Direct observation of the depairing current density in single-crystalline $Ba_{0.5}K_{0.5}Fe_2As_2$ microbridge with nanoscale thickness

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We investigated the critical current density (J_c) of $Ba_{0.5}K_{0.5}Fe_2As_2$ single-crystalline microbridges with thicknesses ranging from 276 to 18 nm. The J_c of the microbridge with thickness down to 91 nm is 10.8 MA/cm^2 at 35 K, and reaches 944.4 MA/cm^2 by extrapolating $J_c(T)$ to $T = 0$ K using a two-gap s-wave Ginzburg-Landau model, well in accordance with the depairing current limit. The temperature, magnetic field, and angular-dependence of $J_c(T, H, \theta)$ indicated weaker field dependence and weakly anisotropic factor of 1.15 (1 T) and 1.26 (5 T), which also yielded the validity of the anisotropic Ginzburg-Landau scaling.

The newly discovered Fe-based superconductors caused increasing attention due to their potential for applications, owing to high superconducting (SC) transition temperature (T_c), high upper critical fields (H_{c2}), and a low critical current (J_c) anisotropy [1]. Compared with the layered cuprate family, although Fe-based superconductors have lower T_c, they demonstrate nearly isotropic transport behavior [1]. Investigation of anisotropic J_c is essential, from the view point of basic physics parameters and potential applications [2–4]. Generally, there are two main methods to explore the J_c. The first one is to study patterned thin film micro-devices. The thin films have been fabricated successfully for several systems, including Fe(Se,Te) [2], $Ba(Fe,Co)_2As_2$ [3], and $LaFeAsO_{1-x}F_x$ [4]. However, one can hardly obtain an ideal single-crystalline film, due to the presence of twins and low-angle grain boundaries resulting from the island-like growth process [5]. Although the existence of grain boundaries can enhance the J_c by increasing pinning, the critical current exhibits exponential decay in the weak-link regime which poses a serious obstacle for practical applications. Up to now, the J_c of Fe-based thin films was reported at the level of a few MA/cm^2 at 4.3 K [3–5]. The other method is to measure the J_c indirectly from magnetization hysteresis loop (MHL) of single crystals. By using the Bean's model the J_c can be evaluated from the vortex penetration profile [6], which is determined by pining force owing to the defects, grain boundary, and geometry of the materials. The J_c value estimated from MHL remains as well of the order of a few MA/cm^2 at 4.3 K [7].

We emphasize that both methods for J_c determination are limited by the vortex motion in presence of a finite pining force, but not the intrinsic transport capability of the material, for which an exploration of the Ginzburg-Landau (GL) depairing current density (J_{dp}^{GL}) is of great importance for understanding the existing limits for increasing J_c [8–10]. The J_{dp}^{GL} corresponds to the critical pair-breaking current, which was theoretically estimated to be as high as 200 MA/cm^2 at 0 K for (Ba,K)Fe_2As_2 [11]. This value is two orders of magnitude larger than previously reported J_c's. Generally, it is rather difficult to reach the J_{dp}^{GL}, even for the conventional superconductors and the cuprates [9]. There are two main reasons for that: first of all, J_{dp}^{GL} is extremely sensitive to crystal quality; secondly, since the Fe-based compounds are metallic, one can hardly apply very high value of the critical currents in a bulk crystal [12]. To avoid these problems, micro- and nano-patterning techniques can be developed to study the maximum supercurrent density.

Theoretically, if the width (W) of the microbridge is reduced to the Pearl length Λ=$2\lambda^2/h$ (λ and h are the London penetration depth and thickness of the bridge, respectively) and h is less than the GL coherence length (ξ), the critical current is determined by the critical pair-breaking current [13]. However, the practical realization of this geometry is, contrary to conventional superconductors, rather challenging for high-T_c superconductors due to their extremely small ξ. A recent work reported on an enormous value J_{dp}^{GL}(4.2 K) = 130 MA/cm^2 for a $YBa_2Cu_3O_{7-\delta}$ thin films nanobridge [9], which is impressive considering that $\xi \ll h$ and the cuprates often suffer from chemical and thermal instability under ion beam treatment [5].

