Angular Dependence of Current Transport Characteristics in a Mixed State of Bi-2223/Ag Multifilamentary Tape

Taketsune Nakamura, Takahiro Yamamoto, Shingo Tsuchiya, Tsutomu Hoshino, and Itsuya Muta, *Member, IEEE*

***Abstract*— We have investigated current transport characteristics in a mixed state of Bi-2223/Ag multifilamentary tape by varying the angle between the external magnetic field and the tape surface. It was shown that the so-called glass-liquid transition magnetic field, which is an important parameter for applications of persistent current mode, as well as the critical currents, was dominated by the c-axis component (perpendicular to the tape surface) of the external magnetic field in a wide range of the field direction.**

***Keywords*— Bi-2223/Ag multifilamentary tape, Current transport characteristics, Anisotropy, Glass-liquid transition field.**

I. Introduction

Silver sheathed $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$(hereafter, stated as Bi-2223/Ag) tape is a promising material for such power application systems as superconducting magnets, power cables, etc, because of its long tape with high quality. Cryocooled 7 Tesla magnets using Bi-2223/Ag coils have been confirmed to be stable for operation [1]. In Detroit, experimental tests of 120 m long power cables have been planned. Furthermore, 500kVA-class superconducting power transformer has been developed and tested successfully [2].

It's crucial to estimate the material parameters such as critical current density for the design of the superconducting power systems. However, it's well known that the current transport property in high-T_c superconductor has a strong anisotropy with respect to the applied magnetic field direction. Therefore, it's important to take into account this magnetic anisotropy for the accurate design of the high-T_c power systems. In this study, we have investigated the anisotropy of the critical currents and current transport characteristics in a Bi-2223/Ag multifilamentary tape. One of the salient features of current transport characteristics in high-T_c superconductors is their scaling characteristics with the aid of so-called glass-liquid transition magnetic field [3],[4]. For the design of the power systems, the importance of glass-liquid transition field will be discussed in due course. And angular dependences of the critical currents and this parameter are also to be presented.

II. Experimental

The Bi-2223/Ag multifilamentary tapes were produced by a powder-in-tube method at Korea Electrotechnology Research Institute (KERI). The parameters of the sample are shown in TABLE I. The tape was cut carefully at 30 mm length for the measurements. The distance between potential taps was 2.0 mm. Current transport characteristics were measured with standard four-probe technique. In order to avoid the thermal fluctuation, the rectangular waves with the repetition frequency of 0.5 Hz were used as transport currents. All measurements were carried out immersed in the liquid nitrogen (77.3 K).

TABLE I
The Parameters of the Sample

sample	Bi−2223/Ag tape
process	PIT method
cross sectional area	4.0 mm^w × 0.23 mm^t
number of filaments	19
Ag/Sc	2.2
critical temperature	103.5 K
critical current density	1.06×10^4 A/cm^2 (77.3 K, 0 T)
n-value	34.0 (77.3 K, 0 T)

Fig.1 shows the schematics of the sample holder, which has a rotatable stage. The sample stage was connected to the vernier gauge set on top of the holder with a 0.2 mm stainless wire (not shown in Fig.1), and the angle of the stage was set by rotating the vernier gauge with the ratio at 2:1. The angular accuracy was better than 0.4°. The angle between applied magnetic field and the tape surface was defined as 0° and 90° for the field perpendicular and parallel to the tape surface, respectively.

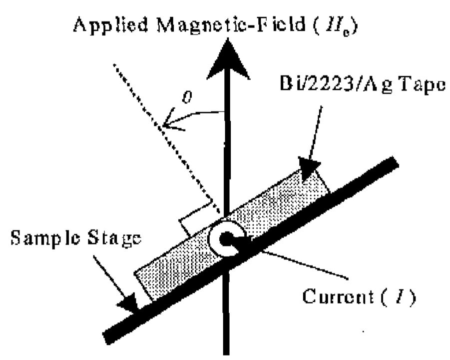

Fig. 1. Schematics of the sample holder. External magnetic field (H_e) is always perpendicular to the currents (I).

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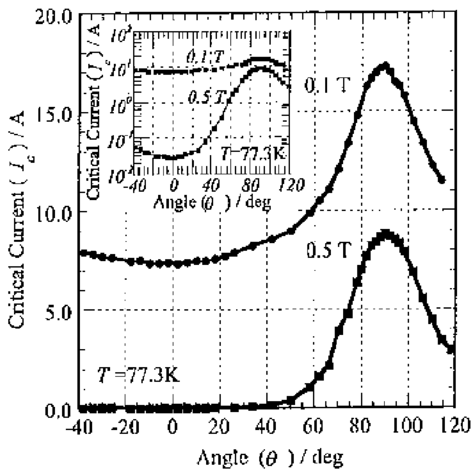

Fig. 2. Angular dependences of critical currents (I_c) at $\mu_0 H_e = 0.1$ and 0.5 T, respectively. Inset shows the semilog plots of the I_c-θ curves.

