Fast Track Communication

Interaction of vortices in anisotropic superconductors with isotropic defects

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Abstract
To assess a superconductor’s suitability for high-current applications, it is imperative to know how its critical current density ($J_c$) depends on magnetic field and its orientation. We present a comprehensive study of the anisotropy of the in-plane $J_c$ in iron-based superconducting single crystals carried out by an advanced magnetometry technique. As $J_c$ is governed by material defects capable of vortex pinning, we investigated three samples with three essentially different defect landscapes representing weak, strong and intermediate pinning. In the latter case, a second maximum in the field dependence of the critical current (fishtail effect) occurred, allowing us to investigate the influence of this effect on the angular dependence of $J_c$ in an intermediate pinning regime for the first time in a quantitative way. For weak and strong pinning, the influence of the field orientation on the in-plane $J_c$ can be described by the anisotropic scaling theory. For weak pinning, we find the predicted scaling for the field ($\gamma^{-2} \sin^2(\theta)$) and for the in-plane current (unity). For strong pinning, we find the same scaling for the field, but show for the first time that an additional scaling factor ($\gamma^{1-\gamma/\gamma} \cos^2(\theta)$) emerges for the in-plane critical current density. We attribute this new scaling rule (double scaling) to the presence of defects which are larger than the vortex core.

Keywords: flux pinning, anisotropy, scaling, critical current, irradiation, artificial defects

(Some figures may appear in colour only in the online journal)

1. Introduction

Flux pinning determines the critical current density, $J_c$, therefore it defines the prospects of a superconductor for high current applications. The interaction of a certain defect structure with individual vortices and the vortex lattice as a whole has been explored for decades, aiming at the optimization of flux pinning in various materials [1–3]. With the advent of the highly anisotropic high temperature superconductors, anisotropy effects have become of great interest for theory and technology. However, our understanding of this subject is far from being complete. If the defect structure is isotropic, the current anisotropy is governed solely by the anisotropy of the effective mass of the charge carriers. It manifests itself in the well-known angular dependencies of fundamental superconducting parameters such as the upper critical field, the coherence length and the magnetic penetration depth, which can be described via

$$\epsilon(\theta) = \sqrt{\gamma^{-2} \sin^2(\theta) + \cos^2(\theta)},$$

where $\gamma$ denotes the anisotropy of the upper critical field, and $\theta$ is the angle between the magnetic field and the crystallographic c-axis of the sample. The basic idea of various scaling approaches is to derive the angular dependence of
further superconducting properties by means of simple rules [4, 5]. For instance, the magnetic field $B$ has to be replaced by $e(\theta)B$ in any function of $B$, in particular in $J_c(B)$. Current scaling on the other hand is not universal since it depends on the type of pinning. The anisotropic scaling theory was originally formulated for weak collective pinning [2]. It was found that no critical current scaling is needed (factor of unity) in the single vortex pinning regime [4] and this result is frequently used [6–9] to describe the angular dependence of $J_c$, although neither the magnitude of the currents nor their field dependence fits the predictions of weak collective pinning theory in many cases.

An experimental assessment of scaling rules is difficult because angle-resolved measurements which allow a quantitative assessment of $J_c$ have been performed only on thin films so far. In these samples, $J_c(\theta)$ was often found to obey the prediction for weak pinning within a limited angular range, while deviations were usually ascribed to the presence of correlated defects, whose form-anisotropy can lead to anisotropy effects not related to the mass anisotropy of the superconductor [10]. The large variety of isotropic and correlated defects in thin films [3] and the unsolved summation of their respective pinning forces render the experimental assessment of scaling rules for a particular defect structure in the case of thin film experiments practically impossible.

In the present paper, the angular dependence of the critical currents is assessed quantitatively for the first time in three dimensional superconductors, namely in single crystals of cobalt- and potassium-doped BaFe$_2$As$_2$ (Ba-122). The defect structure was tuned by introducing different dopants as well as by neutron irradiation; thus pinning ranges from weak to strong [11]. While elastic interactions dominate for weak pinning, plastic deformations enable the flux line lattice to efficiently adapt itself to the defect structure in the case of strong pinning. The transition between these two regimes, i.e. the appearance of plastic deformations in the lattice at higher fields, is evidenced by the emergence of a fishtail in some of the pristine crystals.

