Effect of thickness on magnetic properties of single domain GdBCO bulk superconductors

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To study the influence of thickness on the magnetic properties of ReBCO (Re = Y, Gd, Sm, Nd, etc.) bulk superconductors, a single domain gadolinium barium copper oxide (GdBCO) bulk superconductor fabricated by the Re + 011 top seeded infiltration growth (Re + 011 TSIG) method was continuously sliced along the bottom to obtain samples of different thickness. The levitation force and attractive force of these samples were tested at 77 K in the zero-field-cooled (ZFC) state. It is found that as the sample thickness decreases, the levitation force decreases gradually whereas the attractive force increases. This is related to the varied ability to resist the penetration of magnetic field occasioned by varying sample thickness, which are deeply revealed by combining with the characteristics of the non-ideal type-Ⅱ superconductor. Further, the levitation force exhibits a trend of slow initial change followed by rapid change, which may be attributed to the growth of the sample. Measurement of the trapped field shows that a similar distribution of trapped field at the top and bottom surfaces can be achieved by removing some materials from the bottom of the bulk. These results provide a reference for meeting the actual requirements of ReBCO bulks of different thicknesses and greatly contribute to practical designs and applications.

Keywords: single domain GdBCO bulk superconductor, levitation force, attractive force

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1. Introduction

High-temperature bulk superconductors (HTBSs) have been proven to play an important role in many applications such as superconducting maglev systems,[1,2] flywheels,[3,4] generators,[5] and energy storage systems.[6,7] Single domain ReBCO (Re = Y, Gd, Sm, Nd, etc.) bulk superconductors have attracted considerable attention owing to their higher critical current density, larger levitation force, and stronger trapped field, which are key properties of HTBSs.[8,9] Typically, the levitation force is determined by the radial magnetic field of the permanent magnet and the induced current density of the HTBS as follows:[10]

$$F = AJ_{\mathrm{c}}V\left(\frac{\mathrm{d}H}{\mathrm{d}x}\right), \tag{1}$$

where A is a constant related to the geometric factor of the sample, J_{c} is the critical current density, V is the volume of the bulk superconductor, and $\mathrm{d}H/\mathrm{d}x$ is the gradient of the radial magnetic field. Larger bulks are crucial for enhancing levitation force properties. Similarly, the trapped field is also an important parameter for evaluating the properties of superconductors, and the relation is expressed as

$$B_{\mathrm{tr}} = CJ_{\mathrm{c}}r, \tag{2}$$

where C is a constant relative to the aspect ratio (h/d) of the sample.[11] Evidently, the levitation force and trapped field are both related with J_{c} as well as the dimension of the superconductor. Therefore, many studies are devoted to improving J_{c} of bulks or fabricating larger bulks to improve performance. Inoue *et al.* introduced fullerene (C_{60}) as an effective flux pinning center in YBCO superconductors; the J_{c} and the trapped field of the sample were enhanced with the addition of C_{60}, and the sample with 1.0 wt% C_{60} addition exhibited the highest J_{c} value of approximately 55000 A/cm^2.[12] Sakai *et al.* obtained large GdBCO bulk superconductors with a diameter of 140 mm; the maximum trapped field was 3.66 T (65 K, 4 T), and the levitation force density was twice the value of a 46-mm-diameter bulk.[13] Regarding the increase in sample thickness, previous studies showed that the performance is greatly improved by stacking bulks.[14,15] In Ref. [16], Sakai *et al.* reported that both the trapped field and levitation force properties were considerably enhanced when the sample thickness was increased by stacking bulks, specifically at low temperature. In Ref. [17], Vakaliuk *et al.* mentioned that commercial YBCO assembled as a double-sample stack trapped a reliable and reproducible magnetic field of 9.5 T at 50 K and trapped field of 16.85 T at 30 K, which is comparable to the record reported. Durrell *et al.* found that the highest trapped field currently peaks at 17.6 T (26 K) in a magnetizing field of 17.8 T, which is produced by Ag-doped GdBCO stacking samples.[18]

However, when the sample thickness is decreased, the effects of thickness on the properties for samples fabricated by

