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Magnetic-field-induced crossover from flux-flow to Josephson-junction behavior in a highly transparent weak link

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Magnetic-field-induced Josephson-junction (JJ) behavior in a highly transparent weak link was observed at the 5° tilt low angle grain boundary (LAGB) in a $YBa_2Cu_3O_{7-\delta}$ film. The magnetic field dependence of current density-voltage curves showed that Abrikosov Josephson (AJ) vortices exist in the LAGB. Both JJ and flux-flow (FF) behaviors were observed in a single LAGB depending on the temperature and magnetic field. The crossover from FF to JJ arose from the spread of the phase variation along the junction when the AJ vortex cores overlapped at $B^* = \phi_0/(4.4l)^2$, where l is the characteristic length of AJ vortex.

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Since the pioneering work by Dimos *et al.*,[1] a lot of studies have been dedicated to clarifying the superconducting properties at grain boundaries (GBs) in high temperature superconductors.[2,3] However, they have been still attracting the interest of many physical researchers. The transport properties of GBs were actively examined, and numerous mechanisms for the supercurrent through a GB have been proposed to explain the experimental results. For high angle grain boundaries (HAGBs), Josephson-junction (JJ) behaviors were observed in a self-field and magnetic fields.[3] It is well known that the crossover from FF to JJ occurs at the tilt angle of 8–15° in a self-field.[1,2] Low angle grain boundaries (LAGBs) exhibited flux-flow (FF) behaviors in a self-field[2] and the effects of LAGBs in magnetic fields also have been understood based on FF.[4] However, the crossover from FF to JJ in magnetic fields has not been discussed yet, although the magnetic field is crucial to various superconducting properties. Therefore, it is unclear whether FF or JJ determines the transport properties at LAGBs in magnetic fields.

Gurevich suggested the existence of intermediate Abrikosov vortices (A vortices) with a highly anisotropic Josephson core (J core) to explain the influence of a highly transparent weak link, such as LAGBs, on the transport properties.[5] Although A vortices exist at GBs with an extremely low misorientation angle, the GB vortices turn into Josephson vortices (J vortices) at HAGBs. Abrikosov Josephson vortices (AJ vortices) occur in the crossover between the A vortices and the J vortices. The J cores in the AJ vortices cause a phase difference, φ, which is described by nonlocal Josephson electrodynamics (NJE).[6] The J cores of the AJ vortices are phase kinks whose length scale, l, along GB is greater than the coherence length, ξ. In a high field, the intervortex spacing of the AJ vortices is given by $(\phi_0/B)^{1/2}$, where ϕ_0 is the flux quantum and B is the magnetic field. Gurevich measured the current voltage (I-V) curves in the $YBa_2Cu_3O_{7-\delta}$ (YBCO) film deposited on 7° tilt bicrystal $SrTiO_3$ (STO) and demonstrated that AJ vortices exist at LAGBs.[7] The overlapping of J cores was discussed for the critical current density (J_c)-B behaviors of YBCO films fabricated on miscut substrates.[8,9] However, the behavior of AJ vortices is not well understood and more experimental results are needed to clarify it.

This paper reports magnetic-field-induced JJ behavior at a LAGB where AJ vortices exist. The existence of AJ vortices suggests that JJ behaviors should be considered to discuss the transport properties at the LAGB because the behaviors of AJ vortices are described based on the phase difference like that of J vortices in JJs. However, J_c or I-V characteristics in magnetic fields at LAGBs whose tilt angle is less than 10° have been understood based on the FF of A or AJ vortices in many reports. An anomalous change of curvatures in I-V curves (magnetic-field-induced JJ behavior) was observed in a YBCO film prepared on a 5° tilt bicrystal STO substrate, suggesting that both JJ and FF behaviors were observed in a single LAGB. Based on the behaviors of AJ vortices, FF and JJ behaviors at LAGBs are discussed.

