Critical current densities and force-displacement characteristics of fluxoids in Ba$_{1-x}$K$_x$Fe$_2$As$_2$ single crystal

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Abstract

The superconducting Ba$_{1-x}$K$_x$Fe$_2$As$_2$ ($x = 0.4$) single crystals were prepared by the so-called FeAs self-flux method. The critical temperature by ac susceptibility measurement was estimated to be about 36 K. The magnetic field and temperature dependences of critical current densities were investigated by an ac inductive measurement (Campbell’s method). Unlike the phenomenon of co-existence of the global and local critical current densities observed in many polycrystalline Fe-based superconducting pnictides, it was found that only a uniform critical current density ($J_c$) flows through the whole sample. The value of $J_c$ at 20 K and 1 T was about $5 \times 10^8$ A/m$^2$, which is much smaller than the local critical current density observed in polycrystalline samples. The force-displacement characteristic of fluxoids in sample was investigated. The Labusch parameter was found to increase monotonously with increasing magnetic field, while the interaction distance was proportional to the fluxoid spacing. These results are consistent with the prediction based on a simple flux pinning mechanism.

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Keywords: Ba-122 single crystal; critical current density; flux pinning; Labusch parameter, interaction distance

1. Introduction

As a kind of novel materials, Fe-based superconducting pnictides bring a great attention to not only their physical properties but also their potential capabilities for applications, since Kamihara et al. discovered first superconducting pnictide of LaFeAsO [1]. It is largely expected for its applications
operating at high magnetic field and large current transportation, since the critical temperature is as high as 55 K and the upper critical field is above 200 T for REFeAsO$_{1-x}$F$_x$ (1111-type, with RE a rare-earth element), the superconductivity is almost isotropic for AEFe$_2$As$_2$ (122-type, with AE an alkaline-earth element). However, in spite of pretty high intra-grain critical current density in the polycrystalline of these materials, the transport critical current density still remains at an extremely low level. This is considered to be mainly caused by the significant granularity and poor electrical connectivity in polycrystalline bulks [2]. Therefore as the first step, it is important to enhance the connectivity between grains and the transport critical current properties in polycrystalline pnictides. In fact, some attempts of wire fabrication by the Power-in-Tube process have been carried out [3, 4] by adopting these enhancements. Recently, the transport critical current density in self-field in a (Ba,K)Fe$_2$As$_2$ wire was reported to achieve a value of 1.01×10$^8$ A/m$^2$ at 4.2 K [4].

Nevertheless, in these polycrystalline wires and bulks much of the response comes from extrinsic factors, such as inferior granularity and significant disruption of current path between the grains. These factors usually don’t have an immediate and intrinsic connection with the critical current density. To study intrinsic magnetic properties and flux pinning mechanism that can be related directly to critical current characteristics, single crystals is one of the best choice. Fortunately, many kinds of Fe-based pnictides single crystals can be successfully fabricated nowadays. The quality of single crystals is improved significantly, so that the study on many superconductive properties and substantial flux pinning characteristics can be carried out without paying much attention to those purposeless extrinsic factors.

In this study, we aim to investigate the critical current characteristics and flux pinning properties in (Ba,K)Fe$_2$As$_2$ single crystals. The fluxoid motion in the pinning potential well is discussed by means of analysing the Labusch parameter and the interaction distance, which reflect the strength of pinning interaction and the radius of the averaged pinning potential well, respectively.

2. Experiments

2.1. Sample preparation

Single crystals of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ ($x = 0.4$) were grown by the so-called FeAs self-flux method. Stoichiometric amount of Ba filings, Fe powder, As and K pieces were ground in Ar atmosphere for more than 6 hours using the ball milling method. An alumina crucible containing the starting materials was put into a commercial stainless steel tube. Tight sealing was accomplished by two caps also made of stainless steel which were welded to the both ends of the tube by argon-arc welding. The sealed stainless steel tube was placed into a tube furnace and heated up to a high temperature (above 1100 °C) so that the starting materials melted completely. Then it was cooled down to the temperature below 1000 °C at a very slow speed, followed by a furnace-cooling simply by powering off. Further experimental details were described in the reference [5].