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different methods may be different. For instance, Leblond *et al.* fabricated two types of YBCO bulk superconductors with various Y_2BaCuO_5 components ($Y_{1.5}$ and $Y_{1.8}$) in diameter of 20 mm and thickness of 10 mm using the top seeded melt growth (TSMG) method.[19] Their levitation force initially remains constant with the thickness decreasing and then reduced monotonously at the thicknesses of 6 mm and 8 mm, respectively. The variance in critical thickness is related to the Y_2BaCuO_5 amount. Wang *et al.* observed that the levitation force of the YBCO bulk superconductor prepared by the sinter forging process also tends to remain constant first and then reduces as the thickness decreases, while the critical thickness is 5 mm. This indicates that the sample fabrication method may influence the critical thickness.[20] Shi *et al.* found that the levitation force of single domain YBCO bulk superconductor fabricated by the TSMG method decreases linearly with the decreasing thickness, which may be attributed to the small size of the magnet employed in the study.[21] Kütük *et al.* found that the levitation force density of YBCO bulks fabricated using the flame-quench-melt-growth method improves with the decrease of sample thickness, which is associated with a significant amount of precipitated phase at the bottom of the sample.[22] In Ref. [23], Kütük *et al.* discovered that with the thickness decrease, the maximum levitation force of the polycrystalline YBCO bulk superconductors fabricated by two varying methods exhibit two distinct trends: one increases initially and then decreases, whereas the other increases monotonously, which is because various fabrication methods lead to the $YBa_2Cu_3O_{7-x}$ superconducting phase formation at different locations. In Ref. [24], Eisterer *et al.* demonstrated that a nonlinear relationship exists between the trapped field and sample thickness after reducing the sample thickness by removing the top layers. This is different from the monotone reduction findings in Refs. [25,26], in which the thickness is decreased by bottom slicing. This is due to the macroscopic barriers, including large cracks and badly connected grains in the top layers' removal, hindering the supercurrent flow and directly influencing the trapped field distribution at the top of the sample. In conclusion, the effect of the thickness of bulk superconductor on the superconducting magnetic properties is closely related to the fabrication process of the bulk and many other factors.

The Re + 011 top seeded infiltration growth (Re + 011 TSIG) method,[27] being an improved TSIG method, is widely used in the preparation process of ReBCO bulk superconductors. However, for this method, the effect of sample thickness on the magnetic properties has not been evaluated hitherto. Therefore, this paper reports the relationship between the sample thickness and the magnetic properties (levitation force, attractive force, trapped field) for bulks fabricated by this method. The results provide a reference for the application with requirements on the sample thickness.

2. Experimental procedure

2.1. Sample

A single-domain GdBCO bulk superconductor with a diameter of 30 mm and thickness of 10 mm fabricated by the Re + 011 TSIG method was selected in this work. The commercial $BaCO_3$ and CuO powders were uniformly mixed in a molar ratio of 1 : 1 and then thrice sintered at 910 °C to obtain the black precursor powders of $BaCuO_2$ (RE011). The mixture comprising Gd_2O_3 and RE011 (molar ratio 1 : 1.2) was used as the solid phase powder, whereas the mixture comprising Gd_2O_3, RE011, and CuO (molar ratio 1 : 10 : 6) was used as the liquid phase powder. The solid phase powder was pressed into a cylindrical solid phase pellet with a diameter of 30 mm and height of 10 mm, and the liquid phase pellet with a diameter of 40 mm and height of 12 mm was similarly pressed. Moreover, 5-g Yb_2O_3 powder was pressed into the pellet as the liquid phase support, which was pressed together with the liquid phase. Then, the solid phase pellet, liquid phase pellet, liquid support pellet, and several symmetrically arranged MgO single crystals were laid coaxially on the Al_2O_3 plate. A NdBCO single crystal was placed in the center of the top surface of the solid phase pellet with its *ab* plane parallel to the surface. Finally, the assembled samples were put into a customized furnace with optimized temperature gradient to form the single domain GdBCO bulk. Oxygenation treatment was then conducted to produce the finished superconductor. The details of the fabrication method have been described elsewhere.[28]

