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The physical properties of several HTS coated conductors

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Abstract-- **The superconducting properties of several HTS coated conductors (CC), which had different tape structures, fabricated by KERI, X and Y institutes were compared. We have fabricated the high-J_c SmBCO CC, which has 273.5 A/cm, 1.2 MA/cm^2 and 93.5 K for I_c, J_c and $T_{c\text{-}zero}$, respectively, using the EDDC (Evaporation using Drum in Dual Chambers) process. Both X and Y institutes CCs, however, were purchased. The n-values of KERI, X and Y institutes CCs are 58.5, 40.7 and 31.5 in V = 1 ~ 10 μV criterion, respectively. The in-field properties of I_c at 77 K were investigated and the $J_c(B)/J_c(0G)$ at 0.5 T with $B\perp$ab-plane are 0.31, 0.19 and 0.24 for KERI, X and Y institutes CCs, respectively. From the I_c-θ-B measurement, we observed that the ab-plane of ReBCO phase was tilted for the ab-plane of substrate in the KERI and X institutes CCs. The tilted angle is about 5 degree. We confirmed that the peak shift (as an inclined texture) was observed by X-ray (102) pole figures of the SmBCO for the KERI CC.**

1. INTRODUCTION

Since high-temperature superconductivity (HTS) was discovered in 1986 [1-5], numerous studies for HTS wires have been performed on materials, processes, buffer layers and substrates in order to control and to enhance superconducting properties as commercial products. High-temperature superconducting (HTS) wires were classified by first-generation wire (Bi-family tapes using the PIT (Powder-In-Tube) method) and second-generation wire (called coated conductors, $ReBa_2Cu_3O_{7-\delta}$ (ReBCO) CCs using several deposition methods, such as PLD (Pulsed Laser Deposition) [6], MOD (Metal Organic Deposition) [7-9], MOCVD (Metal Organic Chemical Vapor Deposition) [10], and thermal co-evaporation [11] etc.). First-generation HTS wires, such as $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) tape, have low critical current density (J_c) under magnetic fields, at 77 K. And so, first-generation HTS wires demand low operation temperatures below 20 K for practical applications. However, the critical current density (J_c) of second-generation HTS wires does not drop critically as first-generation ones under high magnetic fields [12-13].

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Therefore, the second-generation HTS CCs have a good promise for high-current, high-magnetic-field applications operating at liquid nitrogen temperatures. ReBCO materials have become the core material for the development of second-generation HTS wires. The wide use of these materials, however, is hindered by the weakness of the trapped magnetic field generated by twin, point defects, dislocations, and stacking faults. Lee et al. and Chen et al. reported that J_c might be affected by both the size and the morphology of the Y211-particles [14] and the number of effective pinning center affected to enhance the J_c-B performance of superconductor [15], respectively. In addition, M. Murakami et al. showed that the $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) and the $SmBa_2Cu_3O_{7-\delta}$ (SmBCO) superconductors not only reveal a higher transition temperature (T_c) than $YBa_2Cu_3O_{7-\delta}$ (YBCO) but also higher J_c in high magnetic fields due to so-called peak effect [16].

In this paper, the angular dependency in magnetic field (at B = 0.5 T) and field dependency (B = from 0 T to 0.5 T) for HTS coated conductors fabricated by KERI, X and Y institutes, have been investigated. These samples have different both structures of tapes and deposition processes of superconducting films.

2. EXPERIMENTAL PROCECURE

The HTS coated conductors prepared by KERI, X and Y institutes were selected for investigation of superconducting properties in low magnetic field. The structure of X institute CC (X-CC) is a Cu / Ag / YBCO / $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 / Cu. This HTS tape is laminated on both sides with 20μm film of copper by electroplating. The Y institute CC (Y-CC) is laminated on both sides with ultra-thin strips of copper for stabilization and strength. The structure of Y-CC is a Cu / solder / Ag / YBCO / CeO_2 / YSZ / Y_2O_3 / Ni-W / solder / Cu. The KERI CC is prepared by EDDC (Evaporation using Drum in Dual Chambers) process. We have previously reported the EDDC (Evaporation using Drum in Dual Chambers) process [17]. The KERI CC is HTS SmBCO tape of which structure is Cu / solder / SmBCO / $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 /

Hastelloy 276. The SmBCO film was deposited by thermal co-evaporation method. Table 1 shows co-evaporation conditions at KERI.

