Magnetic Characteristics of Bulk BPSCCO Magnetic Sensors Fabricated by the Shock Compaction Method: Relationship Between the Magnetic Sensitivity and Thickness of the Magnetic Sensor

H Fujita¹, T Miwa¹, M Itoh¹, H Kezuka², H Matsumoto¹ and H Kishimura³

¹Interdisciplinary Graduate School of Science and Engineering, Graduate School of Kinki University, 3-4-1, Kowakae, Higashi-Osaka, Osaka 577-8502, Japan
²Tokyo University of Technology, Katakura, Hachioji, Tokyo 192-0982, Japan
³National Defense Academy, Hashirimizu, Yokosuka, Kanagawa 239-8686, Japan

E-mail: fujita@kindai.name

Abstract. As one of the basic areas of research for the development of a highly sensitive magnetic sensor, the present authors have fabricated bulk Bi-Pb-Sr-Ca-Cu-O magnetic sensors by use of the shock compaction method, as a new fabrication technique for high-critical temperature superconductors. Values of the thickness \(t\) of the sensors, under a shock compaction pressure \(P\) of 4 GPa, are systematically changed between 0.3 and 1.1 mm to investigate the magnetic sensitivity \(S\) of the sensors. It was found that the value of \(S\) increases as the value of \(t\) decreases. The value of \(S\) for a magnetic sensor (1.1 mm in width, 8.7 mm in length) was about 62 \%//(10^{-4}\ T) over the range of measurement of the magnetic field \(B_{\text{meas}}\) which varied from 0 to \(\pm 5 \times 10^{-4}\ T\), under a constant value of the bias magnetic field \(B_{\text{bias}}\) of \(20 \times 10^{-4}\ T\). Namely, it was approximately 62 times greater than that of giant magnetoresistance sensor. In addition, the present paper examined the dependence of resistivity \(\rho(T)\) on temperature, the dependence of \(\rho(T=77.4\ K)\) of the sensor on current density, the dependence of \(S\) on \(t\), and the dependence of measured resistance of the magnetic field \(R_{\text{meas}}\) on \(B_{\text{meas}}\).

1. Introduction

The application of magnetic sensors can be divided into those related to the direct measurement of magnetic fields, and those related to the measurement of other quantities by means of variations in the magnetic field. With this in mind, it may be necessary to develop a highly sensitive magnetic sensor. Examples of such needs are geophysical applications such as in magnetic exploration, nondestructive tests for circuit boards and IC mapping, and in medical applications for measuring biomagnetic fields such as in a magnetocardiogram (MCG), among many others [1, 2]. Fluxgate and superconducting quantum interference device (SQUID) magnetometers, using structure type sensors, measure the magnetic magnitude and direction of the dc or low frequency magnetic field, and are generally suitable for measurements over the magnetic ranges of approximately \(10^{-10}\) to \(10^{-7}\ T\) and \(10^{-14}\) to \(10^{-10}\ T\), respectively. It is necessary, however, to fabricate a solid-state type magnetic sensor in order to extend the measurement range from the fluxgate magnetometer to the SQUID magnetometer.

As one of the basic areas of research for the development of a highly sensitive magnetic sensor, the
present authors have fabricated bulk Bi-Pb-Sr-Ca-Cu-O (BPSCCO) magnetic sensors by use of the
shock compaction method: a new fabrication technique for a high-critical temperature superconductor
(HTS). Little is unknown, however, of the characteristics and sensitivity when the sensor thickness \( t \) is
changed under conditions of a constant bias magnetic field \( B_{\text{bias}} \). Therefore, the sensors thicknesses,
under a shock compaction pressure \( P \) of 4 GPa, were systematically changed between 0.3 and 1.1 mm
to investigate the magnetic sensitivity \( S \) of the sensor. As a result, it was found that the value of \( S \)
decreases as the thickness \( t \) decreases. As typical example, the sensitivity \( S \) for a sensor with a
thickness \( t \) of 0.3 mm was determined as 62 \%//(10\(^{-4}\) T), which is approximately 62 times greater than
that of giant magnetoresistance (GMR) sensor.

