Automatic development of normal zone in composite MgB$_2$/CuNi wires with different diameters

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Abstract. One of the promising applications with superconducting technology for hydrogen utilization is a sensor with a magnesium-diboride (MgB$_2$) superconductor to detect the position of boundary between the liquid hydrogen and the evaporated gas stored in a Dewar vessel. In our previous experiment for the level sensor, the normal zone has been automatically developed and therefore any energy input with the heater has not been required for normal operation. Although the physical mechanism for such a property of the MgB$_2$ wire has not been clarified yet, the deliberate application might lead to the realization of a simpler superconducting level sensor without heater system. In the present study, the automatic development of normal zone with increasing a transport current is evaluated for samples consisting of three kinds of MgB$_2$ wires with CuNi sheath and different diameters immersed in liquid helium. The influences of the repeats of current excitation and heat cycle on the normal zone development are discussed experimentally. The aim of this paper is to confirm the suitability of MgB$_2$ wire in a heater free level sensor application. This could lead to even more optimized design of the liquid hydrogen level sensor and the removal of extra heater input.

1. Introduction
Recent accelerated progress in information and communications technology has posed the rapid increase in demand of energy, which has led to some crucial blackouts that took place especially in Europe and US in the last decade. Thus, the consumption of energy has been growing year by year, which means that the usage of fossil fuels has also been increasing and the amount of greenhouse gases in the atmosphere known as the source of global warming has become significant so far. To decrease the emission of greenhouse gases, there are alternative fuels and energy sources. One of the promising green fuels is the liquid hydrogen, which is totally free from greenhouse gas emission if both the hydrogen preparation and the liquefaction process are completed with green energy, e.g. solar

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power. It is also expected that the superconducting technology has a prospective potential to contribute to the energy saving. In the beginning of the twenty-first century, a new superconductor, magnesium-diboride (MgB2), was discovered successfully, and this material can become the superconducting state with zero resistivity below the critical temperature of about 39 K [1]. Therefore, one of the promising applications with the superconducting technology for hydrogen utilization is a sensor with the MgB2 superconductor to detect the position of boundary between the liquid hydrogen and the evaporated gas stored in a Dewar vessel [2–8].

In order to obtain a small part of normal zone in the superconducting wire for the level sensor, a heater is usually attached near an upper end of current joint [2,3]. In our previous experiment for level sensor composed of the MgB2 wire with an outer sheath of CuNi, however, the normal zone has been automatically developed and therefore any energy input with the heater has not been required for normal operation of the level sensor [5]. Although the physical mechanism for such a property of the MgB2 wire has not been clarified yet, the deliberate application might lead to the realization of a simpler superconducting level sensor without heater system. One possibility for the cause of automatic production of normal zone is a transfer length of current from the copper terminal to the superconducting filament via the normal metal sheath [9], which has been estimated as about 0.3 to 2 mm in various types of MgB2 wires [10].

In the present study, the automatic development of normal zone with increasing a transport current is evaluated for samples consisting of three kinds of MgB2 wires with CuNi sheath and different diameters immersed in liquid helium. The influences of the repeats of current excitation and heat cycle on the normal zone development are discussed experimentally.

2. Sample preparation

The specifications of three sample wires used in this paper are listed in Table 1. These wires have an identical structure of a monocored MgB2 superconductor surrounded by a CuNi sheath material. The diameters of the sample wires are 0.185, 0.155 and 0.110 mm, and the corresponding diameters of superconductor filament estimated from the photograph of the wire cross section are 0.115, 0.095 and 0.065, respectively. The temperature dependence of resistivity in the sample wires with the diameters of 0.155 and 0.110 mm was observed in advance with a constant current of 10 mA. The critical temperatures $T_c$ of these wires are 32 to 33 K, and the normal resistivity of wires is about 50 $\mu\Omega$·cm. The MgB2 sample wires with the CuNi sheath have a flat dependency on the temperature because the resistivity of CuNi is almost constant for the temperature [11]. Therefore, such an MgB2 wire is expected to be suitable to the level sensor for liquid hydrogen [5,6,8].

