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Record-High Trapped Magnetic Field by Pulse Field Magnetization Using GdBaCuO Bulk Superconductor

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A trapped magnetic field $B_T{}^P$ as high as 4.47 T, which is the highest reported using pulse field magnetization to date, has been realized on the surface of a GdBaCuO bulk superconductor by a modified multi pulse technique combined with stepwise cooling. Following an introduction of a small amount magnetic flux into the bulk center by applying lower pulse fields $B_{ex} = 4.5-4.6$ T twice at a higher starting temperature $T_s = 45-48$ K, higher fields of $B_{ex} = 6.6-6.7$ T are applied three times at a lower $T_s = 28-29$ K. The reduction in the temperature rise due to the already existing trapped flux, in addition to the optimization of the higher B_{ex} value at the lower T_s, is a key point in enhancing $B_T{}^P$. [DOI: 10.1143/JJAP.44.L1221]

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For the practical applications of high temperature superconducting bulks as a high-strength bulk magnet in a magnetic separation system, a magnetron sputtering apparatus and other magnet-based systems, static field-cooled magnetization (FCM) is a standard method of realizing the highest trapped field of the maximum trapping ability. A trapped field $B_T{}^{FC}$ of 17.24 T at 29 K has been realized by FCM between two resin-impregnated YBaCuO disks (26.5 mm in diameter and 15 mm in thickness).[1)] Recently, pulse field magnetization (PFM) has been intensively investigated because of the relatively compact, inexpensive and mobile setup of the apparatus used. The trapped field $B_T{}^P$ and the total trapped flux $\Phi_T{}^P$ attained by PFM are, however, generally smaller than those attained by FCM. The deterioration is probably due to the large temperature rise ΔT caused by the magnetic flux motion against the vortex pinning force F_p and the viscous force F_v. In order to enhance $B_T{}^P$ and $\Phi_T{}^P$, ΔT reduction is an indispensable issue. Yanagi *et al.* reported that $B_T{}^P = 3.8$ T was attained on the surface of the SmBaCuO bulk (36 mm in diameter, 16 mm in thickness) at 30 K by an improved iterative pulse field magnetization method with reduced amplitude (IMRA),[2)] which is the highest published $B_T{}^P$ value to date. Sander *et al.* attempted a multi pulse technique with stepwise cooling (MPSC) and confirmed the enhancement of $B_T{}^P$.[3)] In this technique, the bulk was cooled down below the superconducting transition temperature T_c and magnetic pulses were applied several times. The bulk was further cooled down repeatedly and magnetic pulses with the same amplitude were applied.

We have studied the time evolution and spatial distribution of the temperature rise $\Delta T(t)$ on the surface of cryocooled REBaCuO bulks (RE = Gd, Y, Sm) during PFM and estimated the total generated heat Q on the basis of the maximum ΔT and the specific heat C of the bulk.[4–7)] After applying the successive pulse fields with the same amplitude, ΔT decreases with increasing number of applied pulses and then saturates to a final value. The increment of the trapped field $B_T{}^P$ also decreases with increasing number of pulses similar to the behavior of ΔT. In this letter, we report the PFM procedure using the modified MPSC (MMPSC) for a cryocooled GdBaCuO bulk and the attainment of $B_T{}^P$ as high as 4.47 T, the new highest record by PFM.

