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Fluctuation of mean free path and transition temperature induced vortex pinning in (Ba,K)Fe_2As_2 superconductors

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The vortex pinning mechanisms of $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal have been studied systematically as a function of temperature and magnetic field. The temperature dependence of the critical current density, $J_c(T)$, was analysed within the collective pinning model at different magnetic fields. It was found that both the δl pinning mechanism, i.e., pinning associated with charge-carrier mean free path fluctuation, and the δT_c pinning mechanism, which is associated with spatial fluctuations of the transition temperature, coexist in the $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal in fields smaller than 4 T. Their contributions are strongly temperature and magnetic field dependent. At lower temperature and $B \leq 4$ T, the δl pinning is the dominant mechanism, and its contributions decrease with increasing temperature. At temperatures close to the critical temperature, however, there is evidence for δT_c pinning. At magnetic fields larger than 4 T, the δl pinning mechanism is the only effect. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4714543]

The main physical parameters of interest for using superconducting materials are: a high superconducting transition temperature, T_c, high critical current density, J_c, high upper critical field, B_{c2}, high irreversibility field, B_{irr}, strong magnetic-flux pinning, good grain connectivity, and a small anisotropy. The layered cuprate superconductors have high anisotropy, short coherence length, and high T_c. Therefore, the vortices mainly behave as two-dimensional (2D) pancake vortices at high temperatures and fields. Such vortices can move easily, and their fluctuations are quite strong.[1] Grain boundaries of high-T_c superconductors have been a critical issue in practical applications. It is well known that the critical current exhibits exponential decay in the weak-link regime. In this regime, they have poor grain connectivity and easy melting of the vortex lattice, leading to small J_c in high magnetic fields at relatively high temperatures. For MgB_2 superconductor with $T_c = 39$ K, J_c drops quickly with both field and temperature. The Fe-based superconductors are a new family of high-T_c superconductors and have T_c as high as 56 K (Ref. 2) and B_{c2} above 70–80 T,[3] along with small anisotropy of 5–6 for $REFeAsO_{1-x}F_x$ (RE-1111 phase, with RE a rare-earth element),[4] but are almost isotropic for (Ba,K)Fe_2As_2 (122 phase).[5] These compounds show J_c over $1\text{–}3 \times 10^5\text{–}10^6$ A/cm^2 at 5 K for both $B//ab$ and $B//c$[6,7] (in thin films and crystals with higher J_c). It was also found that grain boundaries are not an important issue in iron pnictide superconductors.[8] These properties make the Fe-based superconductors extremely promising candidates for high magnetic field applications at relatively high temperatures. The current-carrying ability of these superconductors at high fields and temperatures is largely determined by the flux-pinning strength, which is found to be very large, as much as 9100 K in $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal.[9]

At the irreversibility field, H_{irr}, vortices start to move along the direction of the current flow, and hence the critical current vanishes. The current-density decay behaviour is governed by the pinning mechanism. The in-field J_c is mainly controlled by the flux pinning mechanisms. There are two basic pinning mechanisms in type-II superconductors. The first is the pinning due to the randomly distributed spatial variations in the transition temperature T_c, which is called δT_c pinning. The second pinning mechanism relates to spatial fluctuation of the charge-carrier mean free path, the so called δl pinning, mostly due to crystal lattice defects.[1,10] It has been reported that the δT_c pinning is the main flux pinning mechanism in Pr-doped $YBa_2Cu_3O_7$ (YBCO),[11] and pure MgB_2 bulk and thin films.[12–14] It was reported, however, that δl pinning is the important mechanism in stoichiometric Y-based high-T_c superconducting thin films.[10] It was also found that both mechanisms coexist in the nanoparticle doped-MgB_2 samples, depending on the temperature.[15,16]

Preliminary experimental results indicate that the vortex dynamics in Fe-based superconductors may be understood through the thermally activated flux motion model based on collective vortex pinning.[7,9,17–19] Fluctuation of mean free path and transition temperature induced vortex pinning, however, as the flux pinning mechanism for the Fe-based superconductors has not been studied so far.

