Fabrication of a Compact High-field Magnet by Coated Conductor Stacks

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Abstract. A bulk magnet was fabricated by stacking coated conductors with enhanced \( J_c \) by introducing nanorods. The fabricated CC stack consists of 100 pieces of CCs, and it was magnetized by field-cooling method in an applied field of 14.5 T down to 4.2 K. By reducing the magnetic field down to zero at a ramp of rate 1 T/min, we have succeeded in trapping 12.6 T at the center of the CC stack. We also confirmed that the CC stack can sustain the high trapped field for more than 20 min, which demonstrates the practical usefulness of such a staked CC magnet.

1. Introduction

Coated conductors (CCs) are widely used in applications such as carrying large current without energy dissipation and fabricating high-field magnets for various purposes. They can also be used as a trapped-field magnet by stacking short segments of CCs. There are a lot of studies of a trapped-field magnet using bulk superconductors by field-cooling method. Although there are problems of mechanical strength and thermomagnetic instability when magnetizing a magnetic field in a bulk superconductor [1, 2], it is possible to obtain a high and stable magnetic field by stacking CCs [3, 4]. There have been several studies on trapped-field magnet using bulk materials and stacks of CCs [5, 6, 7]. We have fabricated a CC stack with two stacks of 130 pieces of GdBCO CCs and trapped 7.92 T at the center of the stacks [8]. We have also fabricated a CC stack with two stacks of 80 pieces of irradiated GdBCO CCs and trapped 9 T at the center of the stacks, and also reported that flux jump occurred when trying to trap a large magnetic field quickly [9]. It is also reported that the record-high trapped magnetic field of 17.6 T has been achieved by using two kinds of CC stacks [10].

In the present study, we aimed at enhancing the trapped magnetic field by fabricating the bulk magnet using EuBCO CCs with better \( J_c-H \) characteristics. For that purpose, BaHfO\(_3\) nanorods are introduced into EuBCO CCs. Two stacks of each 50 pieces of EuBCO CCs were placed next to each other and miniature Hall probes for measuring the trapped field were placed at the center of the stacks. They were cooled down to 4.2 K in a magnetic field of 14.5 T, and the field was reduced to zero at 1 T/min. In this condition, we have succeeded in trapping 12.6 T at the center of the stacks.
2. Experimental Methods
In the present study, we used EuBCO CCs with BaHfO$_3$ nanorods by using hot-wall pulsed-laser deposition process. 2.5 $\mu$m thick EuBCO CC was deposited on 50 $\mu$m hasteroy tape, and $\sim$3 $\mu$m Ag layer was deposited for protection. The bulk magnet consists of two piles of each 50 CC stack, and local magnetic field at the center of the two stacks was measured with a miniature GaAs Hall probes (HG-0711) made by Asahi Kasei Microdevices as shown in Fig. 1(a). The dimensions of the Hall probe used as a magnetic sensor was 1.2 $\times$ 0.5 mm$^2$ and the thickness was 0.3 mm. It has been confirmed that ion-implanted GaAs Hall probes can be operated even at temperatures much lower than the specified temperature range and linearity with respect to the magnetic field is good enough due to their low mobilities [11]. Two Hall probes were soldered on a thin printed circuit board to be arranged at an interval of 1.8 mm. Therefore, it was possible to measure the local field not only at the center but also at the position 1.8 mm from the center. Since the thickness of the CC is 60 $\mu$m, the total height of the bulk magnet is only 6.5 mm including the part of Hall probes. In addition, in order to investigate the stability of the temperature, the temperature change was also measured using a Cernox sensor (CX-1050, Lakeshore [12]). For trapping magnetic field, we used a 15 T superconducting magnet at national institute for materials science (NIMS). The CC was placed in variable-temperature insert and cooled via liquid helium at 4.2 K and 1 atm helium gas at other temperatures. First, a magnetic field of 14.5 T was applied to the CC stacks at 100 K above $T_c$($\sim$93 K), and the CC stacks was cooled to the target temperature. Finally, the external field was ramped down to zero slowly, leaving a trapped field in the stack.

