Very strong intrinsic flux pinning and vortex avalanches in (Ba, K)Fe2As2 superconducting single crystals

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Abstract
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Keywords
Very, strong, intrinsic, flux, pinning, vortex, avalanches, Fe2As2, superconducting, single, crystals

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Very strong intrinsic flux pinning and vortex avalanches in (Ba,K)Fe$_2$As$_2$ superconducting single crystals

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We report that the (Ba,K)Fe$_2$As$_2$ crystal with $T_c=32$ K shows a pinning potential, $U_p$, as high as $10^4$ K, with $U_0$, showing very little field dependence. The (Ba,K)Fe$_2$As$_2$ single crystals become isotropic at low temperatures and high magnetic fields, resulting in a very rigid vortex lattice, even in fields very close to $H_c_2$. The isotropic rigid vortices observed in the two-dimensional (2D) (Ba,K)Fe$_2$As$_2$ distinguish this compound from 2D high-$T_c$ cuprate superconductors with 2D vortices. The vortex avalanches were also observed at low temperatures in (Ba,K)Fe$_2$As$_2$ crystal. It is proposed that it is the K substitution that induces both almost isotropic superconductivity and the very strong intrinsic pinning in the (Ba,K)Fe$_2$As$_2$ crystal.

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A high critical current density, $J_c$, upper critical field, $B_{c2}$, and irreversibility field, $B_{irr}$, a high superconducting transition temperature, $T_c$, strong magnetic-flux pinning, good grain connectivity, and isotropic superconductivity are the major physical requirements for superconducting materials used in practical applications operating at low and, in particular, high magnetic fields. The conventional low-$T_c$ superconductors, where $H_{c2}$ is also small, can only carry large $J_c$ at very low temperatures. The cuprate high-$T_c$ superconductors suffer from 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 $T_c$ of 39 K, $B_{c2}$ is far below $H_{c2}$, and $J_c$ drops quickly with both field and temperature, preventing its use above 20 K. The newly discovered Fe-based superconductors$^{1–7}$ show $T_c$ as high as 55 K and $B_{c2}$ above 200 T, in combination with a small anisotropy for KFeAsO$_{1–x}$F$_x$ (RE-1111 phase, with RE a rare-earth element)$^8$ and an almost isotropic superconductivity for (Ba,K)Fe$_2$As$_2$ (122 phase).$^9$ 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 and the behavior of the vortex matter. Therefore, the determination of their intrinsic vortex pinning strength is a central issue from both an applied and a fundamental perspective. Both 1111 and 122 phase compounds have typical two-dimensional (2D) crystal structures. In RE1111 phase, where RE is a rare-earth element, the FeAs superconducting layers are separated by insulating LaO layers$^{10}$ while in Ba(K)-122 phase, the FeAs layer is sandwiched between conductive Ba layers.$^5$ It is expected that the 122 phase containing two FeAs layers would have small anisotropy and thus higher intrinsic pinning compared to the single layer 1111 phase. Co-doped BaFe$_2$As$_2$ single crystal shows an anisotropy of 1–3 and upper critical-field values of $B_{c2}(B||ab)=20$ T and $B_{c2}(B||c)=10$ T at 20 K, with $dB_{c2}/dT=5$ T/K.$^1$ For single crystals of the optimally doped Ba(Fe$_{1−x}$Co$_x$)$_2$As$_2$ with $x=0.074$ and critical temperature $T_c=23$ K, the anisotropy of the upper critical field, $y=B_{c2}^{||}/B_{c2}^{ab}$, is in the range of 2.1–2.6, and the critical current density, $J_c$, is over $10^5$ A/cm$^2$ and 3×$10^5$ A/cm$^2$ at 5 K for $B||ab$ and $B||c$, respectively.$^1$ The $B_{c2}$ of (Ba$_{0.55}$K$_{0.45}$)Fe$_2$As$_2$ measured under pulsed magnetic fields exceeds 60 T at 14 K.$^9$ The anisotropy of $B_{c2}$ is moderate (~3.5 close to $T_c$), and it drops with decreasing temperature, becoming isotropic at low temperatures.$^9$ Underdoped BaFe$_2$As$_2$ with $T_c$ of 25 K shows an anisotropy of 3–4.$^{12}$

Another important issue for practical applications is the occurrence of magnetic-flux jumps, which generally occur in larger samples with high critical current densities. Magnetic flux jumps have been observed in thin-film forms of some type II superconductors, such as Nb$_3$Sn (Ref. 13) and MgB$_2$. However, flux jumps have not yet been reported in any Fe-based superconductors so far.

