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Recommended Citation

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Giant magnetic flux jumps in single crystals of $Ba_{0.6}K_{0.4}Fe_2As_2$

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Giant magnetic flux jumps are observed in magnetic hysteresis loops of $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals. The size of the flux jumps, which appear only at low temperatures ($T < 4$ K), is so large that it can transform the whole superconducting state into the normal state. The recovery rate to the superconducting state is rather slow, although the superconducting state is almost fully recovered. We show that theoretical predictions based on the adiabatic approach with nonlocal electrodynamics give a good explanation of the flux jumps observed in the single crystals of $Ba_{0.6}K_{0.4}Fe_2As_2$. © 2011 American Institute of Physics. [doi:10.1063/1.3586777]

Flux jumps in superconductors are quite an interesting phenomenon and have been observed in thin films of many superconductors, such as MgB_2,[1,2] Nb,[3] Nb alloys,[4] YNi_2B_2C,[5] and $YBa_2Cu_3O_{7-x}$.[6] Direct observation of flux jumps by magneto-optical imaging shows magnetic avalanches in thin films with dendritic or fingerlike patterns on a macroscopic scale inside the superconductors. Mostly, this phenomenon appears in the low field and low-temperature regime in the superconducting state. At high temperatures and high magnetic fields, vortex penetration occurs rather gradually, and vortex avalanches are not expected. The origin of this phenomenon is known to be the thermomagnetic instability which is induced by the positive feedback effect of vortex penetration into the superconductor combined with the sudden redistribution of the Abrikosov vortices inside the superconductor.[1] In particular, when the diffusion of magnetic flux is much higher than the diffusion of heat, a superconductor becomes thermally unstable. Ironically, its high critical current density generates substantial amounts of Joule heat by the fast invasion of the vortices and produces the local normal path which subsequently induces the penetration of the vortices in the form of a vortex jump. Although flux jumps were reported to exist in $Bi_2Sr_2CaCu_2O_{8+\delta}$,[7] the occurrence of the vortex jumps is still very rare in polycrystalline superconductors. It was reported that the flux jumps were observed in the special case of YNi_2B_2C single crystals,[8] in which the flux jump was accompanied by a change in the local symmetry of the vortex lattice from low field rhombohedral to high field rhombohedral. This sudden change in the vortex lattice symmetry might be accompanied by local heating, thus triggering the flux jump. In this sense, the origin of the flux jumps in YNi_2B_2C single crystals may not be exactly the same as that of the vortex jumps in other types of superconducting thin films.

In this letter, we report the observation of giant flux jumps in an optimally doped $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystal, which is the only compound that exhibits the flux jumps in single crystals,[9] due to its very high intrinsic flux pinning strength, except for the special case of YNi_2B_2C. We studied single crystals of $Ba_{0.6}K_{0.4}Fe_2As_2$ at temperatures below 4 K. We find that flux jumps appear more closely spaced as the temperature becomes lower and the field sweep rate becomes higher in M-H loops. We further observe that once a flux jump happens, this phenomenon occurs very fast. Also, the size of the flux jumps is large enough to drive the whole superconducting state in a single crystal into the normal state. In this respect, the flux jumps observed in this work differ from those in $Ba_{0.72}K_{0.28}Fe_2As_2$ crystal[9] with flux jumps observed at $T = 5$ K and those in the superconducting thin films, in which vortex invasion is very limited in the sample. We also find that the recovery rate from a flux jump is very slow, which indicates that the vortices invading the superconductor resist being expelled until M-H curve has almost fully recovered to the superconducting state.

The single crystals of $Ba_{0.6}K_{0.4}Fe_2As_2$ were prepared by the high-temperature self-flux method. The detailed procedure of crystal growth is described in Ref. 10. The superconducting transition temperature, T_c, of the single crystal was 37 K. The dimensions of the sample were $2.0 \times 1.5 \times 0.12$ mm³. The M-H loops were collected with a field sweep rate of 1–70 mT/s by using a superconducting quantum interference device-vibrating sample magnetometer (SQUID-VSM, Quantum Design) with the applied field parallel to the c axis ($H \| c$) between −7 and 7 T.