2. Experiment

Optimally doped Ba-122 single crystals (Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and BaFe$_{1.88}$Co$_{0.12}$As$_2$) were grown using the self-flux method [12, 13]. The Ba-122 pnictide family, which is currently the most promising compound for high current applications among the iron based superconductors [14, 15], is well-suited for our studies since (a) it exhibits a significant upper critical field ($R_{c2}$) anisotropy $\gamma = \frac{R_{c2}^b}{R_{c2}^a}$ and (b) crystals which are rather clean (K-doped Ba-122) or have pronounced intrinsic impurities (Co-doped Ba-122) are available. The superconducting transition temperature, $T_c$, was determined by the onset of the AC-Meissner susceptibility (field amplitude: 0.1 mT). The samples showed narrow transitions, typically about 0.4 K and less, and high $T_c$'s (above 38 K for the K-doped sample and above 24 K for the Co-doped sample).

$J_c$ was derived from magnetization measurements at constant temperatures and angles in a 5 T vector vibrating sample magnetometer (VSM), which records both the parallel and the orthogonal components of the magnetic moment with respect to the applied field $H_b$, thus the orientation of the current loops within the sample is directly assessed. As we show schematically in figure 1, the samples were rotated by an angle $\theta$ about an axis perpendicular to both the field and the crystal’s $c$-axis, with $\theta = 0^\circ$ for the field parallel to the $c$-axis. The supercurrents were found to flow parallel to the ab-planes up to $\theta = 80^\circ$ in the pristine crystals, which have a high aspect ratio ($a \approx 2b \approx 20c$) and up to $\theta = 70^\circ$ in the irradiated crystal, which has a somewhat lower aspect ratio ($a \approx 2b \approx 10c$). Along one side, which is $a$ in figure 1(a) and $b$ in figure 1(b), the critical current density is perpendicular to the applied field for any $\theta$, resulting always in a maximum Lorentz force. It is this critical current density we denote with $J_c$. Along the other side, the angle between the critical current ($J_{c\text{VLF}}$) and the field changes with $\theta$, thus leading to variable Lorentz forces (VLF). For the first measurement, the sample was mounted with the rotation axis $\epsilon_{rot}$ of the VSM parallel to $a$. This means that $J_c$ flows parallel to $a$ and $J_{c\text{VLF}}$ parallel to $b$ (see figure 1(a)). Following the anisotropic Bean model, we set $J_c$ and $J_{c\text{VLF}}$ constant but $J_c = J_{c\text{VLF}}$ in general, therefore the irreversible magnetic moment $m_{irr}$, which is the magnetic moment generated by the current loops, is given by [16]:

$$m_{irr}(\epsilon_{rot}||a) = \frac{J_c V b}{4} \left(1 - \frac{b}{3a} \frac{J_{c\text{VLF}}}{J_c}\right)$$

for $\frac{a}{b} \geq \frac{J_c}{J_{c\text{VLF}}}$ (2)

and

$$m_{irr}(\epsilon_{rot}||a) = \frac{J_{c\text{VLF}} V b}{4} \left(1 - \frac{a}{3b} \frac{J_{c\text{VLF}}}{J_c}\right)$$

for $\frac{a}{b} < \frac{J_c}{J_{c\text{VLF}}}$.

where $V$ is the volume of the single crystal. The irreversible magnetic moment is directly acquired from the VSM experiments and is half of the hysteresis width of the magnetic moment, i.e. the moment perpendicular to the current loops, obtained from measurements in increasing and decreasing fields.

