Magnetization relaxation and collective vortex pinning in the Fe-based superconductor $SmFeAsO_{0.9}F_{0.1}$

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(Received 23 June 2008; revised manuscript received 24 July 2008; published 18 September 2008)

By measuring the dynamic and traditional magnetization relaxations we investigate the vortex dynamics of the recently discovered superconductor $SmFeAsO_{0.9}F_{0.1}$ with $T_c=55$ K. It is found that the relaxation rate is rather large reflecting a small characteristic pinning energy. Moreover it shows a weak temperature dependence in wide temperature region, which resembles the behavior of the cuprate superconductors. Combined with the resistivity data under different magnetic fields, a vortex phase diagram is obtained. Our results strongly suggest that the model of collective vortex pinning applies to this superconductor very well.

DOI: 10.1103/PhysRevB.78.092504 PACS number(s): 74.25.Ha, 74.25.Qt, 74.70.Dd

Since the discovery of superconductivity at $T_c=26$ K (Ref. 1) in $LaFeAsO_{1-x}F_x$, the iron-based layered superconductors have exposed an interesting research area on superconductivity. This family of superconductors, $LnFeAsO_{1-x}F_x$, exhibit quite high critical temperatures with the maximum $T_c=55$ K for Ln=Sm (Ref. 2) in electron-doped region, as well as 25 K in the hole-doped case $La_{1-x}Sr_xFeAsO$.[3] Lots of experimental and theoretical works on the physical properties were accomplished. Measurements under high magnetic fields reveal that the iron-based superconductors have very high upper critical fields,[4–6] which indicate encouraging potential applications. It was pointed out that these superconductors exhibit multiband feature[4,7,8] as well as unconventional pairing symmetry.[8–10] Moreover this system has a layered structure with the conducting FeAs layers being responsible for the superconductivity, and the LnO layers behave as the charge reservoirs. All these look very similar to the case of cuprates. For cuprate superconductors, due to the high anisotropy, short coherence length, and high operation temperature, the vortex motion and fluctuation are quite strong. This leads to a small characteristic pinning energy, and the single vortex or vortex bundles are pinned collectively by many small pinning centers.[11] Therefore it is curious to know whether the vortex properties and phase diagram of the cuprate and FeAs-based superconductors are similar to each other or not. The magnetization relaxation was proven to be a very effective way to investigate the vortex dynamics.[12,13] In this Brief Report, we report a detailed study on the vortex dynamics of $SmFeAsO_{0.9}F_{0.1}$ polycrystalline samples.

The $SmFeAsO_{0.9}F_{0.1}$ samples used in our measurements were grown by the high-pressure synthesis method.[2] The sample in this work was first cut into a rectangular shape with dimensions of $4.20\times1.60\times1.08$ mm^3 for the resistance measurement, and it was further shaped into a bar with 268 mm in length (width and thickness unchanged) for the magnetic measurement. The measurements were carried out with a physical property measurement system (PPMS, Quantum Design) with the magnetic field up to 9 T. The magnetic-field sweeping rate can be varied from 0.5 to 600 Oe/s. The magnetic measurements were made by the sensitive vibrating sample magnetometer (VSM) at the vibrating frequency of 40 Hz with the resolution better than 1×10^{-6} emu. The advantage of this technique is that the data acquisition is very fast with quite a good resolution for magnetization.

In the upper inset of Fig. 1(a), we show the diamagnetic transition of the sample measured in the field-cooled (FC) and zero-field-cooled (ZFC) processes. The ZFC curve shows perfect diamagnetism in the low-temperature region when taking the demagnetization factor into account. In Fig. 1(a), we show the ρ-T curves at different magnetic fields.