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In this work, we fabricated microbridges of high quality and chemically stable $Ba_{0.5}K_{0.5}Fe_2As_2$ single crystals with $W = 2$ μm and h from 18 to 276.5 nm. The transport measurements indicated that J_c of the microbridge with $h \leq 91$ nm corresponded to the GL depairing current limit. We also studied the temperature, magnetic field (H), and angle (θ) dependence of $J_c(T, H, \theta)$ which can be well described by the anisotropic GL scaling.

The synthesis of $Ba_{0.5}K_{0.5}Fe_2As_2$ single crystals was introduced elsewhere [14]. The crystal was firstly cleaved into pieces with 1-2 μm thickness, and then glued on Si substrate with the ab-plane parallel to the substrate surface using a thin layer of epoxy. The as-prepared crystal was then milled to a layer of 10 nm thickness by low energy argon ion beam (ion acceleration voltage of 200 V and beam current density of J_{Ar^+} of ~ 0.25 mA/cm^2), and immediately covered by a 100 nm layer of Au. To improve the interface contact between gold and crystal we annealed the sample at 300 °C for 24 hrs under nitrogen atmosphere. This results in a contact resistance as low as 0.5 Ω. The crystals were fabricated as micro-devices as follows: (i) making micro-bridge patterns using the photolithography technique; (ii) argon ions milling the sample into a thickness of 300 nm; (iii) removing the photoresist by acetone and connecting the electrodes with silver epoxy; and (iv) etching the whole device until the crystal was completely removed except the micro-bridge as shown in the inset of Fig. 2(a). Note that the whole sample was etched in step (iv), except the parts under the silver paste.

The temperature dependent in-plane resistances (R_{ab}) were measured in the Physical Properties Measurement System - 9 T (Quantum Design Inc.). $R_{ab}(T)$ curves of the device were measured on the same crystal after etching a certain thickness each time. Fig. 1 shows $R_{ab}(T)$ curves for the microbridge with different thicknesses. At the initial stage with $h = 276.5$ nm, the onset of SC transition was at 39.5 K, suggesting high-quality of the single crystal. As the sample is gradually etched and measured under the same current $I = 50$ μA, the T_c exhibits a slight decrease which may be caused by the increase of the current density. More interestingly, with $h = 91$ nm, the $R_{ab}(T)$ curve demonstrates two steps with decreasing temperature, namely, a sharp drop followed by a weak R decrease, where the last step shows an extent of $\sim$1 K. In addition, once we further reduce the thickness to 18 nm, the steps become more apparent. Indeed, by applying magnetic field the step was weakened but transformed into a flux-flow like $\rho(T)$ tail (see Fig. 2), and such phenomenon is more obvious for the case of the $H \| ab$-plane. With increasing field, the $T_c(H)$ is gradually suppressed, while the transition width is observed to be almost constant for the $H \| ab$-plane but slightly broadened for the $H \| c$-axis, owing to a weak two-dimensional (2D) behavior. Since the crystal contains only a few SC layers, for instance 69 layers for 91 nm and 14 layers for 18 nm [15], this peculiar SC transition may be attributed to inhomogeneity of the material, namely, the SC state may vary