The sample was then remounted with $\epsilon_{rot}$ parallel to $b$ (see figure 1(b)), so that $J_c$ now flows along $b$ and $J_{c\text{VLF}}$ along $a$. In this configuration, $a$ and $b$ have to be exchanged in the above expressions. Consequently, $J_c$ and $J_{c\text{VLF}}$ can be extracted from the two measurements and these equations. To obtain the critical current as a function of the magnetic induction $B = |\mu_0(H_b + H_c)|$, we additionally calculated the self-field $H_c$, which is the magnetic field generated by the critical currents, numerically [21]. Both the absolute value and the orientation of the self-field were taken into account when calculating $B$. Since the self-field is parallel to the $c$-axis during all our measurements, it reduces the angle $\theta$, but
significantly affects the results only at low applied fields, i.e. typically only below 0.1 T in the pristine crystals and 0.3 T in the irradiated crystal. Accordingly, the angle $\theta$ changes with field as a result of this effect, but we point out that $\theta$ can be assumed constant at a sufficiently high applied field. The angles given in the legends of the figures refer to the constant angle between the $c$-axis and the applied magnetic field for the respective measurement. For the evaluation, both the orientation and magnitude of the magnetic induction were taken into account. With this elaborated procedure we could for the first time extract $J_c(B)$ quantitatively from angle-resolved magnetization measurements, since earlier studies did not separate $J_c$ and $J_{c,VLF}$ \cite{22,23}. Without this separation, a systematic error of well above 10% would be caused by the changing Lorentz force, rendering a proper scaling analysis impossible.

The anisotropy of the upper critical field was assessed by resistive measurements, employing a constant transport current of 1 mA. The temperature dependence of the resistivity was measured for different applied fields (up to 15 T). $B_{c2}(T)$ was defined by a 90% criterion with respect to the normal state resistivity extrapolated from the region spanning 2–3 K above the onset of superconductivity.

The neutron irradiation was carried out in the TRIGA-MARK II reactor in Vienna. The resulting fast neutron fluence was established via a nickel foil placed in the same quartz tube as the single crystal during irradiation.

3. Results

We start with the pristine K-doped Ba-122 single crystal ($T_{c\text{onset}} = 38.2$ K). This is the crystal with the weakest pinning structure among our samples (lowest $J_c$, see figure 2(a)) and is therefore most suitable for testing the prediction for weak collective pinning within the BGL (Blatter, Geshkenbein and Larkin) anisotropic scaling approach \cite{4}. Indeed, the field dependencies of the critical current density at different angles $\theta$ roughly collapse onto one curve when we replace $B$ by $\epsilon(\theta)B$, as demonstrated in figure 2(b), i.e. field scaling, as predicted by anisotropic scaling theory for the in-plane current density, works well for this sample. Note that we did not use any fit parameter in $\epsilon(\theta)$ since the upper critical field anisotropy $\gamma \approx 2.2$ at 25 K was determined directly by resistive measurements of the upper critical field. The weak pinning limit is, however, not relevant for applications, where high currents enabled by strong pinning are needed.

We thus proceed with the pristine Co-doped crystal ($T_{c\text{onset}}$ of about 24.2 K), which exhibits significantly higher critical current densities, particularly at high fields (up to tenfold larger currents at 4 T), and in which a fishtail effect (second $J_c$ maximum, figure 3) indicates a cross-over from weak to strong pinning \cite{11} as the field increases. We will denote this behavior as intermediate pinning regime in the following. While elastic forces dominate at low fields, the forces deform the lattice plastically at higher fields, leading to an order–disorder transition of the flux line lattice and hence
Figure 2. (a) $I_c$ as a function of $\theta$ for different fields in the pristine K-doped crystal at 25 K. The critical current density increases with angle $\theta$ at all fields in the K-doped Ba-122 single crystal ($B|c$ at $\theta = 0^\circ$, $T = 25$ K). (b) Application of field scaling. The field dependencies of $I_c$ at all angles collapse onto a single curve upon scaling the field by $\epsilon(\theta)q^{-1}$.