A GdBaCuO bulk superconductor disk (45 mm in diameter and 15 mm in thickness) with a highly *c*-axis oriented structure was used, which was fabricated by Nippon Steel. The bulk is composed of $GdBa_2Cu_3O_y$ (Gd123) and Gd_2BaCuO_5 (Gd211) with a molar ratio of Gd123 : Gd211 = 1.0 : 0.4, 10.0 wt% Ag_2O and 0.5 wt% Pt. The bulk was initially impregnated in vacuum by epoxy resin, and the upper and bottom resin layers were removed from the bulk surfaces in order to enhance the thermal response. The inset of Fig. 1(a) shows the experimental setup around the bulk. The bulk was magnetized while being sandwiched by two soft-iron yokes; the bulk was tightly stacked on the lower soft-iron yoke, (a disk 40 mm in diameter and 20 mm in thickness) on the cold stage of the helium refrigerator in the vacuum atmosphere and was magnetized using a pulse coil dipped in liquid N_2 with the upper soft-iron yoke (a cylinder 40 mm in diameter and 65 mm in thickness). The rise time of the pulse field was ~12 ms and the pulse duration was ~120 ms. The time evolution of temperature $T(t)$ was measured using a chromel-constantan thermocouple (76 μm in diameter) adhered to the bulk surface using GE7031 varnish at a 2 mm distance from the bulk center. Two Hall sensors (F.W. Bell, model BHA 921) were adhered to positions C (bulk center) and E (5 mm away from the bulk edge) and the time evolutions of the local fields $B_L(C)(t)$ and $B_L(E)(t)$ were monitored using a digital oscilloscope. The trapped field $B_T{}^P$ was determined at position C. The time dependence of the applied field $\mu_0 H_a(t)$ was monitored by the current $I(t)$ flowing through the shunt resistor. The maximum strength of the pulse field $\mu_0 H_a(t)$ was defined as B_{ex}.

We performed the modified MPSC (MMPSC); five magnetic pulses were applied at different initial temperatures T_s on the bulk surface. A pulse field $B_{ex} \sim 4.5$ T was applied twice at $T_s \sim 45$ K in order to produce a small magnetic field (~1 T) trapped at the bulk center. Hereafter, we refer to these two applied pulses as No. 1 and No. 2, respectively. Then the bulk was cooled down to $T_s \sim 29$ K and a higher B_{ex} of ~6.6 T was applied three times (No. 3, No. 4 and No. 5), while keeping T_s at ~29 K.

Figure 1 shows the time dependences of the applied field $\mu_0 H_a(t)$ and of the local fields [$B_L(C)(t)$, $B_L(E)(t)$] for applied pulses No. 1 to No. 4. The inset of Figs. 1(b)–1(d)