2.2. Analysis method

In this study, the critical current densities and the force-displacement characteristics of the flux lines were measured and estimated by the Campbell’s method [6, 7]. In this method, an external dc magnetic field ($B$) and a small ac magnetic field ($b_{ac}$) are applied parallel to a superconducting long slab or cylinder. By measuring the ac flux moving into and out of the sample with a pick-up coil, the penetrated ac flux ($\phi$) correspond to the amplitude of ac magnetic field can be obtained and usually shows a $b_{ac}$ dependence as shown in Fig. 1 (a) by the dashed line. Then the penetration depth of the ac flux ($\lambda'$) from the surface of the sample is given by
\[ \lambda' = \frac{1}{2w} \frac{\partial \phi}{\partial b_{ac}}, \tag{1} \]

where \( w \) is the width of the wide surface if the sample is in slab shape (supposing that the width is sufficiently larger than the thickness). \( \lambda' \) vs. \( b_{ac} \) is usually obtained as that shown in Fig. 1 (a) by the solid line. It shows a gradually increasing of ac flux penetration into sample with an increasing ac magnetic field, followed by a saturation when ac flux reaches the center of the sample. According to the Bean-London model, the slope of increasing part of \( \lambda' \) vs. \( b_{ac} \) gives the critical current density \( (J_c) \) in sample as

\[ \frac{\partial \lambda'}{\partial b_{ac}} = \frac{1}{\mu_0 J_c}. \tag{2} \]

Based on the analysis in reference [6], the displacement of flux lines \( (u) \) and their restoring force density \( (F_r) \) are derived as

\[ u = \frac{\phi}{2Bw}, \quad F_r = \frac{Bb_{ac}}{\mu_0 \lambda'}, \tag{3} \]

respectively. The Labusch parameter \( (\alpha_L) \) is determined from the slope of \( F_r \) vs. \( u \) curve in small displacement region, i.e., in the regime of reversible fluxoid motion. The interaction distance \( (d_i) \) is calculated using the equation of \( \alpha_L d_i = J_c B \) as shown in Fig. 1 (b).

Fig. 1. Illustrations of (a) ac magnetic field dependence of penetrated ac flux (dashed line) and penetration depth of ac flux (solid line) from the sample’s surface; (b) fluxoid displacement vs. restoring force density with \( \alpha_L \) and \( d_i \) denote the Labusch parameter and the interaction distance, respectively.

2.3. Measurements

For the measurements in this study, the sample was formed into a slab with a typical size of 8.0 mm × 2.5 mm × 0.20 mm. The critical temperature \( (T_c) \) of sample was estimated by a measurement of ac susceptibility, and was obtained as to be 36.2K. In Campbell’s method measurement, the temperature of sample was varied within the range of 10 – 35 K, while the dc magnetic field was up to 7 T. The
frequency and the maximum amplitude of the ac magnetic field were 97 Hz and 10 mT, respectively. Both $B$ and $b_{ac}$ were applied parallel to the wide surface of the sample, i.e., parallel to the $ab$ plane of the single crystal.

3. Results and Discussion

3.1. Critical current density

Figure 2 shows the magnetic field dependence of the critical current densities ($J_c$’s) at several temperatures. Unlike the situation in many polycrystalline Fe-based pnictides, in which both the large local (intra-grain) and the small global (inter-grain) critical current densities are observed, $J_c$ in the single crystal used in this study shows a fairly good homogeneity, i.e., no concurrent global and local $J_c$’s were observed. The result implies that there are no apparent obstacles in the supercurrent path, such as the problems of granularity and the electrical connectivity reported in other polycrystalline systems. On the other hand, the value of $J_c$ seems to be much small comparing with those observed in polycrystalline samples. Our previous data obtained in a bulk of Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$+10% Pb polycrystalline system were also shown in Fig. 2. The value of local $J_c$ in that sample shown by the dashed line is one order of magnitude larger than the $J_c$ observed in this study. The differential in $J_c$ may be considered to be caused by the dissimilarity of flux pinning mechanism between these two kinds of materials.

