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Doping – Dependent irreversible magnetic properties of $Ba(Fe_{1-x}Co_x)_2As_2$ single crystals

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ABSTRACT

We discuss the irreversible magnetic properties of self-flux grown $Ba(Fe_{1-x}Co_x)_2As_2$ single crystals for a wide range of concentrations covering the whole phase diagram from the underdoped to the overdoped regime, x = 0.038, 0.047, 0.058, 0.071, 0.074, 0.10, 0.106 and 0.118. Samples were characterized by a magneto-optical method and show excellent spatial uniformity of the superconducting state down to at least the micrometer scale. The in-plane properties are isotropic, as expected for the tetragonal symmetry, and the overall behavior closely follows classical Bean model of the critical state. The field-dependent magnetization exhibits second peak at a temperature and doping – dependent magnetic field, $H_p(T,x)$. The evolution of this fishtail feature with doping is discussed. In particular we find that H_p, measured at the same reduced temperature for different x, is a unique monotonic function of the superconducting transition temperature, $T_c(x)$, across all dopings. Magnetic relaxation is time-logarithmic and unusually fast. Similar to cuprates, there is an apparent crossover from collective elastic to plastic flux creep above H_p. At high fields, the field dependence of the relaxation rate becomes doping independent. We discuss our results in the framework of the weak collective pinning and show that vortex physics in iron-based pnictide crystals is much closer to high-T_c cuprates than to conventional s-wave (including MgB_2) superconductors.

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1. Introduction

Superconductivity was recently discovered in polycrystalline $LaFeAsO_{1-x}F_x$ with a zero – field transition temperature of $T_c \approx 23$ K [1]. This breakthrough was followed by the realization of even higher T_c values, as high as 55 K in $RFeAsO_xF_y$ ("1111" system with R = Nd, Sm, Pr) [2–5]. Soon after, superconductors based on the parent AFe_2As_2 system (abbreviated as "122", here A is an alkaline earth element, A = Ca, Sr, Ba) with T_c up to 38 K were synthesized [6]. With such relatively high transition temperatures and an apparent chemical diversity, these iron-based pnictide superconductors have attracted much attention [7,8]. In the 122 system, either the A or Fe sites can be doped to achieve superconductivity with holes or electrons as carriers.

There is an important difference between these two classes of pnictide superconductors. While single crystals of the oxygen-based 1111 system are very difficult to grow and they are still very small, large high-quality flux-grown single crystals of the oxygen-free 122 are available [9–11]. Studying single crystals is very important to determine the baseline properties of these materials unaffected by the extrinsic factors associated with polycrystalline materials, such as grain boundaries, morphological defects and uncertainty in the sample volume and internal structure. These factors often dominate the macroscopic electromagnetic response of the samples.

Thermodynamic, transport and electromagnetic properties of the 122 crystals have been studied in detail in many publications [9–24] (and references therein). Recently, we have focused on the systematic study of the London penetration depth, $\lambda(T)$, in $Ba(Fe_{1-x}Co_x)_2As_2$ ("FeCo-122") with various cobalt doping levels, x [13,14] (see also this special issue of Physica C). To our surprise, we have found an almost universal unconventional behavior of the low-temperature variation of $\lambda(T) \propto T^n$ with the exponent n varying from 2 in the underdoped regime to about 2.5 in the overdoped regime. In addition, an indication of a sudden decrease in the superfluid density below optimal doping was found. Furthermore, in the FeCo-122 system, the underdoped samples also exhibit structural/magnetic transitions at temperatures above T_c [10]. A detailed study of the vortex properties performed on nearly optimally doped (x = 0.074) single crystals found a great deal of similarity between this material and clean high-T_c cuprates. In particular, a fishtail feature (first reported for $(Ba_{1-x}K_x)Fe_2As_2$, "BaK-122", system with x = 0.4 [21]), very fast time-logarithmic magnetic relaxation

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and an apparent crossover from collective elastic to plastic creep [17]. With all these observations, the natural question is how do the vortex properties evolve when the doping level changes?

In this contribution, we first discuss characterization of the superconducting properties of $Ba(Fe_{1-x}Co_x)_2As_2$ single crystals with various x and show that all samples exhibit robust and spatially homogeneous superconductivity as revealed by (1) direct magneto-optical imaging of the Meissner screening; (2) visualization of trapped magnetic flux; (3) direct magnetization measurements of the superconducting transition. We then study the evolution of the fishtail feature when, in addition to the usual peak in the vicinity of $H = 0$, a second peak appears in $M(H)$ at the magnetic field H_P. We find that $H_P(T/T_c = const)$ is a single – valued monotonic function of T_c. Furthermore, we find that magnetic relaxation is non-monotonic function of magnetic field, indicating a crossover to the plastic creep regime. At $H > H_p$, the logarithmic relaxation rate, $S = -|d \ln M/d \ln t|$, increases with applied magnetic field at a rate independent of doping level. Our observations, together with other measurements and reports [21,24], point to unconventional irreversible vortex properties of iron-arsenides, at least as represented by the 122 family. They point to a close similarity with the cuprates and distinctly different from the behavior found in conventional s-wave superconductors, including two-gap MgB_2.

