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Fluctuation of mean free path and transition temperature induced vortex pinning in (Ba,K)Fe$_2$As$_2$ superconductors

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The vortex pinning mechanisms of Ba$_{0.72}$K$_{0.28}$Fe$_2$As$_2$ 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 $\delta l$ pinning mechanism, i.e., pinning associated with charge-carrier mean free path fluctuation, and the $\delta T_c$ pinning mechanism, which is associated with spatial fluctuations of the transition temperature, coexist in the Ba$_{0.72}$K$_{0.28}$Fe$_2$As$_2$ 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 $\delta l$ pinning is the dominant mechanism, and its contributions decrease with increasing temperature. At temperatures close to the critical temperature, however, there is evidence for $\delta T_c$ pinning. At magnetic fields larger than 4 T, the $\delta l$ pinning mechanism is the only effect.

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 $\delta T_c$ pinning. The second pinning mechanism relates to spatial fluctuation of the charge-carrier mean free path, the so-called $\delta l$ pinning, mostly due to crystal lattice defects. It has been reported that the $\delta T_c$ pinning is the main flux pinning mechanism in Pr-doped YBa$_2$Cu$_3$O$_7$ (YBCO), and pure MgB$_2$ bulk and thin films. It was reported, however, that $\delta l$ pinning is the important mechanism in stoichiometric Y-based high-$T_c$ superconducting thin films. It was also found that both mechanisms coexist in the nanoparticle doped-MgB$_2$ samples, depending on the temperature.

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. 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$_2$As$_2$ single crystal have been studied systematically by magnetization loop measurements at different temperatures. It was found that both the $\delta l$ and the $\delta T_c$ pinning mechanisms coexist in the Ba$_{0.72}$K$_{0.28}$Fe$_2$As$_2$ single crystal in fields smaller than 4 T, while the $\delta l$ 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$_2$As$_2$ 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 1:1:2:2:1.

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Ba$_{1-x}$K$_x$Fe$_2$As$_2$: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$_2$As$_2$ 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 $\Delta M$ of the magnetization loop using the Bean model, where for full sample penetration $J_c = 20\Delta M/V(a-b)$, 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 $\Delta M$ 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 $3.3 \times 10^3$ A/cm$^2$ at $B$ = 2 T, and it only decreases to $6.2 \times 10^4$ A/cm$^2$ at $B$ = 6 T. The weak dependence of $J_c$ on magnetic field and temperature suggests that the (Ba,K)Fe$_2$As$_2$ single-crystal superconductor has superior 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 solid lines are the theoretical curves obtained based on the model of the $\delta T_c$ (blue curves) pinning mechanism, the model of the $\delta J_c$ (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, $\mu$ 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 $\mu$ 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 $J_{dp}(T) = J_{dp}(0)/g(t)$ 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:

$$J_c(T) = \frac{J_{dp}(0)/g(t)}{\{1 + [(\mu k_B T c(E_{p0}, t_1)]/U_c(0)]\}^{1/\mu}}$$

(2)

with

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

(3)

which is a temperature independent constant.

In the framework of the collective theory, Griessen et al.10 pointed out that the $\delta J_c$ and $\delta T_c$ pinning mechanisms result in different temperature dependencies of $J(t)$ and $g(t)$. They found:

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

(4)

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

(5)

for $\delta J_c$ pinning, and

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

(6)

$$g(t) = 1 - r^4$$

(7)

for $\delta T_c$ 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

![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$_2$As$_2$ single crystal.](image-url)
two parameters, i.e., C and μ. The theoretical curves obtained based on the model of δl (blue curves) and δTc (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 δTc pinning. Therefore, both the δl and the δTc pinning coexist, while for B > 4 T, the temperature dependence of the Jc is found to be in excellent agreement with the model of the δTc pinning mechanism, and the data cannot be explained by the model of the δl pinning.

To investigate further the real pinning mechanism of the Ba0.72K0.28Fe2As2 single crystal samples, the Jc(T) data were analysed by assuming the coexistence of both the δl and the δTc pinning mechanisms within the following expression:

\[ J_c(T) = P_1J_c^l(T) + P_2J_c^T(T), \]

where \( J_c^l(T) \) and \( J_c^T(T) \) are the expression for the δl and the δTc 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 ± 0.01 for the Ba0.72K0.28Fe2As2 single crystal. The \( μ \) value is in good agreement with \( μ = 0.45 \), which was estimated from studies of E-J curves for Ba(Fe1−xCo)2As2 at B = 0.5 T. 19 Therefore, a positive \( μ \) indicates elastic vortex motion for the Ba0.72K0.28Fe2As2 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 Ba0.72K0.28Fe2As2 single crystal, \( U_0 \) is magnetic field independent in the magnetic field range studied here.9 It was found21 that \( \ln(t/t_{eff} + 1) = \ln[2v_0/B/(dB/dt)] \), 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.

In order to compare the effects of the δl and the δTc pinning mechanisms, the \( P \) parameter was defined as \( P_1 = P_1J_c^l(T)/J_c(T) \) and \( P_2 = P_2J_c^T(T)/J_c(T) \), which represent the δl and the δTc pinning effects, respectively, with \( P_1 + P_2 = 1 \). 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, δTc 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 δTc pinning mechanisms are shown in Fig. 4. Both δl and δTc 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 δTc 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 Ba0.72K0.28Fe2As2 single crystal. At temperatures close to the critical temperature, however, there is evidence for the δTc pinning, while at higher magnetic fields, the δl pinning mechanism is the only effect.

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