \) (which is proportional to the product of \( J_c \) and current loop size) can be extracted from the dependence of \( m_R \) on the applied field \( H_a \) and the particle size. Accordingly, after measurement of each whole sample, we crushed them into tens of pieces and remeasured \( m_R \), finally gently grinding the crushed pieces to powder in a mortar before remeasuring \( m_R \). 

Figure 4 shows the remanent magnetization as a function of increasing applied field for the SmFeAsO\(_{0.85}\) intact large bulk, a second, smaller bulk, the crushed pieces and ground powder. The \( m_R \) data are normalized by their respective sample masses of 30.0, 6.0, 14.2 and 4.3 mg. For the bulk samples, remanent magnetization began to increase on increasing the applied field above \( \sim 5 \) mT, consistent with the reported \( B_{c1} \) of 5 mT for LaFeAs(O,F) [23], and a shoulder appeared at \( \sim 80 \) mT in the \( m_R \) transition. This behavior is clearer in the derivative of \( m_R(H_a) \) shown in figure 5(b) where two quite separate low-field peaks appear at 35 mT for the larger and at 18 mT for the smaller of the two bulk samples. By contrast, the second, higher field peak appeared at the same field of 150 mT for both samples. That the first peak strongly depends on sample size indicates that the bulk current loop is also size dependent, because the field of first penetration should be proportional to \( H_a \sim J_c^{\text{global}} \times \) (sample size). This conclusion is strengthened by further suppression of the first peak in the crushed pieces and its disappearance almost to zero in the ground powder. In contrast, the second peak was found to be size independent, even after fine powdering, which means that the second peak is caused by locally circulating currents with current loop size less than the powder size of 20–50 \( \mu \)m.

Magneto-optical imaging (MOI) was performed to directly observe the local magnetic flux structure of the intact samples. Figure 6 shows MO images on a well polished surface of the SmFeAsO\(_{0.85}\) bulk with a thickness of 440 \( \mu \)m. The light microscope image in figure 6(a) does not reveal any macroscale defects such as cracks or connected second phase fields that would block whole sample current flow. Under the zero-field-cooling (ZFC) condition we observe a bulk Meissner state when a field of 4 mT is applied at 6 K, as shown in figure 6(b), which indicates that the surface shielding current flows over the whole sample (magnetic domains in the MO imaging film are quite obvious too). As the external field increases, flux starts to penetrate at \( \sim 6 \) mT and first reaches the center of the sample at \( \sim 15 \) mT. However the MO images clearly show that flux penetration is quite inhomogeneous. As follows from figures 6(c) and (d), there are many 20–50 \( \mu \)m size black-appearing spots of strong flux shielding in the flux penetrated regions, indicative of local circulating currents with higher current density than the matrix. Similar electromagnetically granular behavior was also observed in the Nd bulk sample, as will be presented in figure 8. After the removal of the external field, the remanent trapped fields are shown in figures 6(e) and (f). These trapped fields were more homogeneous after applying a lower external field of 40 mT and, in contrast, many higher \( J_c \) spots (now white) appeared after applying 120 mT. These results are also consistent with the remanent magnetization data of figure 5(a), where the second peak appeared at 150 mT. Figures 6(g) and (h) show MO images under \( \mu_0 H_{as} = 0 \) mT at \( T = 6.4 \) and 20 K, respectively, for the sample field-cooled in \( \mu_0 H_{as} = 120 \) mT. It is particularly
respectively. (b) Derivatives of 
 normalized by the sample masses of 30.0, 6.0, 14.2 and 4.3 mg, intact small bulk, crushed pieces and ground powder. The data are taken along the same line (line 1) as indicated by arrows in figure 6(g) and (h), respectively. A bulk scale critical state with 
μ
sample field-cooled under 
T
was visible up to 48 K, indicating persistent bulk currents up to almost 90% of 
T
. The profiles are prominent in flux density profiles. Figure 7 shows magnetic flux profiles 
B(x) taken at (a) 6.4 K and (b) 20 K for the Sm sample field-cooled under μ0
H
ex = 120 mT. The profiles are taken along the same line (line 1) as indicated by arrows in figure 6(g) and (h), respectively. A bulk scale critical state with 
75 intact large bulk, intact small bulk, crushed pieces and ground powder. The data are normalized by the sample masses of 30.0, 6.0, 14.2 and 4.3 mg, respectively. (b) Derivatives of 
μ
R at 5 K.