The sample was prepared using pulsed laser deposition with a KrF excimer laser ($\lambda = 248$ nm). The substrates were a single crystal STO and a symmetrical [001] tilt (5°) bicrystal STO. 350 nm thick c-axis oriented YBCO films were deposited at 820 °C under 200 mTorr O_2 pressure. LAGBs consist of an array of edge dislocations, and their spacing is 4.4 nm at the 5° tilt LAGB according to the Read Shockley formula.[2] J_c and current density-voltage (J-V) curves in the magnetic fields parallel to the c axis of the film were measured at 50–80 K and 0–9 T. The current was always perpendicular to the GB. The YBCO films were etched using typical lithography techniques to form 60 μm wide bridges before the measurements. To discuss the JJ behaviors, the width of the junction should be compared with the characteristic length of the vortices at the junction. The l value, which is a similar length scale to Josephson penetration depth, λ_J, was small ($l = 5-30$ nm in this study) at the LAGB as shown below. Thus, the width of the experimentally accessible bridges is much larger than the l values at LAGBs.[10] J_c was given by I_c/A where I_c is the critical current and A is the cross-sectional area of the bridge ($A = 350\ \text{nm} \times 60\ \mu\text{m}$).

The critical temperature (T_c) of the YBCO films was 89.5 K. Figure 1 shows the magnetic field dependencies of J_{cig} and J_{cgb} at 77 K and J_{cgb} at 60 K. J_{cig} and J_{cgb} denote J_c

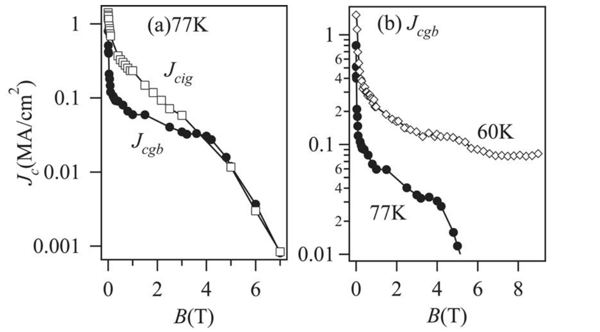

FIG. 1. (a) Magnetic field dependence of J_{cgb} (GB J_c) and J_{cig} (grain J_c) at 77 K, (b) Magnetic field dependence of J_{cgb} at 60 K and 77 K. J_{cgb} was weakly dependent on B at high field.

of YBCO/single crystal STO (grain J_c) and YBCO/bicrystal STO (GB J_c), respectively. At 77 K and self-field, J_{cig} and J_{cgb} were 1.4 MA/cm^2 and 0.8 MA/cm^2, respectively. 0.8 MA/cm^2 is typical for J_{cgb} at 5° tilt LAGB in 77 K and self-field.[2] JJ behaviors appear at 8–15°, as the tilt angle of GB is increased. J_c value of the 8–15° tilt GB was typically about 0.05–0.3 MA/cm^2 at 77 K and self-field.[2] Since the LAGB exhibited the characteristic behaviors due to its transparency, the high J_c value (>0.05–0.3 MA/cm^2) at self-field is reasonable. Although J_{cgb} is smaller than J_{cig} between 0 and 4 T (limited by GB), J_{cgb} and J_{cig} are identical between 5 and 7 T at 77 K (limited by grains). The variations of the J_c limitation mechanism have been frequently observed in YBCO films with GBs.[7,11,12] In this study, the region where J_c is limited by the GB is discussed. J_{cgb} at 77 K and 60 K weakly depend on magnetic field at high field, showing that the determination mechanisms of J_{cgb} and J_{cig} are greatly different.

Figure 2 shows the field dependencies of the J-V curves of YBCO film fabricated on a bicrystal substrate at 77 K and 60 K. The J-V characteristics have nearly linear portions. The linear portion of the J-V curves indicates that dissipation occurs at a GB.[4] As shown in Fig. 2, the J-V characteristics at $J \approx J_{cgb}$ change between 0.2 and 0.3 T at 77 K. Below 0.2 T, the J-V curves have positive curvatures and the voltages are gradually generated. On the other hand, the J-V curves in a field above 0.3 T have negative curvatures and the voltages are abruptly generated at $J \approx J_{cgb}$. This transition is also observed between 2 T and 2.5 T at 60 K. The crossover field is defined as B^*, where the intervortex spacing is a^* and $a^* = (\phi_0/B^*)^{1/2}$. B^* and a^* values at 50–80 K were obtained in the same manner. A similar behavior of the curvature of J-V curves seemed to be observed also in the previous report.[13] The curvature of the I-V curves was also changed in 10° LAGB at a self-field as the temperature was increased.[14]