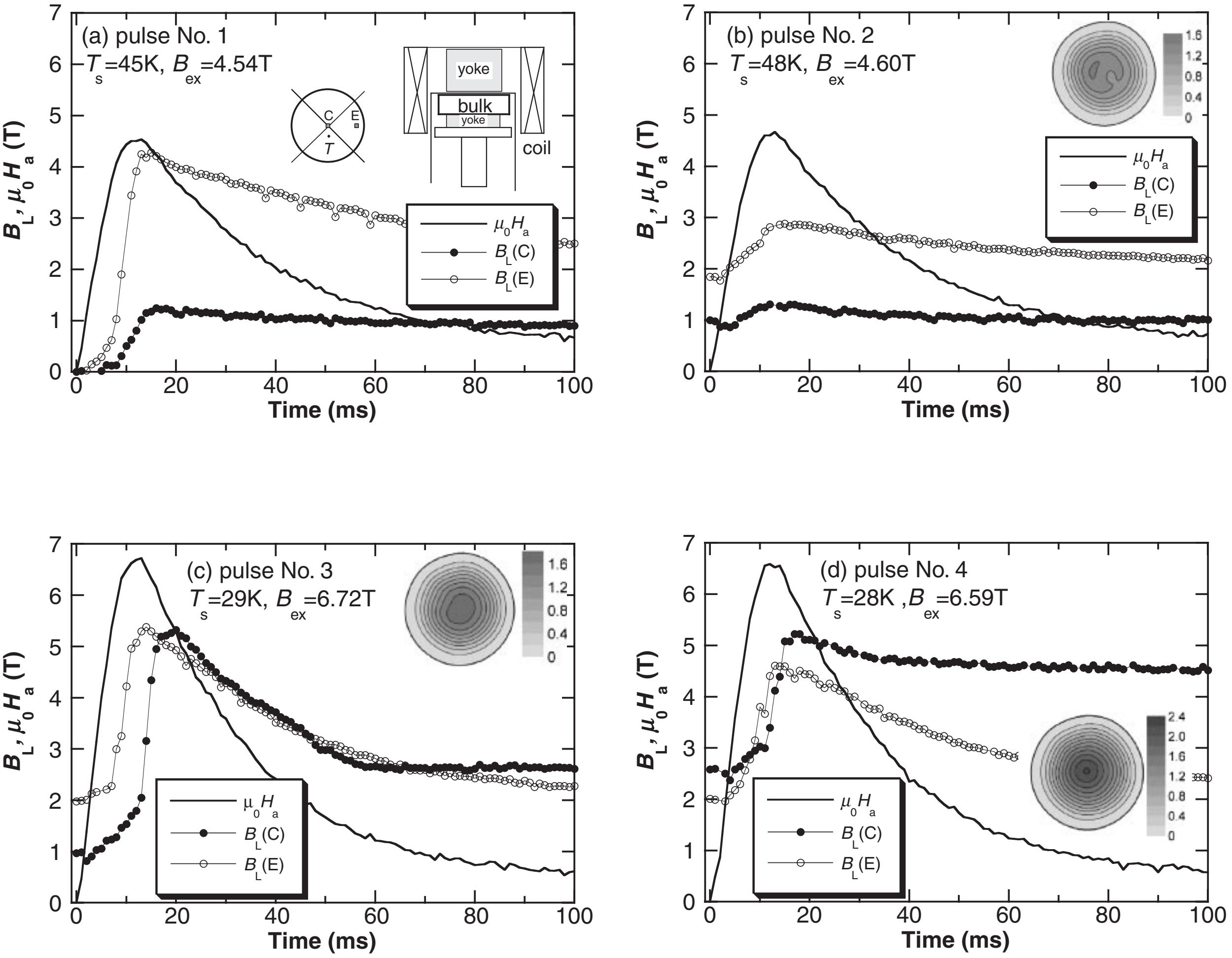

Fig. 1. Time evolutions of applied field $\mu_0H_a(t)$ and local fields $B_L(C)(t)$ and $B_L(E)(t)$ at positions C and E, for (a) pulse No. 1 ($T_s = 45$ K, $B_{ex} = 4.54$ T), (b) pulse No. 2 ($T_s = 48$ K, $B_{ex} = 4.60$ T), (c) pulse No. 3 ($T_s = 29$ K, $B_{ex} = 6.72$ T) and (d) pulse No. 4 ($T_s = 28$ K, $B_{ex} = 6.59$ T). The inset of (a) shows the experimental setup and those of (b)–(d) show the trapped field distribution scanned 3.5 mm above the bulk surface.

shows the trapped field distribution after each pulse, which was monitored 3.5 mm above the bulk surface in open space. For pulse No. 1 in Fig. 1(a), $B_{ex} = 4.54$ T was applied to the virgin-state bulk at $T_s = 45$ K. B_L(C) and B_L(E) rise up, take a maximum within 15 ms and then slowly decrease due to the flux creep to the final stable value. The maximum value of B_L(E) is 4.3 T, nearly equal to B_{ex}. On the other hand, B_L(C) reaches only about 0.9 T. For pulse No. 2 shown in Fig. 1(b), the pulse field of $B_{ex} = 4.60$ T was applied to the bulk at $T_s = 48$ K. Now the maximum B_L(E) is 2.9 T, which is far smaller than 4.3 T for pulse No. 1, suggesting that the already trapped fluxes obstruct the intrusion of the magnetic flux.[6] B_L(C) and the total trapped flux Φ_T^{out} 3.5 mm above the bulk surface slightly increase for pulse No. 2.

Figure 2 shows the time evolution of temperature $T(t)$ after each pulse field. For pulse No. 1, $T(t)$ gradually increases, takes a maximum of ~60 K at 10 s, and then gradually decreases to the initial temperature in 20 min. The temperature rise ΔT (~15 K) for pulse No. 1 to the virgin state mainly comes from the heat generated by flux trapping.[6] For pulse No. 2, ΔT markedly decreases to ~4 K as a result of the very small additional flux trap, and viscous loss should be the dominant origin of the heat as analyzed in our previous paper.[6]