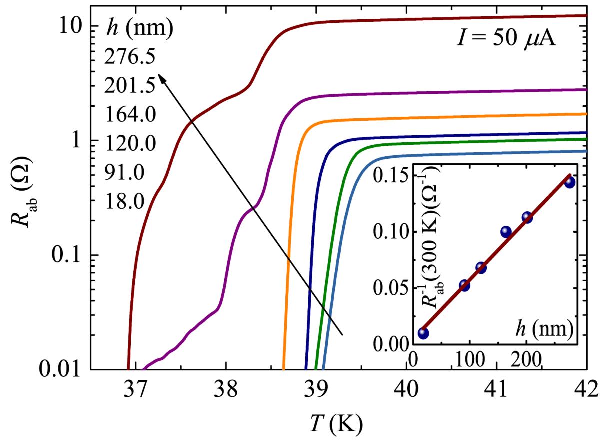

FIG. 1. (Color online) Temperature dependence of the in-plane resistance ($R_{ab}(T)$) for a microbridge with various thicknesses from 276.5 to 18 nm. Here, the $R_{ab}(T)$ curves were measured after each time of ion-milling process. The h was confirmed from ion-milling thickness and R_{ab} at 300 K, according to a linear function between R_{ab}^{-1}(300 K) and h as given by the inset of the figure.

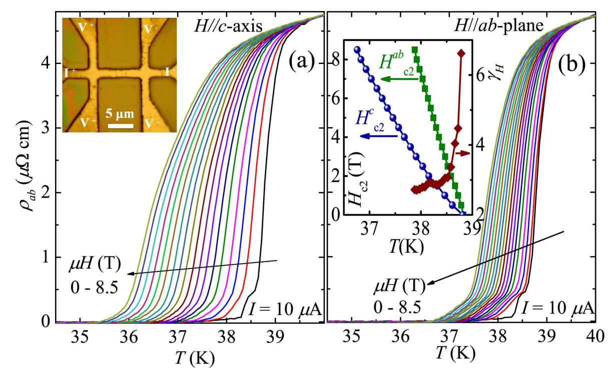

FIG. 2. (Color online) In-plane magnetoresistivity as a function of temperature under fields from 0 to 8.5 T. The microbridge was with $W = 2$ μm and $h = 91$ nm. The fields were applied along the c-axis for (a) and the ab-plane for (b). Inset (a) shows optical microscopic image of the microbridge. Inset (b) gives $H_{c2}^{ab}(T)$, $H_{c2}^{c}(T)$, and the anisotropy factor $\gamma_H(T) = H_{c2}^{ab}(T)/H_{c2}^{c}(T)$ at temperatures near T_c, here the H_{c2} was defined from the resistivity transition midpoint. We can hardly obtain the H_{c2} for 36 K restricted by the used measurement system, instead we can roughly estimate H_{c2}^{ab}(36 K) $\approx$ 26.3 T and H_{c2}^{c}(36 K) $\approx$ 11.8 T from the near linear change of $H_{c2}^{ab}(T)$ and $H_{c2}^{c}(T)$, respectively. The γ_H as well can be roughly considered as constant below 38.5 K, i.e., γ_H(36 K)$\approx$2.7.

depending on the distribution of potassium doping. However, the $R_{ab}(T)$ curves are very similar to those observed in the low-T_c nanowires [16] or high-T_c micro-bridges such as $YBaCu_3O_{7-\delta}$ [17], for which the steps appeared due to the existence of the phase-slip centers or phase-slip lines. Hence, the sharp $R_{ab}(T)$ drop can be interpreted as the SC transition, while the smooth $R_{ab}(T)$ decrease could be associated with thermally activated phase slips.

