Magnetic characterization of superconducting MgB_2

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Abstract

The critical current density J_c of pressed polycrystalline MgB_2 specimen was measured using a DC magnetization and Campbell's method. It was found that the two J_cs are coincident and this result confirms that the intergrain J_c is not deteriorated by grain boundaries. The upper critical field, lower critical field, thermodynamic critical field and Ginzburg-Landau parameter were estimated to characterize the magnetic properties. Observed J_c and irreversibility field could be approximately explained by the flux creep-flow model. To foresee the potential of application of this material, J_c was calculated when strong pins could be introduced.

Keywords: MgB_2 superconductor; irreversibility field; flux creep-flow model.

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1 Introduction

Recently MgB$_2$ was found to have a transition temperature much higher than other metallic superconductors [1]. In addition, it is reported that the critical current property of this material is not influenced by grain boundaries even for polycrystalline sample [2]. Hence, its application in a medium temperature region is expected. However, the improvement of the critical current property of this material is not easy in a short period. In order to foresee the practical applicability of the material, its detailed characterization is necessary.

In this study, the critical current density J_c estimated using a DC magnetization measurement and that estimated using Campbell's method were compared to check if J_c was affected by weak links at grain boundaries. To characterize MgB$_2$ the upper and lower critical fields of the specimen were measured, and the thermodynamic critical field and Ginzburg-Landau parameter were estimated. Observed results of J_c and the irreversibility field H_i were compared with the theoretical results of the flux creep-flow model. Fairly good agreements were obtained. This shows that the critical current property of this material can be described by this theoretical model as well as in existing metallic and oxide superconductors. Finally, the critical current property was calculated for the case of strong pinning by normal precipitates to foresee the potential of application of this material.

2   Experimental

Two pellets of MgB$_2$ were prepared by pressing commercial powder without sintering. The pressed pellets of a disk shape were cut for a magnetic measurement and those sizes are listed in Table 1. T_c of these specimens was 38.8 K. Specimen 1 was used for measurements of J_c using a DC magnetization method and Campbell's method [4]. Specimen 2 was used for a DC magnetization measurement to estimate H_c1. DC magnetization was measured using a SQUID magnetometer. Using the Bean model J_c was determined by

$$J_\mathrm{c} = \frac{6\Delta m}{d^2 l (3w - d)}, \tag{1}$$

where Δm is a hysteresis of magnetic moment and w, l and d are width, length and thickness of the specimen, respectively. The irreversibility field H_i was determined by the field at which J_c was reduced to 1.0×10^5 A/m^2.

In Campbell's method AC magnetic field of 35.0 Hz was superposed parallel to a DC field. Then, AC penetration depth λ' was measured as a function of AC amplitude h_0, and J_c was estimated from $\mathrm{d}h_0/\mathrm{d}\lambda'$.

The J_cs from a two measurements are compared to check if weak links of grain boundaries affect the critical current property.

H_c1 and H_c2 were also observed by DC magnetization measurements. H_c1 was determined by the field at which a deviation started from a linear magnetization M in the Meissner state as shown in Fig. 1. In the determination the

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least squares method was used. H_{c2} was determined by the field at which the magnetic moment reduced to zero.

3 Results and Discussion

An example of the relationship between AC penetration depth and AC field amplitude measured using Campbell's method is shown in Fig. 2. Fig. 3 shows comparison of J_c measured by DC magnetization method and Campbell's method. The two J_cs are coincident and this result confirms that the inter-grain J_c is not appreciably deteriorated by grain boundaries. This agreement is consistent with previous reports [2]. Looking into more detail, J_c observed by Campbell's method is slightly larger than J_c observed by the DC magnetization. This can be explained by the dependence on the electric field criterion, E_c[3]. That is, E_c is estimated to be about 10^{-5} V/m for Campbell's method and about 10^{-9} V/m for the DC magnetization measurement.

Fig. 4 shows temperature dependences of H_{c1}, H_{c2} and H_i. From measured values of H_{c1} and H_{c2}, the thermodynamic critical field H_c and G-L parameter κ can be estimated. In terms of H_c and κ, H_{c1} and H_{c2} are given by

$$H_{c1} = \frac{H_c}{\sqrt{2}\kappa}(\log \kappa + 0.081), \tag{2}$$

$$H_{c2} = \sqrt{2}\kappa H_c. \tag{3}$$

From these equations with observed values of H_{c1} and H_{c2}, H_c and κ can be

estimated. At low temperatures H_{c2} was too high to measure directly. Hence, H_{c2} at lower temperature region were estimated by assuming a linear extrapolate of the data above 28 K. Temperature dependences of H_c and κ are shown in Fig. 4 and Fig. 5, respectively. H_c increases monotonically with decreasing temperature and κ is found to be almost independent of temperature. This behavior of κ seems to be reasonable.

