FAST TRACK COMMUNICATION

Superconductivity in undoped single crystals of BaFe$_2$As$_2$: field and current dependence

To cite this article: J S Kim et al 2009 J. Phys.: Condens. Matter 21 342201

Related content
- Specific heat anomalies for T || Tc in superconducting single crystal doped BaFe$_2$As$_2$: comparison of different flux growth methods
  J S Kim, E G Kim and G R Stewart
- Evidence for coexistence of superconductivity and magnetism in single crystals of Co-doped SrFe$_2$As$_2$
  Jun Sung Kim, Seunghyun Khim, Liqin Yan et al.
- Superconductivity at 23 K in Pt doped BaFe$_2$As$_2$ single crystals
  S R Saha, T Drye, K Kinshenbaum et al.

Recent citations
- Superconductivity in Undoped CaFe$_2$As$_2$
  Single Crystals
  Dong Yun Chen et al
- Superconducting and magnetic anisotropy of Ln FePO (Ln=La, Pr, and Nd) single crystals
  R. E. Baumbach et al
- A possible approach from BCS through HTS to RTS with three examples
  C.W. Chu
FAST TRACK COMMUNICATION

Superconductivity in undoped single crystals of BaFe$_2$As$_2$: field and current dependence

J S Kim, T D Blasius$^1$, E G Kim and G R Stewart$^2$

Department of Physics, University of Florida, Gainesville, FL 32611-8440, USA

E-mail: stewart@phys.ufl.edu

Received 14 July 2009, in final form 23 July 2009
Published 6 August 2009
Online at stacks.iop.org/JPhysCM/21/342201

Abstract

In previous work on undoped MFe$_2$As$_2$, partial drops in the resistivity indicative of traces of superconductivity have been observed for some samples with M = Ba ($T_c \sim 20$ K, up to 25% drop in $\rho$) and M = Ca ($T_c \sim 10$ K, up to 45% drop in $\rho$). A complete drop in the resistivity to $\rho = 0$, along with a finite fraction of Meissner flux expulsion, has been observed for M = Sr, $T_c = 22$ K. Using In-flux grown single crystal samples of undoped BaFe$_2$As$_2$, we find a complete drop in the resistivity to 0 for most samples beginning at $T_{onset}^c = 22.5$ K. However—in contrast to the SrFe$_2$As$_2$ results—there is no measurable Meissner effect and no suppression of the resistive superconducting transition with annealing. The current sensitivity of the superconducting resistive transition in our samples of BaFe$_2$As$_2$ is quite strong, with an increase in the current density of a factor of 15 to $\sim 1.5 \text{ A cm}^{-2}$ not changing $T_{onset}^c$ but broadening the transition significantly and causing $\rho$ to remain finite as $T \to 0$. To investigate whether this unusually low critical current is indicative of filamentary conduction lacking the apparent anisotropy seen in the critical magnetic field, $H_{c2}$, measurements for, e.g., the bulk superconductor Co-doped BaFe$_2$As$_2$, $H_{c2}$ was measured in both crystalline directions. These BaFe$_2$As$_2$ samples show $H_{c2}(T)$ values in the ab-plane and along the c-axis comparable to those seen for BaFe$_{2-x}$Co$_x$As$_2$, which has a similar $T_c$. Since the lack of $T_c$ suppression after annealing argues against strain-induced superconductivity as proposed for the other undoped MFe$_2$As$_2$ materials, another possible cause for the superconductivity in BaFe$_2$As$_2$ is discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The discovery of superconductivity in iron pnictides has caused significant interest [1] in the scientific community. After a $T_c$ of 55 K was achieved [2] in F-doped SmFeAsO, in the so-called ‘1111’ iron arsenic structure, superconductivity was found [3] in a new class of compounds (the ‘122’ structure) at 38 K in K-doped BaFe$_2$As$_2$. Many dopants on the Ba site other than K have since been found to suppress the spin density wave transition in the 122 parent compound, MFe$_2$As$_2$ (M = Ba, Sr, Ca, Eu), and cause superconductivity. In addition, doping on the Fe site with, e.g. Co [4], as well as doping on the As site with, e.g. P [5], have been found to achieve the same result.