To further investigate the latter scenario we measured the current vs. voltage characteristics (IVCs) using both PPMS and a standard measurement setup in a liquid-helium transport dewar as described elsewhere [15]. For these experiments we selected the micro-bridge with $h =$ 91 nm. Inset of Fig. 3 shows the IVCs at temperatures near the T_c. At 35 and 36 K, the $V(I)$ curve jumps from SC (V=0) to normal state ($V \neq 0$) directly at a critical value of current (I_c), with absence of any gradual dissipation process. After slightly increasing temperature to 37 K, a small resistance appears when the bias current is applied close to I_c, which, probably, corresponds to the non-linear flux-flow regime [18]. Note that for $T \leq$37 K, when the current returns along a resistive branch back to the SC state at a return current I_r, a pronounced hysteresis of IVCs demonstrates a Josephson-junction-like behavior [9]. However, the single crystal was confirmed to be of high quality in previous work [14], and we selected the optimally-doped $Ba_{0.5}K_{0.5}Fe_2As_2$ which should not have a nematic state as the under-doped state [19], thus grains or twin boundaries can be also ruled out. In addition, the micro-device has well-designed geometry as shown in the inset of Fig. 2, thus suggesting the absence of weak-link junctions. Therefore, we can hardly attribute the IVCs to the existence of the Josephson junctions. In addition, as the temperature rises up to 38 K, the hysteresis disappears, while a step-like phenomenon is observed on the IVCs. Such steps can also be found on the return branches at relatively low temperatures 35 - 37 K, where the Joule heating may affect the resistance. The successive steps on IVCs and the smooth decrease of $R(T)$ demonstrate characteristics typical for the phase slips as studied on the low-T_c nanowires, high-T_c quasi-1D and quasi-2D superconductors [16, 17]. We will further discuss the phase-slip behavior in details in a forthcoming work.

Using the I_c's we calculated the $J_c(T)$ as shown in Fig. 3. The value of J_c is quite high, J_c (35 K) = 10.8 MA/cm^2, which is at least three orders of magnitude larger than the previously reported results [7, 11]. Since our J_c data were obtained in the vicinity of T_c at $T/T_c >$ 0.87, the ultimate $J_c(0)$ should be considerably higher. The $J_c(T)$ seems to be consistent with the depairing current density, $J_{dp}(T)$, with an additional kink (an effect of multigap supercunductor) near T=0.905. The work using Eilenberger and renormalized BCS equations [20] shows a kink in the $J_{dp}(T)$ near the nucleation of superconductivity on the second band for small values of interband coupling constant. It is not surprising that, if we consider the two bands totally as independent, the J_{dp}^{GL} becomes just the direct sum from two gaps (J_{dp1}^{GL},J_{dp2}^{GL}), i.e. $J_{dp}^{GL}(T) = J_{dp1}^{GL}(0)(1-T/T_{c1})^{3/2} + J_{dp2}^{GL}(0)(1-T/T_{c2})^{3/2}$. This model automatically has a kink in the J_{dp}^{GL} near the second band critical temperature (T_{c2}). We used a zero coupling model, and it seems to match with the experimental curve so well as shown in solid line in Fig. 3. This can indicate that the coupling is very small or that the symmetry of the order parameters and the crystal structure does not allow interband scattering between the two bands. The fitting provides us the following parameters $(T_{c2})/(T_{c1}) = 0.91$, $J_{dp1}^{GL}(0)$=774.82 MA/cm^2, $J_{dp2}^{GL}(0)$=169.6 MA/cm^2, and $J_{dp}^{GL}(0)$=944.4 MA/cm^2. Indeed, the J_{dp} is comparable with the J_{dp}^{GL} only at temperatures nearby the T_c, but not at low-T, e.g. $J_{dp}(0)/J_{dp}^{GL}(0) \approx 0.385$ [21]. Thus, we get to the value $J_{dp}(0) \approx$363.6 MA/cm^2 that is still a bit higher than the estimated one ($\approx$ 200 MA/cm^2 [11]) but of the same order or magnitude. We note that in our model we used a s-wave model for both gaps, and by using a different symmetry of the order parameter the value of the J_{dp} can change at low temperatures. Therefore, from the large value of J_c and the perfect fitting of the theoretical curve, we can conclude that our large J_c value corresponds to a direct measurement of the J_{dp}^{GL} limit.