In this paper, the vortex pinning mechanisms of $Ba_{0.72}$ $K_{0.28}Fe_2As_2$ single crystal have been studied systematically by magnetization loop measurements at different temperatures. It was found that both the δl and the δT_c pinning mechanisms coexist in the $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal in fields smaller than 4 T, while the δl pinning mechanism is the only effect at higher magnetic fields. Their contributions are strongly temperature and magnetic field dependent.

The $Ba_{0.72}K_{0.28}Fe_2As_2$ crystals used in the present work were grown using a flux method. High purity elemental Ba, K, Fe, As, and Sn were mixed in a molar ratio of

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$Ba_{1-x}K_xFe_2As_2$:Sn = 1:45–50 for the self-flux. A crucible with a lid was used to minimize the evaporation loss of K as well as that of As during growth. The crucible was sealed in a quartz ampoule filled with Ar and loaded into a box furnace. The details of the crystal growth are given in Ref. 20. The as-grown single crystal was cleaved and cut into a rectangular shape for measurements. The transport properties were measured over a wide range of temperature and magnetic fields up to 6 T with applied current of 5 mA using a physical properties measurement system (PPMS, Quantum Design).

Magnetization loops were collected for a (Ba,K)Fe_2As_2 single crystal in different magnetic fields, which were perpendicular to the FeAs planes, $B//c$, and temperatures down to 5 K. The critical current density J_c was obtained from the width ΔM of the magnetization loop using the Bean model, where for full sample penetration $J_c = 20\Delta M/Va(1-a/3b)$, where a and b are the width and the length of the sample perpendicular to the applied field, respectively, V is the sample volume, and ΔM is the height of the M-H hysteresis loop. The resulting J_c versus applied field is plotted in Fig. 1. At 5 K, the J_c value is 3.3×10^5 A/cm^2 at $B = 2$ T, and it only decreases to 6.2×10^4 A/cm^2 at $B = 6$ T. The weak dependence of J_c on magnetic field and temperature suggests that the (Ba,K)Fe_2As_2 single-crystal superconductor has superior J_c behaviour, which is beneficial for potential applications in high magnetic fields.

The temperature dependence of the normalised J_c at magnetic fields of 1, 3, 4, and 5 T is presented in Fig. 2. The normalised J_c has a linear dependence on temperature in the low temperature region and a slight enhancement of the log (normalised J_c) in the high temperature region. Actually, similar behaviour was also reported for both single crystal and polycrystalline cuprate superconductors.[11,21] In order to describe the current densities of high-T_c superconductors, Thompson *et al.*[21] explained the temperature dependence of J_c in the framework of the thermally activated flux motion model and the model of collective flux pinning and creep. They found the following expression for the temperature dependence of J_c:

$$J_c(T) = \frac{J_{dp}(T)}{\left\{1 + \left[\mu k_B T \ln\left(\frac{t_1}{t_{eff}} + 1\right)/U_c(T)\right]\right\}^{1/\mu}}, \quad (1)$$

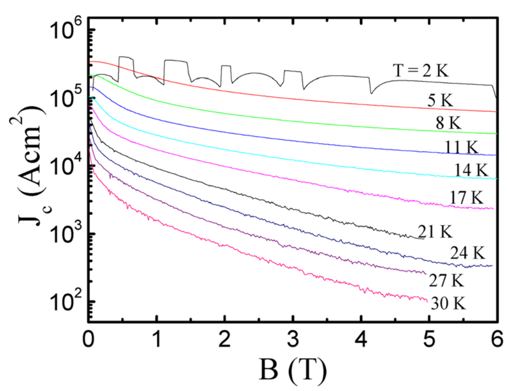

FIG. 1. The J_c-field dependence obtained from the M-H loops at different temperatures measured on a $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal.