Experimental results revealed the dependence of the resistivity \( \rho(T) \), without an application of a
bias magnetic field \( B_{\text{bias}} \), on temperature \( T \), the dependence of resistivity \( \rho(T=77.4 \text{ K}) \) of the specimen
on current density \( J \), the dependence of \( S \) on sensor thickness \( t \), and the dependence of the measured
resistance in the magnetic field \( R_{\text{meas}} \) on the magnetic field \( B_{\text{meas}} \).

2. Experimental procedure

The particle size distribution of BPSCCO powder (Dowa Mining Co., Ltd., DSC-045001) used in the
present experiment was approximately 3 \( \mu \text{m} \), such as was reported in Ref. [3]. For the fabrication of
the bulk BPSCCO specimens to be used as magnetic sensors, the BPSCCO powder was formed into
pellets by a compressor under pressures ranging from 200 to 300 MPa. The pellets were then subjected
to a shock compaction pressure of 4 GPa for approximately 1 \( \mu \text{sec} \), using the shock compaction
system as was reported in Refs. [4-6]. The pellet specimens were annealed under a temperature of
845 \( ^\circ\text{C} \) for 48 hours, by heating in dry air at the rate of 14 \( ^\circ\text{C}/\text{min} \), cooled in dry air to a temperature of
300 \( ^\circ\text{C} \) at the rate of 5 \( ^\circ\text{C}/\text{min} \), and then reduced to room temperature by natural cooling. The pellets,
measuring 5.0 mm in thickness and 20 mm in diameter, were cut into rectangular-shaped test specimens
to be used as magnetic sensors, measuring 8.7 mm in length and 1.1 mm in width. The cutting was performed with a diamond saw at a low cutting rate to limit the effects of heat. The final step involved reducing the various thicknesses of the sensors by sandpaper (No. 1500). The above
procedures resulted in five sensors ranging in thickness from 0.3 to 1.1 mm.

The geometry of a bulk BPSCCO magnetic sensor is illustrated in Fig. 1 (a), where the letters \( I \) and
\( V \) represent the current terminal and voltage terminals, respectively. The four copper leads were
attached to the sensor by a conductive silver paste. The magnetic sensor and calibrated platinum
thermometer were fixed with grease (Apiezon N) to a holder composed of oxygen free, highly
conductive copper (OFHC) with a copper spiral (diameter of about 2.0 mm) used to simplify the
temperature control, such as shown in Fig. 1 (b).

The changes in resistance of the sensor having a thickness of 0.3 mm, for example, due to the
external magnetic flux density \( B_{\text{ex}} \), does not exhibit a normal state for values of \( B_{\text{ex}} \) less than 10\( \times10^{-4}\) T
and values of current density \( J \) less than 40 A/cm\(^2\). Therefore, the magnetic measuring system is
constructed in such a manner to realize a normal state of the sensor, and is biased by a homogeneous

![Figure 1. Schematic illustrations of the geometry of the holder for sensor attachment. Here, (a) and (b) are typical illustrations of the sensor and holder, respectively.](image-url)
DC magnetic flux density $B_{\text{bias}}$ of $2 \times 10^{-4}$ T. The $B_{\text{bias}}$ is applied perpendicular to the surface of the sensor by use of a Helmholtz coil, such as was reported in Refs. [6, 7]. The measuring system for obtaining the magnetic characteristics, in turn, is shielded by two layers consisting of cylinders of a Mu-metal around a metal dewar vessel, as was illustrated in Refs. [7]. The two cylinders were degaussed by an AC magnetic field (60 Hz) at room temperature, prior to performing the experiment.

3. Results and discussion

The dependence of the resistivity $\rho(T=77.4 \text{ K})$, without an application of the bias magnetic field $B_{\text{bias}}$, on temperature $T$ for the magnetic sensors in the absence of an external magnetic flux density $B_{\text{ex}}$ is measured under a constant current density $J$ of 1 A/cm$^2$ (not shown). From these results, the values of the temperature of zero resistance $T_{\text{zero}}$ of sensors were determined. The plotted points in Fig. 2 demonstrate the dependence of the temperature of zero resistance $T_{\text{zero}}$, under a constant current density $J$ of 1 A/cm$^2$, on the value of the sensor thickness $t$. It can be seen that the values of $T_{\text{zero}}$ for the sensors display a nondependence on the values of $t$ in the region between 0.3 and 1.1 mm.