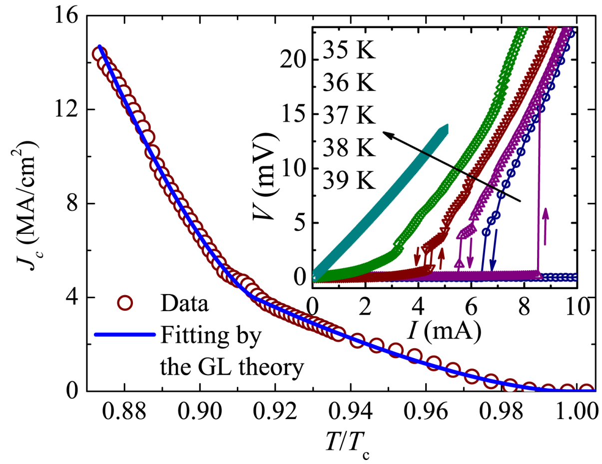

FIG. 3. (Color online) The J_c dependence on normalized temperature (T/T_c) for the microbridge with 2 μm in width and 91 nm in thickness. The experimental data of J_c are from I_cs directly, the solid line is the fitting by a two-gap s-wave GL model. Inset gives the IVCs at temperatures from 35 to 39 K, where the colored arrows indicate current bias increasing and decreasing process.

Considering the Pearl length for appearance of the J^{GL}, the sample geometry should yield with $W < \Lambda = 2\lambda^2/h$, we should emphasize two important physical parameters, i.e. the temperature dependent λ and ξ. At low temperatures, Λ(0 K)=$2\lambda^2/h$ = 0.71 μm $< W$, while λ_{ab} increases with temperature as $\Delta\lambda_{ab}(T) = 1.08\lambda_{ab}(0)(T/T_c)^{2.83}$ [22], from which we can estimate λ_{ab}(36 K) $\approx$ 330 nm, and consequently Λ(36 K)$\approx$ 2.39 μm $> W$. Below, we will focus our study on a relatively high-T, mostly above 36 K. As for the ξ value, it is extremely low for the Fe-based superconductors at low temperatures, of about two unit cells ($\sim$1.3 nm [14]), and it is beyond our reach to fabricate such thin device for transport measurements. The $\xi(T)$ can be calculated by employing the GL theory $\xi(T) = \xi(0)/\sqrt{1-T/T_c}$, hence we can roughly evaluate that ξ_c(36 K) is about 7.22 nm,

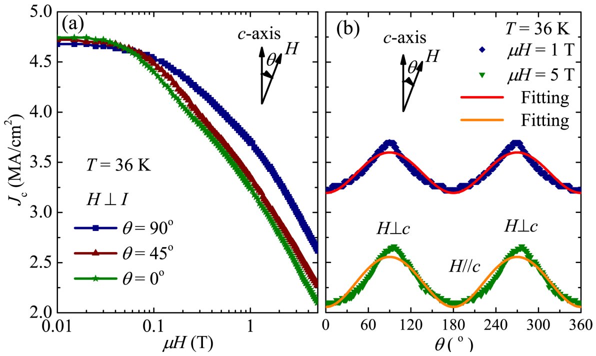

FIG. 4. (Color online) J_c under different magnetic field and field directions. Here all of the data are obtain at temperature of 36 K. The θ corresponds to the angle between H and c-axis, and $I \perp H$. The $J_c(\theta)$ was fit by using the scaling function of effective field $H_{eff} = H\epsilon(\gamma_m, \theta)$, where $\epsilon(\gamma_m, \theta) = \sqrt{\sin^2\theta + \gamma_m^{-2}\cos^2\theta}$, and $\gamma_m^2 = m_c^*/m_{ab}^*$ is the effective mass anisotropy.

which is much smaller than the h. Alternatively, $\xi_c(T)$ can also be calculated from $\xi_{ab}(T) = \sqrt{\Phi_0/2\pi H_{c2}^c(T)}$ and $\xi_c(T) = \Phi_0/2\pi\xi_{ab}(T)H_{c2}^{ab}(T)$ [23]. We estimate ξ_c(36 K) as ~2.4 nm, and it is still much less than the h value. Therefore, the thickness of our microbridges can hardly reach the GL ξ. Similarly, depairing limit of current density was also found in YBCO nanobridges with $\xi \ll h$ and $W < 2\lambda^2/h$ [9], from which the small width seems to be essential for achieving the depairing limit.