Figure 5. (a) Remanent magnetization (mR) as a function of the maximum applied field at 5 K for the SmFeAsO0.85 bulk, intact small bulk, crushed pieces and ground powder. The data are normalized by the sample masses of 30.0, 6.0, 14.2 and 4.3 mg, respectively. (b) Derivatives of 
μ
R at 5 K.

Figure 8 shows MO images taken on the polished surface of the 
NdFeAsO0.85F0.05 bulk. Topographic light microscopy images (figure 8(a)) shows dark-appearing impurity phases 100–300 μm in size and light-appearing particles, which were identified to be Fe–As glassy phase and 
Nd2O3 particles by EDS analyses. Figures 8(b)–(d) show the MO images of the sample after zero-field cooling to 6 K. Figure 8(b) shows that flux penetrates preferentially through the larger impurity phases and reaches the center of the sample under an external field of 40 mT. Granular behavior was also observed after applying a higher magnetic field of 120 mT, as shown in figure 8(e). The 10–20 μm size of the strongly connected white spots was smaller than those of the Sm sample, consistent with our observation that the ~5 μm grain size of the Nd sample is about half that of the Sm sample. Magnetic flux profiles 
B(x) taken along line 2 in figure 8(a) are shown in figure 9, where it is also seen that a bulk critical state is quite visible at 20 K, but that more inhomogeneous behavior is observed at 6.2 K.

Figure 10 shows the derivative of 
mR(Hx) for the SmFeAsO0.85 bulk at 5, 10, 15, 20, 30 and 40 K, while the inset figure shows the temperature dependence of the first and second peaks in the derivative of the 
mR(Hx) plots. The second high-field peak shows a strong temperature dependence and a marked shift towards higher fields below ~15 K, indicative either of a strongly increasing local critical current density or/and a growing current loop size. On the other hand, the low-field global current peak showed a much weaker temperature dependence. These quite different temperature dependences result in a merging of the two peaks at temperatures above 15 K, as is consistent with the MO images seen in figure 6.

Figure 11 shows the derivative of 
mR(Hx) for the NdFeAsO0.85F0.05 bulk sample at 5, 10, 20, 30 and 35 K. Similar to the Sm sample, the second peak shifts rapidly as the temperature decreases. A third peak (~110 mT) appeared at 5 K. Since the ratio of the fields of the second and third peaks is ~4, and this value is comparable to the square root of the resistivity anisotropy ratio ~15 [24], the peak split might be due to an anisotropic 
Jc. The inset to figure 11 shows the temperature dependence of the first, second and third peaks. As for the Nd sample, the temperature dependence of the second and third peaks was strong below ~10 K. A minor peak was observed at ~300 mT and was almost temperature independent. This peak at 200–300 mT was also observed in the Sm and LaFeAsO0.85F0.11 samples. It might have its origin in a minority paramagnetic phase and is not further discussed in this paper.

Global and local 
Jc values for the Sm and Nd bulk samples were calculated independently from the peak positions in the derivative of 
mR(Hx). For the 
Jc calculation we assumed a thin plate in parallel field for the bulk current and spherical grains for the local current. By neglecting the demagnetization factor and anisotropy of 
Jc, both of which are unknown at this stage of oxypnictide studies, the Bean model shows that the global and local 
Jc can be given as 
Jc(global) = 2
Hpeak1/ω
indicate line 1 for magnetic flux profiles shown in figure 7. ((g), (h)) MO images under $\mu$SmFeAsO$_{0.85}$J.The $J_c$ values are also shown in figure 12, as is $J_c$ calculated from MO flux profiles and these values are also shown in figure 12, as is $J_c$ calculated from the width of the flux penetration front in the ZFC image using formulas in [17, 18, 25]. The agreement on $J_c$ between these various methods of extracting the global $J_c$ is excellent.

