Correlation Between In-Plane Grain Orientation and the Reversible Strain Effect on Flux Pinning in RE-$Ba_2Cu_3O_{7-\delta}$ Coated Conductors

D. C. van der Laan, J. F. Douglas, L. F. Goodrich, R. Semerad, and M. Bauer

***Abstract*—The uniaxial pressure dependence of the critical temperature causes a reversible effect of strain on the critical current density and the flux pinning strength in many high-temperature superconductors. Recent experiments on patterned coated conductor bridges have shown that the anisotropic nature of the pressure dependence of the critical temperature of rare earth (RE)-$Ba_2Cu_3O_{7-\delta}$ (REBCO) has a major impact on the performance of coated conductors under strain. The strain effect on the critical current density is most prominent when the strain is along the [100] and [010] directions of the superconducting film, whereas it almost completely disappears when the strain is along [110]. In this paper, we investigate the correlation between the uniaxial-pressure dependence of the critical temperature and the reversible strain effect on flux pinning in REBCO coated conductors. We show that axial strain has a large effect on the irreversibility field and the pinning force in coated conductors when the [100] and [010] directions of the superconducting film are aligned along the conductor axis. The magnitude of the strain effect in these conductors largely depends on the angle at which the magnetic field is applied. On the other hand, the critical temperature is not expected to change with the axial strain in coated conductors when the [110] direction is aligned along the conductor axis. Indeed, the irreversibility field and the magnetic field dependence of the pinning force of these conductors are almost independent of the axial strain for all angles at which the magnetic field is applied. The minor strain dependence of the critical current measured in these conductors could be caused by the average in-plane grain misalignment of between 6° and 8°, which causes a slight variation in the strain alignment with the axes of the superconducting film. The results confirm that the reversible strain effect in REBCO coated conductors is largely determined by the uniaxial pressure dependence of the critical temperature.**

***Index Terms*—Critical current, flux pinning, REBCO coated conductors, strain.**

I. INTRODUCTION

A REVERSIBLE strain effect has been measured in many high-temperature superconductors, where the critical current I_c and the flux pinning force reversibly change with the strain in $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) wires and tapes [1], [2], $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes [3]–[6], and rare earth (RE)-$Ba_2Cu_3O_{7-\delta}$ (RE = Y, Gd, Dy, Sm, etc.; REBCO) coated conductors [7]–[14]. Recent work has ruled out the theory that the reversible strain effect originates from grain boundaries, where dislocations may obstruct the grain boundary supercurrent [15], [16]. Instead, the effect can be fully explained by the uniaxial pressure dependence of the critical temperature T_c in Bi-2212 wires and Bi-2223 tapes [2], [17]. Although such a correlation cannot be easily established in REBCO, due to the anisotropic nature of T_c [18], a clear link between the uniaxial pressure dependence of T_c and the reversible strain effect on I_c has been recently established [19]. By measuring the strain dependence of I_c in bridges that were patterned at various angles with respect to the conductor axis, it was shown that the combination of the anisotropic uniaxial pressure dependence of T_c and the high degree of the in-plane grain alignment in REBCO coated conductors results in an anisotropic in-plane strain dependence of I_c. The largest change in T_c with the axial strain occurred when the strain was along the [100] and [010] directions of the superconducting film, which resulted in the highest strain sensitivity of I_c. The critical temperature did not change with the strain along [110], and consequently, no significant strain effect on I_c was measured.

A magnetic field dependence of the reversible strain effect has been reported [10], [13], [14], [22], in, for instance, REBCO coated conductors that were produced by the metal–organic chemical-vapor deposition (MOCVD) route on an ion-beam-assisted deposition (IBAD) template, which were aligned with the [100] and [010] directions of the superconducting film along the conductor axis [20], [21]. The results suggest that a strain dependence of the irreversibility field B_{irr} and the flux pinning force $F_p = I_c \times B$ exists in these conductors through a change in T_c similar to that in Bi-2212 and Bi-2223, but such a correlation has not yet been drawn. Furthermore, we can expect that the axial strain does not affect B_{irr} or the pinning force in REBCO coated conductors that are produced through the inclined-substrate deposition (ISD) route, because the superconducting film in these conductors is aligned on average with [110] along the conductor axis [22], and T_c is thus not expected to significantly change with the

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axial strain. Here, we relate the effect of the axial strain on B_{irr} and the pinning force in the MOCVD-IBAD and ISD coated conductors, at various magnetic field angles, to their in-plane orientation and consequent changes in T_c with the axial strain.

