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Transport critical current measurements on a Cu-substituted $BaFe_2As_2$ superconductor

T. M. Garitezi,[a)] P. F. S. Rosa, C. Adriano, and P. G. Pagliuso
Instituto de Física "Gleb Wataghin," UNICAMP, 13083-859 Campinas, SP, Brazil

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The critical current density J_c is a crucial parameter to establish the actual technological potential of a superconducting (SC) material. Furthermore, being proportional to the SC gap parameter, it can reveal important information about the microscopic nature of the SC state in a given material. The FeAs-based class of SC materials has been a focus of intense scientific investigation lately, but direct investigation of J_c by transport measurements is rather scarce in literature. For these materials, it is very interesting to map J_c as a function of their distinct SC tuning parameters such as applied pressure and chemical substitution. In this work, detailed investigation of the field, temperature, and pressure dependences of transport critical current density J_c for Cu-substituted $BaFe_2As_2$ single crystals is reported. In this particular material, Cu-substitution has a strong magnetic pair breaking effect. However, with increasing pressure, this sample shows an almost twofold increase of T_c, from 3.2 K to 6.9 K, which is followed by an increase in J_c. These observations are discussed considering the presence of magnetic pinning centers in the Fe-As plane, which, in principle, could suggest effective routes to increase J_c in the this class of materials.
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I. INTRODUCTION

The Fe-based superconductors (SC) have been focus of intense scientific investigation since their discovery owing the intriguing interplay between magnetism and superconductivity in their phase diagrams.[1,2] Furthermore, their discovery has renovated the ambition of attaining high critical temperature superconductors and also to unveil the underlying mechanisms of unconventional superconductors. Regarding their technological applications, an important parameter is the critical current density (J_c) of a superconductor. J_c can be obtained directly by transport measurements or indirectly from magnetization measurements using a Bean model approximation.[3] However, it is highly desirable to directly measure J_c by transport when the available samples allow such experiments.

Particularly, the $BaFe_2As_2$-derived family (122) of superconductors provides high quality single crystals for possible J_c studies, where SC samples can be obtained both by chemical substitutions and by applied pressure.[4–6] Recent works on the 122 family have shown evidence that the suppression of magnetism is accompanied by an increase of occupation of the planar 3*d* Fe bands and a decrease of the magnetic Fe ordered moments.[7–9] Also, it has been reported lately that the Cu localized moments hybridize with conduction electron with increasing pressure,[9] decreasing the pair-breaking effect caused by those moments. Regarding the correlation of these properties with J_c, these ordered moments could cause magnetic flux pinning and increase of J_c. Hence, the suppression of spin density wave order could promote a decrease of J_c while the critical temperature T_c still increases in the underdoped regime. Otherwise, if magnetic pinning is not so important, J_c should follow the behavior of T_c. After the maximum T_c is achieved, the ordered magnetic moments might have been completely suppressed and thereafter there is no magnetic pinning effect and J_c should follow the behavior of T_c. For a given dopant concentration, hydrostatic pressure can be used as a tuning parameter to study J_c and T_c behavior.

In this work, we report transport critical current measurements on $BaFe_{2-x}Cu_xAs_2$ single crystals. This particular system was selected due to existence of an interesting pair-breaking mechanism associated with the Cu^{2+} spin that are strongly affected by applied pressure.[9] Therefore, we study the temperature, pressure, and magnetic field dependence of J_c and T_c and correlate their behavior with magnetic pinning of Fe and Cu atoms in the Fe–As plane.

II. METHODS

$BaFe_{2-x}Cu_xAs_2$ single crystals were grown by In-flux method as described elsewhere.[4] The crystals were thin platelets of typical size $2.0 \times 2.0 \times 0.05$ mm^3 with the *c*-axis perpendicular to the sample plane. Samples were measured as-grown in resistivity and critical current measurements. Resistivity and transport critical current measurements were performed using an AC bridge with a four-wire configuration in a commercial apparatus equipped with a 14 T magnet. Critical temperatures were determined from the maximum in the first derivative of resistivity versus temperature curves. Transport critical currents were determined by performing voltage *versus* current measurements, and then taking the maximum derivative of the curve as the value for the critical current. Measurements under hydrostatic pressure were carried out in a clamp-type cell. Pressure was determined by measuring the T_c shift of a Sn sample.