Figure 1 shows the magnetization hysteresis loops measured at different temperatures for the field sweep rate of 5 mT/s for fields from −7 to 7 T. We draw magnetization loops up to the fifth quadrant curves, since the first quadrant curves usually show fewer flux jumps due to the barrier against the first jump near the lower critical field H_{c1}. The full hysteresis loop at 2 K shows four large-scale flux jumps, while no flux jumps are observed at 4.5 K, and only one flux jump is
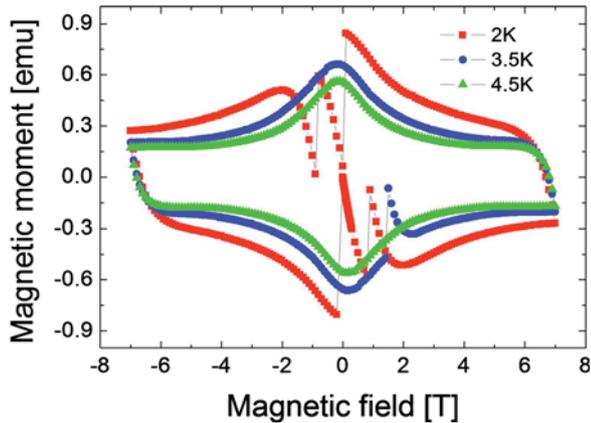
FIG. 1. (Color online) Magnetization hysteresis loops at 2, 3.5, and 4 K at a field sweep rate of 5 mT/s.

observed at 3.5 K, which implies that the flux jumps are limited to low temperature. We note that the field of the first flux jump (H_{fj}) at 2 K is around 1 T, which is orders of magnitude larger compared to the case of thin films. This implies that it is very difficult to achieve the instability condition in a single crystal specimen.

In addition to the flux jumps at such a large field of ~1 T, it is also surprising to observe the large size of the flux jumps in this single crystal. As seen in Fig. 1, each flux jump drives the entire superconducting state into the normal state with $M=0$. This is in sharp contrast with the flux jumps in the superconducting thin films, in which vortex invasion is very limited. Our observations show that this phenomenon occurs so fast that the SQUID-VSM can pick up the data only before and after the flux jump, even at the fastest sweep rate (~70 mT/s) in our measurements. However, the recovery of the superconducting state from the $M=0$ state is quite slow, but once it has recovered, invading flux is almost fully expelled. This has never been observed in superconducting thin films.

Figure 2 shows the M-H curves at 2 K with a sweep rate of 5 mT/s for two different measurements. The two measured M-H curves are different; the first measurement shows four flux jumps while the second shows only two flux jumps. This implies that flux jumping is a stochastic phenomenon which shows different patterns at each measurement for the same sample under the same external conditions.
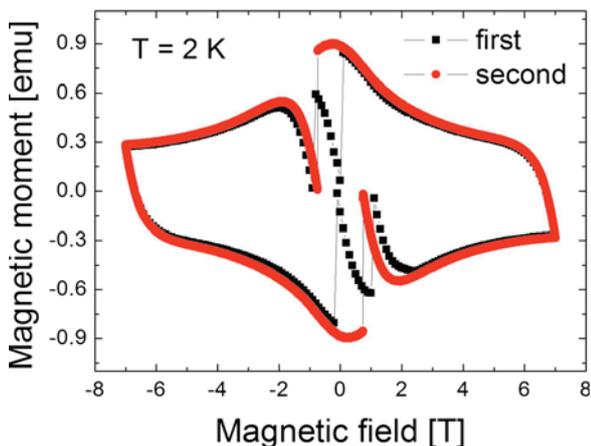
FIG. 2. (Color online) Magnetization hysteresis curves measured at 2 K with a sweep rate of 5 mT/s for two different measurements.
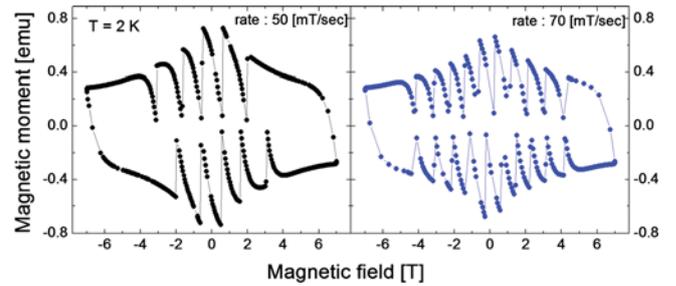
FIG. 3. (Color online) Magnetization hysteresis loops at 2 K for the field sweep rates of 50 mT/s and 70 mT/s, respectively.