The temperature dependence of the global $J_c$ is almost linear, except near $T_c$, and $J_c$ values at 5 K of 3900 and 2100 A cm$^{-2}$ for the Sm and Nd samples, respectively, are obtained.

The temperature dependence of the local $J_c$, for currents circulating only within individual grains, is shown in figure 13. The $J_c$ values are $4.5 \times 10^6$ and $6.7 \times 10^6$ A cm$^{-2}$ at 5 K for the Sm and Nd samples, respectively. These values are considerably higher than those recently deduced by Prozorov et al. ($3 \times 10^7$ A cm$^{-2}$ [13]), by Sentatore et al. ($6 \times 10^4$ A cm$^{-2}$ for 10 $\mu$m grain size and $6 \times 10^6$ A cm$^{-2}$ for 0.1 $\mu$m [14]) and by Wang et al. ($2 \times 10^5$ A cm$^{-2}$ [26]). Both Sm and Nd samples showed strong upward curvature in $J_c(T)$ below $\sim 20$ K.

Finally we plot the ratio of the global and local, that is the deduced intragrain $J_c$ values in figure 14. The ratio $J_c^{\text{global}}(T)/J_c^{\text{local}}(T)$ increases as temperature decreases, reaches a maximum at $\sim 25$ K and drops rapidly at low temperatures. The ratio never exceeds 0.004 and falls to $\sim 0.001$ at $\sim 5$ K when the electromagnetically granular behavior revealed by the MO imaging and remanent field analysis becomes so marked.

4. Discussion

The sample-size-dependent remanent magnetization showed that two (or even three in the case of the Nd sample) distinct scales of current flow exist in these iron oxypnictide samples. The spatial variation of the scales is directly demonstrated by MO imaging where obvious spots of higher $J_c$ appear in a lower $J_c$ matrix in field-cooled images. Here we discuss the origins of this electromagnetically granular behavior, especially the issue of whether the granularity is intrinsic or extrinsic to these samples.

We start discussion with the scales of the global and local currents. The strong sample size dependence of the first peak of the remanent magnetization shown in figure 5(b) strongly suggests that a global current does circulate over the whole sample. This is in strong contrast to the previously reported data on a LaFeAsO$_{0.89}$F$_{0.11}$ sample where almost no bulk current was observed and only one, size-independent (equivalent to the second peak in the present data) peak appeared in the remanent magnetization [12]. Like the La sample data, the size independence of this second peak in figure 5(b) shows that the local current loop size is less than the powder size of $\sim 50$ $\mu$m shown in figure 4(d). Independent evidence of the scale of the locally high $J_c$ domains is provided by the white spots with size of 10–50 $\mu$m in the MO images shown in figure 6(g). We therefore conclude that a significant fraction of the local current loops are on the scale of the grain size, which lies principally in the 5–10 $\mu$m range.

An important scientific and technological issue is whether the substantial restriction of strong current density within the grains of this untextured, or very weakly textured...
sample (unpublished EBSD shows few signs of low-angle grain boundaries in the samples [27]) is intrinsic to the oxypnictides or due to extrinsic features of these particular samples. So far as the possibility of intrinsic granularity is concerned, one important factor is likely to be the low carrier density of $\sim 10^{21}$ cm$^{-3}$ [4] which is very similar to that found in the cuprates, where it contributes significantly to an intrinsic weak-link behavior at high-angle cuprate grain boundaries [28, 29]. However, many additional specific features of the cuprates, including their sensitivity to local oxygen concentration, proximity of the superconducting state to the Mott metal–insulator transition, and cation disorder [30], also play important roles in depressing the superconducting order parameter at grain boundaries. Explicit understanding of the oxypnictides awaits single grain-boundary studies that are not yet possible, so for now we restrict our discussion to extrinsic factors that may be playing a role in the behavior of these two Nd and Sm samples, that actually show much better global current flow than the La oxypnictide sample first studied [12].