Here, the observed results are compared with the theoretical analysis using the flux creep-flow model. According to this model, E-J characteristics can be calculated in terms of the pinning potential:

$$U_0 = \frac{0.835 g^2 k_{\mathrm{B}} J_{c0}^{1/2}}{(2\pi)^{3/2} B^{1/4}}, \tag{4}$$

where J_{c0} is the virtual critical current density without flux creep and g^2 is a number of the flux lines in the flux bundle. The magnetic field and temperature dependencies of J_{c0} are assumed as

$$J_{c0} = A \left[1 - \left(\frac{T}{T_c} \right)^2 \right]^m B^{\gamma - 1} \left(1 - \frac{B}{\mu_0 H_{c2}} \right)^\delta, \tag{5}$$

where A, m, γ and δ are pinning parameters. It is assumed for simplicity that only A representing a magnitude of J_{c0} is distributed as

$$f(A) = K \exp \left[-\frac{(\log A - \log A_{\mathrm{m}})^2}{2\sigma^2} \right], \tag{6}$$

where A_{m} is the most probable value of A, σ^2 is a constant representing the degree of deviation and K is a constant. The value of g^2 is assumed to be determined so that the critical current density under the flux creep might

take on a maximum value [5]. However, g^2 is used as a fitting parameter here for simplicity. Further details of the calculation of the E-J characteristics are described in [6]. Values of the parameters used for the calculation are given in Table 2. J_c was determined with $E_c = 1.0 \times 10^9$ V/m corresponding to the DC magnetization measurement.

In Fig. 6 the theoretical results of J_c are compared with measured values. It is found that the theoretical result agrees well with the experimental result except in high field region at low temperatures. That is, the theoretical result is much higher than the experimental result in this area. As shown in Fig. 4, the theoretical result of H_i shown by the solid line is much higher than measured value at low temperatures, while the agreement is fairly good at high temperatures. The above results show that the critical current property of this material can be described by the flux creep-flow model as well as in existing other superconductors. This means that the critical current property of this material can be estimated when strong pinning centers can be introduced. This is useful for foreseeing its potential for application especially at high fields.

For this purpose, the critical current density will be estimated when fine normal precipitates are successfully dispersed in MgB_2. The virtual critical current density in this case is given by [7]

$$J_{c0} = \frac{\pi N_p \xi D^2 \mu_0 H_c^2}{4 a_f B} \left(1 - \frac{B}{\mu_0 H_{c2}} \right),$$ (7)

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where N_p and D are density and size of normal particles, respectively, ξ is the coherence length and a_f is a flux line spacing. Here we assume that $D = 0.1 \ \mu m$ and the volume ratio of normal particles is $N_p D^3 = 0.15$. Equation (7) can be regarded as a most probable value of J_{c0}, and hence we have $m = 3/2$, $\gamma = 1/2$, $\delta = 1$ and $A_m = 4.8 \times 10^9$ with superconducting parameters estimated here. In addition, $g^2 = 1.5$ and $\sigma^2 = 0.03$ are assumed. Using these parameters the E-J characteristics can be calculated and the critical current density can be defined using the same criterion as in experiment. These results are shown in Fig. 7, in which the present experimental data are also shown for comparison. It is found that a high J_c value can be achieved even at relatively high temperature. Hence, MgB$_2$ seems to be a promising material for high field application.

4   Summary

The characterization of superconducting polycrystalline MgB$_2$ specimens was conducted and the following results were obtained.

(1)Grain boundaries do not appreciably deteriorate superconducting currents.

(2)The upper and lower critical fields, the thermodynamic critical field and the Ginzburg-Landau parameter were estimated.

(3)The critical current density and the irreversibility field were approximately explained using the flux creep-flow model.

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(4)The critical current density expected for a material with pins of fine normal precipitates was estimated using the flux creep-flow theory and it was found that its value was sufficiently high for application.

5   Acknowledgement

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Table 1

Sizes of specimens.

	l (mm)	d (mm)	w (mm)
Specimen 1	5.4	1.7	3.1
Specimen 2	7.1	1.3	5.0

Table 2

Parameters used in numerical calculation.