II. EXPERIMENT

Two types of REBCO coated conductors were studied, i.e., $\mathrm{YBa_2Cu_3O_{7-\delta}}$ (YBCO) coated conductors on an IBAD template, which is designated as IBAD, and $\mathrm{DyBa_2Cu_3O_{7-\delta}}$ (DBCO) coated conductors on an ISD template, which is designated as ISD. The IBAD sample was deposited on a Hastelloy C-276 substrate that is 50-μm thick. The 1 μm thick YBCO superconducting layer was deposited on top of the buffer layers by MOCVD [23], [24]. Such a deposition route results in a twinned superconducting film that is oriented with the [100] and [010] directions along the tape axis [20], [21]. A silver cap layer that is 2–3 μm thick was deposited on top of the superconducting layer, and the conductor was slit from a 12 mm wide tape to a final width of 4 mm. The sample was surround plated with 20 μm of copper for electrical and thermal stability. The ISD sample had a 1 μm thick DBCO film that was deposited on an ISD MgO template [25]. A silver cap layer, which is 10 μm thick, was deposited on top of the superconducting layer. The twinned superconducting film that was deposited on the ISD template was aligned with the [110] direction along the tape axis [22].

The effect of the strain on the critical current in the presence of a magnetic field was measured with the setup outlined in [14]. The samples were soldered on a 98-wt. %-Cu and 2-wt. %-Be bending spring, and the sample was strained by bending the spring. The strain was measured with two strain gauges, one of which mounted on the bottom of the bending spring and one mounted on top of the sample. The bending spring and the sample were located at the tip of a measurement probe, which was inserted in the center of an 8 T split-pair superconducting magnet. The magnetic field was oriented perpendicular to the spring and sample current, and the entire probe assembly was mounted on a rotating flange that was operated by a stepper motor. The magnetic field angle relative to the sample surface was changed by rotating the probe assembly in the magnet, while the magnetic field always remained perpendicular to the transport current in the sample. The probe was placed in a reentrant dewar that was placed in the liquid helium bath of the superconducting magnet. The surrounding liquid helium would slowly subcool the liquid nitrogen to about 73 K, although the insert dewar was vacuum insulated from the helium bath. The subcooling of the nitrogen bath enabled a precise temperature control of the sample with a polyamide-encapsulated foil heater operating at 75.9 ± 0.02 K. The temperature of the liquid nitrogen was lowered in some cases to 65 K by reducing the pressure of the bath to 17.2 kPa. The critical current of the sample was determined by means of a four-probe measurement having an uncertainty of about 1 % at an electric-field criterion of 1 μV/cm. This uncertainty includes the influence of the uncertainty in the angle of the applied magnetic field.

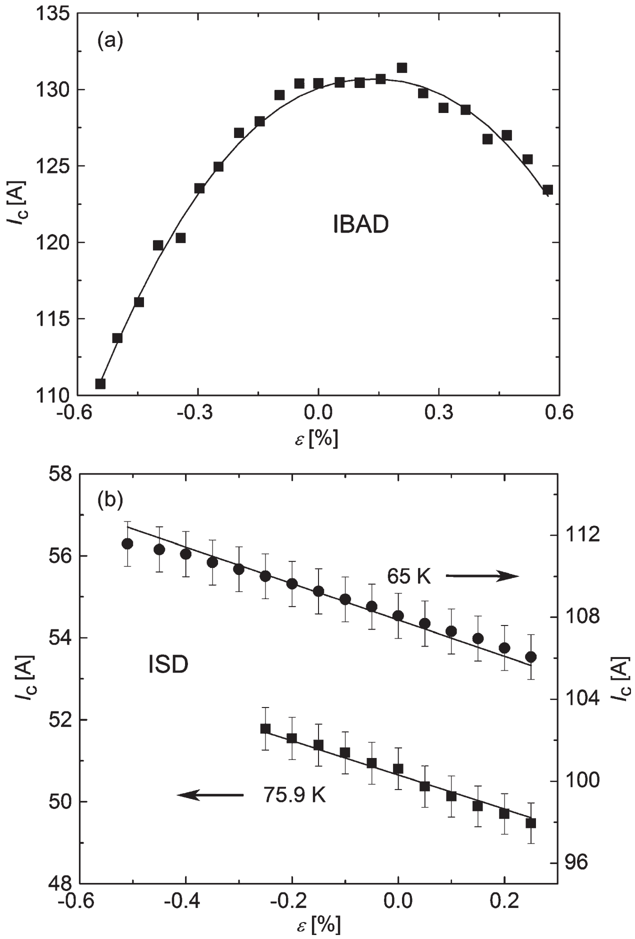

Fig. 1. (a) Strain dependence of I_c of sample IBAD at 75.9 K in self-field within the strain range at which I_c reversibly changes. (Solid line) Fit to the data, derived from (1). (b) Strain dependence of I_c of sample ISD at 75.9 and 65 K in self-field. The error bars are ± 1 %. (Solid lines) Linear fit to the data with (3).