In this paper, we report that the vortex lattice in (Ba,K)Fe$_2$As$_2$ crystals appears to be quite rigid, with pinning potentials as high as $10^4$ K which show only weak-field dependences up to 10 T. The rigid three-dimensional (3D) vortex lattice in the two-dimensional (Ba,K)Fe$_2$As$_2$ seems to differ from the two-dimensional high-$T_c$ cuprate superconductors with their more 2D pancakelike vortex lattices. Flux jumps were observed in one of our large samples at low temperature. The very strong intrinsic supercurrent carrying ability and flux pinning observed in the (Ba,K)Fe$_2$As$_2$ superconducting single crystals make this compound very promising for future applications in high magnetic fields.

The 122 crystals used in the present work was grown

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using a flux method. High purity elemental Ba, K, Fe, As, and Sn were mixed in a mol ratio of (Ba_{1-x}K_x)Fe_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. 15.

The electrical resistance $R$ versus temperature curves of a Ba$_{0.72}$K$_{0.28}$Fe$_2$As$_2$ crystal for magnetic fields up to 13 T, applied parallel to the $ab$ plane and to the $c$ axis, are shown in Fig. 1. The resistance starts to drop toward zero at $T=31.7$ K in zero magnetic field, indicating that the crystal is not optimally doped.\textsuperscript{16} It can be seen that the onset of $T_c$ decreases with increasing magnetic field very similar to $T_c(R=0)$, such that the transition width $\Delta T_c$ remains almost constant for both $B\parallel ab$ and $B\parallel c$ [see the inset in Fig. 1(a)]. When the field changes from 0 up to 13 T, the shape of $R(T)$ changes very little. This behavior is reminiscent of the magnetotransport behavior of conventional low-$T_c$ superconductors and significantly different from that of cuprate high-$T_c$ superconductors. In cuprate high-$T_c$ superconductors, the $T_c$ onset temperature does not change much but the $T_c(R=0)$ shifts to low temperature very quickly with field. The field-independent transition width $\Delta T_c$ is also quite different from what is observed in NdFeAsO$_{0.8}$F$_{0.8}$ single crystals, which show a broadening of $T_c(R=0)$ as the field increases.\textsuperscript{8} In the following we define the temperature-dependent upper critical field $B_{c2}(T)$ by $R(T,B_{c2})=0.9R_n$, where $R_n$ is the normal-state resistance just above the onset of $T_c$. In a similar way we define the irreversibility field $B_{irr}(T)$ by $R(T,B_{irr})=0.1 R_n$. The $B_{c2}$ and $B_{irr}$ obtained for both $B\parallel ab$ and $B\parallel c$ are denoted as $B_{c2}^{|ab|}$, $B_{c2}^{|c|}$, $B_{irr}^{|ab|}$, and $B_{irr}^{|c|}$, respectively.

It can be seen from Fig. 2 that the $B_{c2}$ values for the (BaK)Fe$_2$As$_2$ are quite large ($B_{c2}^{|ab|}=13$ T at 30.7 K and $B_{c2}^{|c|}=13$ T at 29 K). The slope $dB_{c2}/dT$ is $-7.5$ and $-4.4$ for the $ab$ and the $c$ directions, respectively, for our Ba$_{0.72}$K$_{0.28}$Fe$_2$As$_2$ crystal. From Fig. 2, one can see that $B_{irr}$ is very close to $B_{c2}$ in both field directions, indicating that flux lattice melting in our the (Ba, K)Ba$_2$As$_2$ crystals seems to occur only over a relatively small area of the $B$-$T$ phase diagram.
and Y-123 (Ref. 21) single crystals in Fig. 4, even though their $T_c$'s are different.

It has been reported that the pinning potential of bismuth strontium calcium copper oxide (BSCCO) crystals exhibits a power-law dependence on magnetic field, $U_0(B) \propto B^{-n}$, with $n=1/2$ for $B<5$ T and $n=1/6$ for $B>5$ T for $B||c$.$^{20,22}$ However, for the (BaK)Fe$_2$As$_2$ crystal, $U_0$ drops very slowly with field as $B^{-0.09}$ and $B^{-0.13}$ for $B||ab$ and $B||c$, respectively (Fig. 4). This means that $U_0$ is almost field independent, which is a remarkable result. The values of $U_0$ for (Ba,K)Fe$_2$As$_2$ are three to four times larger than that of Bi-2212 (Ref. 21) and about ten times larger than that of Bi-2223 (Ref. 17) crystals. These values are also more than three times larger than those for NdO$_{0.35}$Fe$_{1.18}$FeAs$_3$. Also, the $U_0$ for our (Ba,K)Ba$_2$As$_3$ crystal is about one order of magnitude higher than that of Y-123 crystals for fields above 1 T.$^{18}$ Thus the value of $U_0(B)$ of our (Ba,K)Fe$_2$As$_2$ single crystal is of record high compared to any other superconductor in single-crystal form.