First it is clear from the MO images of figure 8(b) that the macroscale impurity phases (principally RE$_2$O$_3$ and the glassy Fe–As phase) shown in figures 4(b) and 8(a) do allow flux to easily penetrate the Nd sample. It is also seen that the global $J_c$ of the Nd sample is less than the Sm sample which has fewer second phases, a correlation that does suggest that macroscale impurities limit the global current, in analogy to the case of porous, polycrystalline MgB$_2$ where voids and impurity insulating MgO significantly reduce percolating current paths and limit the normal-state conductivity and critical current density [31, 32]. Considering the very different length scales of superconducting coherence length (<5 nm) and these impurities (several tens to several hundreds of microns), the macroscale secondary phases are more likely to block global current flow, rather than to contribute to vortex pinning.

Second it is possible that many superconducting grains are isolated from each other by non-superconducting layers, particularly the grain-boundary wetting, Fe–As amorphous phase. A TEM study in progress does show that some grain boundaries are covered by such wetting phases with a thickness of several tens of nanometers, although some clean grain boundaries are also observed [27]. Depending on the thickness and properties of the wetting phase, such layers might act as barriers that completely decouple the grains or act as weakly coupled Josephson junctions with rather different temperature- and field-dependent critical current density compared to the vortex pinning current density circulating within grains. Indeed the strong temperature dependence of $J_c^{\text{global}}(T)/J_c^{\text{local}}(T)$ in figure 14 shows very clearly that two different mechanisms control the inter and intragranular current densities. The temperature dependence of the global $J_c$ near $T_c$ with upward curvature is found to be well fitted by a quadratic function $J_c \propto (T_c - T)^2$ suggestive of an SNS proximity coupled Josephson junction [33, 34] which has also been observed on low-angle grain boundaries in cuprate superconductors [35, 36]. Therefore we may conclude that the intergranular current transport in the present samples is limited by the proximity coupled conductive wetting glassy As–Fe phase or by the intrinsic weak coupling. $H_{c2}$ measurements on these two samples suggest that $H_{c2}(0)$ is well over 100 T, making the coherence length shorter than 2 nm, thus adding weight to the concern that there is an intrinsic aspect to the limitation of current across high-angle grain boundaries. The already noted negligible global current observed in the LaFeAsO$_{0.89}$F$_{0.11}$ sample surprised us due to its relatively low normal-state resistivity ($\sim 0.15$ m$\Omega$ cm) and high $RRR$ of 15 ($\sim 3$ for the present samples), both factors which might suggest higher intergranular $J_c$ behavior for the LaFeAsO$_{0.89}$F$_{0.11}$ sample. However, the measured normal-state resistivity at $T_c$ ($\sim 0.5$ m$\Omega$ cm) of the Sm and Nd samples may be significantly overestimated if the second phase content forces strong current percolation. This would of course be fully consistent with a suppressed $J_c^{\text{global}}(T)/J_c^{\text{local}}(T)$. We therefore conclude that our present data are insufficient to decide on the balance between intrinsic and extrinsic limitation of $J_c$ in the present samples and that there is evidence to support both mechanisms.

Another point to address is the comparative behavior of the polycrystalline oxypnictides to randomly oriented.

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**Figure 7.** Magnetic flux profiles $B_z$ taken at (a) 6.4 K and (b) 20 K along the line 1 in figures 6(g) and (h), respectively. The sample was field-cooled under $\mu_0H_{dc} = 120$ mT down to 6 K followed by removal of the external field, and then the temperature was increased.
Figure 8. Magneto-optical images taken on the polished surface of the NdFeAsO$_{0.94}$F$_{0.06}$ bulk sample. (a) Surface image by optical microscopy. MO images of different stages of magnetic flux penetration into the sample for ZFC to $T = 6$ K and (b) after application of $\mu_0 H_{ex} = 40$ mT, (c) then reducing the field $\mu_0 H_{ex} = 0$ mT, (d) then after applying $\mu_0 H_{ex} = 120$ mT, (e) and finally after reducing $\mu_0 H_{ex} = 0$ mT. An arrow shown in (a) indicates line 2 for magnetic flux profiles shown in figure 9.