III. RESULTS AND DISCUSSION

A. *Strain Effect on the Critical Current*

The critical current of the MOCVD-IBAD conductor shows a nonlinear strain dependence at zero applied field and at 75.9 K [see Fig. 1(a)], which is often described with a power-law fitting function [12], [14] of

$$I_c(B,\alpha,\varepsilon)=I_c(B,\alpha,0)\Big(1-a(B,\alpha)|\varepsilon-\varepsilon_m(B,\alpha)|^{2.2\pm0.02}\Big). \tag{1}$$

Parameter $a(B,\alpha)$ represents the strain sensitivity of I_c, and $\varepsilon_m(B,\alpha)$ is the location of the peak in I_c that is related to the initial strain state of the YBCO layer [12], [15], [16], [26]. The field angular dependence of these parameters is indicated by α. The parameter values that result from the fit of (1) to the data shown in Fig. 1(a) are $I_c(0,0,0) = 130.45$ A, $a(0,0,0) = 8050$, and $\varepsilon_m(0,0) = 0.13$ %, as was initially reported in [14]. The data that are shown in Fig. 1(a) are fully reversible; the critical current returns to its initial value after the strain has been released. The reversible strain effect has been related to the uniaxial pressure dependence of T_c, and the power-law dependence of I_c on the strain is a direct result of the twinning

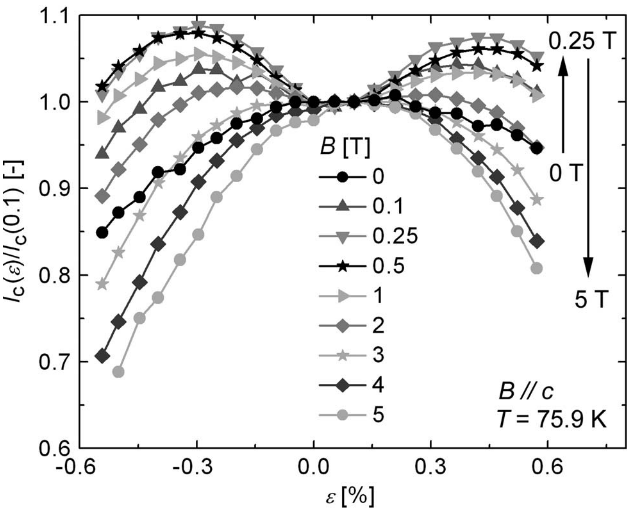

Fig. 2. Critical current of sample IBAD at 75.9 K, normalized to its value at 0.1 % strain, as a function of strain at various magnetic fields applied parallel to the c-axis.

of the superconducting film and the alignment of the [100] and [010] directions with the conductor axis in MOCVD-IBAD conductors [19]–[21].

The strain dependence of I_c for sample ISD in self-field at 75.9 K and 65 K is shown in Fig. 1(b). The strain dependence of I_c is fully linear and shows a change in I_c with a strain of -9.1 ± 2.0 %/% at 75.9 K and -6.7 ± 2.0 %/% at 65 K (defined as %/% from now on). The data shown in Fig. 1(b) are also completely reversible and are comparable with those reported elsewhere [27]–[30], where I_c linearly decreases with the strain for the ISD-DBCO sample and linearly increases with the strain for the ISD-YBCO sample.

The superconducting film in sample ISD is aligned with [110] along the conductor axis [22], which results in an almost equal lattice deformation along the a- and b-axes with the axial strain. The change in T_c with the strain along the a-axis is expected to cancel the change of T_c with the strain along the b-axis [18], and the T_c value of sample ISD is thus expected to be independent of the axial strain. The relatively small change in I_c with the strain could be the result of a small remnant change in T_c that occurs with the strain, because the average in-plane grain misalignment in ISD coated conductors is about 6°–8°, and the strain is thus not always aligned with [110] throughout the sample.

B. *Strain Effect on B_{irr} and Pinning Force*

Previous work [10], [11], [13], [14] has shown that the magnetic field influences the strain sensitivity of the critical current in many coated conductors, including MOCVD-IBAD. An overview of the strain dependence of I_c of sample IBAD at 75.9 K, for different magnetic fields applied perpendicular to the conductor surface and parallel to the c-axis of the superconducting film, is shown in Fig. 2. This figure has been reproduced from [14], where we discussed the strain effect on I_c decreasing at low field and becoming much larger at high magnetic field. This behavior could be potentially caused by a difference in the strain dependence of intra- and intergrain pinning.