A_{m}	σ^2	m	γ	δ	g^2
3.0×10^8	0.03	2.0	0.3	1.0	1.5
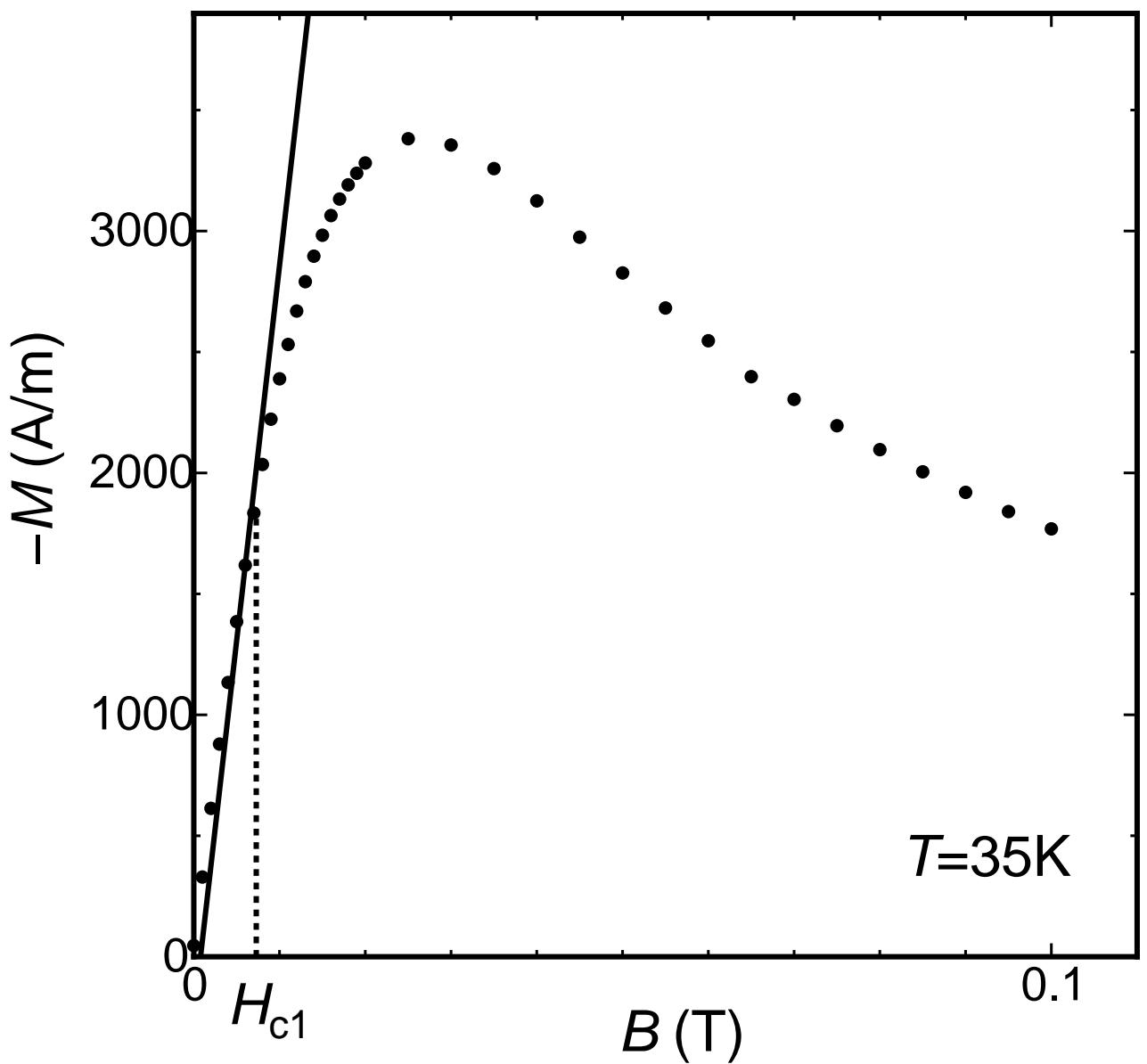
Figure 1: M. Fukuda *et al.*
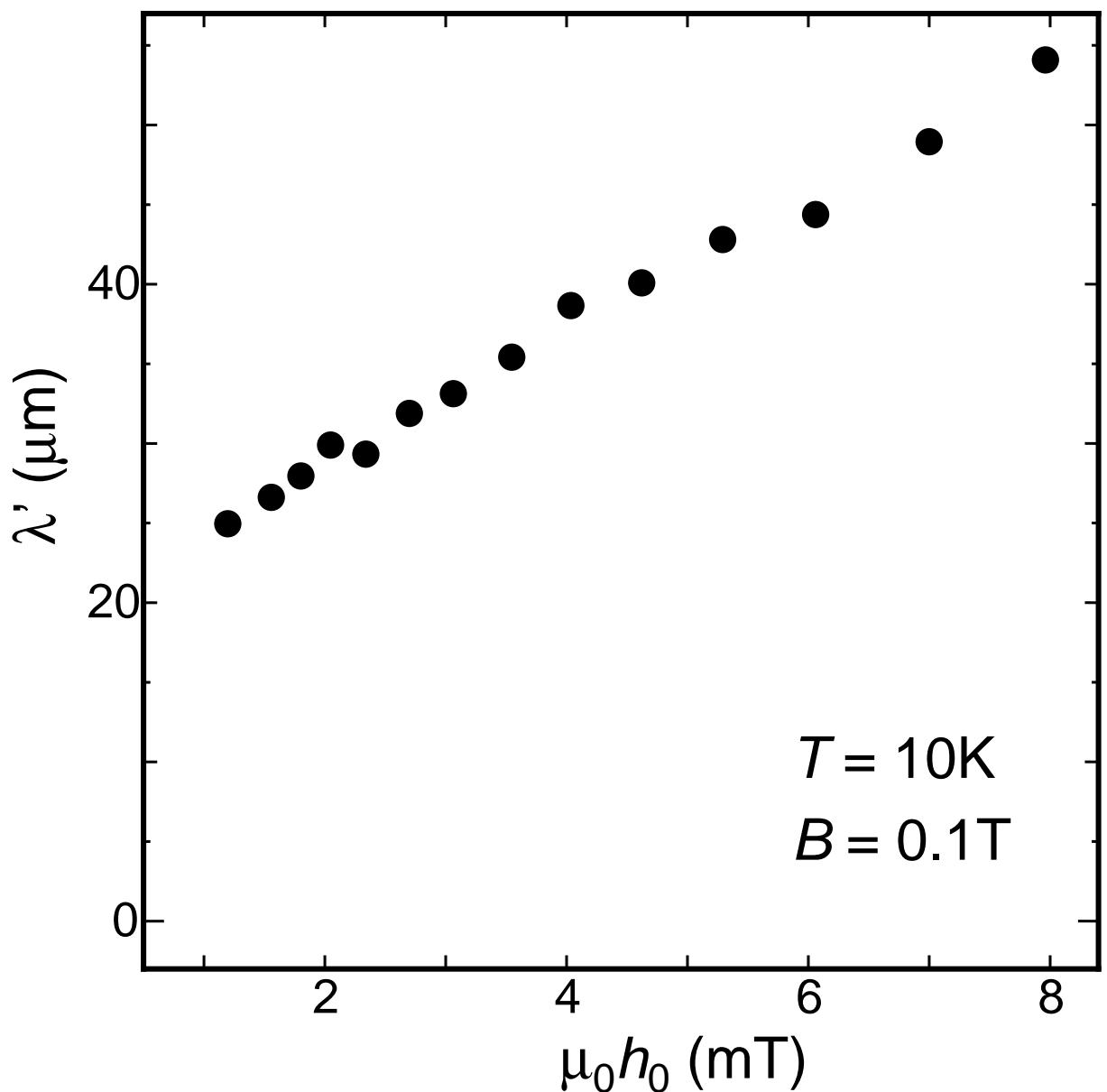
