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Disorder induced effects on the critical current density of iron pnictide $BaFe_{1.8}Co_{0.2}As_2$ single crystals

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ABSTRACT

Investigating the role of disorder in superconductors is an essential part of characterizing the fundamental superconducting properties as well as assessing potential applications of the material. In most cases, the information available on the defect matrix is poor, making such studies difficult, but the situation can be improved by introducing defects in a controlled way, as provided by neutron irradiation. In this work, we analyze the effects of neutron irradiation on a $Ba(Fe_{1-x}Co_x)_2As_2$ single crystal. We mainly concentrate on the magnetic properties which were determined by magnetometry. Introducing disorder by neutron irradiation leads to significant effects on both the reversible and the irreversible magnetic properties, such as the transition temperature, the upper critical field, the anisotropy, and the critical current density. The results are discussed in detail by comparing them with the properties in the unirradiated state.

The recent discovery of a new class of superconducting materials – the so-called iron pnictides – has initiated a lot of research aiming at understanding the theoretical background and verifying the potential for applications of these materials. Significant information may be acquired from studying the effect of disorder, which influences both the reversible and the irreversible superconducting properties. In this paper, we report on the effects of introducing defects into $BaFe_{1.8}Co_{0.2}As_2$ [1–4] by neutron irradiation. We mainly concentrate on the irreversible magnetic properties in fields parallel and perpendicular to the Fe-pnictide layers.

The magnetic properties of a $BaFe_{1.8}Co_{0.2}As_2$ single crystal with a size of $a \times b \times c \simeq 1.40 \times 0.70 \times 0.10\ mm^3$ were investigated by SQUID and VSM magnetometry. The sample was investigated in the as-grown state and again after exposing it to neutrons of various energies in our research reactor to a fluence ($E > 0.1$ MeV) of $4 \times 10^{21}\ m^{-2}$. Neutrons typically create defects of different sizes by collisions or nuclear reactions with the lattice atoms. These defects increase the scattering rate and thus will change the superconducting properties and may serve as new pinning centers.

We started by measuring the transition temperature in a SQUID using the *ac*-mode with a field amplitude of 0.1 mT parallel to *ab* (parallel to the Fe–As layers). $T_c \simeq 23.4$ K was found in the unirradiated state. Although the slope of (the in-phase) magnetic moment – $m(T)$ – is quite steep just below T_c, we still observe a small decay (i.e. a small rise of $|m(T)|$) at 5 K, indicating minor inhomogeneities, maybe from Co doping. Measuring the Meissner slope (i.e. $\partial m/\partial H_a$ in the Meissner state) at 5 K allows to approximately determine the sample volume, since geometry effects are insignificant for the chosen arrangement. Accordingly, the whole sample volume is superconducting.

Upon neutron irradiation, T_c decreases slightly to about 23.1 K. The slope at T_c becomes somewhat steeper which shows that the radiation induced disorder is homogeneously distributed. The Meissner slope at 5 K is slightly flatter now (by ~6%) which could indicate surface degradation or minor experimental errors (e.g. misalignment). A small decay of T_c is quite common in anisotropic superconductors and can be related to two effects in our sample, i.e. (i) more disorder provides additional scattering centers for electrons, and (ii) a decay of anisotropy with irradiation. Further reversible properties were discussed in Ref. [4]. Briefly, we found a slight drop of the anisotropy from about 2.9 to 2.5 at high temperatures and $B_{c2}^c(T)$ that may be extrapolated to roughly 35–40 T at 0 K.

The irreversible properties were determined from magnetization loops – $m(H_a)$ – with $H_a \| ab$ or $H_a \| c$ measured in a VSM at fields of up to 5 T and a field sweep rate of 10^{-2} T/s. Since the current flow in the *ab* plane is assumed to be isotropic for $H_a \| c$, $J_{c,ab}^{H\|c}$ – the critical current density – can be evaluated by applying Bean's model for rectangular samples: $J_{c,ab}^{H\|c}(B) = [|m_i^{H\|c}(B)|/\Omega][12a/b(3a-b)]$, $\Omega = abc$, $m_i^{H\|c}(B)$ denotes the irreversible magnetic moment, i.e. half of the hysteresis width at fixed B (see Ref. [5] for more details).