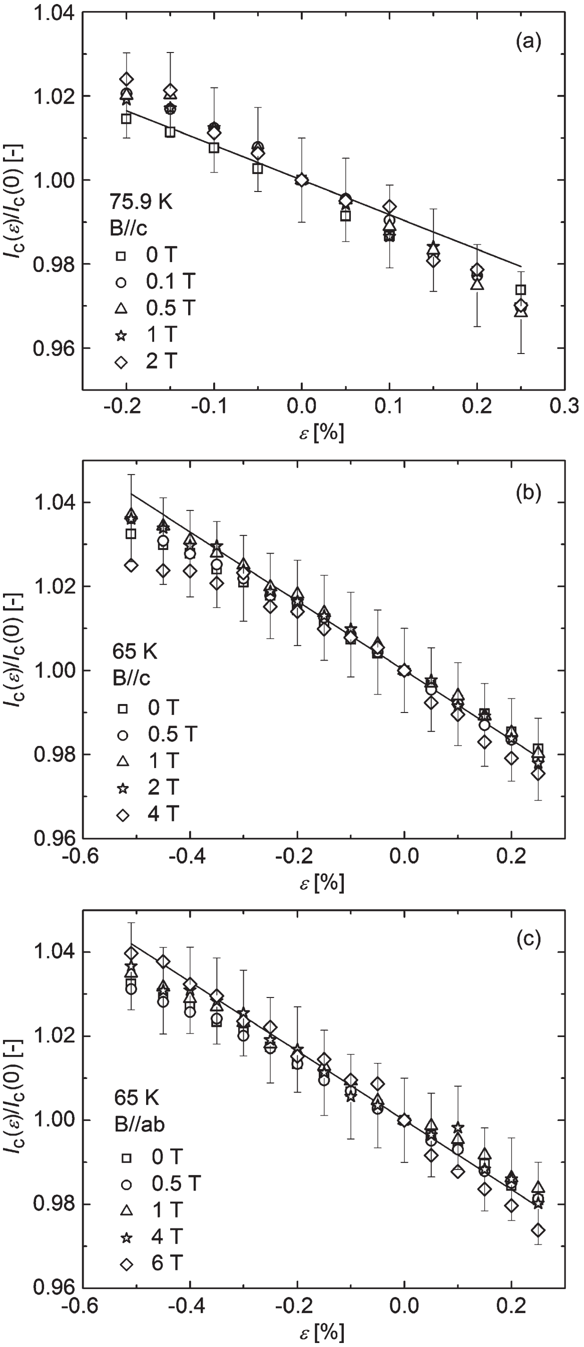

Fig. 3. Critical current of sample ISD, normalized to its value at 0 % strain, as a function of strain at various magnetic fields, (a) at 75.9 K with the field applied parallel to the c-axis, (b) at 65 K with the field applied parallel to the c-axis, and (c) at 65 K with the field applied parallel to the ab-plane. (Solid lines) Linear fit to the data with (3).

Fig. 3(a) shows the normalized I_c at 75.9 K as a function of the strain for various magnetic fields applied parallel to the c-axis of the superconducting film in sample ISD, which corresponds to an angle of about 60° with respect to the conductor plane, since the c-axis in ISD coated conductors is tilted sideways by about 30°. The linear strain dependence of I_c does not change much with the magnetic field within the measurement uncertainty of I_c. The same holds for the strain dependence of I_c measured at 65 K when the magnetic field is applied parallel to the c-axis [see Fig. 3(b)] and at 65 K