It should be noted that the pinning potential of the (BaK)Fe$_2$As$_2$ crystal is almost field independent for the field range we have measured from 0 up to 13.5 T. However, it is expected that the $U_0$ should behave differently with field for higher fields, in particular, for fields close to $H_c$. Further study on the $U_0$ for the doped BaFe$_2$As$_2$ in higher fields is necessary.

A small (Ba,K)Fe$_2$As$_2$ single crystal in the shape of a long thin strip, obtained by cleaving along the $ab$ plane, was investigated using magneto-optical imaging. The left inset in Fig. 5 is a magneto-optical image of the flux penetration into the sample, which was collected while applying a perpendicular field of 50 mT at 20 K. It is evident that the sample is of high uniformity, i.e., without any microcracks or weak links perturbing the flow pattern of the shielding current. Such regular flux patterns allow precise measurements of the critical current density $J_c$ using the Bean critical state model formula for partial penetration in long thin strip geometry,$^{23}$

$$\cosh(\pi H / J_c d) = w / (w - 2a),$$

where $a$ is the advancement of the flux front into the strip at an applied field $H$, and $w$ and $d$ are the width and thickness of the strip, respectively. The obtained values for $J_c$ in the temperature range 10–25 K are plotted in the right inset of Fig. 5.

Magnetization loops (Fig. 6) were collected for a relatively large (Ba,K)Fe$_2$As$_2$ single crystal (4.2 x 2.85 x 0.15 mm$^3$) at different fields $B||c$ and temperatures down to 5 K. The $J_c$ was obtained from the width $\Delta M$ of the magnetization loop using the Bean model, where for full sample penetration

$$J_c = 20\Delta M w (1 - \sqrt{3}l).$$

Here $l$ is the length of the sample. The resulting $J_c$ versus applied field is plotted in Fig. 5. For $B<4.5$ T and $T<10$ K the $J_c$ is larger than 10$^5$ A/cm$^2$. The slow decrease in $J_c$ with increasing field seems to correlate with the weak-field dependence of the pinning potential $U_0$. At 5 K, the $J_c$ value is 2.7 x 10$^5$ A/cm$^2$ at $B=2$ T, and it only decreases to 2.2 x 10$^5$ A/cm$^2$ at $B=4$ 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 a superior
the lattice imperfections may act as intrinsic pinning centers in the Fe-based superconductors. It has been reported that for the (Ba,K)Fe$_2$As$_2$ crystal, which implies that the strength of the superconductivity is not uniform throughout the FeAs planes. The inhomogeneous superconducting strength may act as a source of pinning centers once magnetic flux exists inside the superconductor.

The nearly isotropic superconductivity as indicated in the inset of Fig. 2, correlates well with the observed large critical current densities and large $U_0$ values in our (Ba,K)Fe$_2$As$_2$ single crystals. In NdO$_{0.82}$Fe$_{0.18}$As the pinning potential was found to be smaller, $U_0=2000$–3000 K. This might be understood in terms of the stronger superconducting coupling between the FeAs superconducting layers in the FeAs-122 phase compared to the FeAs-1111 phase. In the FeAs-122 phase, there are two superconducting FeAs layers, and the coupling between the superconducting layers is stronger than in the FeAs-1111 phase, which results in nearly isotropic superconductivity as well as in a more 3D vortex lattice.

In conclusion, we found that the (Ba,K)Fe$_2$As$_2$ crystal shows very high intrinsic flux-pinning strength, almost field independent high values of critical current density, high pinning potential of 10$^3$ K, high $H_{c2}$, high $H_{c1}$, and low values of anisotropy of 1–3. The obtained $U_0$ values are record high compared to any existing superconducting single crystal. The isotropic rigid vortices observed in the two-dimensional (Ba,K)Fe$_2$As$_2$ distinguish this compound from high-$T_c$ cuprate superconductors such as BSCCO where layers of 2D pancake vortex lattices interact relatively weakly with each other.

In high magnetic fields.

FIG. 7. High-resolution TEM image of a Ba$_{0.75}$K$_{0.25}$Fe$_2$As$_2$ crystal. The insets contain (a) a SEM image of the crystal surface and (b) an electron-diffraction pattern along the (001) direction.

The very strong intrinsic supercurrent carrying ability and the very strong intrinsic pinning in the 122 compounds.

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