Figure 1(a) shows the top view of the GdBCO bulk superconductor. As illustrated, the sample exhibited epitaxial growth from the seed to the whole surface, indicating that the sample is of typical single domain morphology.[29] A diamond cutting machine was used to continuously slice 3 mm, 2 mm, and 2 mm from the bottom of the sample, as indicated in Fig. 1(b). After layer-by-layer slicing, a group of specimens with thicknesses of 7 mm, 5 mm, and 3 mm were obtained. It should be noted that the bottom of the specimen was polished prior to each slice to obtain a flat surface to facilitate accurate measurement of thickness and properties.

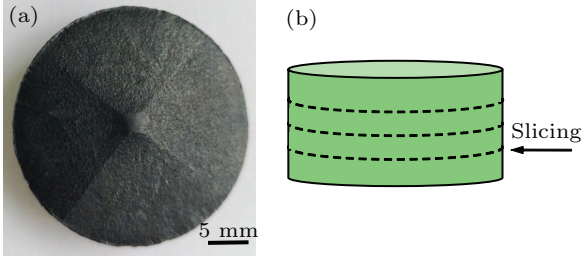


Fig. 1. Top view morphology of the GdBCO bulk superconductor and a schematic illustration of slicing: (a) top-surface morphology of the sample, (b) illustration of sample slicing from the bottom upward.

2.2. Measurement of levitation force and trapped field

The levitation force was measured using a novel self-designed 3D measurement system[30] at 77 K liquid nitrogen temperature. A cylindrical NdFeB magnet ($\Phi = 30$ mm, $B = 0.5$ T) was used to test the levitation force–distance curve in the zero-field-cooled (ZFC) state through the descending and ascending processes. In the course of testing, the NdFeB magnet and GdBCO superconductor remain axisymmetric, with the closest distance between them being 0.5 mm. For the trapped field measurement, the samples were magnetized using an electromagnet as a source of uniform magnetic field in the field-cooled (FC) state with an applied field of 1 T. Next, the trapped field was measured using Hall probes located at 0.5 mm above the sample surface.

3. Results and discussion

Figure 2 shows the levitation force curves of samples with thicknesses (h) of 10 mm, 7 mm, 5 mm, and 3 mm. The levitation force varies for samples of various thicknesses. The maximum levitation force corresponds to the 10-mm-thick unsliced sample, whereas the minimum corresponds to the thinnest sample (3 mm thick). Furthermore, as the thickness decreases, the slope of the curve gradually eases; it also presents a leftward trend, which implies that decreases in sample thickness result in the diminution of levitation force and stiffness.

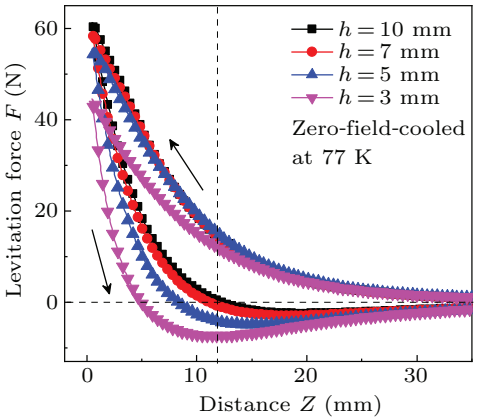


Fig. 2. Levitation force of samples with varying thicknesses vs the distance between the permanent magnet and GdBCO bulk superconductor.