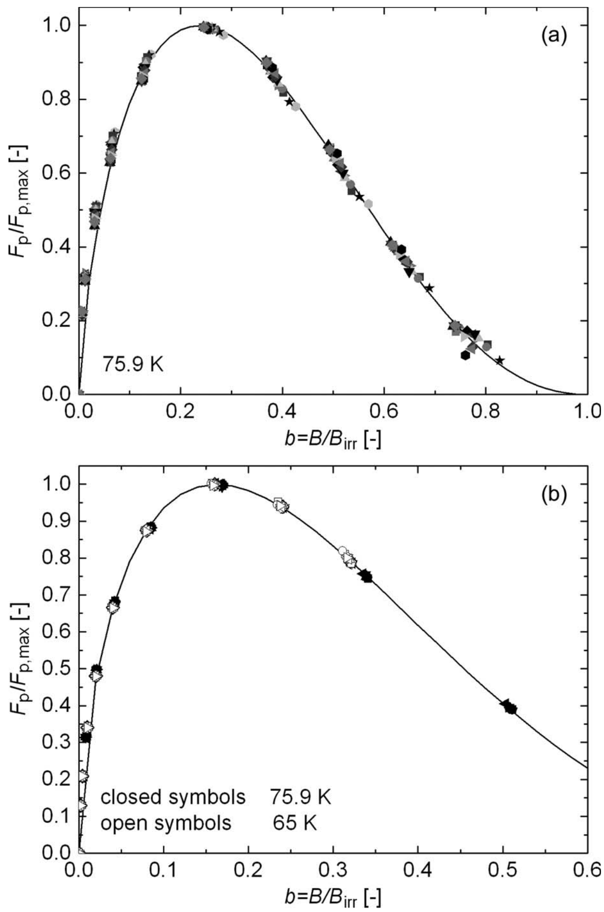

Fig. 4. Normalized pinning force as a function of reduced field for fields applied parallel to the c-axis for different strains. (a) Sample IBAD at 75.9 K. (b) Sample ISD at 65 K and 75.9 K. (Solid lines) Fit to the data with (2).

when the magnetic field is applied parallel to the ab-plane [see Fig. 3(c)]. The strain dependence of I_c can be described with a linear function, within the measurement uncertainty, with a slope of -8.2 ± 2.0 % I_c per % ε for both temperatures, all magnetic fields, and both field directions. The linear function in Fig. 3(a)–(c) represents (3), which is discussed below.

The strain dependence of the pinning force and the irreversibility field is studied by plotting the macroscopic pinning force, normalized to its maximum value, against the reduced magnetic field $b = B/B_{\mathrm{irr}}$ for different strains. The normalized pinning force at 75.9 K of sample IBAD, in which significant changes in the reversible strain effect with the magnetic field were measured, is shown in Fig. 4(a). The normalized pinning force is often described with the following fitting function [10], [31], [32]:

$$\frac{F_p(B,T,\varepsilon)}{F_{p,\max}(B,T,\varepsilon)} = b^p(1-b)^q \qquad (2)$$

where p and q are fitting parameters, which, for sample IBAD, have values $p = 0.7$ and $q = 2.3$. The normalized pinning force of sample ISD as a function of the reduced field for different strains is plotted in Fig. 4(b), including (2), with $p = 0.6$ and $q = 3.0$. The graph includes data taken with fields applied parallel to the c-axis of the superconducting film at 75.9 K (closed symbols) and 65 K (open symbols), which clearly shows that the functionality of the normalized pinning force of sample ISD at this particular field orientation does not depend on temperature; in other words, p and q are temperature independent.