The prepared HTS tapes were cut into 6 cm for I_c measurement, individually. The critical current I_c was measured by the four-probe method at liquid nitrogen temperature and determined by the criterion of 1 μV/cm. The angular dependence of I_c was also measured. The current lead was soldered by $_{66.3}In\text{-}_{33.7}Bi$ solder (melting point = 72°C) to prevent I_c degradation from thermal shock. The microscopy and EDX analysis was performed on a FESEM S-4800 (Hitachi) operated at 15keV. X-ray microanalysis was performed using a GADDS (General Area Detector Diffraction system, Bruker AXS) with a two dimensional detector.

TABLE I
DEPOSITION CONDITIONS OF CO-EVAPORATION (KERI).

Parameters	Conditions
Deposition temperature	720 °C
Deposition time	90 min.
Deposition rate	~25 nm/m
Rotating speed of drum	30 rpm
Oxygen pressure of upper chamber	1.5 x 10^{-3} torr
Oxygen pressure of bottom chamber	1 x 10^{-4} torr

3. RESULTS AND DISCUSSION

We have fabricated the high-J_c SmBCO CC (KERI CC) using the EDDC process by thermal co-evaporation. The X-CC and Y-CC were purchased. We cannot estimate the J_c of the X-CC and Y-CC because of lacking the information of ones' geometrical structure. Simply, we express the I_c instead of J_c, in the case of these samples. Fig. 1 shows critical current of KERI, X and Y institutes coated conductors at 77 K in self-field. The I_c values are 109.4 A (273.5 A/cm), 96.3 A (240.8 A/cm) and 77.9 A (177 A/cm) for the KERI, X and Y institutes', respectively. The J_c of KERI CC is 1.2 MA/cm^2.

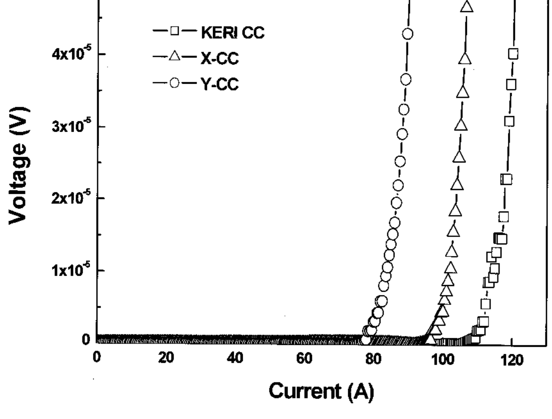

Fig. 1. Critical current I_c values at 77 K, self-field.

Fig. 2 shows the n-value of KERI CC, X- and Y-CCs. The n-value was estimated by fitting the curve $V \propto I^n$ within the range of V = 0.1~1 μV (below I_c criterion), and V = 1~10 μV (above I_c criterion). The n-values, which are resistance transition exponents, at the V = 0.1~1 μV criterion are 50.5, 51.9, 50.9, and at the V = 1~10 μV criterion are 58.5, 40.7, 31.5 for KERI CC, X- and Y-CCs, respectively. The Fault Current Limiter (FCL) of resistance type needs the high n-value to limit disorder current, in addition to high current density (J_c) and low ac loss. We can expect that the KERI CC could be promising for FCL application from the aspect of resistance transition exponent.

Fig. 3 shows the J_c-B data for the KERI CC, X- and Y-CCs. Magnetic field was applied in the directions perpendicular (*B* ⊥ *ab-plane*) and parallel (*B//ab-plane*) to the film surface. J_c values are normalized for critical current density at self-field. The I_c and J_c of KERI CC was 85.5 A/cm and 0.3 MA/cm^2 at *B* ⊥ *ab-plane*, 100.3 A/cm and 0.47 MA/cm^2 at *B//ab-plane*, with a 0.5 T. The I_c of X-CC was 45.5 A/cm (*B* ⊥ *ab-plane*) and 53.5 A/cm (*B//ab-plane*) with a 0.5 T. The I_c of Y-CC was 42.7 A/cm (*B* ⊥ *ab-plane*) and 64.3 A/cm (*B//a-b plane*) with a 0.5 T. The KERI CC and Y-CC show a monotonous decreasing J_c value with increasing external field, while the X-CC shows a sharply decreasing behavior.