Figure 3. In the pristine Co-doped Ba-122 sample ($T = 17.5$ K), a second peak of $I_c$ is observed, which shifts to higher fields and becomes lower with increasing $\theta$.

to a second peak in $I_c(B)$ [24, 25]. Pinning in this crystal is stronger in comparison to the K-doped crystal. The Co-doped crystal in combination with our magnetometry technique offer the possibility of studying the influence of the fishtail on the angular dependence of $I_c$ for the first time in a quantitative manner, since in thin films a second peak effect is almost never observed. The results, presented in figure 3, show that both the position of the second peak and its magnitude vary with $\theta$. The shift in the position of the second $I_c$ maximum (indicated by the solid black line in figure 3), which was also observed in MgB$_2$ [17] crystals, should be describable by field scaling, $B \to \epsilon(\theta)B$. Indeed, figure 4(b) shows the peak position (vertical black line) to scale reasonably well with $\epsilon^{-1}(\theta)$ from 0 to about $65^\circ$. However, the curves of our sample do not coincide after field scaling (figure 4(b)) but are shifted downwards with increasing $\theta$. As a result, the scaling behavior predicted for weak collective pinning does not apply in this intermediate regime. Once again we point out that $\gamma$ in $\epsilon(\theta)$ was determined from resistive measurements of the upper critical field and was not a fit parameter.

Comparing figure 4(a) with figure 2(a) reveals a completely different behavior of $I_c(\theta, B = \text{const})$ in the intermediate pinning regime and the weak pinning limit. In the latter, we observe an increase of $I_c$ with $\theta$ (figure 2(a)). In the intermediate pinning regime, $I_c$ decreases with $\theta$ for fields below 3.5 T, whereas a non-monotonic curve with a peak around $\theta = 45^\circ$ is observed for $B = 4.4$ T.

The strong pinning limit was established in another Co-doped single crystal by neutron irradiation, which is a proven technique for creating an isotropic pinning landscape in various superconductors [17, 26]. The sample was irradiated to a fast neutron ($E > 0.1$ MeV) fluence of about $5.5 \times 10^{11}$ m$^{-2}$, which made $T_c$ drop from 24 to 23.6 K. The created defects have a spherical shape with a radius of up to several nanometers [26, 27]. Added to the already existing intrinsic defect landscape, the radiation induced defects often dominate the pinning behavior, resulting in a strongly increased critical current, as is the case in our sample. After irradiation, the fishtail disappears, i.e. the flux line lattice does no longer undergo an order–disorder transition, because strong pinning deforms the vortex lattice plastically at all fields. $I_c$ decreases with field and increases with growing $\theta$ for high fields, as in the K-doped sample, while a decrease with $\theta$ is observed at low fields (figure 5(a)). The $I_c(\theta)$ dependence in the irradiated crystal is similar to the results obtained for the pristine Co-doped sample. The critical current densities at different $\theta$ are plotted against $\epsilon(\theta)B$ in figure 5(b). The individual curves do not collapse onto a single one, analogous to the pristine Co-doped crystal. The $I_c(\epsilon(\theta)B)$ dependencies are nearly parallel to each other, just like in figure 4(b). A scaling factor different...
from unity is necessary for the in-plane critical current density to describe the results obtained in this pinning limit.

It turns out that all critical current curves of the irradiated sample again collapse onto a single curve when we scale not only the field, by \( \epsilon(\theta) \), but also the critical current, in this case by \( \epsilon(\theta) J_c \). This scaling rule was motivated by the pinning specifics of defects with radii larger than the coherence length, as we will discuss in the next section. Using this additional scaling factor for the in-plane critical current density in the intermediate pinning regime does not lead to a collapse of all experimental curves onto the a single curve. However, note that the form and size of the pinning centers in the pristine Co-doped crystal are basically unknown. These two parameters are the key to the additional scaling factor necessary in the strong pinning scenario, as we will discuss in the next section.