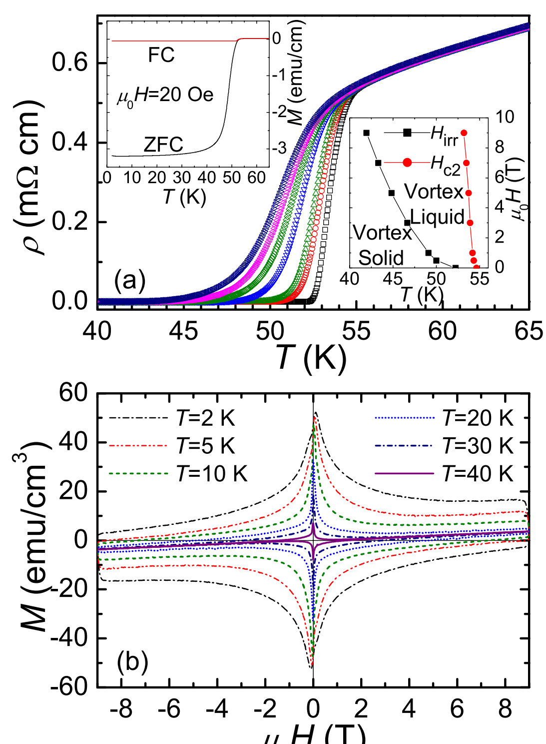

FIG. 1. (Color online) (a) Temperature dependence of resistivity at various fields of 0, 0.5, 1, 3, 5, 7, and 9 T. The upper inset in (a) shows the temperature dependence of the diamagnetic moment measured in the ZFC and FC processes at a field of 20 Oe, while the inset below shows the vortex phase diagram (see text). (b) Magnetization hysteresis loops M vs H at different temperatures of the same sample.

The onset transition temperature taken with a criterion of 99%ρ_n at zero field is about 55.2 K, while the zero-resistance temperature is about 52.2 K. Both the narrow magnetic and resistive transition widths indicate good quality in the polycrystalline sample. The coherence length of the iron-based superconductor is supposed to be larger than that of cuprates, and the sample grown by the high-pressure synthesis method is very dense, so it warrants a further detailed investigation on vortex dynamics. From the ρ-T curves, we obtained the phase diagram as depicted in the inset of Fig. 1(a) [the $H_{c2}(T)$ was obtained by using the criterion of 95%ρ_n]. The ratio between the irreversibility line $H_{irr}(T)$ and the upper critical field $H_{c2}(T)$ is close to that of $YBa_2Cu_3O_{7-\delta}$ (YBCO) but much larger than that of the more anisotropic Bi-based cuprate system. The calculated $H_{c2}(0)$ at zero temperature is 312 ± 26 T by using the Werthamer-Helfand-Hohenberg (WHH) formula[14] $H_{c2}(0)=-0.69 dH_{c2}(T)/dT|_{T_c}T_c$ roughly, and 444 ± 16 T by fitting $H_{c2}(T)$ with the expression $H_{c2}(T)=H_{c2}(0)[1-(T/T_c)^2]/[1+(T/T_c)^2]$ based on the Ginzburg-Landau theory. In Fig. 1(b) we show the magnetization hysteresis loops (MHL) measured at different temperatures from 2 to 50 K. The symmetric curves indicate that the bulk current instead of the surface shielding current dominates in the sample. It is remarkable that the superconducting MHL can still be measured at temperatures very close to T_c, with only a weak magnetic background. This indicates that the sample contains negligible magnetic impurities. Based on the Bean critical state model,[15] the superconducting current density $j\propto\Delta M$, where $\Delta M=M^- - M^+$, and M^+ (M^-) is the magnetization associated with increasing (decreasing) field.

In a type-II superconductor, the vortices normally move through thermal activation over the effective pinning barrier $U(j,T,B)$ with an average velocity $\bar{v}=v_0\exp[-U(j,T,B)/k_BT]$. Here v_0 is the attempt hopping velocity. The effective pinning barrier or the activation energy can be written as[16]

$$U(j,T,B)=\frac{U_c(T,B)}{\mu(T,B)}\left[\left(\frac{j_c(T,B)}{j(T,B)}\right)^{\mu(T,B)}-1\right], \qquad (1)$$

where U_c is the characteristic pinning energy, μ is the glassy exponent,[17,18] and j_c is the critical current density. The dissipation is associated with an electric field $E=\bar{v}B=v_0B\exp[-U(j,T,B)/k_BT]$, where B is the local magnetic induction. As proposed by Schnack *et al.*[19] and Jirsa *et al.*,[20] the magnetization-relaxation measurements can be measured with different magnetic sweeping rates dB/dt which was called as the dynamic magnetic relaxation measurements. The term "dynamic" here originates from a comparison with the traditional relaxation method that is to measure the time dependence of the magnetization after the field sweeping is stopped. The corresponding magnetization-relaxation rate is defined as $Q\equiv d\ln j/d\ln(dB/dt)=d\ln\Delta M/d\ln(dB/dt)$. As shown in Fig. 2, ΔM are obviously different from each other with different field sweeping rates 200 and 50 Oe/s; a faster sweeping rate corresponds to a higher instant current density. A surprising observation here is that the gap between ΔM measured at 200 and 50 Oe/s can be easily distinguished even at a low temperature, this indicates a relatively large vortex creep rate, or as called as giant vortex creep in the cuprate superconductors. The calculated Q from Fig. 2 is as large as 5% at 1 T. This value is similar to the one in cuprate superconductors, e.g., 4% in YBCO,[12,21] but one order of magnitude larger than that in MgB_2 at such a small field.[22] In order to check the relaxation rate derived from the dynamic relaxation method, we also did the traditional magnetization-relaxation measurements on this sample. In this case, the normalized magnetization-relaxation rate S is defined as $d\ln(-M)/d\ln t$. The time (t) dependence of the nonequilibrium magnetization (M) is shown in Fig. 3 on a log-log plot. It shows that $\ln(-M)$ decays with time in a logarithmic way at 1 T, which is actually expected by the model of thermally activated flux motion.