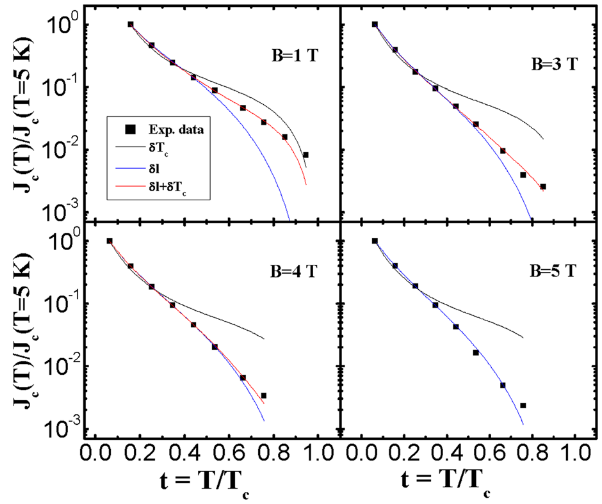

FIG. 2. Temperature dependence of the normalised measured current density J_c at magnetic fields of 1, 3, 4, and 5 T. The solid lines are the theoretical curves obtained based on the model of the δl (blue curves) pinning mechanism, the model of the the δT_c (black curves) pinning mechanism, and the coexistence of both (red curves) pinning mechanisms.

where $J_{dp}(T)$ is the depinning current density, $U_c(T)$ is the characteristic pinning potential, μ is the glassy exponent, t_1 is the time at which the data was recorded, and t_{eff} is the effective attempt time for a flux segment/bundle to jump over the potential barrier. The glassy exponent μ gives the influence on the current dependence of $U_c(T)$, depending on the flux creep regime.[22] By assuming $U_c(T) = U_c(0)\, g(t)$ and $J_{dp}(T) = J_{dp}(0)J(t)$ with $U_c(0)$, and $J_{dp}(0)$ the corresponding values at T = 0 K and $t = T/T_c$, the following temperature dependence for $J_c(T)$ can be obtained:

$$J_c(T) = \frac{J_{dp}(0)J(t)}{\{1 + [\mu k_B TC/g(t)]\}^{1/\mu}} \quad (2)$$

with

$$C = \ln\left(\frac{t_1}{t_{eff}} + 1\right)/U_c(0) \quad (3)$$

which is a temperature independent constant.

In the framework of the collective theory, Griessen *et al.*[10] pointed out that the δl and δT_c pinning mechanisms result in different temperature dependencies of $J(t)$ and $g(t)$. They found:

$$J(t) = (1 - t^2)^{7/6}(1 + t^2)^{5/6}, \quad (4)$$

$$g(t) = (1 - t^2)^{1/3}(1 + t^2)^{5/3}, \quad (5)$$

for δT_c pinning, and

$$J(t) = (1 - t^2)^{5/2}(1 + t^2)^{-1/2}, \quad (6)$$

$$g(t) = 1 - t^4 \quad (7)$$

for δl pinning. One can easily find from Eqs. (1), (4), and (6) that at T = 0 K, $J_c(0) = J_{dp}(0)$, and therefore, we can fit the critical current density data with Eq. (1) by adjusting only two parameters, i.e., C and μ. The theoretical curves obtained based on the model of δl (blue curves) and δT_c (black curves) pinning are shown in Fig. 2. At magnetic field lower than 4 T, one can see that the experimentally obtained critical current density value resides in between the δl and δT_c pinning. Therefore, both the δl and the δT_c pinning coexist, while for B > 4 T, the temperature dependence of the J_c is found to be in excellent agreement with the model of the δl pinning mechanism, and the data cannot be explained by the model of the δT_c pinning.

To investigate further the real pinning mechanism of the $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal samples, the $J_c(T)$ data were analysed by assuming the coexistence of both the δl and the δT_c pinning mechanisms within the following expression:

$$J_c(T) = P_1 J_s^l(T) + P_2 J_s^{T_c}(T), \quad (8)$$

where $J_c^l(T)$ and $J_c^{T_c}(T)$ are the expression for the δl and the δT_c pinning, respectively. P_1 and P_2 are fitting parameters. The $J_c(T)$ data were well described by Eq. (8) at magnetic fields lower than 5 T, as shown by the red solid curves in Fig. 2. The best-fitted value of μ is $0.38 \pm 0.0.1$ for the $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal. The μ value is in good agreement with $\mu = 0.45$, which was estimated from studies of E-J curves for $Ba(Fe_{1-x}Co_x)As_2$ at B = 0.5 T.[19] Therefore, a positive μ indicates elastic vortex motion for the $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal. This is because from studies of E-J curves, it was suggested that a negative μ value corresponds to plastic vortex motion, while a positive μ indicates elastic vortex motion.[20]