4. Discussion

Scaling is a well-established and successful tool for exploring vortex pinning. In particular, the volume pinning force \( F_p(B) = J_c(B)B \) (note that \( J_c \) is the critical current perpendicular to the applied field in our setup) is widely used for identifying the pinning mechanism, since \( F_p \) is thought to be a characteristic function for each pinning mechanism, provided
that $B$ and $F_p$ are normalized appropriately $[28]$. While, for simplicity, $F_p$ is often scaled by its maximum, $B$ has to be normalized by $B_{c2}(T)$ or the irreversibility field, where the critical currents approach zero. The collapse of the scaled volume pinning force curves obtained at various temperatures onto one single curve indicates the prevalence of the same pinning mechanism at all temperatures. Anisotropic scaling generalizes this idea for describing angular dependent anisotropy instead of temperature effects and hence scales the field by $B_{c2}(\theta)$ instead of $B_{c2}(T)$. Since $B_{c2}(\theta) = B_{c2}^{(0)} \epsilon(\theta)^{-1}$, this is, apart from the factor $B_{c2}$, equivalent to field scaling. It is noteworthy that the irreversibility field and $B_{c2}$ scale with the same factor if pinning is isotropic. We will motivate the scaling of $F_p$, which is closely related to the scaling of $J_c$, in the limit of strong vortex pinning in the following.

We now consider the interaction of a vortex with a single spherical defect in the low-field limit. In the case of core pinning, the pinning energy is basically proportional to the volume mutually occupied by the defect and the vortex core, as this is the volume where the condensation energy is saved. When a vortex is tilted from the $c$-axis, the cross section of its core decreases and becomes elliptical, since the minor axis, which is not parallel to the $ab$-planes, shrinks as $\Xi_{ab} \epsilon(\theta)$ due to the interaction of a large defect (radius $\Xi_{ab}$) with the vortex core in each case, while (c) and (f) illustrate the constant pinning energy ($E_p \propto r_d^3$) when a small defect pins the vortex core.

**Figure 6.** The figure shows the significance of the size of a defect which pins a vortex core. (a) shows an unpinned vortex core for $H_a || c$, while (d) illustrates the shrinkage of a vortex core with $\theta$. (b) and (e) show the change in the pinning energy from $E_p \propto \Xi_{ab} \epsilon(\theta)$ to $E_p \propto \Xi_{ab} \epsilon(\theta)r_d$ due to the interaction of a large defect (radius $\Xi_{ab}$) with the vortex core in each case, while (c) and (f) illustrate the constant pinning energy ($E_p \propto r_d^3$) when a small defect pins the vortex core.
a result, $f_p$ now grows with $\theta$ due to $f_p \sim E_p/\xi(\theta) \propto E_p r_d^3/(\xi_{ab} \epsilon(\theta))$. The differences in the interaction of vortices with large and small defects form the basis of the different angular dependencies of $J_c$ resulting from weak collective pinning (point-like defects) and strong pinning by large defects.

We now assume that $F_p(\theta)$ has the same functional dependence on $\theta$ as the elementary pinning force $f_p(\theta)$. This is expected for instance for strong dilute pins of low density, where all pins exert their maximum force: $F_p = n_p f_p$, with $n_p$ being the density of pinning centers [29]. In more elaborated models for strong pinning, the maximum elementary pinning force: $f_p$, has to be replaced by an average value [11], and the low-field $F_p$ is not necessarily directly proportional to $f_p$. However, it is evident that the angular dependence of $F_p$ and consequently of $J_c$ is expected to be different for a varying $f_p(\theta)$ (the case of small defects) and a constant $f_p$ (the case of large defects). With regard to our experimental results in the irradiated sample, we look for scalability in the form $J_c(B, \theta) = S_0(\theta)J_c(\epsilon(\theta)B)$, which requires $S_0 = \epsilon(\theta)$ for an angle independent $F_p(\theta) \sim f_p$ (large defects): $F_p(B, \theta) = J_c(B, \theta)B = S_0(\theta)J_c(\epsilon(\theta)B)B = J_c(\theta)\tilde{b}$, where $\tilde{b}$ is defined as $\epsilon(\theta)B$. This maps $F_p$ at all angles to $F_p(B, \theta = 0)$, thus the Lorentz force stays constant at constant $\theta$. For a pinning force $F_v \propto \epsilon(\theta)^{-1}$ the respective requirement is $S_0 = 1$, which is equivalent to the result from the anisotropic scaling approach for weak collective pinning. The outcome of this discussion reproduces exactly the experimentally observed scaling behavior, namely $S_0 = 1$, for the K-doped sample, associated with small defects, and $S_0 = \epsilon(\theta)$, in the irradiated Co-doped sample, where the defects are large. The latter case is demonstrated in figure 7.