To demonstrate the effect of sample thickness on the levitation force, the maximum levitation force ($F_{\rm mlf}$) values were collected and plotted against the sample thickness, as shown in Fig. 3. Evidently, the levitation force decreases with the thinning of sample thickness; it exhibits a trend of gradual decrease initially and rapid decrease later. When the thickness is reduced from 10 mm to 7 mm, $F_{\rm mlf}$ decreases by 3.2%; when the thickness is reduced from 7 mm to 5 mm and from 5 mm to 3 mm, $F_{\rm mlf}$ decreases by 10.53% and 27.4%, respectively. In addition, the hysteresis behavior[31] becomes more evident with the decrease in thickness (see Fig. 2). As the permanent magnet moves away from the bulk superconductor (during the ascending process), the F–Z curve changes from a relatively gradual trend to an obvious deep valley shape, the tip of which corresponds to the maximum attractive force ($F_{\rm maf}$). As illustrated in Fig. 3, when the sample thickness is 10 mm, $F_{\rm maf}$ is 2.47 N; when the thickness is reduced to 7 mm and 5 mm, $F_{\rm maf}$ increases to 2.99 N and 4.88 N, respectively. Moreover, when the sample thickness is 3 mm, $F_{\rm maf}$ reaches 7.43 N. This indicates that a thinner sample has less levitation force and greater attractive force, i.e., as the sample thickness decreases, the levitation force decreases gradually whereas the attractive force increases. Table 1 shows the $F_{\rm mlf}$ and $F_{\rm maf}$ values of samples with varying thicknesses and the corresponding distance between the permanent magnet and bulk superconductor.

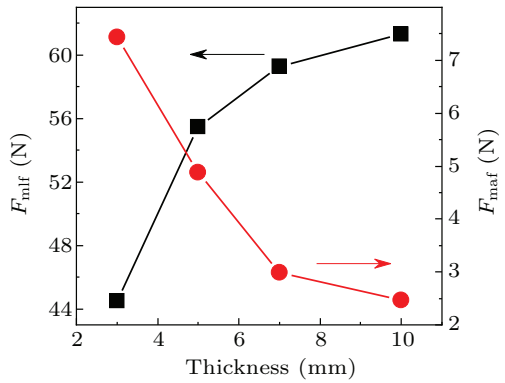


Fig. 3. Maximum levitation force $F_{\rm mlf}$ and the maximum attractive force $F_{\rm maf}$ versus the sample thickness.

Table 1. The $F_{\rm mlf}$ and $F_{\rm maf}$ of samples with various thicknesses and the corresponding distance between the permanent magnet and GdBCO superconductor.

Thickness h (mm)	$F_{\rm mlf}$ (N)	Distance $Z_{\rm mlf}$ (mm)	$F_{\rm maf}$ (N)	Distance $Z_{\rm maf}$ (mm)
10	61.32	0.5	2.47	19.7
7	59.28	0.5	2.99	18.3
5	55.48	0.5	4.88	15.5
3	44.50	0.5	7.43	11.55

The variation of levitation force with sample thickness has been investigated by several groups. Qin *et al.*[32] and Alqadi *et al.*[33] calculated and found that the levitation force of superconductors unchanged first and then reduced with the decrease of sample thickness. Antončík *et al.*[34] discovered that the levitation force of the YBCO bulk superconductor fabricated by the TSMG method shows a similar change law to reference.[32,33] In this literature, the levitation force decreases slowly first and then rapidly when the sample thickness decreases from 10 mm to 2 mm, which is consistent with our results. However, the levitation force remains constant with the thickness from 18 mm to 10 mm, which is not reflected in our results due to the initial thickness of our sample being very small, only 10 mm.

It is well known that superconductors have two fundamental characteristics: zero resistance and perfect diamag-

netism. Depending on the critical magnetic field, it can be divided into two types, one called the type-I superconductor and the other the type-Ⅱ superconductor. In this work, the single domain GdBCO bulk superconductor is a non-ideal type-Ⅱ superconductor. When the bulk is in a mixed state, the magnetic flux penetrates into the superconductor in quantized form;[35] at this time, the bulk superconductor presents incomplete diamagnetism. The diamagnetic ability of a superconductor, i.e., the ability to resist the penetration of a magnetic field, is associated with the total maximum current the superconductor can carry. The greater the total maximum current, the stronger the ability of a superconductor to resist the magnetic field. The total maximum current (I_{max}) that a superconductor can carry is expressed as

$$I_{max} = J_c R h, \tag{3}$$

where J_c represents the critical current density of the superconductor, R and h are the radius and the thickness of the superconductor, respectively.[36] The corresponding schematic diagram of formula (3) is shown in Fig. 4. For the GdBCO superconductors with various thicknesses, the J_c and R are the same, thus the ability to resist the magnetic field penetration closely depends on its thickness. The thicker the bulk, the larger the maximum current I_{max} it can carry, which means the stronger ability to resist the penetration of magnetic field. Conversely, the thinner the bulk superconductor, the smaller the maximum current it can withstand, and the lesser the ability to resist magnetic field penetration.