[a)]Electronic mail: thalesmg@ifi.unicamp.br

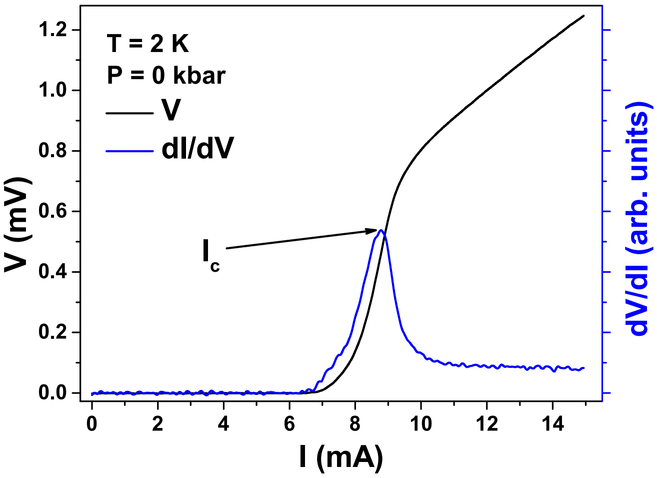

FIG. 1. Typical voltage versus current measurement used in the determination of critical current density experiments.

III. EXPERIMENTAL RESULTS

Figure 1 shows a typical voltage versus current measurement in a superconductor. In Fig. 2, we show resistivity as function of temperature for the $BaFe_{1.87}Cu_{0.13}As_2$ single crystal used here at ambient pressure and zero magnetic field.

Transport critical currents were measured in-plane on near-optimally doped $BaFe_{1.87}Cu_{0.13}As_2$ crystals under hydrostatic pressure and magnetic fields applied perpendicular to the c-axis and parallel to the applied current. The studied sample presented a T_c of 3.2 K at zero pressure and magnetic field. Transport critical current density (J_c) at 2 K and critical temperature (T_c) as function of pressure at constant magnetic fields are shown in Fig. 3.

IV. DISCUSSION

First, it is important to emphasize that we have been able to perform reliable transport J_c measurements on our In-

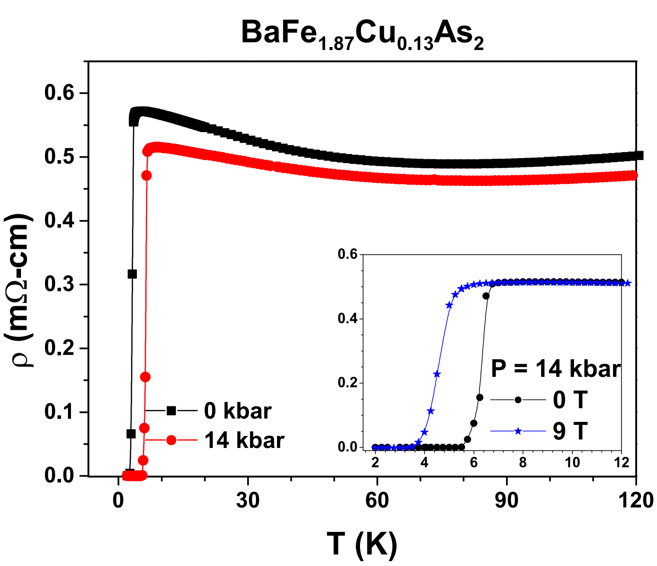

FIG. 2. Resistivity as function of temperature at zero field and pressure for the $BaFe_{1.87}Cu_{0.13}As_2$ single crystal studied here. Lines are guides to the eyes.

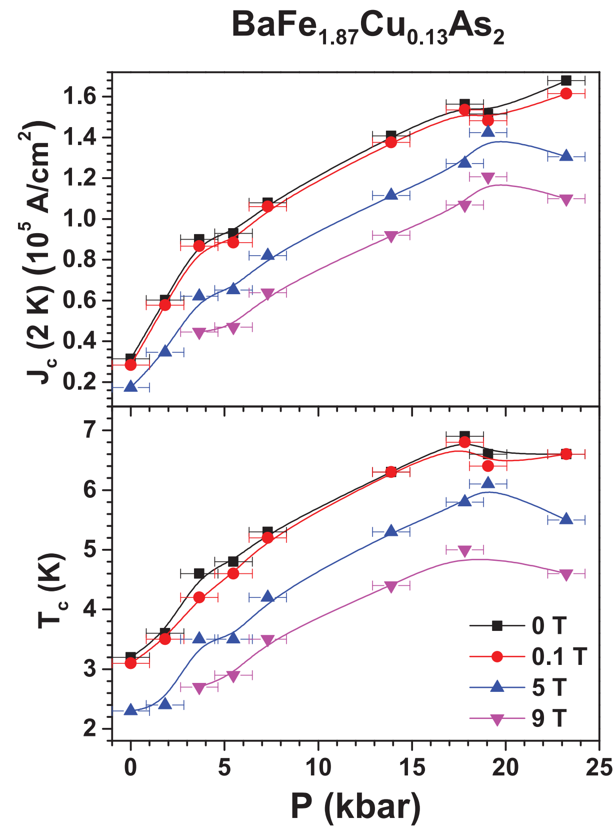

FIG. 3. Critical current density and critical temperature as functions of hydrostatic pressure for Cu-doped $BaFe_2As_2$ at different magnetic fields. Lines are guides to the eyes.