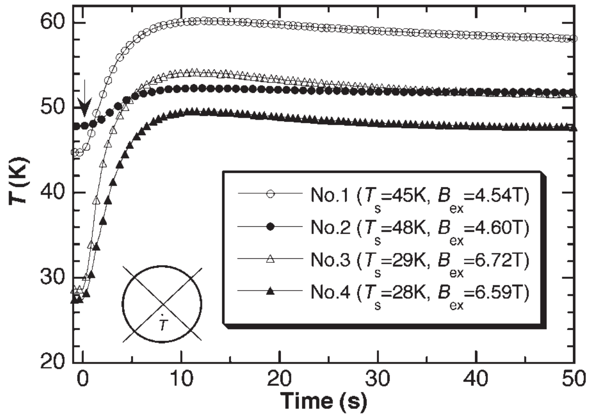

Fig. 2. Time evolutions of temperature $T(t)$ on bulk surface after each pulse field application. The arrow shows the origin of the time t.

After cooling the bulk down to $T_s = 29$ K, a higher magnetic pulse No. 3, $B_{ex} = 6.72$ T was applied. In Fig. 1(c), $B_L(C)(t)$ and $B_L(E)(t)$ rise up, take a maximum (~5.2 T) and then slowly decrease. The rise time of $B_L(C)(t)$ is long (~19 ms) compared with that of $B_L(E)(t)$ (~14 ms). This time delay of $B_L(C)(t)$ roughly corresponds to the flux traveling time from points E to C.[7] In contrast to Figs. 1(a) and 1(b), the maximum values of $B_L(C)$ and $B_L(E)$ are almost the same, which suggests that the flux fully reaches the central region of the bulk for this strength of B_{ex}. For pulse No. 4 shown in Fig. 1(d), the pulse field of $B_{ex} = 6.59$ T was applied after cooling to $T_s = 28$ K. The maximum $B_L(E)$ decreases to 4.6 T, again suggesting the obstruction of the flux intrusion by the trapped flux. On the other hand, the maximum $B_L(C)$ remains at 5.1 T and the trapped field $B_T{}^P$ [$= B_L(C)$ ($t \to \infty$)] settles at 4.47 T. In Fig. 2, the maximum T is 54 K for pulse No. 3 and decreases to 49 K for pulse No. 4 in spite of the similar strength of B_{ex}. This suppressed ΔT for pulse No. 4 obstructs the outflow of the magnetic flux. After removing the pulse coil with the upper yoke from the bulk in order to measure the trapped field distribution, $B_T{}^P$ decreased to 4.27 T. The measured $B_T{}^P$ is slightly enhanced by the upper yoke, which is magnetized by the trapped field of the bulk. The trapped field $B_T{}^{out}$ and the total trapped flux $\Phi_T{}^{out}$ in open space at 3.5 mm above the bulk was about 2.45 T and 17.02×10^{-4} Wb, respectively. For pulse No. 5 with $B_{ex} = 6.80$ T at $T_s = 28$ K, $B_T{}^P$ remains at 4.47 T, while $\Phi_T{}^{out}$ slightly increases to 17.35×10^{-4} Wb. Actually, pulse No. 5 is not necessary to efficiently realize the maximum $B_T{}^P$.

Figures 3(a) and 3(b) show the pulse number dependences of the maximum temperature rise ΔT_{max} and the trapped field $B_T{}^P$ for the present MMPSC method. For comparison, the results of five successive magnetic pulse applications (SPA) with the same strength are also shown for $B_{ex} = 4.5$ T at $T_s = 45$ K and for $B_{ex} = 6.6$ T at $T_s = 29$ K. In the SPA process, as we mentioned beforehand, ΔT_{max} decreases and $B_T{}^P$ increases gradually with increasing number of pulses and then both saturate to their final values. These results indicate that the heat generation is directly related with the increment of $B_T{}^P$. The ΔT_{max} and $B_T{}^P$ values after pulse No. 3 ($B_{ex} = 6.6$ T at $T_s = 29$ K) are almost the same both in the MMPSC and SPA processes. However, the $B_T{}^P$ values after pulse No. 4 are quite different; 4.47 T in MMPSC and 2.93 T in SPA, respectively, despite nearly equal B_{ex} and T_s for both No. 4 pulses. At the present stage, $B_T{}^P$ cannot be exactly predicted only from the macroscopic conditions of the bulk such as the $B_T{}^P$ and T_s just before applying the pulse field. There seems to be a saddle point for the $B_T{}^P$ enhancement, and another parameter such as the minute trapped field distribution in the bulk may critically govern the final $B_T{}^P$ value attained by PFM. The suitable choice of the initial temperature T_s and the optimization of B_{ex} for each step are of crucial importance to attain a $B_T{}^P$ value higher than 4 T. The successive pulse application with the same strength is very effective in reducing the temperature rise, and at least two pulses with the same B_{ex} are necessary for each T_s.