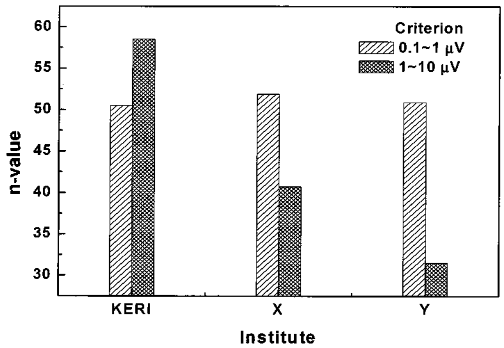

Fig. 2. The n-value of KERI CC, X- and Y-CCs.

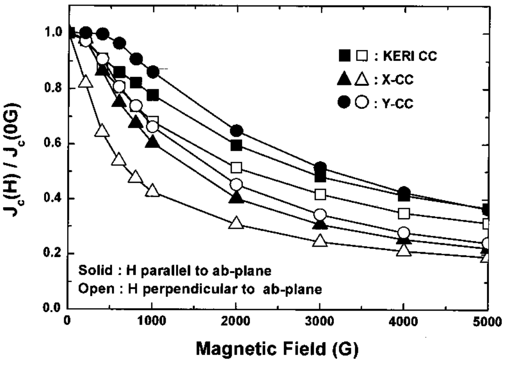

Fig. 3. The magnetic field dependence of normalized critical current density ($J_c(B)/ J_c(0G)$) at 77 K and self-field.

The normalized critical current $(I_c)/I_c(B//ab\text{-}plane)$ as the function of field angle, between the normal direction of the sample surface and the magnetic field (I_c-θ-B curve), was shown in Fig. 4. As indicated in the figure, $\theta = 0^o$ corresponds to B//c-axis, and $\theta = 90^o$ to B//ab-plane. We observed peaks at $\theta = 85^o$, 85^o and 90^o (B//ab-plane) for KERI CC, X-CC and Y-CC tapes, respectively. These peak positions of B//ab-plane shift about 5 degree for the KERI CC and X-CC. Although the shift of the peak position may be occurred from an imprecise measurement, we think that the SmBCO phases for KERI CC can be inclined for the substrate plane because of the inclined IBAD-MgO buffer layer in the IBAD process. The I_c of the KERI CC and X-CC at the B//c-axis are slightly elevated. The elevation of I_c at the B//c-axis did not appear in the Y-CC. The measured CC samples show the difference of J_c-B and I_c-θ-B data, resulted from materials, their compositions, effective pinning centers and processes.

The X-ray diffraction pattern of the $Sm_{1+x}Ba_{2-x}Cu_y O_{7-\delta}$ was shown in Fig. 5. All the major peaks could be indexed as SmBCO (00n) peaks, as shown in the X-ray diffraction pattern of the $Sm_{1+x}Ba_{2-x}Cu_y O_{7-\delta}$. The full width at half maximum (FWHM) of SmBCO (006) is 0.29^o. The relative intensity ratio of SmBCO (005) and SmBCO (103) is 99.9 %. From these results, this sample is very sharply textured in c-axis direction.

Fig. 6 shows the X-ray pole figure of SmBCO (102) plane that the SmBCO CC is fabricated by KERI. The rocking curve for the SmBCO (005) plane was investigated, with the value of FWHM $\sim 1^o$. The value of FWHM for the SmBCO (102) β-scan was 6.9^o. From the results of Fig. 5 and Fig. 6, the $Sm_{1+x}Ba_{2-x}Cu_yO_{7-\delta}$ film prepared on the $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 template has been sharply bi-axial texture.