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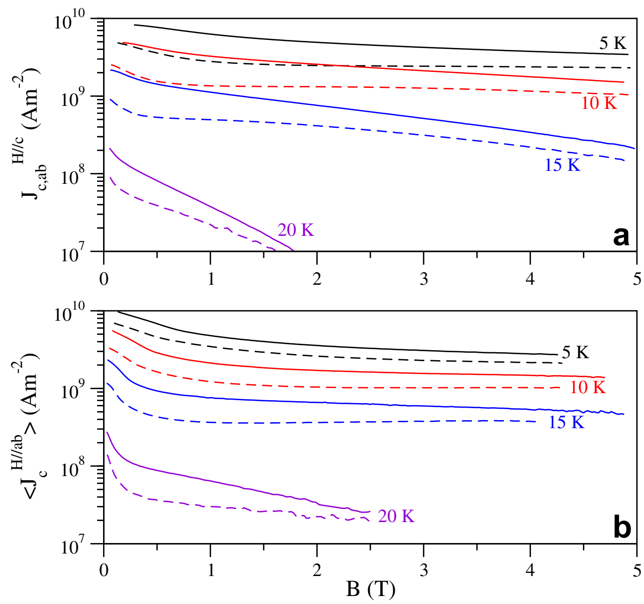

Fig. 1. Critical current density for $H_a \| c$ (a) and $H_a \| ab$ (b) before (dashed lines) and after (solid lines) neutron irradiation as a function of magnetic induction.

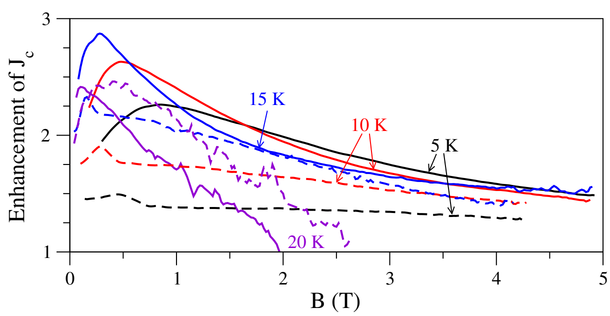

Fig. 2. Ratio of critical currents after and before neutron irradiation for $H \| c$ (solid lines) and $H \| ab$ (dashed lines) as a function of applied field at different temperatures.

For $H_a \| ab$ we expect different current densities along $c\left(J_{c,c}^{H\|ab}\right)$ and $ab\left(J_{c,ab}^{H\|ab}\right)$. In this case, J_c can only be calculated from m if one of the components dominates the magnetic properties, namely via $J_c^{H\|ab}(B) = \left[|m_i^{H\|ab}(B)|/\Omega\right][4/s]$, where s is the sample dimension perpendicular to H_a and $J_c^{H\|ab}$. Since we cannot predict the J_c relations, we apply the isotropic method also in this case ($H_a \| ab$) resulting in an averaged value $\left\langle J_c^{H\|ab}\right\rangle$ which should be somewhere between $J_{c,c}^{H\|ab}$ and $J_{c,ab}^{H\|ab}$.