Figure 1 illustrates the basic structure of samples to evaluate the voltage-current characteristics around a current terminal experimentally. The sample superconducting wire was located on the sample holder of Glass Fiber Reinforced Plastic (GFRP) or aluminum nitride (AlN), and both the ends were soldered to a pair of Cu plates for current terminals. A potential tap was attached to one of the current terminals of sample holder by soldering and another one was soldered directly to superconducting wire a few tens of millimeters away from the terminal. When a potential difference between these two taps in the sample wire transporting a current is measured, the effective length, in which almost all the voltage drop arises, can be considered as a distance between the position of the potential tap on the

| Diameter of wire       | 0.185 mm | 0.155 mm | 0.110 mm |
|------------------------|----------|----------|----------|
| Sheath material        | CuNi     | CuNi     | CuNi     |
| Number of filament     | 1        | 1        | 1        |
| Diameter of filament   | 0.115 mm | 0.095 mm | 0.065 mm |
| Critical temperature, $T_c$ | - 33 K  | 32 K     |
| Normal resistivity of wire just above $T_c$ | - 48 $\mu\Omega$·cm | 46 $\mu\Omega$·cm |
| Normal resistivity of wire at 300 K | - 54 $\mu\Omega$·cm | 51 $\mu\Omega$·cm |
Figure 1. Basic structure of samples.

Table 2. Characteristics of samples.

| Sample name | Diameter of wire | Material of sample holder | Effective length between taps | Threshold current for normal zone | Power index in low current | Threshold wattage for normal zone |
|-------------|-----------------|---------------------------|-----------------------------|-----------------------------------|-------------------------------|---------------------------------|
| A-1         | 0.185 mm        | GFRP                      | 25 mm                       | 2.1 A                             | 1.3                          | 6.9 mW                          |
| A-2         | 0.185 mm        | GFRP                      | 40 mm                       | 1.1 A                             | 2.5                          | 30 mW                           |
| A-3         | 0.185 mm        | AlN                       | 15 mm                       | 0.9 A                             | 1.1                          | 78 mW                           |
| B-1         | 0.155 mm        | GFRP                      | 40 mm                       | 0.85 A                            | 1.2                          | 18 mW                           |
| B-2         | 0.155 mm        | GFRP                      | 20 mm                       | 0.8 A                             | 1.6                          | 20 mW                           |
| C           | 0.110 mm        | GFRP                      | 25 mm                       | 0.52 A                            | 1.1                          | 19 mW                           |

superconducting wire and the nearest edge of the current terminal plate as shown in figure 1.

Table 2 gives the characteristics of six samples fabricated according to the basic structure shown in figure 1. The capital letters “A”, “B” and “C” appearing in the sample names mean the uses of wires with the diameters of 0.185, 0.155 and 0.110 mm, respectively. Three kinds of samples (A-1, A-2 and A-3) with different holder materials and several effective lengths between the potential taps were prepared with the MgB$_2$ wire of 0.185 mm in diameter, whereas there are two kinds of samples (B-1 and B-2) for the 0.155-mm wire. On the other hand, only a sample (C) with the 0.110-mm wire was fabricated. All the measurements described in the next section were carried out in the liquid helium.

3. Experimental results

3.1. Automatic development of normal zone with increasing current

Figure 2 shows the dependence of potential difference between the taps in Samples A-1, B-1 and C on the current increased discretely step-by-step with each individual holding time of 5 seconds or more. It is found that every potential difference suddenly jumps with increasing the current. These threshold currents are much smaller than their critical currents. Furthermore, the potential differences are almost proportional to the current both before and after the voltage jumping. When the applied currents are larger than the threshold current, the equivalent resistances, which were obtained by dividing the instantaneous voltage drop by the current, can be estimated averagely as 0.51, 1.1 and 1.3 Ω for Samples A-1, B-1 and C, respectively. Since these resistances can be converted into the average resistivity of about 50 μΩ·cm in all the samples, it is considered that the entire regions between the potential taps become the normal state in which the temperature is larger than the critical temperature. It is very important that such a normal zone is developed automatically at the threshold current below the critical current without any energy input from outside and with only increasing the current. In the smaller currents before the voltage jumping, on the other hand, the equivalent resistances in Samples A-1, B-1 and C are almost equal to 1.4, 22 and 71 mΩ, respectively. These resistances roughly correspond to the length of about 0.1 to 1 mm as the normal zone, so that it can be considered that there are two possibilities as types of triggers for the automatic development of normal zone. One is local heating in the superconducting wire just near the current joint such as a current transfer from the copper terminal to the monofilament superconductor via the normal metal sheath [9,10], while the
other is almost uniform power dissipation all over the wire between the potential taps such as due to the effect of connectivity among MgB$_2$ crystal grains on the transport property of wire [12]. The power dissipations, which were calculated from a simple product of the potential difference and applied current, just before the voltage jumping in figure 2 were also estimated as about 7 to 20 mW, as already given in table 2.