We also increased the field sweep rate up to 70 mT/s. Figure 3 shows that different sweep rates of the magnetization hysteresis at the same temperature result in different patterns of flux jumps. As the field sweep rate is increased, the activity of the flux jumps becomes enhanced, and the flux jumps appear more closely spaced.

The flux jump is an avalanche phenomenon that takes place when the first penetration of vortices induces subsequent vortex motion. It occurs when the magnetic diffusion rate is faster than the thermal diffusion rate in the superconductor.[11] When the applied field is increased to a certain critical value, the Lorentz force at a local point inside the superconductor exceeds the vortex pinning force, and lines of magnetic vortices move suddenly into the superconductor, thus triggering a flux jump. This flux jump does not proceed when the energy dissipated by the flux jump is rapidly absorbed by the superconducting sample. In our single crystals, the energy dissipated is so large that the full superconducting state can be driven into the normal state.

The question then arises whether magnetic instability of the $Ba_{0.6}K_{0.4}Fe_2As_2$ crystal has the same origin as in the thin films or not. Since the thickness of our sample used in this experiment is much smaller than the width of the sample, we treat our sample in the thin film limit and apply the formula based on the adiabatic approach with nonlocal electrodynamics.[12,13] The first flux jump field, H_{fj}, from thermomagnetic origin, is explained as follows:[13]

$$H_{fj} = \frac{J_c d}{\pi}\cosh^{-1}\left(\frac{w}{w - l^*}\right), \tag{1}$$

$$l^* = \frac{\pi}{2}\sqrt{\frac{\kappa}{|J_c'|E}}\left(1 - \sqrt{\frac{2h_0}{nd|J_c'|E}}\right)^{-1}. \tag{2}$$

Here, we assume that the thickness d is much smaller than half of the sample width w. The parameter $n \gg 1$ implies a strongly nonlinear current-voltage characteristic of the superconductor with the relation of $E \propto J^n$. We set n to be 30, which is a commonly used value. For our sample we use the thermal conductivity, κ, at 2 K of 0.45 W/Km.[14] The temperature dependence of the critical current density is given by $J_c(T) = J_{c0}(1 - T/T_c)$, where we estimate J_{c0} as 8 $\times 10^9$ A/m^2 from Bean's critical state model. The heat transfer coefficient to the surrounding environment, h_0, is taken to be $10^4(T/T_c)^3$ W/K m^2.[15] The induced electric field E in the formula is fitted to our experimental results, yielding $E = 2.2(1.8)$ mV/m at the field sweep rate of 70 (50) mT/s, under the assumption that a fast sweep rate generates a higher electric field. Using the above parameters, we obtain H_{fj} as 0.83 T at 70 mT/s and 1.02 T at 50 mT/s, which is in

good agreement with experimentally observed first jump fields, 0.84 T (1.03 T) at 70 mT/s (50 mT/s).

Such a good agreement reveals that the magnetic flux jumps observed in our $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystal belong to the same class as the vortex jumps that are mostly observed in thin films, even though the H_{fj} values are orders of magnitude different. The high value of H_{fj} in the single crystal can be also explained by the geometric effect due to the larger thickness in a single crystal. Since d is much larger in the single crystals than in the thin films, we can see from Eq. (2) that H_{fj} in the single crystals becomes much larger than in the thin films.

In conclusion, we have observed giant magnetic flux jumps in single crystal $Ba_{0.6}K_{0.4}Fe_2As_2$ superconductor. The flux jumps appear at low temperatures below 4 K. The number of flux jumps depends on the sweep rate, and they occur more frequently at a higher field sweep rate. The size of the flux jumps is large enough that the whole superconducting state can be transformed into the normal state. The recovery rate of the superconducting state is quite slow, but once it has recovered, the invading flux vortices are almost fully expelled outside the superconductor. The critical state model based on the adiabatic approach with nonlocal electrodynamics was applied to explain this magnetic instability.

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