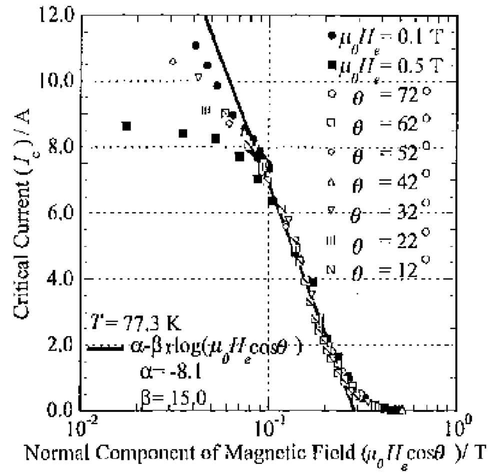

Fig. 3. I_c-$\mu_0 H_e \cos\theta$ characteristics. Data were obtained from Fig.2 (solid symbols), and from field dependent I_c data at a fixed angle (other symbols). Solid line was obtained by eq.(1).

III. Results and Discussion

A. Anisotropy of critical currents

Fig.2 shows the angular dependences with respect to the applied magnetic field direction of the critical currents for the field of 0.1 T and 0.5 T, respectively. The voltage criterion of the critical current was 100 nV, which corresponds to the electric field criterion of the 0.5 μVcm^{-1}. In this low voltage region, the effect of the sharing currents in the Ag sheath can be neglected. As is well known, strong anisotropy of I_c values is evident in Fig.2. Semilog plots of I_c-θ features are also plotted in the inset of Fig.2. As seen, the ratio of the $I_c(\theta = 90°)$ and $I_c(\theta = 0°)$ varies drastically by increasing the applied field from 0.1 T to 0.5 T, i.e. $I_c(\theta = 90°)/I_c(\theta = 0°)$=2.35 for $\mu_0 H_e = 0.1$ T and $I_c(\theta = 90°)/I_c(\theta = 0°)$=305 for $\mu_0 H_e = 0.5$ T, respectively.

As pointed out by Tinkham [5], if the superconductors are 2-dimensional, I_c-θ curve shows cusp at $\theta = 90°$. However, the obtained results show rather rounded structure near the peak as seen in Fig.2. In this case, it's known that the anisotropy can be described by the effective mass model [6]. Furthermore, we found experimentally that the width near the peak of I_c-θ curve increases as the so-called n-value of the voltage-current characteristics decreases (Data will be reported elsewhere). Because the n-value describes the statistical distribution of the local critical current densities as pointed out by Kiss et al. [7], it's to be deduced that the structure around the peak shows the inhomogenity of the sample.

I_c values are replotted with the normal component of the applied magnetic field ($\mu_0 H_e \cos\theta$) in Fig.3. Solid symbols were obtained from Fig.2, and other symbols were obtained from the applied field dependent I_c data at a fixed angle. It's shown that almost all I_c data lie on the same curve except at $\mu_0 H_e \cos\theta < 0.1$ T. That is, I_c values are dominated by the normal component of the applied magnetic field in a wide range of the field direction. However, I_c values tend to saturate at $\mu_0 H_e \cos\theta < 0.1$ T by deviating from the master curve, and the saturation values are decreased as the applied fields are increased. The same results have also been obtained by Hensel et al. [8]. This can be explained by the misorientation of the crystals [8]. Furthermore, scaling curve for the angular dependence of critical currents has been proposed experimentally by Kobayashi et al. [9], as follows,

$$I_c = \alpha - \beta log(\mu_0 H_e cos\theta) \qquad (1)$$

Solid line in Fig.3 shows the fitted result by eq.(1) with $\alpha = -8.1$, $\beta = 15.0$. As seen, magnetic field and angular dependences of the critical currents are estimated in a wide region with eq.(1).

