WBP7-1

Competing flux pinning of columnar defects in different directions for high-T_c superconductors

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We studied competing effect for flux pinning between columnar defects (CDs) along the *c*-axis and crossing at $\pm\theta_i$ relative to the *c*-axis in high-T_c superconductors, through the angular behaviors of critical current density J_c in $YBa_2Cu_3O_y$ thin films with the CDs installed by heavy-ion irradiations. A large enhancement of J_c centered at $B \parallel c$ occurs for the CD-configurations composed of CDs along the *c*-axis and with $\theta_i \le \pm60°$: the angular region where J_c is enhanced by CDs is more expanded for the CD-configuration with larger crossing angle $\pm\theta_i$, whereas the enhancement of J_c at $B \parallel c$ is slightly weakened. A J_c peak at $\pm\theta_i$, however, cannot be seen even for the film including CDs with $\theta_i = \pm60°$. These results demonstrate that the synergy effect of flux pinning between CDs along the *c*-axis and with $\theta_i \le \pm60°$ can occur in angular range from $-\theta_i$ to θ_i, since the trapping angle of CDs along the *c*-axis is about 60°. In the vicinity of $B \parallel ab$, on the other hand, CDs in any direction hardly contribute to flux pinning for the CD-configurations with $\theta_i \le \pm60°$. For the CD-configuration composed of CDs along the *c*-axis and with $\theta_i = \pm80°$, by contrast, the J_c drastically enhances around $B \parallel ab$: the J_c peak emerges at the two irradiation angles $\theta_i = \pm80°$ and the value of J_c increases even at $B \parallel ab$ where the J_c shows not a peak but a dip behavior. The appearance of the J_c peak at $\theta_i = \pm80°$ means that the CDs crossing at $\theta_i = \pm80°$ contribute to the flux pinning independently from CDs along the *c*-axis, since the crossed CDs exist out of the trapping angle of CDs along the *c*-axis. On the other hand, there is a little enhancement of J_c with no peak around $B \parallel c$ even though the CDs are also installed along the *c*-axis: CDs in closer directions to the *ab*-plane induce sliding motion of flux lines along the CDs at $B \parallel c$, leading to the deterioration of flux pinning by CDs along the *c*-axis.

Keywords: high-Tc superconductors, critical current density, anisotropy, columnar defects

WBP7-2

TDGL Simulation of Critical Current Density introducing z axis Anisotropy γ_z

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The relationship between anisotropy strength and critical current densities J_c in small superconducting cube exposed to a transport current and a transverse magnetic field were investigated. The TDGL equations for the superconducting cube was numerically solved by using the Euler method. In this case, the vector potential $\boldsymbol{A}$ depends only on the external magnetic field $\boldsymbol{B}$. We show the three-dimensional dynamics of the quantized magnetic flux lines by plotting the contour surfaces of the superconducting electron density $|\Psi|^2$, where Ψ is the order parameter.

In this study, the parameters using in the original TDGL equations were normalized using the coherence length ξ and the upper critical field B_{c2} and so on for reducing the number of the constants in the TDGL equations.

We considered a superconducting cube of which side length is 10ξ in the vacuum. In addition, 4 columnar pins of diameter ξ were introduced with the distance d of pins as shown in Fig. 1(a). Here, we define the order parameter Ψ as 0 inside of the pins. We give the boundary condition corresponding to the normal component of the electric current density $\boldsymbol{J}$ is zero at the surfaces of the cube. $\boldsymbol{J}$ and $\boldsymbol{B}$ are applied to the y axis and the z axis, respectively. Hence, the vector potential can be given by $(A_x, A_y, A_z)=(0, Bx, 0)$ for the transverse magnetic field. The electric current density and the magnetic field at each time were kept constant at a normalized value.

Fig. 1(b), (c) and (d) shows the flux lines with different γz of columnar pins. Calculations were made with external magnetic field $B = 0.1, 0.2, \ldots, 0.6$, current density $J = 0.01, 0.02, \ldots, 0.30$, and z axis anisotropy strength $\gamma_z = 1, 2, 4, 8$.