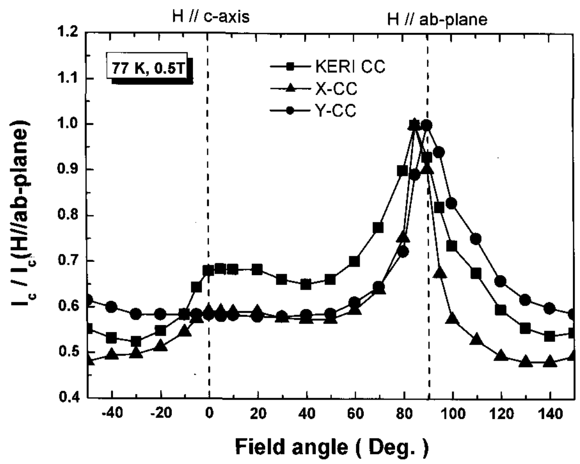

Fig. 4. The normalized critical current $(I_c)/I_c(B//\text{ab-plane})$ as the function of field angle between the normal direction of the sample surface and the magnetic field (@77 K, self-field).

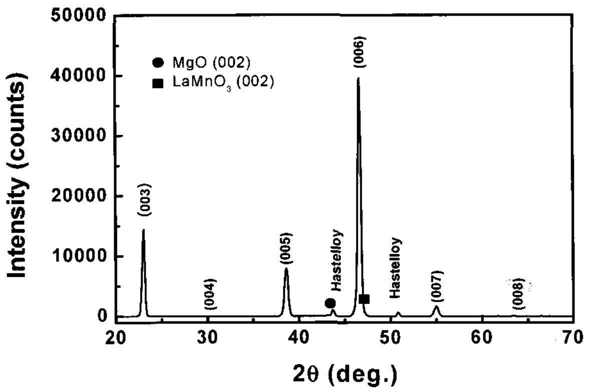

Fig. 5. X-ray diffraction pattern of the $Sm_{1+x}Ba_{2-x}Cu_y O_{7-\delta}$ film prepared on the $LaMnO_3$ / IBAD-MgO /Y_2O_3 / Al_2O_3 / Hastelloy C276 template, here x = 0.04 and y = 0.06, which is KERI CC.

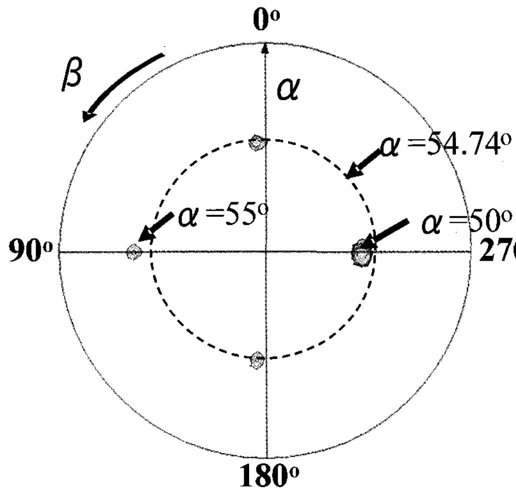

Fig. 6. X-ray (102) pole figures of the $Sm_{1+x}Ba_{2-x}Cu_yO_{7-\delta}$ film prepared on the $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 template, here x = 0.04 and y = 0.06, which is KERI CC.

In the case of parallel to the ab-plane of both SmBCO phase and substrate, the SmBCO (102) peaks emerged at $\alpha = 54.74^o$, every $\beta = 90^o$ with the film rotation. Although the SmBCO (102) peaks emerged at every 90^o with the film rotation, we know that SmBCO phases are inclined about 5^o; peak shift of SmBCO (102) plane from the center of pole figure. This result agrees with I_c-θ-B curve of the KERI CC and X-CC.

The compositional ratio of Sm:Ba:Cu = 1:1.9:2.9 was measured by EDX. We can estimate Sm-Ba substitution quantity from the third order simultaneous equation for 1+x, 2-x and y. The values of x and y are 0.04 and 0.06. Fig. 7 shows the FE-SEM image of the $Sm_{1.04}Ba_{1.96}Cu_{3.06} O_{7-\delta}$ film. The surface of SmBCO film is very smooth, but shows unknown nano dots.

