Characteristics of a Bulk High-Critical Temperature Superconductor Fabricated by the Shock Compaction Method: Possible Use as a Highly Sensitive Magnetic Sensor

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Abstract. A magnetic sensor, constructed of bulk Bi-Pb-Sr-Ca-Cu-O (BPSCCO), was fabricated by use of the shock compaction method, employing a propellant gun-system, and then sintered under through use of an electronic furnace. The specimen as a magnetic sensor was maintained in the superconducting state at 77.4 K, under a current density \( J \) of approximately 40 A/cm\(^2\) in the absence of an excitation magnetic field \( B_{ex} \). The superconducting state was then broken and the specimen exposed to a \( B_{ex} \) value of 40\( \times 10^{-4} \) T. That is, the resistance \( R_{meas} \) of the specimen occurred when exposed to 40\( \times 10^{-4} \) T under a constant \( J \) of 40 A/cm\(^2\). The magnetic sensitivity \( S \) of the specimen was estimated as 13\%/(10\(^{-4} \) T) over the range of measurement of the magnetic field \( B_{meas} \) from 0 to ±5\( \times 10^{-4} \) T, under a constant 40\( \times 10^{-4} \) T for the value of \( B_{ex} \), being approximately 13 times greater than that of a giant magnetoresistance (GMR) sensor. It was, consequently, determined that it was possible to apply the bulk BPSCCO specimen as a highly sensitive magnetic sensor.

1. Introduction
In constructing highly sensitive magnetic sensors, the present authors have been studying the use of bulk Bi-Pb-Sr-Ca-Cu-O (BPSCCO) as the magnetic sensor, which was fabricated by use of the shock compaction method, employing a propellant gun-system [1]. The BPSCCO specimen as a magnetic sensor was maintained in a superconducting state at 77.4 K, under a current density \( J \) of about 40 A/cm\(^2\) in the absence of an excitation magnetic field \( B_{ex} \). The superconducting state was then broken and the specimen exposed to a \( B_{ex} \) value of 40\( \times 10^{-4} \) T. That is, the resistance \( R_{meas} \) of the specimen occurred when exposed to 40\( \times 10^{-4} \) T under a constant \( J \) of 40 A/cm\(^2\). The magnetic sensitivity \( S \) of the specimen was estimated as 13\%/(10\(^{-4} \) T) over the range of measurement of the magnetic field \( B_{meas} \) from 0 to ±5\( \times 10^{-4} \) T, under a constant 40\( \times 10^{-4} \) T for the value of \( B_{ex} \), being about 13 times greater than that of a giant magnetoresistance (GMR) sensor [2]. Consequently, it was determined that the bulk BPSCCO specimen could be possibility used as a highly sensitive magnetic sensor.

Experimental results revealed the dependence of \( R(T) \) on temperature, the dependence of resistivity \( \rho \) of the specimen on \( J \), the dependence of the magnetic sensitivity \( S \) on \( \rho \), and the dependence of \( R_{meas} \) on the \( B_{meas} \). In addition, the characteristics of magnetic sensors constructed with and without use of the shock compaction method are compared and discussed.

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2. Experimental procedure
In the fabrication of the bulk BPSCCO specimens to be used as magnetic sensors, commercial
BPSCCO powder (Dowa Mining Co., Ltd., DSC-045001) was formed into pellets by using a
compressor under pressures ranging from 200 to 300 MPa. The pellets were further subjected to shock
compaction pressures of about 4 GPa for about 1 μsec, such as reported in Ref. [1]. The specimens
were sintered under a temperature of 845 °C for 48 hours, by heating in dry air to a temperature of
845 °C at the rate of 14 °C/min, cooled in dry air to a temperature of 300 °C at the rate of 5 °C/min,
and then cooled to room temperature by a natural cooling. The pellets, measuring 0.5 mm in thickness
and 10 mm in diameter, were cut into rectangular-shaped test specimens using a diamond saw at a low
cutting rate to reduce the effects of heat.

The magnetic characteristics were evaluated with all sensors placed in an excitation magnetic flux
density $B_{ex}$, that is, a homogeneous DC magnetic field. The $B_{ex}$ was applied perpendicular to the
surface of the sensors which measured 9.4 mm in length and 1.7 mm in width. The measuring system
used in obtaining the magnetic characteristics was shielded by two Mu-metal cylinders around a metal
dewar vessel. The four-terminal method was used during resistance measurements of the sensors.

3. Results and discussion
Figure 1 shows the resistance $R(T)$ as a function of temperature $T$ for magnetic sensors in the absence
of an excitation magnetic flux density $B_{ex}$. The values of $R(T)$ have been normalized by the value of
$R(T=150 \text{ K})$ at 150 K. The values of the DC current densities $J$ applied to the current terminals of the
sensors are 3 A/cm$^2$. Curves (a) and (b) display typical characteristics of the specimens constructed
with and without the shock compaction method, respectively. The temperature characteristics of curve
(a) are shifted toward higher temperatures than those of curve (b), and demonstrate the effect of the
shock compaction method, as can be seen in this figure.

The plotted results in Fig. 2 show the magnetization $M$ as a function of $T$ for the specimens using a
DC SQUID magnetometer. In this figure, curves (a) and (b) reveal characteristics of specimens with
and without the shock compaction method, respectively. It is found that the values of $M$ for the
specimen with the shock pressure is improved by approximately $32.1 \times 10^{-3}$ emu/g over that of the
specimen without the shock compaction method at a temperature of 5 K.