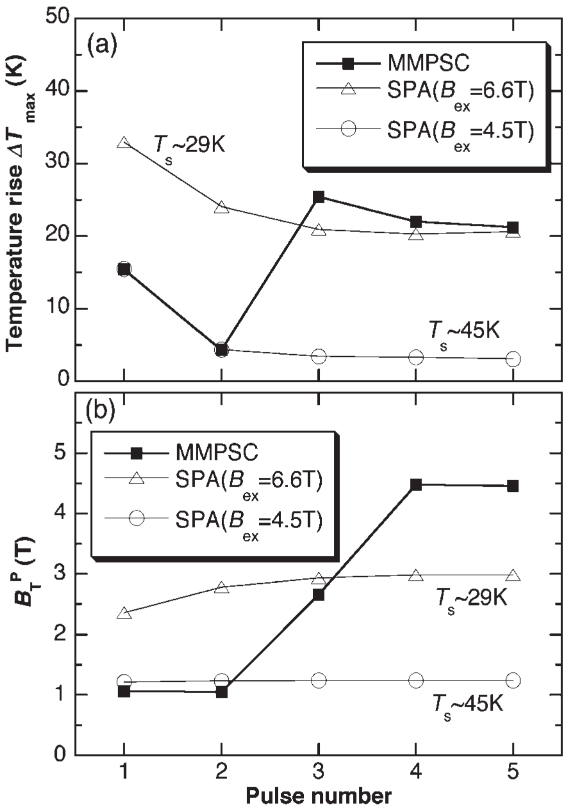

Fig. 3. Pulse number dependences of (a) maximum temperature rise ΔT_{max} and (b) trapped field $B_T{}^P$ for MMPSC. The results of five SPA with the same strength are also presented for $B_{ex} = 4.5$ T at $T_s = 45$ K and for $B_{ex} = 6.6$ T at $T_s = 29$ K.

For the FCM method, the maximum B_T is expected to be proportional to the diameter of the bulk, if J_c of each bulk superconductor is identical. In the PFM method, however, $B_T{}^P$ is governed by a complicated flux motion and a resultant local temperature rise. Taking account of the results in SPA, however, the attainment of the $B_T{}^P = 4.47$ T value is mainly attributable to the present MMPSC technique, and the effect of the size of the bulk disk may be of secondary importance for the present results. We tested the reproducibility by performing the exact same procedure and confirmed that $B_T{}^P \sim 4.2$ T can be consistently trapped at position C by this technique.

In summary, a trapped magnetic field $B_T{}^P$ as high as 4.47 T has been attained on the surface of a GdBaCuO superconducting bulk (45 mm in diameter and 15 mm in thickness) sandwiched by two soft-iron yokes using the modified multi pulse technique with stepwise cooling (MMPSC). After a small amount of magnetic flux ($B_{ex} \sim 4.5$ T) is applied into the bulk center twice at $T_s \sim 45$ K, the bulk is cooled down to $T_s \sim 29$ K and then a higher B_{ex} of $\sim$6.6 T is applied three times. The introduction of the trapped field of about 1 T near the bulk center at a high T_s, which results in the reduction of the temperature rise, and the optimization of B_{ex} at a low T_s are very important in enhancing the trapped field. A $B_T{}^P$ of 4.47 T is attained for pulse No. 4, which is the highest value ever reported as being attained by the pulse field magnetization method. In order to clarify the relevant physical mechanisms, detailed studies are in progress.

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