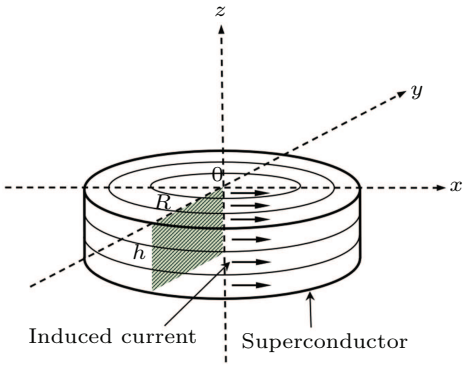


Fig. 4. Distributions of the total maximum current the sample can carry.

When the permanent magnet approaches the bulk superconductor (during the descending process), as the external magnetic field increases, the flux lines gradually penetrate into the sample. As mentioned above, the thinner sample has the weaker ability to resist the magnetic field penetration, so there are more flux lines penetrating into the sample. This is demonstrated by a schematic diagram presented in Figs. 5(a) and 5(b), showing the distribution of magnetic field in the sample when the permanent magnet is close to the samples with different thicknesses. Clearly, the thinner sample is accompanied by more flux lines passing through. Therefore, a smaller levitation force is obtained in the ZFC state. In contrast, the thicker sample has the stronger ability to resist the penetration of magnetic field, and the fewer flux lines penetrate into the sample, resulting in a greater levitation force.

When the permanent magnet moves away from the bulk superconductor (during the ascending process), the external magnetic field decreases gradually, resulting in the decrease of the magnetic flux acting on the superconductor. Consequently, the induced circulation generated in the superconductor is opposite to the original direction. Therefore, the levitation force decreases gradually. However, owing to the flux pinning ability of the non-ideal type-Ⅱ superconductor,[37] part of the flux lines originally penetrating into the superconductor were pinned, so that the superconductor has a trapped field distribution in the same direction with the external magnetic field. Therefore, when the distance between the two reaches a certain value, the force is called the attractive force.[38] Figures 5(c) and 5(d) present the trapped field distribution inside the sample when the permanent magnet is away from the sample (Z_{maf} is the position at which F_{maf} occurs). For the thinner sample, more flux lines penetrate into it, and the corresponding trapped field is also stronger, resulting in a higher attractive force. Moreover, the attractive force of the thinner sample reaches the F_{maf} earlier, as shown in Fig. 2 and Table 1, which is because the induced current of the thinner sample is more easily saturated in the reverse direction during the ascending process. Here, the distribution of magnetic field in the sample is simplified for illustrative purposes and is far more complex in reality. Furthermore, the above results are obtained under the assumption that J_c is uniformly distributed and the material is of homogeneity.

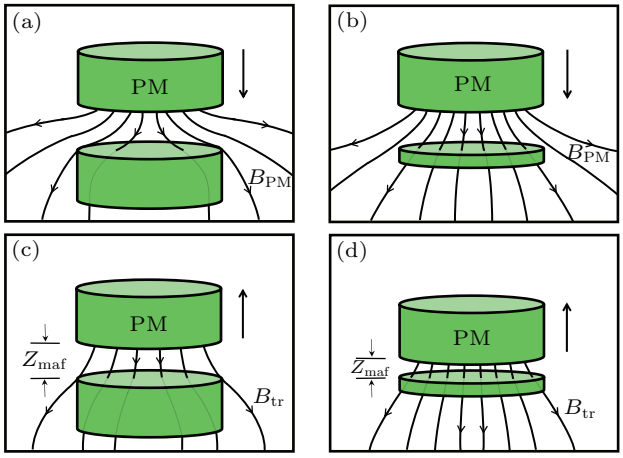


Fig. 5. Schematic diagram of magnetic field and trapped field distribution in the samples with different thicknesses: (a) and (b) the magnetic field distribution during the descending process, (c) and (d) the trapped field distribution during the ascending process.