One of the more intriguing results to date in the 122 iron pnictides is the occurrence of partial superconducting transitions in the undoped parent compounds: BaFe$_2$As$_2$, where in one work [6] $\rho$ in two out of five samples falls up to 25% starting at $\sim 20$ K; CaFe$_2$As$_2$ where $\rho$ in at least one sample has been seen [7] to fall by almost 1/2 although at the much lower temperature of 10 K; and SrFe$_2$As$_2$, where the resistivity, $\rho$, actually goes to 0 along with partial diamagnetic...
screening [8] at \( T_c \sim 22 \) K. The explanation to date of this behavior [6–8] has been lattice distortion/strain, i.e. a sort of an effective pressure-induced superconductivity in a small fraction of the sample. Annealing of the superconducting samples of SrFe\(_2\)As\(_2\) at 200°C for 5 min was found to decrease the drop in \( \rho \) below an unaltered \( T_c \) by \( \sim 50\% \), while annealing at 300°C for 2 h destroyed all traces of the superconductivity [8].

We report here on characterization of single crystals of BaFe\(_2\)As\(_2\) grown in In-flux [9, 10] with residual resistivity ratios of between 3.7 and 5.0, which are only slightly higher than values around 3.5 in self-flux grown crystals reported [6] previously. The majority of these In-flux grown crystals show a full drop in their resistivity, with significant sample dependence in both \( T_c \) onset (19–23 K) and the temperature where \( \rho \rightarrow 0 \) (7–19 K).

2. Experimental details

Since Saha et al [8] find that annealing their SrFe\(_2\)As\(_2\) crystals at 200°C for 5 min markedly degrades the superconducting transition, it is important to note the different thermal history in their growth of SrFe\(_2\)As\(_2\) crystals versus that for our In-flux grown BaFe\(_2\)As\(_2\) crystals. Growing [9, 10] in In-flux involves a slow cool from 1000 down to 500°C, followed by a 75 °C h\(^{-1}\) cool down to room temperature. As well, removing the sample from the In-flux involves heating on a hot plate to \( \sim 200°C \) for 5–10 min, followed by curing of Epo-tek H31LV Ag-epoxy resistivity contacts at 120°C for 40 min. The thermal history of the self-flux-grown SrFe\(_2\)As\(_2\) crystals involves growth [8, 11] in an FeAs flux by cooling from 1100 to 900°C at 4°C h\(^{-1}\) followed by cooling at \( \sim 250°C \) h\(^{-1}\) (furnace shut-off) down to \( \sim 400°C \) and approximately 50°C h\(^{-1}\) thereafter.

A second issue to emphasize here is that the crystals we have obtained from this first growth batch (i.e. not under optimized conditions) of BaFe\(_2\)As\(_2\) from In-flux are quite small, typically 1 mm on a side and 0.1 mm thick. Thus contacting these crystals was done under a microscope and the geometrical factor necessary to determine absolute resistivity values is only accurate to about 25%. The residual resistivity ratio, RRR \( (= \rho(300 \text{K})/\rho(T \rightarrow 0)) \), is however quite accurate since the geometrical factor cancels in the ratio.

Finally, as also reported by all the other works on such superconducting ‘indications’ in the MFe\(_2\)As\(_2\) superconductors [6–8], there is a certain uncontrolled sample dependence present in these results which may be linked to the as-yet poorly understood cause of this superconductivity. For example, when changing contacts on the surface of one of our crystals some material on the surface was accidentally stripped away due to their micaceous nature. The sample afterward showed a narrower transition, with the temperature where \( \rho \rightarrow 0 \) increased by several degrees. Thus, either the surface is important or the reheating to 120°C when reapplying new epoxy resistivity contacts caused this change.

Resistivity was measured using a four contact dc method, with the current switched in direction for a total of 40 measurements in each current direction at each temperature. The current is supplied by a Keithley 220 current source and the voltage is measured by a high sensitivity, low noise Keithley 2001 voltmeter. Critical field data were taken up to 8 T with the field both in and perpendicular to the \( ab \)-plane. Determining \( T_c \) as either the midpoint or the onset of the resistive transition did not change the value of the slope of \( H_c2 \) at \( T_c \).