Fig. 1a shows results on $J_{c,ab}^{H\|c}(B)$ at temperatures from 5 to 20 K. The dashed line indicates the as-grown and the solid line the irradiated state. The radiation induced enhancement of $J_c(B)$, i.e. $J_c^{\text{irrad.}}/J_c^{\text{as-grown}}$, is illustrated in Fig. 2 by the solid lines. A maximum enhancement of roughly 3 is found at 15 K and ~0.5 T. The effect clearly decreases with increasing field and with decreasing temperature. A pronounced maximum at small fields is found at all temperatures, which presumably is the signature of a more ordered flux line phase in the as-grown state at these fields. The newly created pinning centers are held responsible for the enhancement, since only minor changes in the reversible properties were found (e.g. T_c, coherence length, and anisotropy [4]). Thus $BaFe_{1.8}Co_{0.2}As_2$ is another material (such as many cuprates and MgB_2), in which neutron irradiation creates defects, that are well suited for flux pinning.

Results on $\left\langle J_c^{H\|ab}\right\rangle$ are presented in Fig. 1b. At low fields, the values are slightly higher than that of panel a (up to ~40%) and the irreversibility field at high temperature is obviously enhanced (which may be mainly a consequence of the higher upper critical field in this direction). As already mentioned, the interpretation of $\left\langle J_c^{H\|ab}\right\rangle$ is not straightforward. Note that the front of $J_{c,ab}^{H\|ab}$ penetrates into the sample in c direction, and that of $J_{c,c}^{H\|ab}$ along ab, and $c \simeq 0.1(ab)^{1/2}$ ($(ab)^{1/2}$ indicates the mean sample size parallel to the ab plane, i.e. the Fe–As layers). Thus as long as the currents in ab direction are not much higher than those in c direction (roughly for $J_{c,ab}^{H\|ab} < 5J_{c,c}^{H\|ab}$) the ab currents dominate the magnetic properties and we can calculate that component giving: $J_{c,ab}^{H\|ab} \simeq \left\langle J_c^{H\|ab}\right\rangle$. Similarly, the c component dominates for roughly $J_{c,c}^{H\|ab} < 20J_{c,ab}^{H\|ab}$, which leads to $J_{c,c}^{H\|ab} \simeq 0.1\left\langle J_c^{H\|ab}\right\rangle$ (the factor 0.1 follows again from the ratio of the sample dimensions). Thus, we may deduce that $J_{c,c}^{H\|ab}$ cannot be lower than about $0.1\left\langle J_c^{H\|ab}\right\rangle$ (e.g. 7×10^8 Am^{-2} at 5 K and low fields) which is approximately $0.1J_{c,ab}^{H\|c}$. The minimum case would also imply strongly anisotropic pinning for $H_a \| ab$, similar to the highly anisotropic cuprates due to a large modulation of the superconducting order parameter perpendicular to the planes. Such modulations are not excluded in our sample, since the pnictides have also a layered structure.

It seems more plausible, however, that the current anisotropy is not very large since the anisotropy of the coherence length is only 2–3 (see also [2]). Also recent STM studies [6] on flux line pinning led to the conclusion that pancake vortices do not exist in this material. Thus $\left\langle J_c^{H\|ab}\right\rangle$ might rather represent $J_{c,ab}^{H\|ab}$. In this case $J_{c,ab}^{H\|ab}$ would be slightly higher than $J_{c,ab}^{H\|c}$ but the differences almost disappear upon neutron irradiation, since $\left\langle J_c^{H\|ab}\right\rangle$ increases only by a factor of about 1.5–2.2 at 5–15 K. In contrast to $H_a \| c$, the enhancement is almost constant with field within this temperature range as shown in Fig. 2. A more pronounced field dependence is only found at 20 K.

In summary, we found $J_{c,ab}^{H\|c}$ values of up to about 5×10^9Am^{-2} (5 K) in a $BaFe_{1.8}Co_{0.2}As_2$ single crystal, which increases by up to a factor of 3 upon neutron irradiation. For $H \| ab$ we showed that $J_{c,c}^{H\|ab}$ cannot be lower than about 0.1 $J_{c,ab}^{H\|c}$, but much smaller differences are more likely. The enhancement of the irreversible magnetic properties upon neutron irradiation is lower for this field direction.

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