Gurevich indicated that the I-V curves of the AJ vortex flow have positive curvature.[6,15] The I-V curves of the usual YBCO GB junctions, which are well described by the resistivity shunted junction (RSJ) model,[3,16] have negative curvature. The FF of a vortex in periodic potential also exhibit I-V curves with negative curvature.[17] The J-V characteristics obtained in low fields are due to the FF of the A or AJ

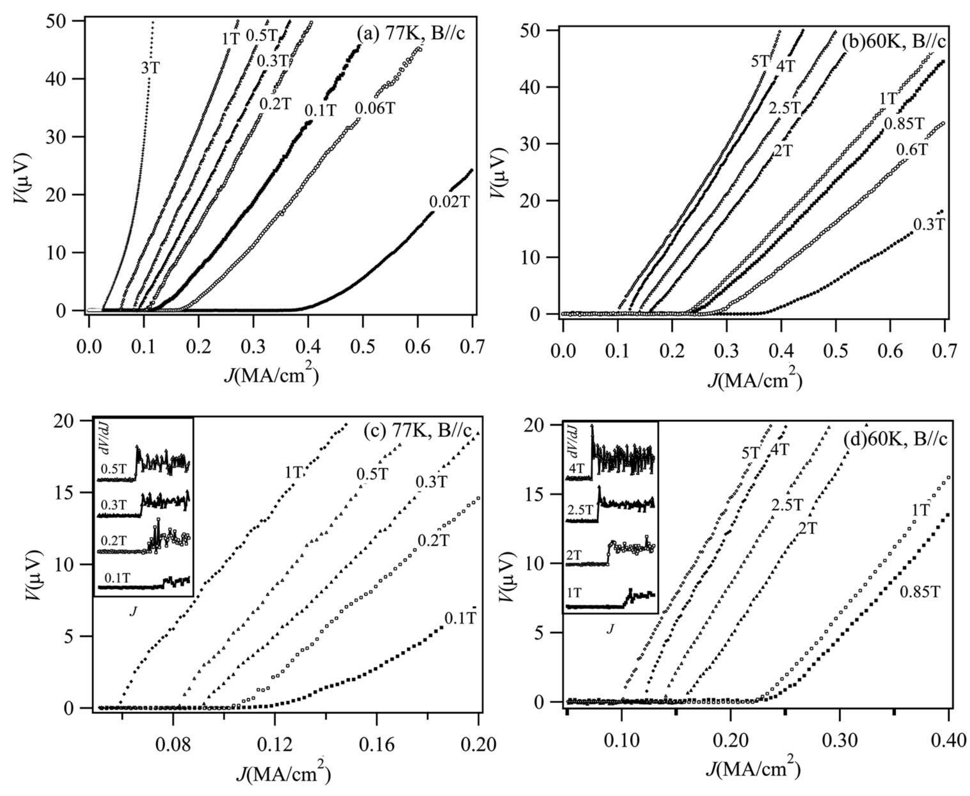

FIG. 2. Magnetic field dependence of the J-V curves at 77 K (a, c) and 60 K (b, d). (c) and (d) are enlarged views of (a) and (b), respectively. dV/dJ as a function of J is also shown in inset of (c) and (d). In the vicinity of B^*, which is 0.25 T and 2.25 T for 77 K and 60 K, respectively, the behavior of the J-V characteristic changes.

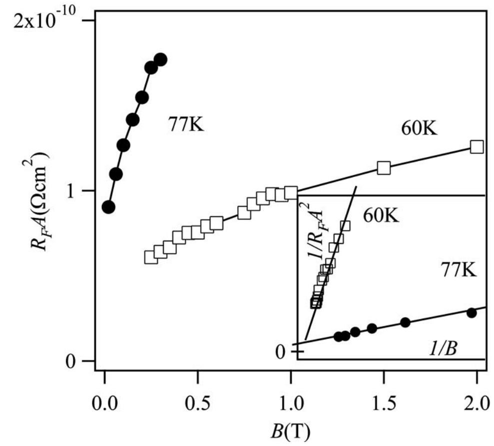

FIG. 3. Magnetic field dependence of R_FA at 77 K and 60 K. Inset shows $1/R_FA^2$ as a function of $1/B$. R_FA-B curves are well described by $R_F=\sqrt{B/(B+B_0)}$, which Gurevich obtained for the FF of AJ vortices (Refs. 6 and 7).