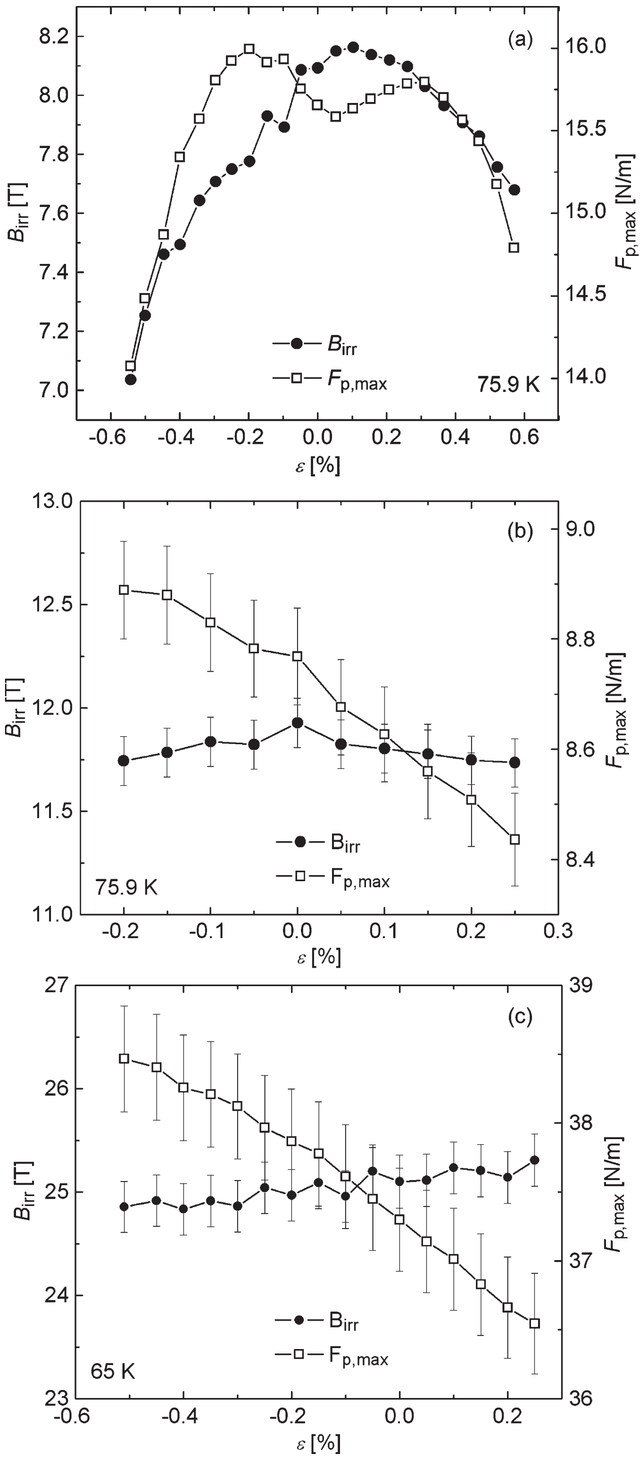

Fig. 5. Strain dependence of the maximum pinning force and the irreversibility field for fields applied parallel to the c-axis. (a) Sample IBAD at 75.9 K. (b) Sample ISD at 75.9 K. (c) Sample ISD at 65 K. The error bars are ±1 %.

The strain dependences of the maximum pinning force and the irreversibility field of sample IBAD are shown in Fig. 5(a). The maximum pinning force shows a strain dependence similar to that of the critical current at low magnetic field. It first increases with strain for both compressive and tensile strains, and decreases when the strain exceeds either -0.2 % or 0.3 %. The strain dependence of B_{irr} of sample IBAD has a clear maximum of 8.16 T near 0.1 % applied strain and decreases to about 7.68 T at 0.6 % and 7.04 T at -0.55 % strain. The strain dependence of B_{irr} is most likely due to a change in T_c with strain, as has been shown for Bi-2212 and Bi-2223 [2], [17].

The strain dependences of $F_{p,\max}$ and B_{irr} of sample ISD at 75.9 and 65 K are shown in Fig. 5(b) and (c), respectively. The maximum pinning force at both temperatures shows a linear strain dependence with a slope of about -8.2 ± 2.0 %/%, which is comparable with the slopes in I_c versus the strain, which is expected, because $F_p = I_c \times B$. The irreversibility fields of sample ISD at 75.9 K and 65 K are almost independent of the strain within an uncertainty of about 1 %. Since the irreversibility field is highly sensitive to T_c [33], we can conclude that T_c does not significantly change with the axial strain in sample ISD. Still, the slope in the strain dependence of I_c and $F_{p,\max}$ is likely caused by a small change in T_c with the strain, due to the in-plane grain misalignment of between 6° and 8°. The small deviation from the linearity of the strain dependence of I_c at high compressive strain and high magnetic field could be a result of the small change in T_c with the strain [see Fig. 3(a)–(c)]. A small remnant strain effect was also measured in MOCVD-IBAD coated conductor bridges that were patterned along the [110] direction of the superconducting film [19]. The remnant strain effect was explained by the small misalignment of the strain with [110] and the average in-plane grain misalignment of about 4°.

C. Strain Effect on I_c at Various Magnetic Field Angles

The magnetic field dependence of the critical current of REBCO coated conductors depends on the angle at which the field is applied. The critical current of sample IBAD is shown in Fig. 6(a) as a function of field angle at magnetic fields of 1 and 4 T and strains of -0.15 %, -0.35 %, and -0.55 %. Flux pinning between the CuO planes in the REBCO film causes a sharp maximum in I_c when the magnetic field is applied parallel to the ab-planes, which is at a field angle of 90°. The relatively small peak at 0° with the magnetic field applied parallel to the c-axis is caused by correlated pinning defects in the YBCO layer. The critical current of sample IBAD is highly affected by the strain for all magnetic field angles. The reversible strain effect has a larger impact on I_c at certain magnetic field angles, such as at 0°, as compared with 85° at a field of 4 T, at which angle I_c is almost independent of the strain. The angular dependence of the strain sensitivity of I_c in sample IBAD is highlighted in Fig. 6(b), where the angular dependence of I_c at -0.55 % strain, normalized to I_c at the lowest applied strain (-0.15 %), is shown. The normalization of I_c shows that, at 1 T, I_c decreases by at least 10 % at an angle of 25° when the strain is increased from -0.15 % to -0.55 %, whereas it is almost independent of the strain at an angle of 80°. At 4 T, I_c decreases by almost 45 % at 25°, whereas it decreases only by about 5 % at 83°. The field-angular dependence of the reversible strain effect in sample IBAD is likely caused by the change in B_{irr} with the strain, which is highly dependent on the magnetic field angle.