![Figure 1](image.png)

Figure 1. (a) Schematic vertical cross section of a bulk magnet consisting of double stack of GdBCO CCs and (b) arrangements of Hall probes between the two CC stacks. (c) A photo of the bulk magnet and its casing.

3. Results and Discussion
It is important to have good high-field performance to trap large magnetic field. Fig. 2(a) shows the external magnetic field dependence of $J_c$ of EuBCO CCs at seraval temperatures. $J_c - H$ characteristics of GdBCO CC used in our previous study [9] is also shown in Fig. 2(b). It demonstrates that $J_c$ of the EuBCO CC is improved especially at the high magnetic field compared with GdBCO CC.
Figure 2. Magnetic field dependence of $J_c$ at various temperatures of the (a) EuBCO and (b) GdBCO CCs.

Magnetization processes at the center and 1.8 mm away from the center as functions of applied field at 4.2 K are shown in Fig. 3. It is clear that we have succeeded in trapping 12.6 T in the center of CCs. This trapped field value is much larger than 9 T trapped by 80 stacks of CCs reported in our previous study [9]. Although the trapped field is lower than the latest report by Cambridge group [10], the height of our CC stacks is 1/6 of their stacks, and time to trap field is 37 times faster. It should be noted that the initial rapid temperature change above 12 T is due to the fact that the experiment was started from a slightly lower temperature. A part of temperature increase below 12 T (~0.035 K) is due to the magnetoresistance of Cernox sensor, and the rest of the increase (~0.03 K) is induced by the flux motion during the magnetization process.

Figure 3. Local magnetic field in the magnetization process with the field-ramp rate of 1 T/min at two locations of the CC stack magnet at 4.2 K. Temperature of the stack is also plotted.
The field trapped in the center of the CC stacks at different temperatures are shown in Fig. 5(a). The ramp rates used for applied field were 1 T/min at 77 K, 30 K, 20 K and 4.2 K. This means that it took only 15 min to trap high magnetic field at 4.2 K. At 10 K, when the ramp rate was 1 T/min, flux jumps were observed and the trapped field rapidly decreased due to low heat capacity and insufficient cooling by helium gas as is shown in Fig. 4(a). Therefore, the ramp rate was reduced to 0.3 T/min at 10 K (Fig. 4(b)). It clearly demonstrates that as the temperature is decreased, the trapped field increases. However, the enhancement of the trapped field becomes weaker below 10 K. This behavior is similar to $J_c - T$ dependence shown in Fig. 5(b).

**Figure 4.** Local magnetic field in the magnetization process with field-ramp rates of (a) 1 T/min and (b) 0.3 T/min at two locations of the CC stack magnet at 10 K. Temperature of the stack is also plotted.

**Figure 5.** Temperature dependence of (a) the trapped magnetic field in the stack and (b) $J_c$ of the EuBCO CC.
In the real application of the stack magnet of CCs, it is important to sustain a large magnetic field for a long time. In order to check the stability of the trapped field, flux creep was measured for the trapped field up to 20 min after field cooling as shown in Fig. 6.

![Figure 6. Flux creep measurements for trapped field at different positions in the first 20 min after magnetization. The field-ramp rate of the magnetization process is 1 T/min. $B_0$ is the trapped field 3 s after magnetization.](image)

It can be seen that the normalized relaxation rate ($\frac{d\ln M}{d\ln t}$) is 0.012 even after 20 min. It is necessary for the application to examine how much the trapped field is maintained after magnetizing the CC stacks. When one attempts to use CC stacks as a high-field permanent magnet at higher temperature, a similar confirmation of long-term stability of the trapped field is important.

4. Summary
We have fabricated a bulk magnet by stacking 100 pieces of EuBCO coated conductors with BaHfO$_3$ nanorods. A large magnetic field of 12.6 T was successfully trapped in this CC stack after field-cooling and reducing the field at a rate of 1 T/min. The trapped field was very stable, and more than 95% of the field was maintained at the center of the stack even 20 min after the magnetization.

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