The plotted points in Fig. 3 denote the typical dependence of the resistivity $\rho(T=77.4 \text{ K})$, without an application of a $B_{\text{bias}}$, on the external magnetic flux density $B_{\text{ex}}$ for values of 0 to $\pm 50 \times 10^{-4}$ T, under a constant temperature of 77.4 K. In this figure, solid and open circles represent the magnetic characteristics of sensors with thicknesses of 0.3 and 0.7 mm, under a constant $J$ of 40 A/cm$^2$, respectively. It can be seen in this figure that no hysteresis characteristics are observed over the range of $B_{\text{ex}}$ values from 0 to $\pm 50 \times 10^{-4}$ T. In the addition, the characteristics of sensor are symmetrical with respect to $B_{\text{ex}}=0$ T during the application and withdrawal of $B_{\text{ex}}$. In this figure, the values of $T_{\text{zero}}$ are determined for the sensor thicknesses of 0.3 and 0.7 mm, respectively. The arrows denote the critical magnetic flux density $B_{\text{c}}$ for $t=0.3$ mm and 0.7 mm.

![Figure 2](image1.png)

Figure 2. The values of the temperature of zero resistance $T_{\text{zero}}$, without an application of the bias magnetic field $B_{\text{bias}}$, as a function of sensor thickness $t$, under a constant current density $J$ of 1 A/cm$^2$.

![Figure 3](image2.png)

Figure 3. Typical dependence of the resistivity $\rho(T=77.4 \text{ K})$, without an application of the bias magnetic field $B_{\text{bias}}$, on the external magnetic flux density $B_{\text{ex}}$ of the sensor, under a constant current density $J$ of 40 A/cm$^2$ and constant temperature of 77.4 K. Solid and open circles are the results for the sensor thicknesses of 0.3 and 0.7 mm, respectively. The arrows denote the critical magnetic flux density $B_{\text{c}}$ for $t=0.3$ mm and 0.7 mm.
$B_c(t=0.3 \text{ mm})$ and $B_c(t=0.7 \text{ mm})$ are termed the critical magnetic flux densities $B_c$, under a constant $J$ of 40 A/cm$^2$.

Figure 4 shows the dependence of $B_c$ on sensor thickness $t$ (ranging from 0.3 mm to 1.1 mm), at 77.4 K. It can be seen in this figure that the values of $B_c$ increase as the values of $t$ increase.

The plotted points in Fig. 5 denote the dependence of the resistivity $\rho(T=77.4 \text{ K})$ for two sensors, $J_c(t=0.3 \text{ mm})$ and $J_c(t=0.7 \text{ mm})$.

**Figure 4.** Dependence of the critical magnetic flux density $B_c$ on sensor thickness $t$ at the temperature of 77.4 K, under a constant current density $J$ of 40 A/cm$^2$.

**Figure 5.** Characteristics of the $\rho(T=77.4 \text{ K})$ of two sensors as functions of the current density $J$, with an application of a $B_{\text{bias}}$ of $20 \times 10^{-4}$ T. Solid and open circles are the results for the sensor thicknesses of 0.3 and 0.7 mm, respectively. Note that the values of $\rho$ increase when the value of current density reaches a critical value $J_c$ for each sensor.

**Figure 6.** Dependences of the critical current density $J_c$ on sensor thickness $t$ at a temperature of 77.4 K, with an application of a $B_{\text{bias}}$ of $20 \times 10^{-4}$ T.
with an application of a $B_{bias}$ of $20 \times 10^{-4}$ T, on current density $J$, under a temperature condition of 77.4 K. In this figure, the solid and open circles represent the results for the sensor thicknesses of 0.3 and 0.7 mm, respectively. From the present results, it is found that the values of $\rho(T=77.4 \text{ K})$ for the sensors increase as the values of $J$ increase beyond the value of critical current density $J_c$.

Figure 6 shows the dependence of the critical current density $J_c$ on sensor thickness $t$ at 77.4 K, under a constant $B_{bias}$ of $20 \times 10^{-4}$ T. Measurements of the values of $J_c$ were determined for specimens constructed with values of $t$ from 0.3 to 1.1 mm. It can be seen in this figure that the values of $J_c$ increase as the values of $t$ increase, and exhibit a similar tendency as was found for $B_c$ in Fig. 4.