Figure 3 represents the comparison of the voltage-current characteristics among the samples for the wire of 0.185 or 0.155 mm in diameter with increasing the current. The experimental results for Samples A-1, A-2 and A-3 are plotted in figure 3(a), whereas figure 3(b) is for Samples B-1 and B-2. In both the cases, the potential differences suddenly increase with the current, and the normal zone is automatically produced probably due to the small power dissipation in the low current range. The voltages in figure 3(a) jump at a threshold current different from one another, whereas the voltage jumping in figure 3(b) arises at almost same current as each other. It is also found that the potential differences are almost proportional to the applied current after the voltage jumping. The equivalent resistances for Samples A-1, A-2 and A-3 in figure 3(a) can be estimated as 0.51, 0.72 and 0.30 Ω.
respectively, and they correspond to the average resistivity of 53 μΩ·cm. In figure 3(b), on the other hand, the resistances become 1.1 and 0.56 Ω for Samples B-1 and B-2, respectively, and their average resistivity is equal to 52 μΩ·cm. Therefore, each average resistivity after the voltage jumping is almost equal to the normal resistivity of the wire. When the applied currents are lower, the voltage-current characteristics strongly depend on the samples themselves. Table 2 contains the values of the threshold current and the power index in the low current range for each sample. The latter was estimated from a slope of approximated line in the logarithmic plot. It can be seen that there are some types of the transport properties in the low current range because of the different power indexes. Furthermore, the power dissipations for Samples A-1, A-2 and A-3 just before the voltage jumping are different from one another, while the power dissipations in Samples B-1 and B-2 are almost same as each other, as shown in table 2.

3.2. Hysteretic behavior of voltage-current characteristics
The experimental results of the transport properties in Samples A-1, B-2 and C during initially

![Graphs](https://example.com/graphs)

**Figure 4.** Hysteretic behaviour of voltage-current characteristics during initially increasing and subsequently decreasing currents in (a) Sample A-1, (b) Sample B-2 and (c) Sample C. The solid lines are a guide to the eye.
increasing and subsequently decreasing the currents are given in figure 4, where the reproducibility for repeating the current excitations was very good and the hysteretic characteristics were observed clearly. For Sample A-1 shown in figure 4(a), for example, the full normal zone was automatically produced at about 2.1 A with increasing the current. After the current excitation up to 2.5 A, the normal zone suddenly disappeared at about 0.9 A with decreasing the current. These phenomena can be understood with the stability theory of a composite superconductor [13], and the sudden transition currents during ramping up and down are usually recognized as “a minimum propagating current” and “a recovery current,” respectively. The minimum propagating and recovery currents for Sample B-2 in figures 4(b) were obtained as about 0.8 and 0.7 A, respectively, and the corresponding currents for Sample C in figure 4(c) were about 0.52 and 0.44 A, respectively. Although the similar hysteretic behaviour of the voltage-current characteristics in different kinds of MgB$_2$ wires has been evaluated for the application of a transport current above the critical current in an external magnetic field [14], the experimental results in this study were obtained for the MgB$_2$ sample wires with the current much less than the critical current in no external field.

3.3. Influence of heat cycle on voltage-current characteristics
Figure 5 shows the experimental results of the influence of heat cycle on the voltage-current characteristics in Samples A-1 and B-2. It can be seen for Sample A-1 in figure 5(a) that the transport properties after the initial cooling down to the liquid helium temperature and the second cooldown with preliminarily warming up to the room temperature are different from each other clearly. This may be caused by a mechanical damage originating in the repeat of heat cycle because it has been confirmed visually that the length of the MgB$_2$ wire in every sample listed in table 2 is extended just after the first cooldown and warmup due to the difference between the thermal expansion coefficients for the MgB$_2$ wire and the material of sample holder, in which the former is larger than the latter. For Sample B-2 in figure 5(b), on the other hand, the transport properties after the first, second and third cooldowns almost agreed with one another, and the effect of repeating the cooldown and warmup was scarcely observed. From such a viewpoint of the influence of heat cycle, it is indicated again that the voltage-current characteristics strongly depend on the samples themselves.

4. Conclusions
The results of the experiments for the MgB$_2$ wires with the CuNi sheath gave us valuable data for the
level sensor application research. It was clearly observed that the normal zone was automatically developed between the potential taps in all the fabricated samples without any energy input from outside while the transport current was increased monotonically from the virgin state. The detected potential difference after the voltage jumping was almost proportional to the current, which meant that the entire region between the potential taps became the normal state. Although the voltage-current characteristics in the low current range strongly depended on the samples themselves and it was confirmed that there were some different types of transport properties, the reproducibility for the automatic production of normal zone was very fine in every sample after the experience of only one heat cycle. By referring to the experimental results described in this paper, the heater less system could be an interesting subject on a simpler superconductor based level sensor for liquid hydrogen in the future.

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