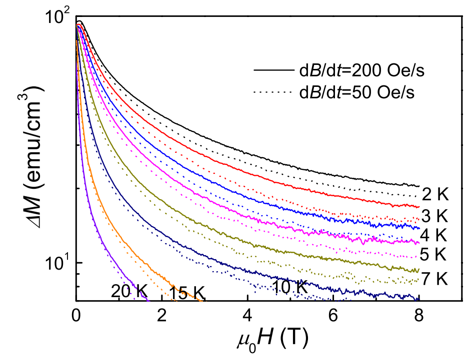

FIG. 2. (Color online) Field dependence of ΔM with different field sweeping rates of 200 and 50 Oe/s.

In Fig. 4(a), we present the temperature dependence of the two relaxation rates Q and S and they exhibit the similar temperature dependence. Obviously, there is a plateau in the intermediate temperature region for each curve, and the region of the plateau increases with the decreasing magnetic field. This plateau cannot be understood within the picture of single vortex creep with the rigid hopping length as predicted by the Anderson-Kim model. Exactly the same behavior was observed in YBCO (Ref. 23) and was attributed to the vortex collective pinning in the cuprate superconductor. However, this is in contrast to the data in MgB_2 where the relaxation

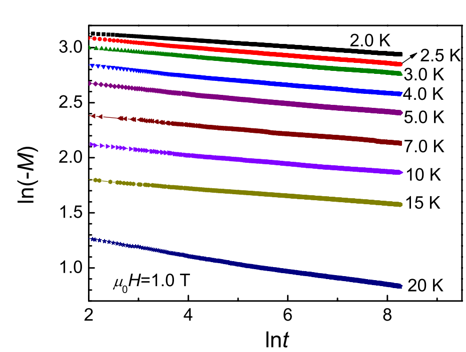

FIG. 3. (Color online) Log-log plot of magnetization $-M$(emu/cm^3) vs time t (s) at various temperatures at $\mu_0H=1.0$ T.

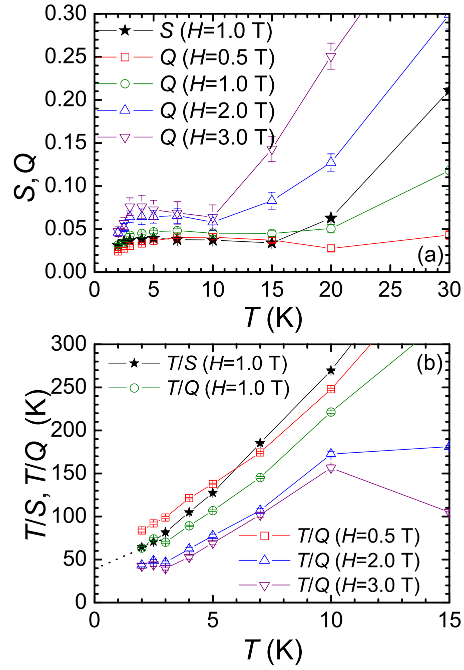

FIG. 4. (Color online) (a) Temperature dependence of the dynamic relaxation rate Q at different magnetic fields and the normalized relaxation rate S at 1 T. (b) Temperature dependence of T/S or T/Q at various fields.

rate increases linearly with temperature, indicating a thermally activated hopping of vortices with rigid length.[22] The general feature of relaxation rate shown in Fig. 4(a) is very similar to the case of cuprate superconductors, especially in YBCO.[24] In our experiment, the lowest temperature was only down to 2 K. So it is difficult to know whether the quantum tunneling of vortices occurs at a much lower temperature. To get a comprehensive understanding of the vortex motion in the intermediate temperature region, we use the following expression to calculate the characteristic pinning energy:[25]

$$\frac{T}{Q(T,B)}\left(\text{or } \frac{T}{S(T,B)}\right) = \frac{U_c(T,B)}{k_B} + \mu(T,B)CT, \qquad (2)$$