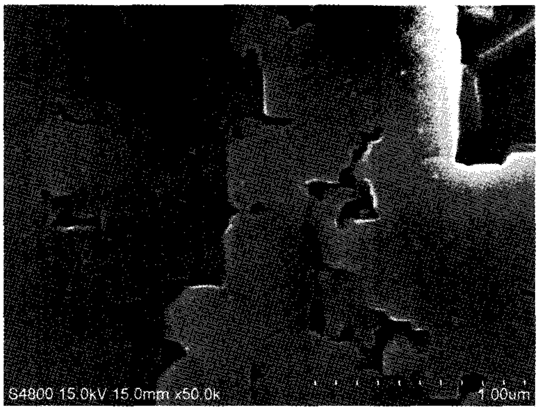

Fig. 7. SEM image of the $Sm_{1+x}Ba_{2-x}Cu_yO_{7-\delta}$ film prepared on the $LaMnO_3$ / IBAD-MgO /Y_2O_3 / Al_2O_3 / Hastelloy C276 template, which have x = 0.04 and y = 0.06 (KERI CC, and its thickness ~ 2.2μm).

Sudoh et al. reported that the Sm-Ba substitution influenced the smoothness and the stability on the surface of the SmBCO thin films, and they speculated that the surface morphology of the SmBCO thin films was influenced by the Sm-Ba substitution and its migration potential. And, in the Sm-rich (x = 0.08 and 0.12) targets by PLD, they observed the microstructure of the step-and-terrace features due to 2D-nucleation growth [18]. Their SmBCO thin films with a high critical temperature could be obtained reproducibly by using targets with x = 0.00, 0.04, 0.08 and 0.12 [19]. KERI CC prepared by thermal co-evaporation method, however, does not show the step-and-terrace features. Fig. 8 shows resistance behavior of KERI CC. The temperature dependence of resistance was determined by the four-probe method using the PPMS (Physical Properties Measurement System). The $T_{c\text{-}zero}$ of KERI CC is 93.5 K.

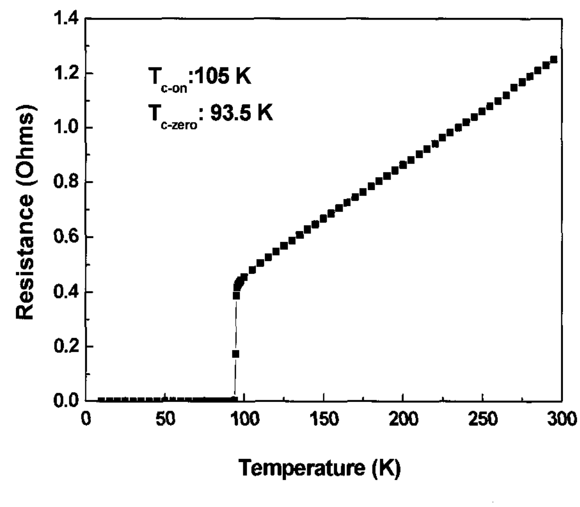

Fig. 8. Temperature dependence of resistance in $Sm_{1+x}Ba_{2-x}Cu_yO_{7-\delta}$ film prepared on the $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 template, here x = 0.04 and y = 0.06, which is KERI CC.

4. SUMMARY

We have fabricated the high-J_c SmBCO CC on $LaMnO_3$ / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 template, using the EDDC deposition system, which is one of batch type co-evaporation method. Its I_c, J_c and $T_{c\text{-}zero}$ results were obtained with 273.5 A/cm, 1.2 MA/cm^2 and 93.5 K at 77 K and self-field, respectively.

The physical properties of coated conductors (CCs) prepared by KERI, X and Y institutes have been investigated. Their I_c values were measured with 273.5, 240.8, and 177.9 A/cm at 77 K and self-field, 85.5, 45.5 and 42.7 A/cm in the direction of $B \perp$ ab-plane at 0.5 T and 77 K, and the n values at V = 1 ~ 10 μV criterion are 58.5, 40.7 and 31.5 for KERI CC, X-CC and Y-CC, respectively. In addition, we observed peaks at $\theta = 85^o$ ($\theta = 90^o$ is B//ab-plane) for KERI CC and X-CC tapes. These peak positions of B//ab-plane shifted about 5 degree. We temporary interpret that the SmBCO phases of KERI CC were inclined for the substrate plane because of the inclined IBAD-MgO buffer layer in the IBAD process. Further works to investigate the cause of this are underway.

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