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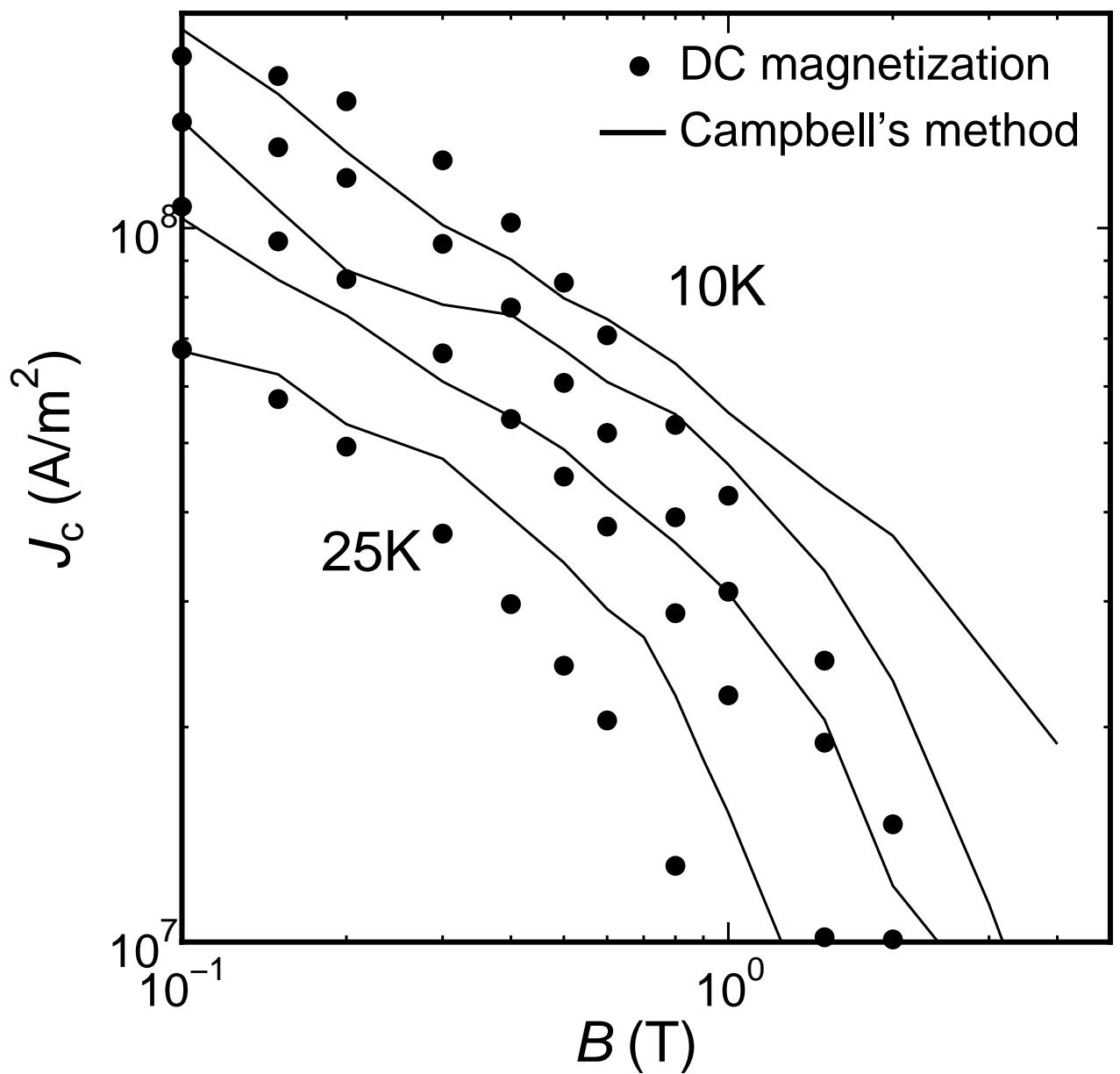
Figure 3: M. Fukuda *et al.*