The trapped field profiles of samples with various thicknesses were measured using a Hall probe positioned 0.5 mm above the surface of the sample with a 30 mm × 30 mm scanned area after the samples were magnetized in the FC

state. Figure 6 shows the three-dimensional trapped field distribution at the top and bottom of the samples. As can be seen, the trapped field of each sample forms a conical envelope with a single peak morphology, which implies that slicing did not affect the single domain of the sample and no macro-cracks or imperfections appeared in the process.[39] To better understand the relationship between the trapped field and the sample thickness, the data of the maximum trapped field ($\boldsymbol{B}_{\max}$) and sample thickness in Fig. 6 were collected and redrawn in Fig. 7 (note that the trapped field at the bottom is the absolute value of that in Fig. 6). As can be seen, the trapped field at the top surface exhibits a gradually decreasing trend as the thickness decreases. This is also related to the ability to resist magnetic field penetration based on the different sample thicknesses. As mentioned above, the thinner the sample is, the easier it is for the magnetic field to penetrate into the sample and, likewise, the easier to escape from the sample. Now, samples of various thicknesses are magnetized for a certain period in the FC state; once the applied magnetic field is removed, the flux lines penetrating into the thinner sample can easily escape, resulting in less magnetic flux trapped by the sample and a weaker trapped field.

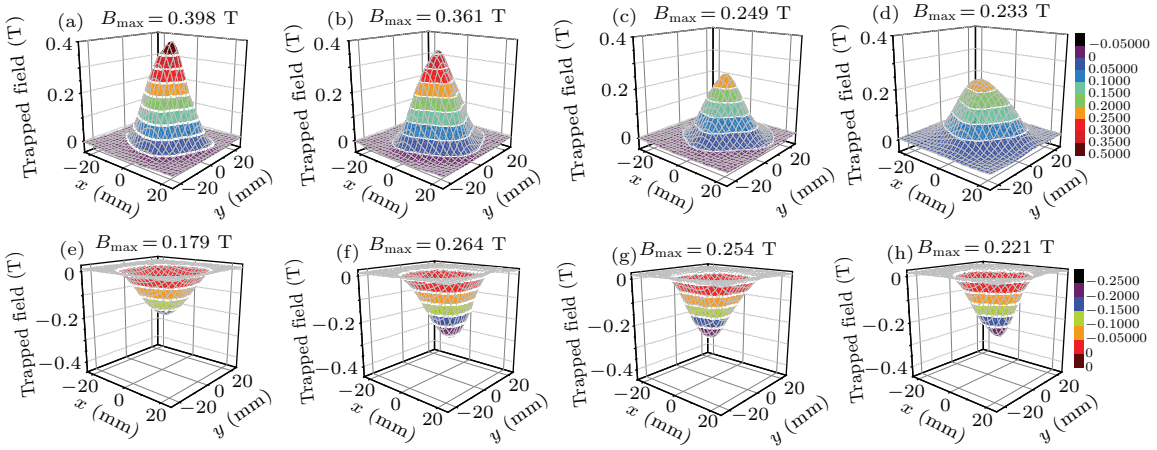


Fig. 6. Trapped field distributions at the top and bottom surfaces of samples with different thicknesses at 77 K in the FC state, $\boldsymbol{B}_{\text{app}} = 1$ T: (a) and (e) 10 mm, (b) and (f) 7 mm, (c) and (g) 5 mm, (d) and (h) 3 mm.