Note that the proposed generalization agrees very well with the experimental data without the need of any fit parameters.

These geometrical effects on the pinning energy illustrate the crucial importance of the relation between the size of the defects and $\xi(\theta)$ for the pinning energy $E_p$, and consequently $J_c$, as pointed out previously by van der Beek et al. [30]. Since $\xi_{ab}$ is between 2 and 3 nm in Ba-122 [19, 20], the radiation induced defects fulfill the requirement $r_d > \xi_{ab}$ and $E_p$ hence declines with $\theta$.

One important aspect of our study is that scaling depends solely on the interplay between an isotropic pinning landscape within the superconductors crystallographic structure and the flux line lattice. Therefore this model can be applied to any superconducting material which exhibits an isotropic defect structure.

Numerous previous results from literature are incompatible with $S_0 = 1$ [18, 31] or can be described only with an anisotropy parameter different from $\gamma$ [6, 8]. We have shown that a failure in describing critical current data with pure field scaling ($S_0 = 1$) does not necessarily demonstrate the presence of an anisotropic defect structure. Our approach provides (at the very least) a qualitative explanation for a decreasing or non-monotonic $J_c(\theta)$ even for an isotropic defect structure and thus explains a lot of literature data, where the applied scaling failed. In YBCO-based TFA-MOD coated conductors, for instance, BaZrO$_3$ particles, whose typical diameters of about 5–20 nm [32] are larger than the coherence length of the superconductor, were introduced. This meets the requirements for $S_0 = \epsilon(\theta)$ and a broad maximum in $J_c(\theta)$ centered around $B || c$ was indeed observed [32–34]. Additionally, broad peaks in the angular dependence of $J_c$ not centered at 0 or 90° [10, 35, 36] can result from an isotropic defect structure, as observed at 4.4 T in figure 4(a). Since scaling the field formally means that the field in the $J_c(B, \theta = 0)$ curve is reduced by $\epsilon(\theta)$, the peak in $J_c(\theta)$ could in principle just result from the peak in $J_c(B, \theta = 0)$, which is projected to $J_c(\theta)$. Note, however, that this is not the case in our (unirradiated) Co-doped sample, because all points of the $J_c(\theta)$ curve at 4.4 T, which is the one with the pronounced peak, lie above the field of the peak in $J_c(B)$. Similar maxima can be observed also in the irradiated crystal (figure 5(a)), but the peak is less pronounced because of the strong field dependence of $J_c$ in the irradiated crystal. These peaks at intermediate angles are expected to be more significant in YBa$_2$Cu$_3$O$_7$ because of the higher anisotropy of the cuprate-based superconductors in combination with a weaker $J_c(B)$ dependence. For instance, local maxima in the angular dependence of $J_c$ in coated conductors were found as a result of the introduction of an isotropic defect structure by neutron irradiation [36].

5. Conclusion

In conclusion, we successfully employed an advanced magnetization technique to extract the in-plane $J_c$ anisotropy in pristine and irradiated Ba-122 single crystals. In the limit of weak pinning, the predictions of the BGL scaling approach
(S_p = 1, pure field scaling) were confirmed. In the opposite limit of strong pinning, achieved by neutron irradiation, field scaling alone does not suffice to describe the data. An additional scaling factor for the in-plane critical current density (S_p = \epsilon(\theta)) was introduced (double scaling) and justified for the case of large defects. The experimental data was described successfully by applying field scaling as well as S_p = \epsilon(\theta) without using any fit parameters. The model represents an extension of scaling rules for isotropic strong pinning structures, thus extending its applicability to other superconducting materials which are relevant for applications.