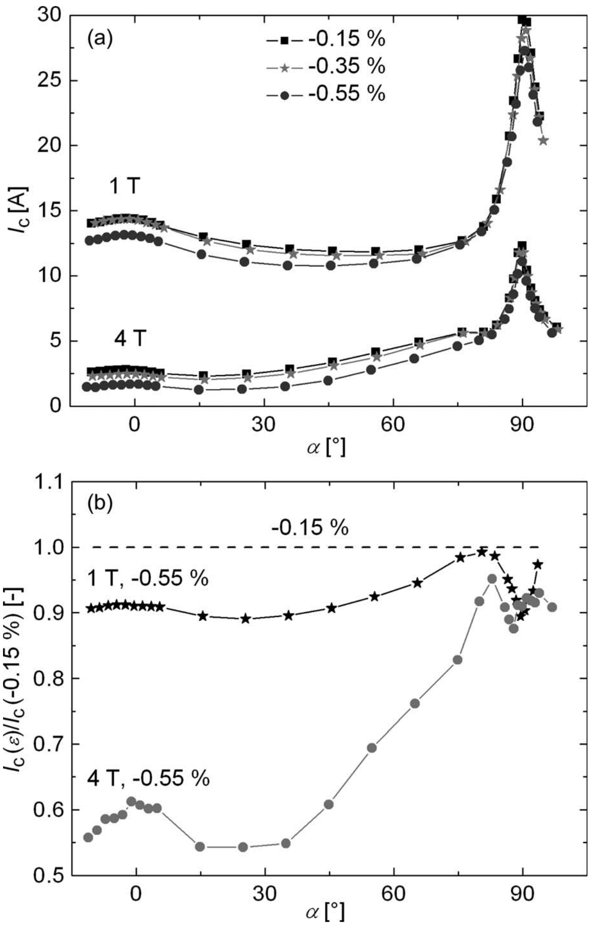

Fig. 6. (a) Magnetic field angular dependence of I_c at 1 and 4 T of sample IBAD at 75.9 K for three different strains. (b) Field angular dependence of I_c of sample IBAD at 1 and 4 T at -0.55 % strain, normalized to I_c at -0.15 %.

The critical current of sample ISD also changes with the field angle, as shown in Fig. 7(a) for a field of 1 T at 75.9 K and in Fig. 7(b) for 4 T at 65 K, for strains of -0.4 %, 0 %, and 0.2 %. A peak in I_c is measured when the magnetic field is applied along the ab-planes (at 90°), but no peak in I_c exists when field is applied along the c-axis (at 0°). The strain does affect I_c at each magnetic field angle in sample ISD, but no significant angular dependence of the strain sensitivity of I_c was measured. This directly follows from the angular dependence of I_c at different strains, normalized to the angular dependence of I_c at 0 % strain, as shown in Figs. 7(b) and (c). We can conclude that B_{irr} of sample ISD is almost independent of the strain not only for fields applied along the c-axis but for all other field angles as well, which is a direct consequence of the largely strain-independent T_c in ISD coated conductors with the strain applied along the conductor axis.

Even with the relatively high spread of the in-plane grain misalignment of 6°–8° in sample ISD, the strain dependence of I_c can be described with the following function:

$$I_c(\varepsilon, T, B, \alpha) = (k\varepsilon + 1) I_c(T, B, \alpha) \tag{3}$$

in which $I_c(T, B, \alpha)$ is the temperature, magnetic field, and magnetic field angular dependence of I_c, and k is the slope