flux grown single crystals down to 2 K. The vast majority of works aimed to obtain the critical currents for the 122 system have used an indirect measurement via Bean model in magnetization loops. We found that, due to the higher quality of our crystals and less concentration of defects, we were able to measure critical currents that amount to a maximum of 60 mA for our samples' dimensions. Negligible heating effects ($\Delta T < 0.2$ K) have been observed when the applied currents in I–V experiments surpass I_c, as detected by a thermometer (Sn sample manometer) near the samples in the sample holder. For $I > I_c$, small slopes in the derivative ($<10\%$) which depend on field and temperature in non-systematic way were observed. This may be related to vortex dynamics but further experiments are needed to make any claim. The derivative criterion for the definition of J_c gives the same qualitative behavior of $J_c \times T$ as a (constant) voltage criterion and also avoids possible voltage offsets that may arise in some measurements.

It is already known that pressure can increase T_c for some atom substitutions in the Ba122 family.[1,9] The studied Cu-doped sample has a twofold increase in T_c, reaching the maximum $T_c = 6.9$ K at 17 kbar before starting to decrease at higher pressures, as shown in Fig. 3. This huge improvement of T_c with pressure is in agreement[9] with previous for smaller Cu concentrations and indicates that Cu local moments are being shielded by conduction electrons and diminishing pair-breaking effects on superconducting electrons.[9] This is presumably due to an increase in the hybridization of the Cu^{2+} local moments with conduction electrons. This decrease of the pair breaking mechanism associated with the Cu spins could in principle also affect J_c.

However, as we can see by Fig. 3 that J_c follows the trend of T_c closely. This suggests that the pressure effects on the flux pinning potential are not the dominant effect on the pressure evolution of J_c. One could expect that the suppression of the Cu^{2+} local moments by pressure would decrease the flux pinning potential and therefore decrease J_c. On the contrary, the results indicate that J_c closely follow T_c. As such, at higher pressures, both T_c and J_c start to decrease. That is not unexpected, since on the one hand pressure decreases pair-breaking on the Cu^{2+} local moments, on the other hand it also drives nearly optimally doped samples away from the vicinity of the magnetic phase, presumably weakening the pairing potential.[1,2,9,10]

Another interesting point is to compare the actual J_c values for distinct samples within the 122 family. To the best of our knowledge, there are no previously reported J_c values for Cu-doped Ba122 samples. Optimally Co-doped samples grown from self-flux show typically $J_c \approx 2 \times 10^5$ A/cm^2 at 2 K (from magnetization measurements) and $J_c \approx 2 \times 10^3$ A/cm^2 from transport measurements near T_c.[11] Compared to our Cu-doped sample as measured by transport, we have a maximum $J_c \approx 1.5 \times 10^5$ A/cm^2 at 2 K (Fig. 3) and $J_c \approx 2 \times 10^4$ A/cm^2 near T_c (not shown). The fact that the Cu-doped sample has an equivalent J_c to the Co-doped sample (which has a T_c three times larger) is indicative of stronger pinning in the studied Cu samples. This larger value of J_c may be related to a larger presence of defects and/or to the existence of Cu^{2+} spins in these materials.

V. CONCLUSIONS

In summary, we have performed transport critical current experiments on a nearly optimally doped $BaFe_{1.87}Cu_{0.13}As_2$ single crystal under different pressures and applied magnetic fields. We find that J_c follows qualitatively the pressure dependence of T_c which increases by a factor of 2 before saturates at higher pressures. We interpret our results in terms of Cu^{2+} magnetic pair-breaking in the Fe–As plane being suppressed with increasing pressure.

This effect favors the SC state and causes the increase of both T_c and J_c. However, the higher J_c values found for our samples compared to other substitutions in the 122 family suggest that there might be effects of Cu^{2+} magnetic pinning potential in the Cu-substituted 122 samples. Ongoing studies in other Cu-substituted samples in the underdoped region will be valuable to confirm this scenario.

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