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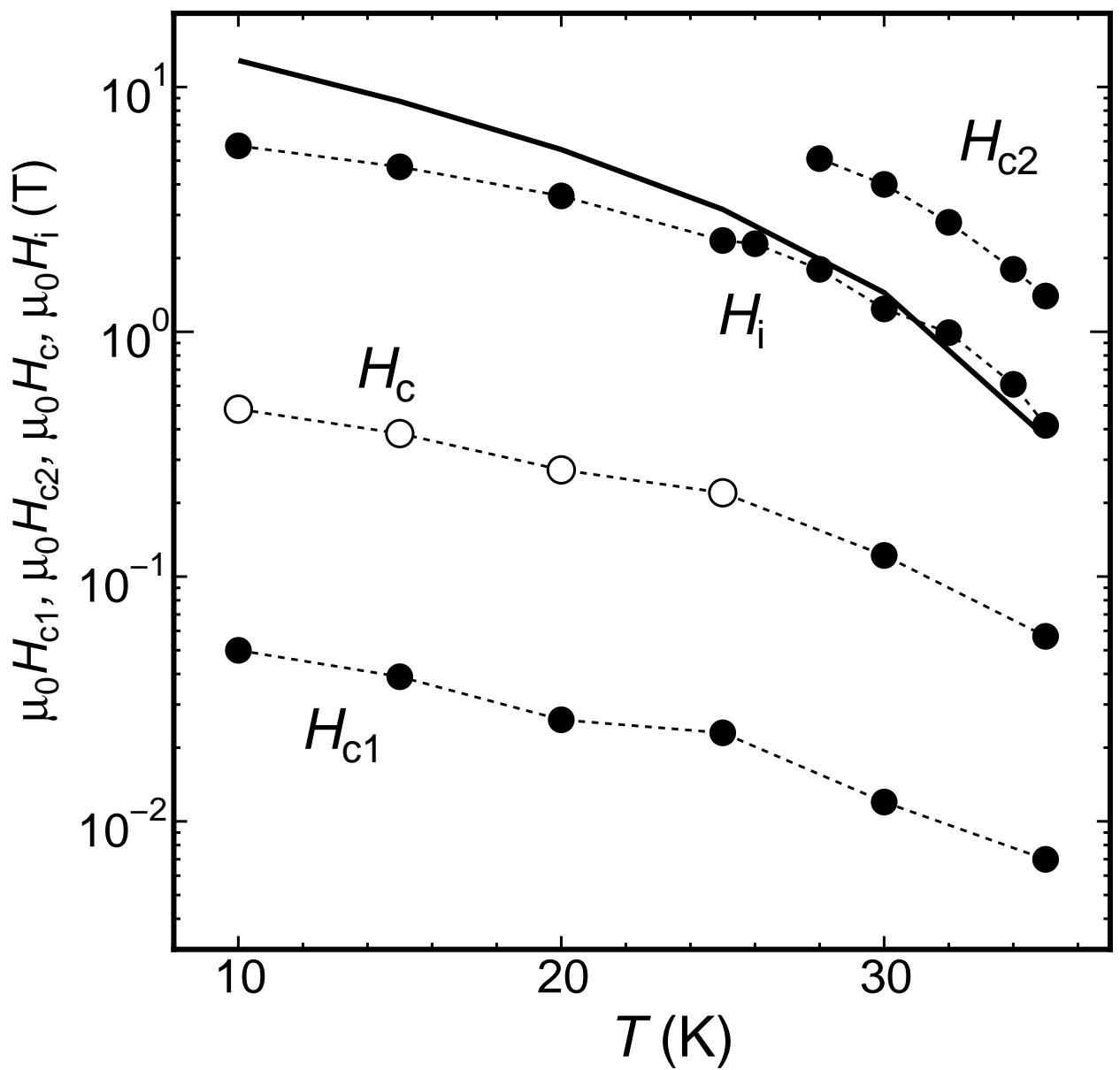
Figure 4: M. Fukuda *et al.*