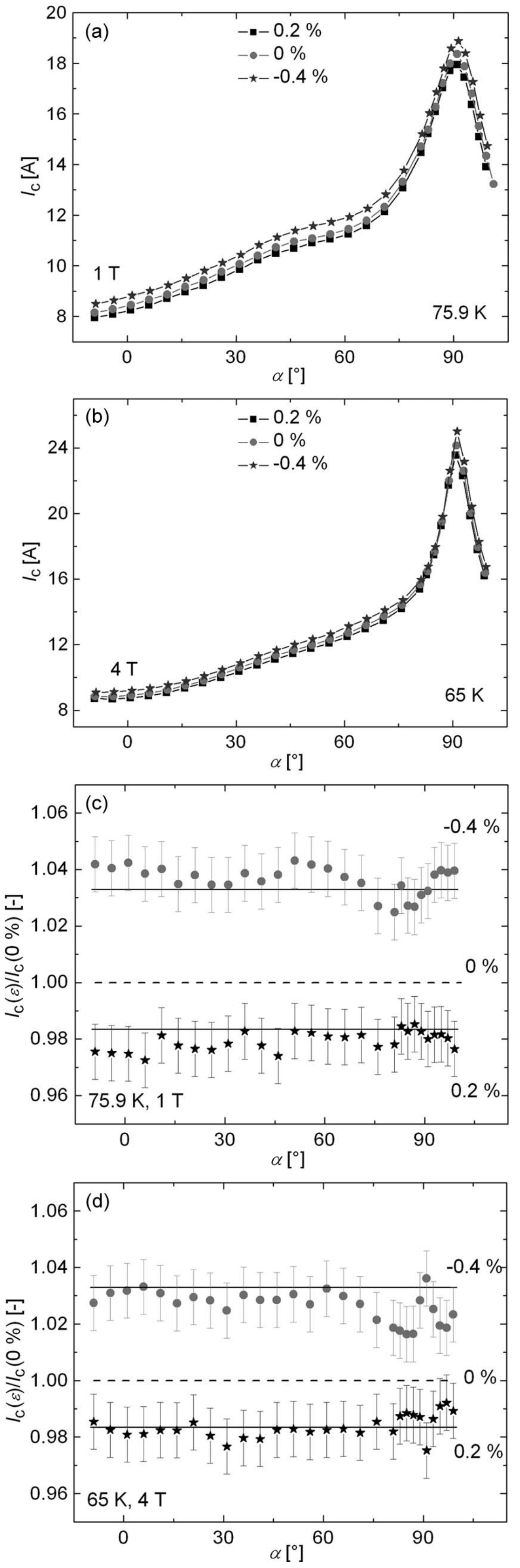

Fig. 7. (a) Magnetic field angular dependence of I_c at 1 T of sample ISD at 75.9 K for three different strains. (b) Magnetic field angular dependence of I_c at 4 T of sample ISD at 65 K for three different strains. (c) Field angular dependence of I_c at 1 T of sample ISD at 75.9 K, normalized to I_c at 0 % strain. (d) Field angular dependence of I_c at 4 T of sample ISD at 65 K, normalized to I_c at 0 % strain. (Solid lines) Fit to the data with (3).

in I_c with the strain. The small remnant change in T_c causes the slope in I_c with the strain to slightly change with temperature, which is shown when Fig. 3(a) and (b) are compared. The change in slope is relatively small and well within the measurement uncertainty of I_c of 1 %. Therefore, parameter k is left independent of temperature, magnetic field, and field angle. Equation (3) is used to fit the strain dependence of I_c in self-field at 75.9 K and 65 K shown in Fig. 1(b); the normalized I_c for different magnetic fields shown in Fig. 3(a)–(c); and the normalized I_c at different strains, magnetic fields, field angles, and temperatures shown in Fig. 7(c) and (d), resulting in $k = -8.2\ \%/\%$.

The fact that T_c in sample ISD does not significantly change with the strain applied along the conductor axis is due to the alignment of the strain with the [110] direction of the superconducting film. We would expect that the strain will affect T_c in these conductors when the strain is applied at different angles with respect to the conductor axis, which is similar to what has been measured in bridges that were patterned in MOCVD-IBAD coated conductors. A power-law dependence of I_c on the strain and a strain-dependent B_{irr} are expected in ISD coated conductor bridges that are patterned at an angle of 45° from the conductor axis.

IV. CONCLUSION

We have compared the reversible strain effect on the performance of REBCO coated conductors that were produced with either the MOCVD-IBAD or ISD method. A large effect of the strain on the dependence of the critical current, the irreversibility field, and the macroscopic pinning force has been measured in MOCVD-IBAD coated conductors. A relatively small linear change in the critical current with strain of $-8.2 \pm 2.0\ \%/\%$ has been measured in ISD coated conductors, whereas no significant dependence on strain has been measured in the irreversibility field and the field dependence of the pinning force. The differences between the strain effects in both conductors can be explained by the orientation of the strain with respect to the superconducting film and its consequent strain dependence of T_c. The strain has a large effect on the critical temperature in MOCVD-IBAD coated conductors, which affects the irreversibility field and the pinning force, whereas the critical temperature in ISD coated conductors is almost independent of the strain. The small linear change in I_c with the strain in ISD coated conductors is likely due to the fact that the strain is not perfectly aligned with [110], because the average in-plane grain misalignment is about 6°–8°.

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Certain commercial materials are referred to in this paper to foster understanding. Such identification implies neither recommendation nor endorsement by the National Institute of Standards and Technology, nor that the materials identified are necessarily the best available for the purpose.

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