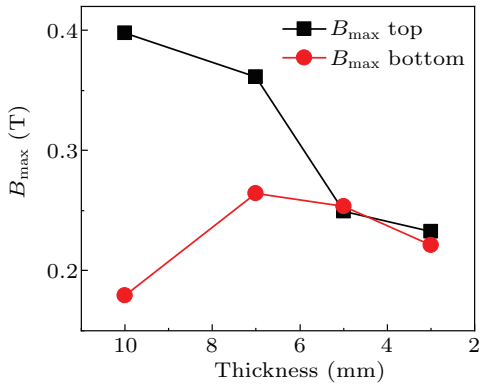


Fig. 7. Maximum trapped field $\boldsymbol{B}_{\max}$ as a function of the sample thickness.

However, the trapped field at the bottom surface presents a different distribution that initially increases (from thickness of 10 mm to 7 mm) and then decreases (from 7 mm to 3 mm). This behavior is occasioned by the poor growth of the sample. Figure 8 displays the macroscopic morphology cross section at the bottom of the 10-mm and 7-mm-thick samples. Before slicing, excessive Gd-211 and inhomogeneous distribution of rich Ba and Cu liquid phases accumulate in large quantities ("green phase" marked in red lines), indicating that the un-grown region was larger, as opposed to a smaller amount of associated Gd-123 superconducting phase. Therefore, at the beginning of slicing, the levitation force decreased slowly as discussed above. However, after slicing, the un-grown region shrunk while the as-grown area expanded, leading to an increase in J_c and inevitably resulting in a higher distribution of trapped field.[40] Moreover, when the sample thickness was decreased from 7 mm to 5 mm or less, more Gd-123 superconducting phase was removed, and the trapped field underwent a gradual natural decline. This is the reason why the levitation force decreases rapidly with the decrease of thickness in the late slicing.

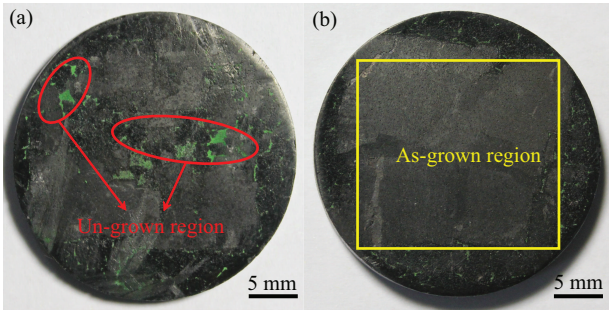


Fig. 8. Macro-morphology cross section of samples with different thicknesses: (a) $h = 10$ mm, (b) $h = 7$ mm.

When the sample thickness is reduced to 5 mm (i.e., 0.5 of the total height), the trapped fields at the top and bottom surfaces are approximately equal. This is consistent with the finding of 0.44 in Ref. [34], in which the trapped fields of

both the top and bottom surfaces are close at a height of 8 mm by bottom-slicing a sample with an original height of 18 mm. This implies that the same distribution of trapped field can be achieved at the top and bottom surfaces by bottom slicing, i.e., a distribution of homogeneous trapped field can be obtained by removing material of a certain height from bottom of the bulk. This method can be used to produce a uniform magnetic field similar to that of a permanent magnet, and thus has considerable advantages for practical applications.

4. Conclusions

In this study, thickness is taken as the main factor that affects magnetic properties of single domain GdBCO bulk superconductors by the Re + 011 TSIG method, and the relationship between the thickness and the magnetic properties (levitation force, attractive force, trapped field) are described in detail. The results show that as the sample thickness decreases, the levitation force decreases gradually whereas the attractive force increases. This may be due to the different ability to resist the penetration of magnetic field, which is dependent on the different thickness of the sample. In the ZFC state, the thinner the sample, the weaker its ability to resist the penetration of magnetic field. Therefore, the more flux lines would penetrate into the sample during the descending process, leading to the decrease of its levitation force; while the more flux lines would be pinned by the sample at the same time, leading to the increase of attractive force during the ascending process. Moreover, the levitation force increases slowly first and then rapidly, which may be related to the growth of the sample. Measurement of the trapped field reveals that a similar distribution of trapped field at the top and bottom surfaces can be achieved by removing some materials from the bottom of the bulk, which is important for practical applications. These results provide a reference for meeting the actual requirements of samples of different thickness and are helpful for understanding self-stable levitation characteristics of ReBCO bulks.

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