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References

[1] Campbell A M and Evetts J E 1972 Flux vortices and transport currents in type-II superconductors Adv. Phys. 21 199
[2] Blatter G, Geiselmann M V, Geshkenbein V B, Larkin A I and Vinokur V M 1994 Vortices in high-temperature superconductors Rev. Mod. Phys. 66 1125–388
[3] Foltyn S R, Civale L, MacManus-Driscoll J L, Jia Q X, Maiorov B, Wang H and Maley M 2007 Materials science challenges for high-temperature superconducting wire Nat. Mater. 6 631–42
[4] Blatter G, Geshkenbein V B and Larkin A 1992 From isotropic to anisotropic superconductors: a scaling approach Phys. Rev. Lett. 68 875
[5] Klemm R A and Clem J R 1980 Lower critical field of an ideal type-II superconductor Phys. Rev. B 21 1868
[6] Gutiérrez J et al 2007 Strong isotropic flux pinning in solution-derived YBa_2Cu_3O_7-\delta nanocomposite superconductor films Nat. Mater. 6 367–73
[7] Holesinger T G et al 2008 Progress in nano-engineered microstructures for tunable high-field, high-current superconducting wires Adv. Mater. Prog. Rep. 20 391–407
[8] Ilordès A et al 2012 Nanoscale strain-induced pair suppression as a vortex-pinning mechanism in high-temperature superconductors Nat. Mater. 11 329–36
[9] Kidszun M, Haindl S, Thersleff T, Hänisch J, Kauffmann A, Iida K, Freudenberger J, Schultz L and Holzapfel B 2011 Critical current scaling and anisotropy in oxide superconductors Phys. Rev. Lett. 106 137001
[10] Wimbush S C and Long N J 2012 The field angle dependence of the critical current in defect-engineered superconductors New J. Phys. 14 083017
[11] Blatter G, Geshkenbein V B and Koopmann J A G 2004 Weak to strong pinning crossover Phys. Rev. Lett. 92 067009
[12] Kihou K et al 2010 Single crystal growth and characterization of the iron-based superconductor KFe_2As_2 synthesized by KAs flux method J. Phys. Soc. Japan 79 124713
[13] Nakajima M et al 2010 Evolution of the optical spectrum with doping in BaFe_2(1-x)Co_xAs_2 Phys. Rev. B 81 104528
[14] Weiss J D, Tarantini C, Jiang J, Kamei T, Polyanskii A A, Larbalestier D C and Hellstrom E E 2012 High intergran critical current density in fine-grain (Ba_0.6K_0.4)Fe_2As_2 wires and bulks Nat. Mater. 11 682–5
[15] Lee S et al 2013 Artificially engineered superlattices of pnictide superconductors Nat. Mater. 12 392–6
[16] Gyorgy E M, van Dover R B, Jackson K A, Schneemeyer L F and Waszczak J V 1989 Anisotropic critical currents in Ba_2YCu_3O_7 analyzed using an extended Bean model Appl. Phys. Lett. 55 283
[17] Zehetmayer M, Eisterer M, Jan J, Kazakov S M, Karpinski J, Birajdar B, Eibl O and Weber H W 2004 Fishtail effect in neutron-irradiated superconducting MgB_2 single crystals Phys. Rev. B 69 054510
[18] Eisterer M, Mishev V, Zehetmayer M, Zhigadlo N D, Katrych S and Karpinski J 2014 Critical current anisotropy in Nd-1111 single crystals and the influence of neutron irradiation Supercond. Sci. Technol. 27 044009
[19] Yuan H Q, Singleton J, Balakirev F F, Baiy S A, Chen G F, Luo J L and Wang N L 2009 Nearly isotropic superconductivity in (Ba, K) Fe_2As_2 Nature 457 565–8