At lower temperature regions, a peak effect (fishtail phenomenon) can be seen in Fig. 2 (because of the limitation of applied $b_{ac}$, the $J_c$ at $B > 2$ T and $T = 11$ K could not be obtained). This phenomenon has been observed in some other Fe-based pnictides [8, 9]. Furthermore, similar phenomena were also reported in many cuprate single crystal superconductors so far. It was pointed out that the peak effect in Fe-based pnictides is caused by a crossover from the elastic collective creep to the plastic vortex creep [10], while another report insists that it associates with the structural phase transition from a rhomb lattice at low field to a square lattice above a transition field [11]. Further investigation may be necessary.

Fig. 2. Magnetic field dependence of the critical current densities at several temperatures. A peak effect clearly appears at 11K. For the comparison with polycrystalline systems, the local $J_c$ previously obtained in a bulk of Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$+10% Pb polycrystalline is also shown by the dashed line, and it turned out to be one order of magnitude larger than that in single crystal.
3.2. Force-displacement characteristics

The magnetic field dependence of Labusch parameter and the interaction distance at several temperatures were shown in Fig. 3 (a) and (b) respectively. Solid lines in Fig. 3 (a) show the approximations of each experimentally obtained $\alpha_L$ with the relationships of $\alpha_L \propto B^{3/2}$, while the solid line in Fig. 3 (b) denotes the calculated values proportional to the fluxoid spacing ($a_f$). Supposing that only single kind of dominant flux pinning centers exists and other factors, e.g., the peak effect and the disruption of current path, do not affect $J_c$ very much, $d_i$ is expected to be simply proportional to $a_f$ [12]. Excepting those in lower temperatures and higher magnetic field regions, where the peak effect or the influence from the irreversibility field becomes apparently, our experimentally obtained $d_i$ shows a fairly good agreement with the theoretical predication. If we assume that $d_i = \alpha_f / \zeta$, where $\zeta$ is defined as a constant, then we can obtain $\zeta \approx 5$ from Fig. 3 (b). It is empirically known in some conventional superconductors that the value of $\zeta$ varies from 4 to 30 [6, 13], and the theoretical estimate [14] gives $d_i = \beta a_f / 4$ where $\beta < 1$ for the case of low pin concentration. Supposing that the pinning mechanism in our sample is similar to those in conventional superconductors, i.e., a kind of condensation energy interaction plays a dominant role in flux pinning, the value of $\zeta$ obtained in this study can be regarded as a reasonable result. Since we have the relationship of $\alpha_L d_i = J_c B$, if $J_c$ does not altering largely with the alteration of $B$, the Labusch parameter can be simply derived as $\alpha_L \propto B^{3/2}$, which fits our experimental data fairly well in Fig. 3 (a). The result implies that the flux pinning mechanism in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal can be explained with conventional flux pinning theory, although it is not yet clear that what the dominant pinning center is in our sample.

![Fig. 3. Magnetic field dependence of (a) the Labusch parameter and (b) the interaction distance. Solid lines in (a) show the approximations of each experimentally obtained $\alpha_L$ with the relationship of $\alpha_L \propto B^{3/2}$, while the solid line in (b) denotes the calculated values proportional to $a_f$.](image)

4. Conclusion

In this study, we investigated the magnetic field and temperature dependences of critical current densities and the force-displacement characteristics by the Campbell’s method. It was found that only a uniform critical current density flows through the whole sample, quite different from those results of co-
existence of the global and local critical current densities observed in many polycrystalline Fe-based superconducting pnictides. However, the value of $J_c$ is much smaller than the local critical current density observed in polycrystalline samples, implies a dissimilarity of flux pinning mechanism between these two kinds of materials. The Labusch parameter and the interaction distance were found to be well consistent with the theoretical prediction based on a simple flux pinning mechanism.

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