We further studied the magnetic fields and fields direction dependent $J_c(H, \theta)$ as shown in Fig. 4. In Fig. 4(a), the J_c was suppressed by 34 % by applying μH of 5 T along the c-axis. On the other hand, from the angular-dependence of $J_c(\theta)$ under μH (see Fig. 4(b)), the J_c anisotropic factor $\gamma_J = J_c^{ab}/J_c^c$ was calculated to be 1.15 and 1.26 for $\mu H = 1$ and 5 T, respectively. The present J_c anisotropy is less than those obtained for Fe(Se,Te) (10 for 6 T) [2], $Ba(Fe,Co)_2As_2$ (2.6 for 4 T) [3], and $LaFeAsO_{1-x}F_x$ (5 for 9 T) [4] thin films. Since the J^{GL} is inversely proportional to λ^2 and ξ, taking into account λ and ξ anisotropy we obtain magnetic field angular-dependent $J^{GL}(\theta)$. Van der Beek and co-workers [24] theoretically calculated anisotropy of J_c for $(Ba,K)Fe_2As_2$ with different pinning force contributions from defects, and they proposed that the J_c anisotropy factor mainly depends on the coherence length anisotropy as $\gamma_J \approx \gamma_\xi$ and defects features. In the first approximation, one may expect for a single-gap superconductor with absence of defects [25], $\gamma_\xi = \xi_{ab}/\xi_c = \sqrt{m_c^*/m_{ab}^*} = H_{c2}^{ab}(T)/H_{c2}^c(T)$, and it is ~2.7 at 36 K, about twice of the γ_J(36 K). By using the scaling function for the effective field $H_{eff} = H\epsilon(\gamma_m, \theta)$, where, $\epsilon(\gamma_m, \theta) = \sqrt{\sin^2\theta + \gamma_m^{-2}\cos^2\theta}$, and $\gamma_m^2 = m_c^*/m_{ab}^*$ is the effective mass anisotropy, we fit the $J_c(H, \theta)$ data, and obtain $\gamma_m = 1.12$ and 1.25 for $\mu H = 1$ and 5 T, respectively. The results are in accordance with those of γ_J(36 K), while being half of γ_H and γ_ξ. We note that the fitting is working well for the $J_c(H, \theta)$ dependencies, except for the maximum at 90°, which can be explained by the presence of the intrinsic pinning due to comparable ξ_{ab} and SC interlayer thickness (1.3 nm) [4].

In summary, we here studied the transport properties of microbridges of high quality $Ba_{0.5}K_{0.5}Fe_2As_2$ single crystals with $W = 2$ μm and $h = 276 \sim 18$ nm. The IVCs of the microbridges showed the Josephson-like behavior with an obvious hysteresis. The J_c was found to be 10.8 MA/cm^2 at temperature 35 K and 944.4 MA/cm^2 by the extrapolation to $T = 0$ K using a two-gap s-wave GL model. We suggest that the high value of J_c and the Josephson-like IVCs are consistent with the GL depairing limit. We also propose that, in order to observe the J_{dp}^{GL}, the width of the sample should be less than the Pearl length, while for the thickness it is not necessary to be less than the GL coherence length. The temperature, magnetic field, and angular dependence of $J_c(T, H, \theta)$ indicated weaker field dependence and weakly anisotropic factor of 1.15 (1 T) and 1.26 (5 T), which also yielded the anisotropic GL scaling.