Figure 9. Magnetic flux profiles $B_z(x)$ taken along line 2 in figure 8(a) at (a) 6.2 K and (b) 19 K. The sample was field-cooled under $\mu_0 H_{ex} = 120$ mT down to 6 K followed by removal of the external field and increase of temperature to 19 K.

Figure 10. Derivatives of the remanent magnetization as a function of the maximum applied field for the SmFeAsO$_{0.85}$ small bulk. Data are normalized by sample mass. Inset shows the temperature dependences of the peak fields $\mu_0 H_{peak}$ for the first and second peaks.

The global $J_c$ values of 4000 and 2000 A cm$^{-2}$ at 5 K obtained for the Sm and Nd samples is significantly lower than those seen in random bulks of MgB$_2$ which generally attain $10^6$A cm$^{-2}$ at 4 K [37, 38]. However, it was very early established that grain boundaries were not intrinsic obstacles to current flow in MgB$_2$ [39]. Of greater interest is the comparison to the least anisotropic of the cuprates, those with the RE-123 structure, randomly oriented polycrystalline examples of which have global $J_c$ values of only $\sim 100$ A cm$^{-2}$ at 4 K due to large intrinsic
weak-link effects [15, 16]. Thus it may be that any intrinsic weak-link effect at oxypnictide grain boundaries is less serious than in the cuprates. The lower $H_{c2}$ anisotropy $\gamma$ and higher carrier density in the iron oxypnictides ($\gamma \sim 4$) compared to the cuprates such as YBCO ($\gamma \sim 7$) could be the reasons for the higher bulk $J_c$ in the randomly oriented Sm and Nd polycrystalline samples.

Finally, the temperature dependence of local $J_c$ is briefly discussed. A rather linear temperature dependence of local $J_c$ is observed near $T_c$ for both the Sm and Nd samples, as shown in the inset to figure 13. This temperature dependence, very high $J_c(0) \sim 8 \times 10^6$ A cm$^{-2}$ and a wide magnetization hysteresis loop indicate that strong intragrain vortex pinning is present in these samples. On the other hand, an upward curvature in $J_c(T)$ is observed below $\sim 20$ K and $J_c(T)$ decreases rapidly with increasing temperature. This behavior may indicate significant thermal fluctuation of vortices, which result in a similar upturn of $J_c(T)$ at low temperature in the cuprate single crystals [17]. The $J_c(T)$ curves at low temperature can be fitted by an exponential function as shown in the inset to figure 13 using $J_c(T) = J_c(0) \exp(-T/T_0)$. This form is often used to describe the temperature dependence of the critical current density in high-temperature superconductors and other systems with similar properties.
an equation $J_c = A \left(1 - T/T_c\right) \exp(-T/T_0)$, with $T_0 = 8\text{–}10\, \text{K}$. The exponential factor can be understood using the following simple model. Vortex fluctuations smear out the pinning potential, reducing the elementary pinning forces by the Debye–Waller factor $\exp\left(-u^2/\alpha^2\right)$ where $u$ is the thermal displacement of a vortex from the pinning well of size $a$ [40].

Then from the equipartition theorem, thermal fluctuations provoke the rapid decrease of the local doping level than in the cuprates. the actual doping states differ from the nominal composition, and the temperature dependence of global
terature coupled intergranular current was suggested from the tem-
cal state over the whole sample showed that a global cur-
iment measurements and it was found that the two currents
had quite different temperature dependences and that their ratio $J_c^{\text{local}}(T)/J_c^{\text{global}}(T)$ never exceeded $~0.004$. An SNS proximity
ity coupled intergranular current was suggested from the tem-
perature dependence of global $J_c$. The local $J_c$ value at self-
field and 5 K is estimated to be $~5 \times 10^6\, \text{A cm}^{-2}$. Temperature
dependence of local $J_c$ showed strong upturn below 15 K which is similar to the cuprate superconductors. Similar to the cuprates, we also found evidence for electromagnetic granularity, though with not quite so much reduction of $J_c$ in polycrystalline bulks. To fully understand the balance of intrinsic and extrinsic factors, study of individual grain boundaries of known misorientations will be very helpful.

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