Fig. 2 shows the numerical results of J_c - B at the z axis anisotropy strength $\gamma_z = 1, 2, 4, 8$. A large peak appears at $B = 0.4$. This is due to the peak effect. And there is almost no difference due to the strength of the anisotropy. Therefore, it was confirmed that the peak effect works similarly even when the z axis has anisotropy.

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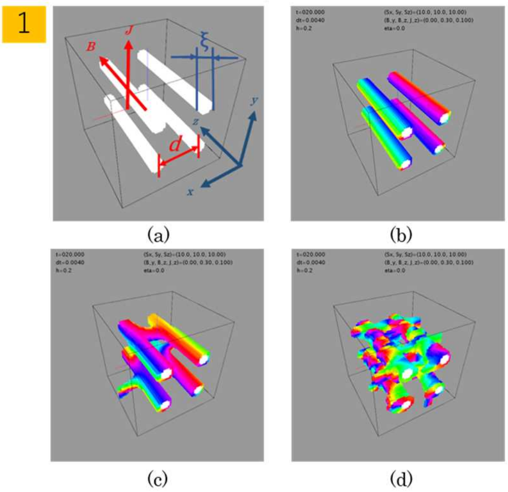

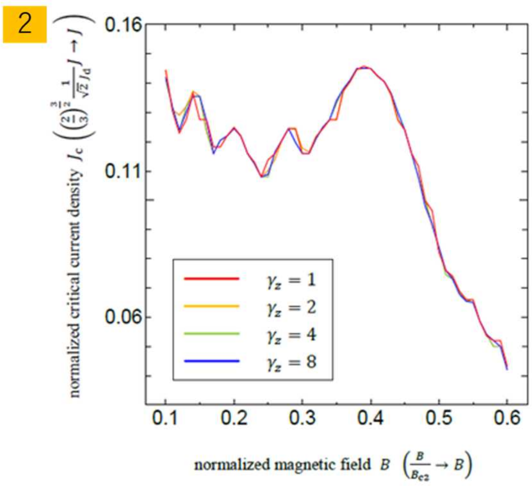

Fig. 1: (a) Geometry of the superconducting cube. Calculated results of flux lines for (b) $\gamma_z^2 = 1$, (c) $\gamma_z^2 = 8$ and (d) $\gamma_z^2 = 512$.
Fig. 2: Numerical results of Jc - B at the z axis anisotropy strength $\gamma_z = 1, 2, 4, 8$.

Keywords: Critical current density, time-dependent Ginzburg-Landau equations

WBP7-3

J_C control by hybrid pinning of nanorods and nanoparticles in $YBa_2Cu_3O_{7-x}$ film

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Improvement of critical current density (J_C) and suppression of J_C anisotropy are required to develop high performance $YBa_2Cu_3O_{7-x}$ (YBCO) tapes. While introduction of nanorods comprising of $BaZrO_3$, $BaSnO_3$, $BaHfO_3$ is effective for improving the J_C in magnetic fields, the nanorods result in anisotropic vortex pinning and significant J_C anisotropy. The J_C anisotropy should be reduced with maintaining high J_C in YBCO films. For this purpose, we prepared the YBCO films containing nanorods and nanoparticles to realize hybrid pinning, and investigated influence of the nanorod and nanoparticle distributions on J_C.

YBCO films were fabricated on $SrTiO_3$ substrate by PLD (Pulsed Laser Deposition) method. Here, BHO nanorods and Y_2O_3 nanoparticles were incorporated using the 6wt%BHO-doped YBCO target and Y_2O_3 sectors on targets (pure YBCO/YBCO+BHO targets), respectively. We prepared two types of samples of YBCO+BHO+Y_2O_3 films and YBCO+BHO/YBCO+Y_2O_3 films in addition to the YBCO+BHO single layer film (SL). The superconducting properties of fabricated samples were evaluated at 77 K, 65 K, 40 K and 20 K in magnetic fields.