[20] Yamamoto A et al 2009 Small anisotropy, weak thermal fluctuations, and high field superconductivity in Co-doped iron pnictide Ba(Fe_1-xCo_x)2As_2 Appl. Phys. Lett. 94 062511
[21] Zehetmayer M 2009 Simulation of the current dynamics in superconductors: application to magnetometry measurements Phys. Rev. B 80 104512
[22] Zhukov A A, Perkins G K, Bugoslavsky Yu V and Caplin A D 1997 Geometrical locking of the irreversible magnetic moment to the normal of a thin-plate superconductor Phys. Rev. B 56 2809
[23] Silhanek A, Niebieskikwiat D, Avila M A, Billoni O, Casa D and Civale L 1999 Anomalous behavior of the irreversible magnetization and time relaxation in YBa_2Cu_3O_7 single crystals with splayed tracks Phys. Rev. B 60 13189
[24] Giamarchi T and le Doussal P 1997 Elastic theory of flux lattices in the presence of weak disorder Phys. Rev. B 55 6577
[25] Mikić K and Brandt E H 2001 Peak effect, vortex-lattice melting line, and order–disorder transition in conventional and high-Tc superconductors Phys. Rev. B 64 184514
[26] Frischherz M C, Kirk M A, Zhang J P and Weber H W 1993 Transmission electron microscopy of defect cascades in YBa_2Cu_3O_7–\delta produced by ion irradiation Phil. Mag. A 67 1347
[27] Martinek I, Tarantini C, Lehmann E, Manfrinetti P, Palenzona A, Pallecchi I, Putti M and Ferdeghini C 2008 Direct TEM observation of nanometric-sized defects in neutron-irradiated MgB_2 bulk and their effect on pinning mechanisms Supercond. Sci. Technol. 21 012001
[28] Dew-Hughes D 1974 Flux pinning mechanisms in type II superconductors Phil. Mag. 30 293–305
[29] Brandt E H 1995 The flux-line lattice in superconductors Rep. Prog. Phys. 58 1465–594
[30] van der Beek C J, Konczykowski M and Prozorov R 2012 Anisotropy of strong pinning in multi-band superconductors Supercond. Sci. Technol. 25 084010
[31] Maiorov B, Kursumovic A, Stan L, Zhou H, Wang H, Civale L, Feenstra R and MacManus-Driscoll J L 2007 Vortex pinning landscape in YBa_2Cu_3O_7–\delta films grown by hybrid liquid phase epitaxy Supercond. Sci. Technol. 20 S223
[32] Miura M, Katoh T, Yoshizumi M, Yamada Y, Izumi T, Shiohara T and Hirayama T 2008 Enhancement of flux pinning in Y_1-xSm_xBa_2Cu_3O_7 with Sm nanoparticles Appl. Phys. Express 1 051701
[33] Miura M, Katoh T, Yoshizumi M, Yamada Y, Izumi T, Hirayama T and Shiohara Y 2009 Rare Earth substitution effects and magnetic field dependence of critical current in Y_1-xRE_yBa_2Cu_3O_7 with RE nanoparticles (RE = Sm, Gd) Appl. Phys. Express 2 023002
[34] Awaji S, Namba M, Watanabe K, Miura M, Yoshizumi M, Izumi T and Shiohara Y 2010 Flux pinning properties of TFA-MOD (Y,Gd) Ba₂Cu₃Oₓ tapes with BaZrO₃ nanoparticles Supercond. Sci. Technol. 23 014006

[35] Ercolano G, Bianchetti M, Wimbush S C, Harrington S A, Wang H, Lee J H and MacManus-Driscoll J L 2011 State-of-the-art flux pinning in YBa₂Cu₃O₇₋ₓ by the creation of highly linear, segmented nanorods of Bₙ₂(Y/Gd)(Nb/Ta)O₆ together with nanoparticles of (Y/Gd)₂O₃ and (Y/Gd) Ba₂Cu₄O₈ Supercond. Sci. Technol. 24 095012

[36] Chudy M, Fuger R, Eisterer M and Weber H W 2011 Characterization of commercial YBCO coated conductors after neutron irradiation IEEE Trans. Appl. Supercond. 21 3162–5