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[1] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, J. Am. Chem. Soc. **130**, 3296 (2008); J. Paglione and R. L. Greene, Nat. Phys. **6**, 645 (2010).
[2] K. Iida *et al.*, Phys. Rev. B, **87**, 104510 (2013).
[3] D. Rall *et al.*, Phys. Rev. B **83**, 134514 (2011); S. Lee *et al.*, Nat. Mat. **9**, 397 (2010); T. Katase *et al.*, Nat. Commun. **2**, 409 (2011).
[4] M. Kidszun *et al.*, Phys. Rev. Lett. 106, 137001 (2011).
[5] J. H. Durrell *et al.*, Rep. Prog. Phys. **74**, 124511 (2011); H. Hilgenkamp and J. Mannhart, Rev. Mod. Phys. **74**, 485 (2002).
[6] C. P. Bean, Rev. Mod. Phys. **36**, 31 (1964).
[7] X.-L. Wang *et al.*, Phys. Rev. B **82**, 024525 (2010); S. R. Ghorbani *et al.*, Appl. Phys. Lett. **100**, 212601 (2012).
[8] A. A. Abrikosov, Rev. Mod. Phys. **76**, 975 (2004); B. Rosenstein and D. Li, Rev. Mod. Phys. **82**, 109 (2010).
[9] S. Nawaz, R. Arpaia, F. Lombardi, and T. Bauch, Phys. Rev. Lett. **110**, 167004 (2013).

[10] S. Tahara *et al.*, Phys. Rev. B **41**, 11203 (1990); W. A. Jones *et al.*, Appl. Phys. Lett. **97**, 262503 (2010).
[11] L. Fang *et al.*, Appl. Phys. Lett. **101**, 012601 (2012).
[12] R. Prozorov *et al.*, Phys. Rev. B **78**, 224506 (2008).
[13] M. Y. Kupriyanov and V. F. Lukichev, Fiz. Nizk. Temp. **6**, 445 (1980) [Sov. J. Low Temp. Phys. **6**, 210 (1980)]; K. K. Likharev, Rev. Mod. Phys. **51**, 101 (1979); K. Xu, P. Cao, and J. R. Heath, Nano Lett. **10**, 4206 (2010).
[14] J. Li *et al.*, Phys. Rev. B **85**, 214509 (2012).
[15] J. Li *et al.*, J. Am. Chem. Soc. **134**, 4068 (2012).
[16] A. G. Sivakov *et al.*, Phys. Rev. Lett **91**, 267001 (2003); M. Sahu *et al.*, Nat. Phys. **5**, 504 (2009).
[17] J. A. Bonetti, D. S. Caplan, D. J. Van Harlingen, and M. B.Weissman, Phys. Rev. Lett. **93**, 087002 (2004); P. Mikheenko *et al.*, Phys. Rev. B **72**, 174506 (2005).
[18] A. V. Silhanek *et al.*, New J. Phys. **14**, 053006 (2012).
[19] I. R. Fisher, L. Degiorgi, and Z. X. Shen, Rep. Prog. Phys. **74**, 124506 (2011).
[20] E. J. Nicol, J. P. Carbotte, Phys. Rev. B **72**, 014520 (2005).
[21] J. M. E. Geers, M. B. S. Hesselberth, J. Aarts, Phys. Rev. B **64**, 094506 (2001).
[22] G. Li *et al.*, Phys. Rev. Lett. **101**, 107004 (2008); R. Prozorov and V. G. Kogan, Rep. Prog. Phys. **74**, 124505 (2011).
[23] H. Q. Yuan *et al.*, Nature. **457**, 565 (2009); M. M. Altarawneh *et al.*, Phys. Rev. B **78**, 220505(R) (2008).
[24] C. J. van der Beek, M. Konczykowski, and R. Prozorov, Supercond. Sci. Technol. **25**, 084010 (2012).
[25] V. G. Kogan, Phys. Rev. B **24**, 1572 (1981).