At 77 K, the YBCO+BHO single layer showed F_{PMAX} = 25.1 GN m^{-3} (77 K, 5 T) which was higher than that for the YBCO films containing both nanorods and nanoparticles. However, at 20 K, F_{PMAX} = 806 GN m^{-3} (20 K, 12 T) which was the highest at 20 K among the present films was obtained in the YBCO+BHO+Y_2O_3 film. The J_C minimum was observed at 40°, and the J_C minimum was 1.67 $MAcm^{-3}$ and 3.58 $MAcm^{-3}$ for the YBCO+BHO+Y_2O_3 and the YBCO+BHO in a temperature of 20 K and a magnetic field of 16 T, respectively. The in-between value of 2.32 $MAcm^{-3}$ was observed for the YBCO+BHO/YBCO+Y_2O_3 films. By tuning the distribution of nanorod and nanoparticle, the J_C values and J_C anisotropy can be controlled in YBCO films.

Keywords: voltex pinning, YBCO

WBP7-4

Enhanced pinning properties by refining Gd_2O_3 particles trapped in the $GdBa_2Cu_3O_{7-\delta}$ films via RCE-DR

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The pinning properties of $GdBa_2Cu_3O_{7-d}$ (GdBCO) coated conductors(CCs) fabricated by reactive co-evaporation by deposition and reaction (RCE-DR) should be further improved because in-field critical current densities (J_c) properties of GdBCO CCs are relatively lower than those of REBCO CCs produced by other processes such as metal-organic deposition (MOD), pulsed laser deposition (PLD), metal-organic chemical vapor deposition (MOCVD). To improve in-field J_c of GdBCO CCs fabricated by the RCE-DR process, employing the nominal composition of Gd:Ba:Cu=1:1:2.5, we tried to refine the Gd_2O_3 particles trapped in the GdBCO superconducting matrix by controlling nucleation and growth rates of Gd_2O_3 in the liquid phase before crystallization of GdBCO. For this purpose, the processing conditions were carefully selected from the GdBCO stability phase diagram experimentally determined for the nominal composition of Gd:Ba:cu=1:1:2.5. By lowering the nucleation and growth temperature of Gd_2O_3 in the liquid from 860 to 800°C in the oxygen pressure of 20, 30 mTorr, the average particle size of Gd_2O_3 particles trapped in the GdBCO matrix could be refined from 137 ± 52 to 73 ± 31 nm, respectively. The pinning properties could be significantly improved by the refinement of Gd_2O_3 so that the refinement strategy might be applied to the RCE-DR process. Details will be presented for a discussion.

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Keywords: GdBCO, Gd2O3, Pinning properties, stabilitty phase diagram

WBP7-5

Effect of post-annealing on the pinning properties of $GdBa_2Cu_3O_{7-\delta}$ coated conductors via RCE-DR

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We investigated the effect of post-annealing on the pinning properties of $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) coated conductors (CCs) fabricated by the reactive co-evaporation deposition & reaction (RCE-DR) process. On the basis of the stability phase diagram of GdBCO, as-grown GdBCO CCs were post-annealed at the temperatures ranging from 450 to 750℃ in various oxygen pressures. Interestingly, for the same PO_2 of 300 mTorr, the $GdBa_2Cu_4O_{16}$ (Gd124) phase was observable in the sample annealed at the temperatures lower than 600℃ while the density of stacking faults (SFs) was decreased in the samples annealed at the higher temperatures of 650 and 750℃. The pinning properties of post-annealed GdBCO samples were sensitive to the annealing conditions, including oxygen pressure, temperatures, and time. In comparison with as-grown sample, the minimum J_c values of samples annealed at 750℃ in the PO_2 of 300 mTorr for 5 min are improved at relatively low temperatures in high field region, which is due to a significant reduction in the density of SFs. On the other hand, the GdBCO CCs annealed 500℃ in the PO_2 of 300 mTorr for 1 h exhibit enhanced pinning properties at relatively high temperature in low field region, which is ascribed to the formation of Gd124 phase. Detailed relationship between microstructures and pinning properties will be presented for a discussion.