B. Anisotropy of current transport characteristics

Magnetic field dependent current transport characteristics as a function of the field direction were studied. All measurements were performed under zero-field cooling condition. Typical example of the measured voltage-current (V-I) characteristics at the field direction of 42.0° are shown as open circles in Fig.4. In order to obtain the precise V-I curves of the superconductor, it's important to correct the sharing current flowing in the Ag sheath. We assume the sample as the parallel circuit of the superconducting layer and the Ag sheath, then supercurrent flowing in the superconducting layer (I_{sc}) will be corrected using the measured current (I) and the sharing current flowing in the Ag sheath (I_{ag}) as, $I_{sc} = I - I_{ag} = I - V/R_{ag}$. Where, R_{ag} is a resistance of the Ag sheath. Solid circles in Fig.4 show the corrected results. Hereafter, corrected $V - I$ curves with I_{sc} will be discussed. Fig.5 shows the magnetic field variation of the V-I_{sc} characteristics at $\theta = 12.0°$. As seen, the curvature of $\log V - \log I_{sc}$ curves change from convex to

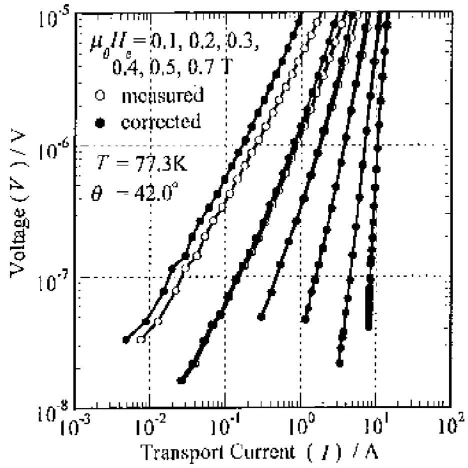

Fig. 4. Magnetic field dependence of the V-I characteristic at $\theta = 42.0°$. Open and solid circles were obtained for without and with the correction of sharing currents in the Ag sheath.

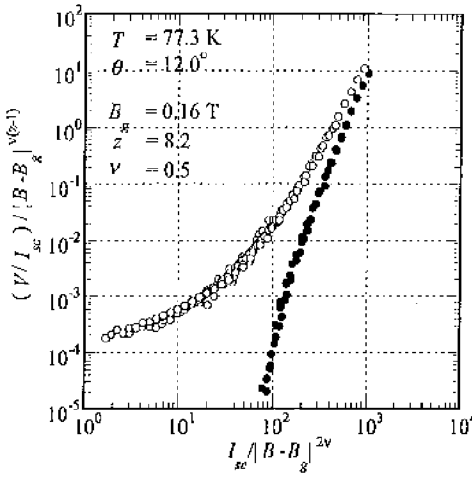

Fig. 6. Scaling collapses of the V-I_{sc} curves obtained from Fig.5. $B_c = 0.16$ T, $z = 8.2$, and $\nu = 0.6$ were obtained by the critical scaling analysis.

concave shape as the external magnetic field increases. We define so-called glass-liquid transition magnetic flux density ($B_g = 0.16$ T) at whitch $V - I_{sc}$ curve shows the power law feature as shown by solid line in Fig.5 [3],[4]. Furthermore, all curves are collapsed on two master curves by normalizing the V to $(V/I_{sc})/|B-B_g|^{\nu(z-1)}$, and I_{sc} to $I_{sc}/|B-B_g|^{2\nu}$ as shown in Fig.6. Parameters $z(= 8.2)$ and $\nu(= 0.6)$ denote critical indices, and especially z is proportional to the n-value at B_g. By separating fields with B_g, solid and open circles were obtained from $V - I_{sc}$ curves in lower and higher fields, respectively. Many models have been proposed for the physical meaning of the scaling of $V - I_{sc}$ curves [3],[4],[10-12]. Here, we focus on the importance of B_g for the practical applications. That is, as seen in Fig.6, dissipation is induced even applying small current in higher magnetic fields (open circles). On the other hand, dissipation reduces drastically by decreasing the transport current in lower fields (solid circles). Therefore, magnetic field region adequately below B_g has to be used for the design of the superconducting power systems with persistent current mode. In other words, B_g is one of the important material parameters for such applications.

Fig.7 shows the $V - I_{sc}$ charactristics at B_g for various field directions. As seen, all data lie on the same curve without depending on the field directions. Furthermore, B_gs are plotted as a function of the external magnetic field direction in Fig.8. As shown, B_g increases as θ increases. B_gs are also plotted for $\cos^{-1}\theta$ in Fig.9. As can be seen, B_g is proportional to $\cos^{-1}\theta$ at lower $\cos^{-1}\theta$ region, corresponding to the lower angle region. From these results, we can say that not only critical currents but also B_g is only dominated by the normal component of the external mag-