3. Results and discussion

The resistivities at low temperatures of five samples of In-flux grown single crystals, current in the \( ab \)-plane, of BaFe\(_2\)As\(_2\) are shown in figure 1. Although three of the samples show complete resistive transitions to \( \rho = 0 \), none of the samples show any dc magnetic susceptibility indication of superconductivity at the resistive transitions, in contrast to the results [8] for SrFe\(_2\)As\(_2\).

Clearly, there is a wide range of normal \( \rho_{ab} \) extrapolated from above the superconducting transition \( (\sim 0.07–0.64 \text{ mΩ cm}) \) which, at least for the superconducting samples we have measured and within the ±25% geometrical uncertainty mentioned above, appears to be correlated with \( T_c \) onset: the smaller the normal state resistivity, the higher is \( T_c \).

However, our result for sample #5 spoils this tentative correlation, since it is not superconducting. Also, the literature values for normal \( \rho_{ab}(T \rightarrow 0) \) in self-flux grown single crystals of BaFe\(_2\)As\(_2\) are certainly comparable to the values reported here, e.g. [6] report values between about 0.06 and 0.1 mΩ cm and the samples with traces of a superconducting transition have the larger values, while [12–14] (all with no trace of superconductivity) report \( \rho_{ab}(T \rightarrow 0) \sim 0.15 \text{ mΩ cm}, 0.4 \text{ mΩ cm}, 0.6 \text{ mΩ cm} \) respectively. Thus, there does not seem to be a basis for associating the occurrence of superconductivity with the values of the normal \( \rho_{ab}(T \rightarrow 0) \). This is consistent with arguments for the nature and cause of the superconductivity presented below.

Figure 2 shows the sensitivity of the superconductivity to current: 1.5 mA through the cross section of sample
are shown in figure 3. Clearly, the superconductivity in our In-flux grown crystals of undoped BaFe$_2$As$_2$ possesses the same broader superconducting transitions. In sample 1, the higher current (corresponding to a current density of only 1.5 A cm$^{-2}$) actually prevents $\rho$ from falling to 0 above 4 K. Annealing sample #4 (300 °C for 2 h under vacuum sealed in pyrex), solid red diamonds, sharpens the transition a factor of ~2 while changing neither $T_{c}$ onset (which is very gradual in the unannealed sample) nor the measured finite value of $\rho$ as $T \rightarrow 0$. The growth of the small feature around 14.5 K in the unannealed sample #4 into a clear shoulder almost 3 K broad centered at 18 K in the annealed sample is under investigation. The inset shows the resistivity versus temperature of sample #3 before (solid circles) and after (solid squares) peeling and recontacting. As discussed in the text, the fact that sample #3 shows a sharper, higher $T_c$ after peeling and being recontacted may imply a surface effect.

One way to check this is to measure the critical field behavior of the resistive transitions; such data for one sample are shown in figure 3. Clearly, the superconductivity in our In-flux grown crystals of undoped BaFe$_2$As$_2$ possesses the same apparent anisotropy near $T_c$ of the critical magnetic field seen in bulk [15, 16] and film [17] samples. One sample dependent superconductivity at $T_c \sim 20$ K with low critical current densities indicative of restricted dimension is observed in undoped In-flux grown single crystals of BaFe$_2$As$_2$. This superconductivity shows the same apparent anisotropy in its critical magnetic fields as bulk samples, and remains after the same annealing regimen that destroys superconductivity in undoped SrFe$_2$As$_2$.

Acknowledgments

The authors gratefully acknowledge helpful discussions with Art Hebard, Peter Hirschfeld, Pradeep Kumar, Dmitri Maslov, Johnpierre Paglione, Shanta Saha and Joe Thompson. Thanks as well to Johnpierre Paglione for supplying their numerical results for $H_{c2}(T)$ for SrFe$_2$As$_2$ shown in figure 3. Work at Florida performed under the auspices of the United States Department of Energy, contract no. DE-FG02-86ER45268.
References

[1] Norman M R 2008 Physics 1 21