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WBP7-6

Effect of growth condition on lattice strain of $SmBa_2Cu_3O_y$ films induced by $BaHfO_3$ nanorods

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$BaMO_3$ (BMO, M=Zr, Sn, Hf etc) self-organizes into a nanorod shape within $REBa_2Cu_3O_y$ (REBCO, RE=Y, Sm, Nd etc) films grown by vapor phase deposition method such as pulsed laser deposition (PLD). In order to improve flux pinning in a high magnetic field, it is necessary to introduce high number density of BMO. However, excess amount of the BMO causes T_c reduction due to lattice strain of REBCO induced by BMO nanorods. If the diameter of nanorods becomes smaller, we can expect that lattice strain become smaller. From our previous studies, diameter of BMO nanorods can be controlled by substrate temperature, deposition rate and volume fraction of BMO [1-3]. In this study, in order to control nanorods diameter and evaluate lattice strain, $SmBa_2Cu_3O_y$ (SmBCO) films including 16 vol% of $BaHfO_3$ (BHO) were prepared by low temperature growth (LTG) technique [3].

The BHO-doped SmBCO films were deposited on $LaAlO_3$(100) (LAO) single-crystal substrates using a conventional PLD method with a Nd: YAG laser. To control nanorod diameter, we used the LTG technique. In the LTG technique, a thin SmBCO layer (seed layer) was deposited at a relatively high substrate temperature (T_s) of 880ºC, and then a SmBCO layer (upper layer) was homo-epitaxially grown on the seed layer at 790ºC – 880ºC.

Fig. (a) shows critical current density (J_c) depending on magnetic field. From this figure, slope of the J_c-B curves is changed at a magnetic field and the magnetic field was defined as B_{end}. Except for 790ºC sample, B_{end} increased with decreasing T_s. This indicates that number density of BHO nanorods increased and the diameter of the BHO nanorods decreased due to constant volume fraction of BHO. Figs. (b) and (c) indicate lattice strain of REBCO and BMO as a function of T_s. Except for the 790ºC sample, with decreasing T_s, tensile strain applied to SmBCO reduced, on the other hand, compressive strain applied to BHO increased. It indicates that narrow nanorods grown at low T_s are easy to compress.

Figs. (a) J_c of SmBCO films as a function of magnetic field. T_s dependence of lattice strain (b) in SmBCO and (c) in BHO.

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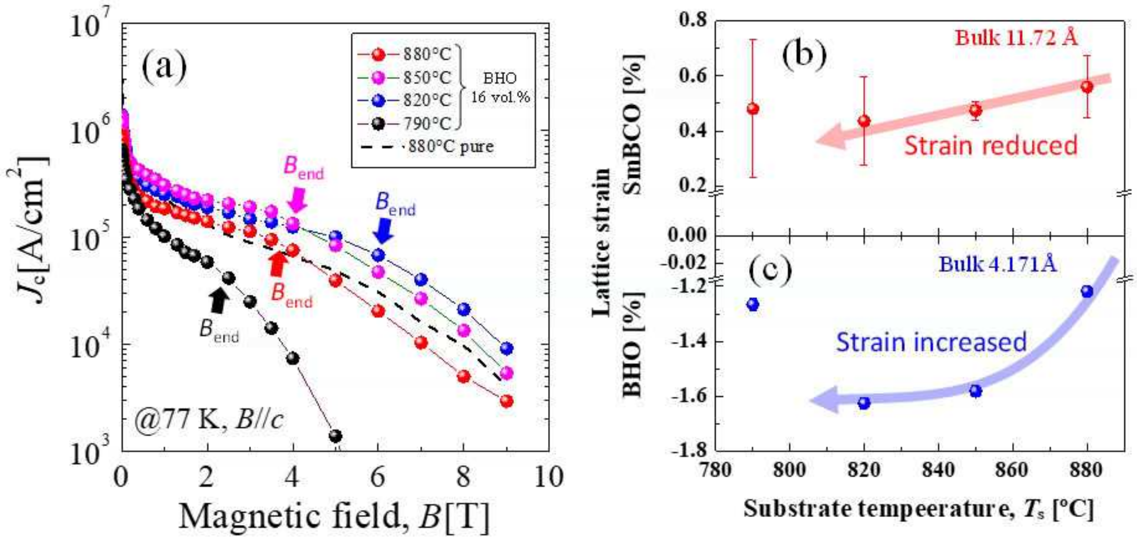