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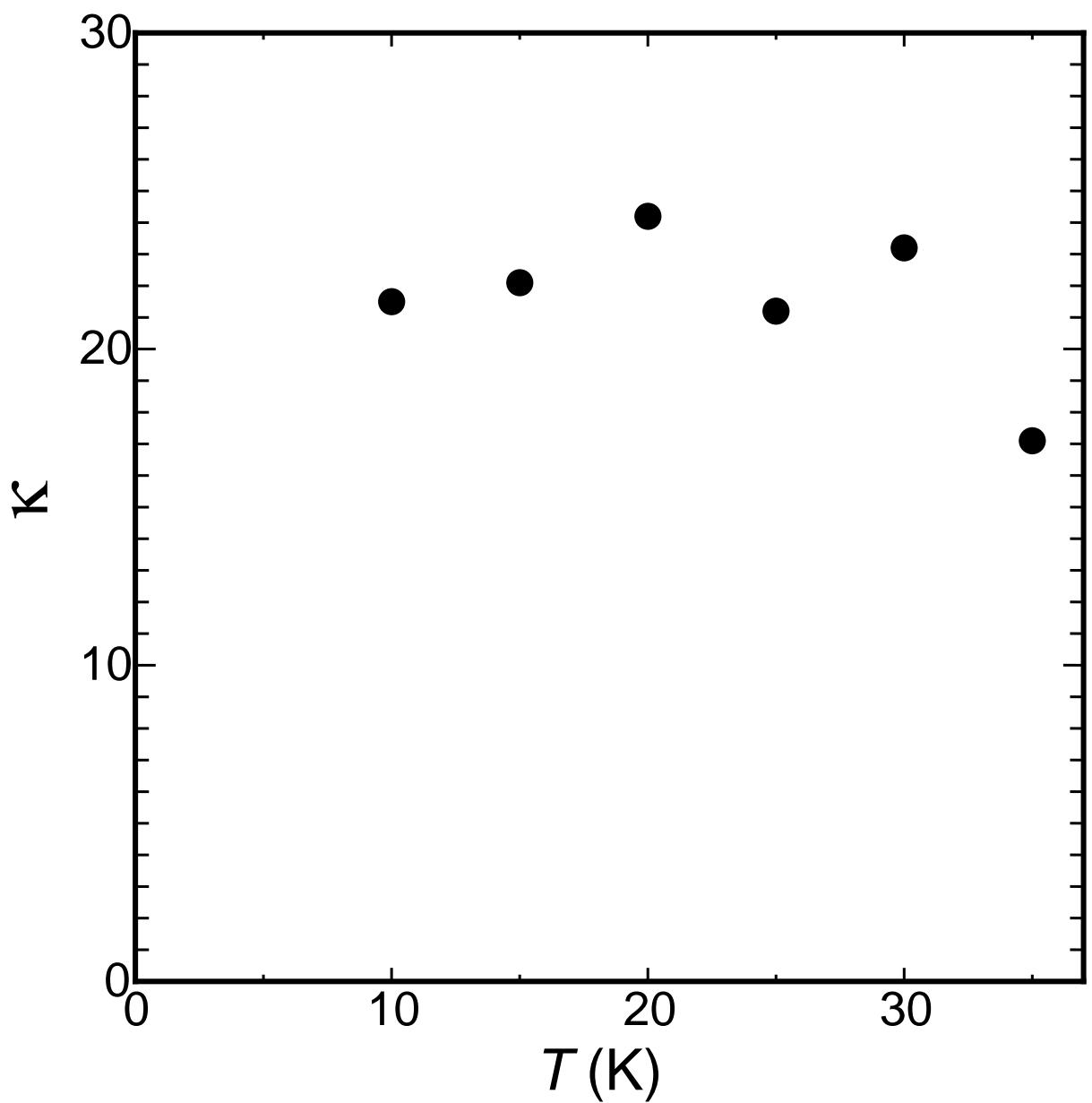
Figure 5: M. Fukuda *et al.*
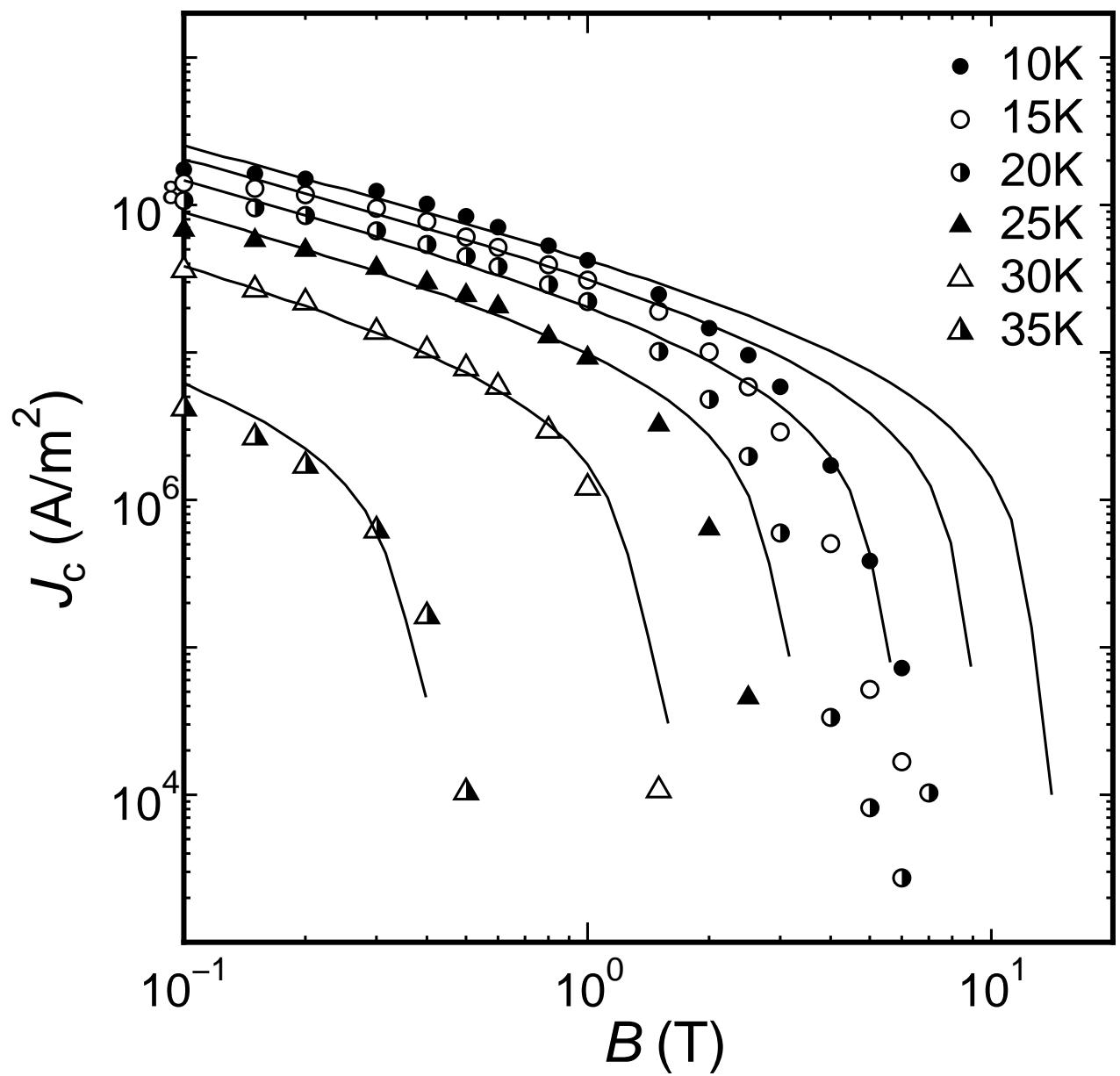
Figure 6: M. Fukuda *et al.*
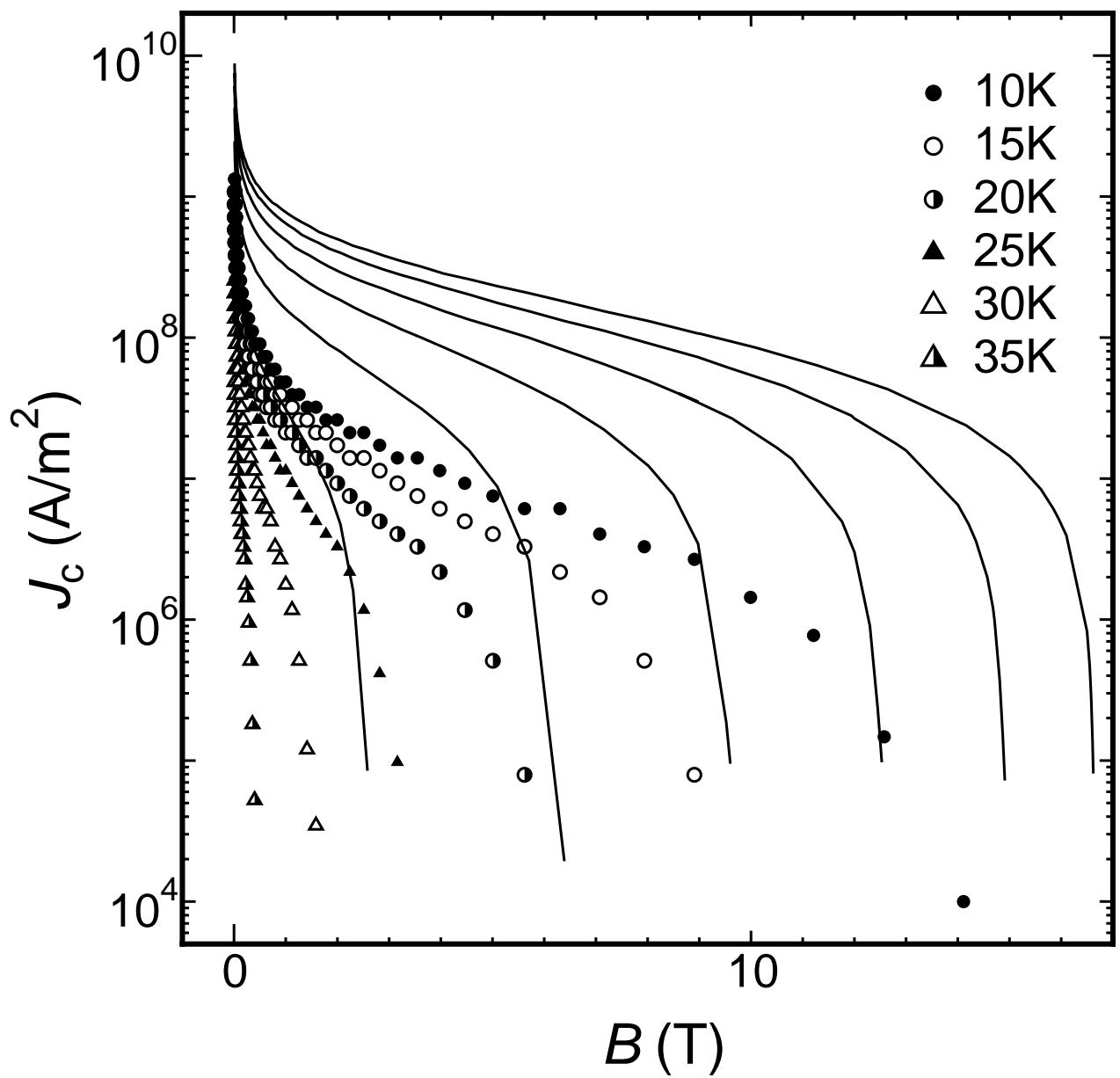
Figure 7: M. Fukuda *et al.*

Figure caption

Fig. 1. Field dependence of magnetization to estimate H_{c1} at $T = 35$ K.

Fig. 2. AC penetration depth vs AC field amplitude at $T = 10$ K and $B = 0.1$ T.

Fig. 3. Comparison of J_c observed by DC magnetization method (symbols) and Campbell's method (solid lines) at 10, 15, 20 and 25 K.

Fig. 4. Upper and lower critical fields, thermodynamic critical field and irreversibility field of MgB_2. Solid line is theoretical result of irreversibility field and dotted lines are guide for eye. Open symbols are estimated values assuming a linear extrapolation of H_{c2}.

Fig. 5. Temperature dependence of G-L parameter κ.

Fig. 6. Theoretically analysed J_c (solid lines) compared with experimental results (symbols) at 10, 15, 20, 25, 30 and 35 K.

Fig. 7. Calculated J_c (lines) assumed effect of normal precipitates compared with previous theoretical results (symbols).