Figure 7 displays the magnetic sensitivity $S$ as a function of the sensor thickness $t$, under constant conditions of $J$ of 40 A/cm$^2$ and $B_{bias}$ of $20 \times 10^{-4}$ T. Here, $S$ is defined by

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

(1)

where $R_{meas}(B_{meas})$ and $R_{meas}(B_{meas} = 0 \text{ T})$ are the resistances in the measurement of the magnetic field $B_{meas}$. It is found that the values of $S$ decrease as the values of $t$ increase. Namely, a highly sensitive sensor can be obtained by making use of low values of $t$, contrary to the results found for measurements of critical current density, such as were shown in Fig. 6. Stated in different terms, the value of magnetic sensitivity $S$ for thin sensors is greater than those of thick sensors.

Figure 8 shows the typical dependence of resistance $R_{meas}(B_{meas})$ for sensors with thicknesses $t$ of

![Figure 7](image-url)  
**Figure 7.** Magnetic sensitivity $S$ as a function of sensor thickness $t$, under constant conditions of current density $J$ of 40 A/cm$^2$, $B_{bias}$ of $20 \times 10^{-4}$ T, and temperature of 77.4 K.

![Figure 8](image-url)  
**Figure 8.** Dependence of the resistance $R_{meas}(B_{meas})$ of sensors on the measurement of magnetic flux density $B_{meas}$. The solid and open circles are the results for sensor thicknesses of 0.3 and 0.7 mm, respectively.
0.3 and 0.7 mm, on the measurement of the magnetic field $B_{\text{meas}}$ for values between 0 T to $\pm 5 \times 10^{-4}$ T, under constant conditions of $B_{\text{bias}}$ of $20 \times 10^{-4}$ T and $J$ of 40 A/cm$^2$. In this figure, the values of $R_{\text{meas}}(B_{\text{meas}})$ have been normalized by the value of $R_{\text{meas}}(B_{\text{meas}}=0)$ T. The solid and open circles represent the results for magnetic sensors having the thicknesses of 0.3 and 0.7 mm, respectively. In this case, the sensitivity of the $t=0.3$ mm sensor is about 62 $\%/(10^{-4}$ T) over the range of $B_{\text{meas}}$. This is about 62 times greater than that of a GMR sensor. Furthermore, it was found that the magnetic sensors exhibit directional and linear characteristics in the values of $B_{\text{meas}}$. In addition, no evidence of hysteresis was found in these characteristics.

After testing sensor specimens through more than 20 thermal cycles between temperatures of the boiling point of liquid nitrogen (77.4 K) and room temperature (300 K), the characteristics such as shown in Figs. 2-8 were found to exhibit no significant changes.

4. Conclusions
In the present research, bulk BPSCCO magnetic sensors were constructed by incorporating the shock compaction method as a new fabrication technique for bulk HTSs. The sensor thicknesses $t$ were systematically changed, from 0.3 mm to 1.1 mm in order to investigate the in relationships with the values of magnetic sensitivity $S$, temperature of zero resistance $T_{\text{zero}}$, critical current density $J_c$, and critical magnetic flux density $B_c$.

The values of magnetic sensitivity $S$ for the sensors decrease as the values of $t$ increase, such as was shown in Fig. 7. That is, a highly sensitive sensor can be obtained by making use of low values of $t$, contrary to the results found for measurements of critical current density $J_c$, such as was shown in Fig. 6. Stated in different terms, the value of $S$ for thin sensors is greater than those of thick sensors.

The sensitivity of the sensor with a $t$ of 0.3 mm was found to be about 62 $\%/(10^{-4}$ T) over the range of measurement of the magnetic field $B_{\text{meas}}$ between 0 T to $\pm 5 \times 10^{-4}$ T, under constant conditions of $B_{\text{bias}}$ of $20 \times 10^{-4}$ T and $J$ of 40 A/cm$^2$. Namely, it was about 62 times greater than that of a GMR sensor. Furthermore, it was found that the measured resistances in the magnetic sensors exhibited directional and linear characteristics for the values of $B_{\text{meas}}$. In addition, no evidence of hysteresis was found in these characteristics.

It was determined from the present results that the characteristics of the sensors were significantly influenced by the value of the sensor thickness $t$. These results were found to be important criteria for fabricating more highly sensitive magnetic sensors.

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