The value of 0.5 ± 0.1 was obtained for parameter C, which is roughly magnetic field independent. This parameter may depend on magnetic field through the $\ln(t/t_{eff} + 1)$ factor and the temperature independent pinning potential U_c in Eq. (3). For the $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal, U_0 is magnetic field independent in the magnetic field range studied here.[9] It was found[21] that $\ln(t/t_{eff} + 1) = \ln[2v_0 B/a(dB/dt)]$, where v_0 is the attempt velocity, which is expected to be field dependent, since single-vortex hopping occurs at low fields, while flux-bundle motion is expected at high fields. a is the lateral dimension of the sample and dB/dt is the sweep rate of magnetic field B. Therefore, the variation of C with magnetic field through the $\ln(t/t_{eff} + 1)$ factor is logarithmic and for the field range under examination could be roughly constant.

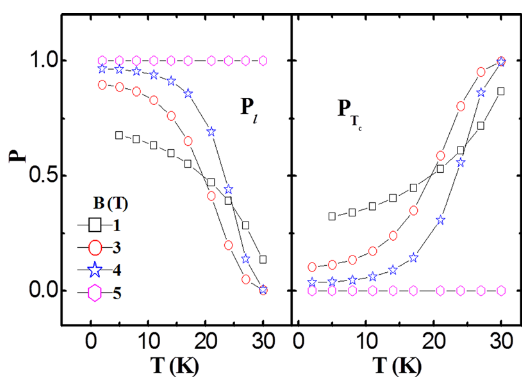

FIG. 3. δl and δT_c pinning contributions as functions of temperature in $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal at different magnetic fields.

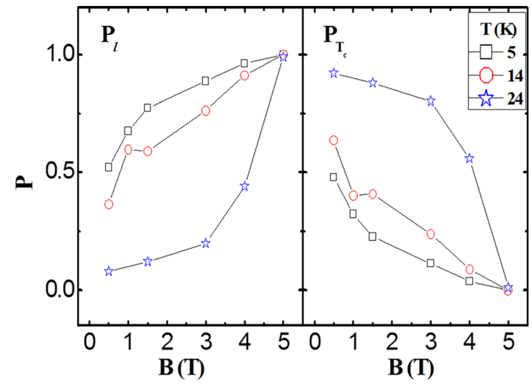

FIG. 4. Magnetic field dependences of the δl and the δT_c pinning contributions in $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal at different temperatures.

In order to compare the effects of the δl and the δT_c pinning mechanisms, the P parameter was defined as $P_l = P_1 J_c^l(T)/J_c(T)$ and $P_{T_c} = P_2 J_c^{T_c}(T)/J_c(T)$, which represent the δl and the δT_c pinning effects, respectively, with $P_l + P_{T_c} = 1$. The results of both pinning effect contributions are shown in Fig. 3. As can be seen in Fig. 3, the pinning mechanism strongly depends on the temperature. Between 20 and 23 K and for B ≤ 4 T, the two pinning mechanisms have roughly equal effects, while above these temperatures, δT_c pinning is dominant. For temperatures close to T_c and B ≤ 4 T, the T_c fluctuation increases, and therefore, the δl pinning is suppressed completely. When the temperature is far below T_c, the T_c fluctuation disappears, and the δl pinning is dominant.

The magnetic field dependences of both the δl and the δT_c pinning mechanisms are shown in Fig. 4. Both δl and δT_c pinning coexist at magnetic fields lower than 4 T. The δl pinning is dominant at high magnetic fields and low temperatures; it decreases with decreasing field and increasing temperature, while the δT_c pinning shows the opposite trend up to B = 4 T and is suppressed completely at B = 5 T. Therefore, at higher magnetic field, the δl is the only effective pinning mechanism.

In conclusion, from the temperature dependence of the critical current density within the collective pinning model at different magnetic fields, we have found that the δl pinning due to spatial fluctuations of the charge-carrier mean free path is strongly dominant at low temperature and low magnetic fields in $Ba_{0.72}K_{0.28}Fe_2As_2$ single crystal. At temperatures close to the critical temperature, however, there is evidence for the δT_c pinning, while at higher magnetic fields, the δl pinning mechanism is the only effect.

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