X-ray diffraction measurements were then carried out for the two specimens, that is, with and
without the shock compaction method, in order to analyze the crystallographic structure. The X-ray
source is copper Kα, and examples of diffraction patterns are shown in Fig. 3. The curves in Fig. 3 (a)
and (b) are the results of the specimens with and without the shock compaction method, respectively.
It is found that the Bi-2223 phase appears more clearly in the specimen constructed with the shock
compaction method.

Figure 1. Typical characteristics of the dependence of the resistance $R(T)$ on the $T$, for (a) the sensor with the shock compaction method, and (b) the sensor without the shock compaction method.

Figure 2. Magnetization $M$ as a function of $T$ for specimens, for (a) the sensor with the shock compaction method, and (b) the sensor without the shock compaction method.
Figure 3. X-ray diffraction patterns for specimens with and without the shock compaction method.

Figure 4 shows the characteristics of resistivity $\rho$ for the magnetic sensors with and without the shock compaction method as a function of the current density $J$ applied to the sensors, under temperature conditions of 77.4 K. The solid triangles, solid circles, and solid squares are the results for the sensor made with the shock compaction method for applied magnetic fields $B_{ex}$ of 0, $40 \times 10^{-4}$, and $100 \times 10^{-4}$ T, respectively. The open triangles, open circles, and open squares are the results for the sensor without the shock compaction method for applied magnetic field $B_{ex}$ of 0, $40 \times 10^{-4}$, and $100 \times 10^{-4}$ T, respectively. The values of $\rho$ for the magnetic sensors are found to increase with increasing values of $J$ and $B_{ex}$. Therefore, the value of $\rho$ can be readily controlled by the values of $J$ and $B_{ex}$ [3].

The change in resistance of the sensor with the shock compaction method due to the measuring flux density $B_{meas}$ do not exhibit a normal state for values of $B_{ex}$ under $40 \times 10^{-4}$ T and values of $J$ less than 35 A/cm$^2$, such as shown in Fig. 4. Therefore, a magnetic measuring system can be constructed in order to realize a normal state of the sensor, and is biased for a homogeneous DC magnetic flux density $B_{bias}$ of $40 \times 10^{-4}$ T. The $B_{bias}$ is applied perpendicular to the surface of the magnetic sensor by use of a Helmholtz coil. These, in turn, are shielded by a metal dewar which holds liquid nitrogen at room temperature (300 K), and two layers of permalloy sheets. The details of the measuring system were reported in Ref. [3].

The magnetic sensitivity $S$ such as reported in Ref. [4] can be defined as

$$S = \frac{100 \times \left( \frac{R_{meas}(B_{meas}) - R_{meas}(B_{meas} = 0 T)}{R_{meas}(B_{meas} = 0 T)} \right)}{\%/(10^{-4} \text{ T})}.$$ (1)

Here, $R_{meas}(B_{meas})$ and $R_{meas}(B_{meas} = 0 \text{ T})$ are the resistance in a measure magnetic field $B_{meas}$, and that in

Figure 4. The characteristics of the resistivity $\rho$ for the sensors as a function of the $J$. The solid and open symbols are the results for the sensors constructed with and without the shock compaction method, respectively.

Figure 5. The sensitivity $S$ for the sensor constructed with (solid circles) and without (open circles) the shock compaction method as a function resistivity of $\rho$, under a constant condition of $B_{bias}$ of $40 \times 10^{-4}$ T.
the absence of a magnetic field, respectively. The values of magnetic sensitivity $S$ increase as the values of $\rho$ decrease, such as shown in Fig. 5. These results demonstrate that, the value of $S$ can be readily controlled by the value of $J$. Solid and open circles are the results for the sensors with and without the shock compaction method, respectively.

A typical voltage noise power $VNP$ spectrum of a sensor with the shock compaction method for applied value of $J$ of 40 A/cm$^2$ in the absence of an applied $B_{ex}$, under temperature of conditions of 77.4 K, is presented in Fig. 6. This result exhibits a white noise spectrum of approximately $2.5 \times 10^{-8}$ V/(Hz)$^{1/2}$ on the frequency region from 10 Hz to 5 kHz.

The solid circles in Fig. 7 reveal the dependence of resistance $R_{meas}(B_{meas})$ of the sensor constructed with the shock compaction method on the measure magnetic field $B_{meas}$ over the region of $\pm 5 \times 10^{-4}$ T, under temperature condition of 77.4 K. Here, the values of $R_{meas}(B_{meas})$ have been normalized by the value of $R_{meas}(B_{meas}=0 \ T)$. It was found that no hysteresis characteristics occurred over the range of $B_{meas}$ values of $\pm 5 \times 10^{-4}$ T. The $S$ of the sensor constructed with the shock compaction method was about 13 $(10^{-4}$ T) over the range of measurement of the magnetic field $B_{meas}$, being approximately 13 times greater than that of a giant magnetoresistance (GMR) sensor. In addition, the open circles in Fig. 7 are the results for the sensor without the shock compaction method. From the results of Figs. 4, 5, and 7, it was found that the sensitivity $S$ of the magnetic sensor was improved by use of the shock compaction method.

4. Conclusions

As one of the basic areas of research for the fabrication of a highly sensitive magnetic sensor, the present paper has examined a superconducting magnetic sensor, namely, that constructed from bulk BPSCCO, by use of the shock compaction method. From all characteristics of the sensor constructed with the shock compaction method, it was found that the sensitivity $S$ of the magnetic sensor was improved by the shock compaction method. These results were found to be important criteria for designing a highly sensitive magnetic sensor.

References

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