where $C \simeq \ln(2v_0B/l\mathrm{d}H/\mathrm{d}t)$ is a parameter that is weakly temperature dependent. In the low-temperature region (below 3 K), the relaxation rate has a clear tendency to drop with temperature. This can be understood based on the picture of vortex collective pinning; according to Eq. (2), when μCT becomes smaller than $U_c(T,B)$, we have $T/Q \approx U_c(T,B)/k_B$ and Q rises almost linearly with T. In the intermediate temperature region, μCT is getting gradually larger than $U_c(T,B)$; the relaxation rate Q is thus determined by the balance between them. In Fig. 4(b), we show the temperature dependence of T/Q or T/S vs T. By extrapolating the curve T/S or T/Q down to zero temperature, one can get the value of $U_c(0)$. The value of $U_c(0)/k_B$ at 1 T calculated from Fig. 4 is about 40 K, which is a very small value. The $U_c(0)$ is about 100–400 K in YBCO thin films[21] but beyond 3000 K in MgB_2.[26] Meanwhile, parameter C in Eq. (2) can be determined from the curve $-\mathrm{d}\ln j/\mathrm{d}T$ vs Q/T.[25] And here we find $C=7.3\pm0.3$. The slope of T/Q vs T that

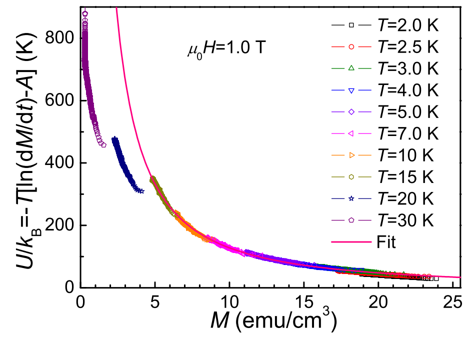

FIG. 5. (Color online) Magnetization dependence of the scaled activation energy U obtained by following the Maley's technique with parameter $A=8$. The line is a fitting result by Eq. (1) with $U_c/k_B=39.7$ K and $\mu=1.11$.

gives the value of μC in low-temperature region at 1 T is about 11.8, so we get the parameter $\mu=1.62$. This value is close to $\mu=3/2$ predicted for collective pinning of small bundles.

In the following we analyze the $U(j)$ relation by Maley's method,[27] which proposed a general equation $U/k_B = -T[\ln(\mathrm{d}M/\mathrm{d}t)-A]$ to scale the data measured at different temperatures, where A is a time-independent constant associated with the average hopping velocity. In Fig. 5, we present the correlation between the scaled activation energies U and M. Obviously, at the temperatures below 15 K, all the curves can be scaled together, but the scaling fails at temperatures above 20 K. The reason may be is that the original Maley's method is valid only in low-temperature regime (below $T_c/3$) where the explicit temperature dependence of $U_c(T)$ is weak.[27] It should be noted that the relaxation rate at 1 T has a sudden increase which starts at about 20 K after the plateau, this may correspond to a crossover between different vortex creep regimes. A recent work by the magneto-optical imaging technology showed that the local current density exhibited different temperature dependence above and below 20 K,[28] which may be caused by the similar reason. According to Eq. (1), we can fit the activation energy data by the thermally activated vortex motion theory. The U-M curves at the temperature below 15 K can be well fitted (as shown by the solid line in Fig. 5). The fitting parameter U_c/k_B is 39.7 K, which is close to 40 K mentioned above. From the fit we get $\mu=1.11$, so the value $\mu=3/2$ for small bundle is just in between the two calculated values of μ obtained by different methods in this work. Our work strongly suggests that the collective pinning model is applicable in this kind of superconductors. This is consistent with a recent work on the vortex dynamics of the polycrystalline $NdFeAsO_{0.9}F_{0.1}$ sample measured by local magneto-optical imaging technique.[29] From the U-M relation shown in Fig. 5, one can also see that the activation energy increases sharply by decreasing the current density. In the resistive measurements, the current density is usually very small (about 0.3 A/cm^2 in this work), so the activation energy obtained from the Arrhenius plot of R-T curves may reach a quite large value.[30]

In conclusion, dynamic and traditional magnetization relaxations have been measured on $SmFeAsO_{0.9}F_{0.1}$ samples in wide temperature and magnetic-field regions. The model of collective vortex pinning seems to work in understanding the vortex properties of this material. The relaxation rate is quite large, which is comparable with the cuprate superconductors and much larger than the value in MgB_2. The characteristic pinning energy is only about 40 K, but the vortex (or vortex bundles) is pinned collectively by many weak pinning centers.

We are grateful to Zhongxian Zhao and Zhian Ren for providing us the high quality $SmFeAsO_{0.9}F_{0.1}$ samples made by high-pressure technique. This work is supported by the Natural Science Foundation of China, the Ministry of Science and Technology of China ("973" Projects No. 2006CB601000 and No. 2006CB921802), and Chinese Academy of Sciences (Project ITSNEM).

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