Keywords: SmBa2Cu3Oy, BaHfO3, nanorod, film

WBP7-7

Improvement of critical current asymmetricity in $BaHfO_3$-doped $SmBa_2Cu_3O_y$ superconducting films by ion milling etching

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$REBa_2Cu_3O_y$ (REBCO) high-temperature superconductor has a high T_c and is expected for various applications. Superconducting diodes with asymmetric I_c depending on the current direction have been proposed [1]. The previous studies clarify that the origin of the asymmetricity is the difference of I_c where the vortices penetrate from the film surface to the substrate or the opposite direction[1,2]. For practical application, the rectification rate needs to be improved. We have reported that the small surface roughness (δR) intensifies the asymmetricity [3].

In this study, the asymmetricity was improved by controlling the δR of the REBCO film by a post-treatment using the Ar ion milling.

$BaHfO_3$ (BHO)-doped $SmBa_2Cu_3O_y$ (SmBCO) films were fabricated on $LaAlO_3$ (100) substrates with a thickness of 400 nm by using the pulsed laser deposition method. Several samples were etched by the Ar ion milling. The etching rate and time was 15 nm/min and 4 min, respectively. The films were patterned into bridges with a width of 200 μm and a length of 1 mm. The asymmetricity was measured in an in-plane magnetic field of 0 to 0.4 T at 77.3 K. Fig. 1 shows a typical *I*-*V* characteristic in the etched sample. The schematic diagram in the figure shows the current and the magnetic field directions for the sample. I_c^{up} corresponds to I_c with the flux motion from the substrate toward the film surface and I_c^{down} is the one with the opposite polarity. Asymmetricity *(Asym.)* was defined by the following equation.

The maximum of *Asym.* for the magnetic field is defined as $Asym.^{max}$. Fig. 2 shows δR dependence of $Asym.^{max}$ at 77.3 K in the BHO-doped films. $Asym.^{max}$ tends to increase with decreasing δR. δR decreased by 20 nm and $Asym.^{max}$ increased by 2% for etching. The results indicate that the Ar ion milling enhances the asymmetry. We will discuss why δR reduction by Ar ion milling improves *Asym.* and will report the results for the inclined Ar ion milling.

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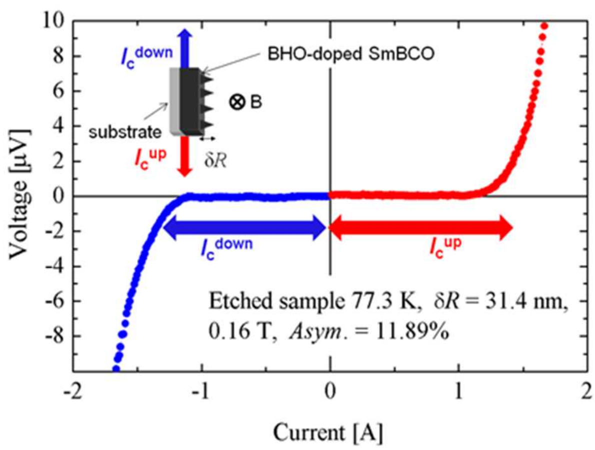

Fig.1 Typical *I-V* characteristics obtained at 77.3 K and 0.16 T in the etched sample.

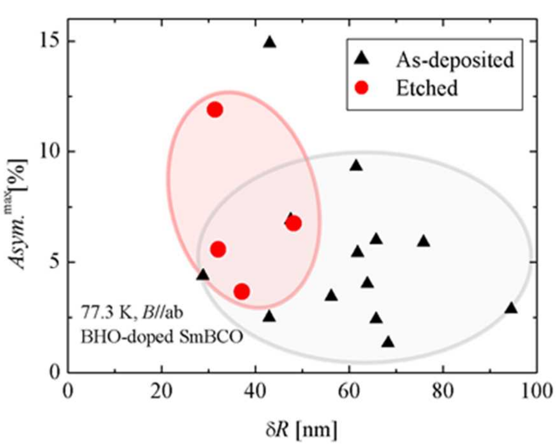

Fig. 2 δR dependence of $Asym.^{max}$ at 77.3 K for BHO-doped SmBCO.

Keywords: REBCO, diode, etching, asymmetricity