2. Experimental

2.1. Samples and characterization

Single crystals of $Ba(Fe_{1-x}Co_x)_2As_2$ with $x = 0.038$, 0.047, 0.058, 0.071, 0.074, 0.10, 0.106 and 0.118 were grown out of self-flux (FeAs) [10]. The actual cobalt concentration was determined by wavelength dispersive X-ray spectroscopy in the electron probe microanalyzer of a JEOL JXA-8200 superprobe. The superconducting transition temperature, T_c, has been determined from the onset of a diamagnetic signal as well as from temperature when resistance became zero. It ranged from 8 to 24 K. The quality of the samples was checked with magneto-optical imaging as described below in detail. Extensive thermodynamic and transport studies of the crystals from the same batches were reported elsewhere [10].

Conventional characterization was done using a commercial magnetometer (*Quantum Design* MPMS) and general purpose systems for specific heat and transport measurements (*Quantum Design* PPMS).

2.2. Magneto-optical imaging

Magneto-optical imaging of the component of the magnetic induction perpendicular to the sample surface was conducted by utilizing the Faraday effect in bismuth-doped iron garnet ferrimagnetic films with in-plane magnetization [25]. Such a film is grown on the transparent substrate and then covered by a thin metallic layer to serve as a mirror. The whole structure is called an "in-plane magneto-optical indicator". When linearly polarized light passes through the indicator and reflects off the mirror sputtered on its bottom, it picks up a double Faraday rotation proportional to the intensity of the magnetization along the light path – perpendicular to the indicator (and sample) surface. This component of magnetization, in turn, is proportional to the perpendicular component of the magnetic induction at a given location on the sample surface. Observed through the (almost) crossed (with respect to polarizer) analyzer, we recover a real-time 2D image where the intensity is proportional to the magnetic field on the sample surface [26]. To study superconductors, a flow-type liquid ^{4}He cryostat with the sample in vacuum was used. The sample was positioned on top of a polished copper cold finger and an indicator was placed on top of the sample. In the experiment, the indicator is placed with the active side down in direct contact with the flat surface of the sample. It is the distance between the surface of the active layer and layer thickness itself that mostly determine the spatial resolution of the technique. Without special contrivances, we obtain spatial resolution of about 2 to 4 μm. The cryostat was positioned under the polarized-light reflection microscope and the color images could be recorded on video and high-resolution CCD cameras. Note that some images contain various "defects" – spots (sometimes bright) and streaks. These are optical artifacts due to dirt, grease, dust and scratches on the substrate or mirror and they do not affect the underlying image of magnetic field in any way.

3. Results

3.1. Sample characterization

Fig. 1a shows screening of a 1.5 kOe applied magnetic field at 5 K after cooling in zero field in a nearly optimally doped $Ba(Fe_{1-x}Co_x)_2As_2$ ($x = 0.074$) single crystal. Fig. 1b was obtained after the magnetic field was turned off and some flux was trapped at the sample perimeter. Fig. 1c shows an optical image of the sample and Fig. 1d shows trapped magnetic flux after the sample was cooled in a 1.5 kOe magnetic field to 5 K and the field was turned off. These observations clearly show robust and strong superconductivity of FeCo-122 superconductors with very uniform

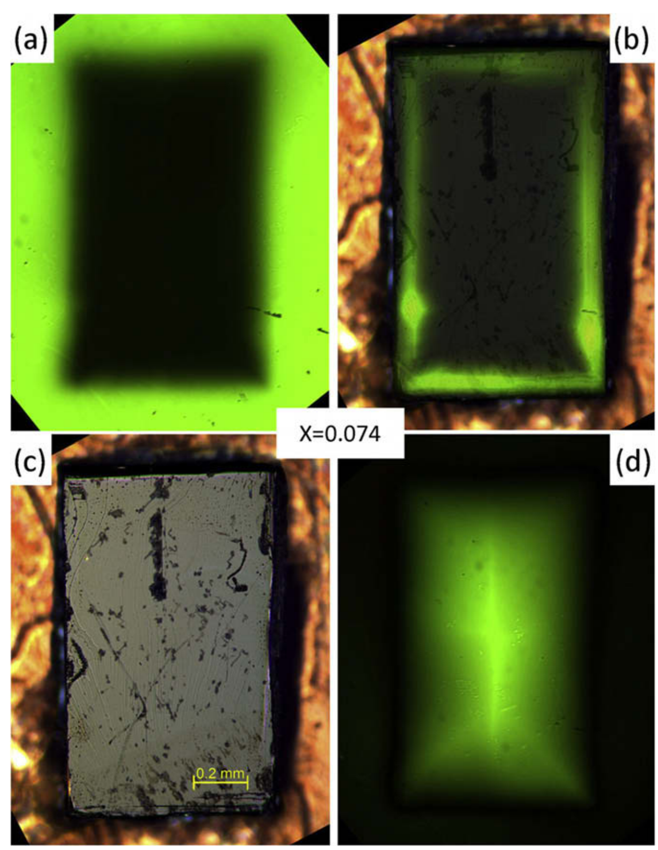

Fig. 1. A nearly optimally doped sample with $x = 0.074$ ($T_c = 22.8$ K). (a) Meissner screening of a 1.5 kOe applied magnetic field. (b) Trapped flux after 1.5 kOe was turned off. (c) Optical image of a sample and (d) trapped flux after cooling in 1.5 kOe and turning it off.