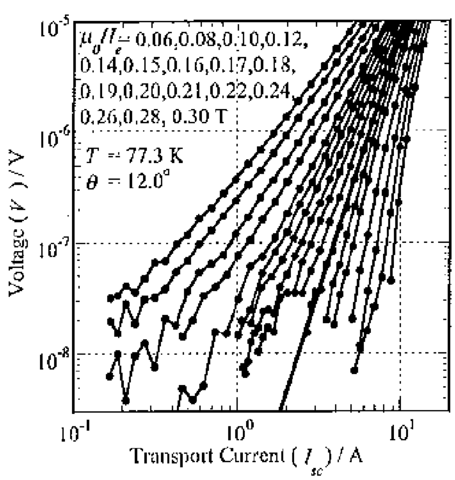

Fig. 5. Magnetic field dependence of the V-I_{sc} characteristics at $\theta = 12.0°$. Solid line shows the power-law characterictics at so-called glass-liquid transition flux density (B_g).

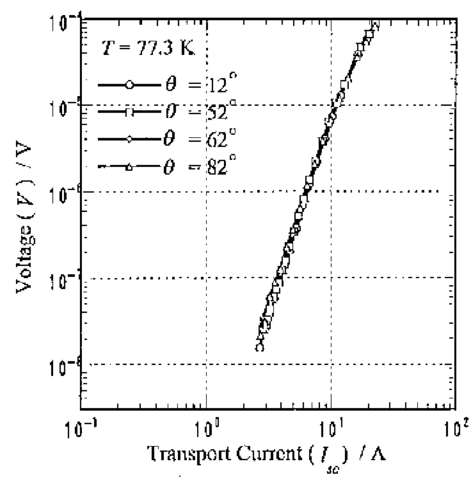

Fig. 7. $V - I_{sc}$ characteristics at B_g for various field direction. B_g was determined as the magnetic flux density at which $V - I_{sc}$ curves show power law features.

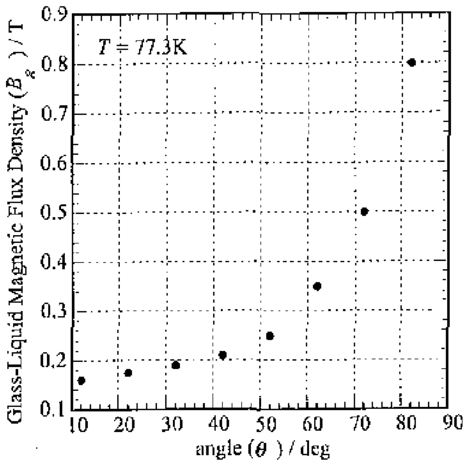

Fig. 8. $B_g - \theta$ characteristics.

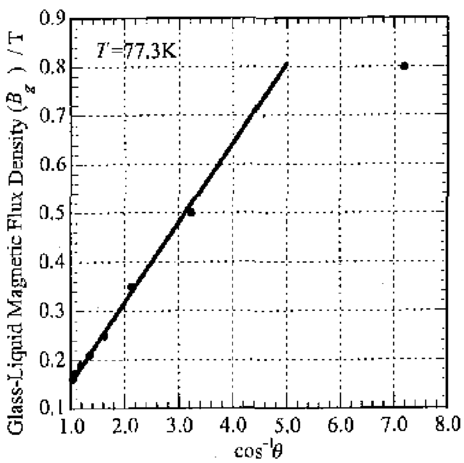

Fig. 9. $B_g - \cos^{-1}\theta$ characteristics obtained from Fig.8.

netic field. The deviation at higher angle region will be because of the same reason of that of $I_c - \theta$ characteristics in Fig.3.

Aforementioned anisotropy is usually discussed by effective mass model. Based on the model, magnetic anisotropy is expressed by using that of the upper critical flux density (B_{c2}) as follows [6],

$$B_{c2}(\theta) = B_{c2}(0°)[cos^2\theta + \left(\frac{B_{c2}(0°)}{B_{c2}(90°)}\right)^2 sin^2\theta]^{-\frac{1}{2}} \quad (2)$$

High-T_c superconductors, however, are effected by the thermal fluctuation, and the definition of the B_{c2} is very ambiguous. Furthermore, it's questioned whether clear transition occur at B_{c2} for high-T_c superconductors. Therefore, the anisotropy of the material paramerers has to be studied with consideration of the thermal fluctuation such as B_g. More study is necessary for the accurate design of the high-T_c power systems.

IV. Conclusion

Critical currents and current transport characteristics in a mixed state of Bi-2223/Ag multifilamentary tape were studied as a function of the external magnetic field and the field direction. It was shown that the so-called glass-liquid transition magnetic flux density as well as the critical currents were determined by the normal component of the external magnetic field in a wide range of the field direction. The importance of this parameter for the power applications with persistent current mode was also discussed.

Acknowledgments

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