vortices. When GB vortices are AJ vortices, they are pinned by the structural inhomogeneties and the magnetic interaction with neighboring A vortices.[7,18,19] J_{cgb} increases with B if the magnetic interaction determines J_{cgb}.[18,19] As shown in Fig. 1, J_{cgb} decreased with B, indicating that the motion of a single AJ vortex row in periodic potential due to the magnetic interaction was not dominant for the J-V characteristics. Therefore, the J-V curves obtained in high field are not generated by FF. It is considered that the J-V curves with negative curvature originated from the quasiparticle resistance although they deviated from the RSJ behavior. According to NJE,[6] the J-V curves approach to the RSJ-like behavior as the phase difference becomes homogeneous when they are dominated by the quasiparticle resistance. The deviation from the RSJ behavior may be due to the spatial distribution of φ.[20] Both FF and JJ behaviors can be observed in a single LAGB. To discuss the mechanism of such behaviors, the structure of the GB vortex is important.

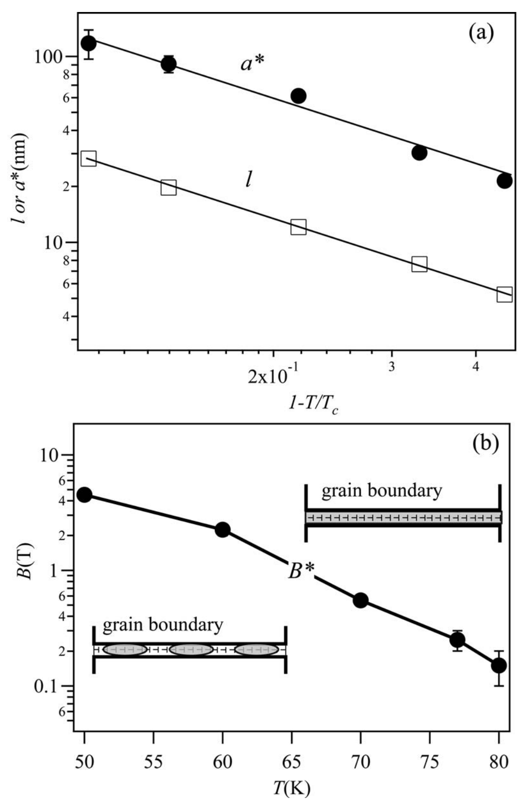

FIG. 4. (a) a^* and l as a function of $(1-T/T_c)$ in the temperature range, 50–80 K. l is proportional to $(1-T/T_c)^{-1.1}$. $a^*\approx 4.4l$ is independent of T. (b) J_{cgb} and I-V curve mechanism. Although the phase variation is localized at a field lower than B^*, it begins to spread along the GB at B^*.

To evaluate the existing vortices in the GB, the flux-flow resistance, R_FA, is given by dV/dJ, which is obtained by the linear approximation in nearly linear portion in the J-V curves. R_F does not correspond to the normal state resistance in the usual JJs and should be obtained only in the FF region. Figure 3 shows the field dependencies of R_FA at 77 K and 60 K. Gurevich obtained a magnetic field dependence of R_F by solving NJE. Theoretically, R_F is given by

$$R_F = R_0\sqrt{\frac{B}{B+B_0}} \tag{1}$$

for low current density, where $B_0=\phi_0/(2\pi l)^2$ and R_0 is a proportionality constant.[6,7] l is the characteristic length, given by $l\approx(3\sqrt{3})/4\ J_d\xi/J_b$ where J_d is the depairing current density ($J_d=c\phi_0/12\sqrt{3}\pi^2\lambda^2\xi$, where c is the speed of light), and J_b is the GB depairing current density.[6,7] As shown in the inset of Fig. 3, the R_FA-B curves were well described by Eq. (1), suggesting that AJ vortices existed in the LAGB.[7] By fitting the experimental result using Eq. (1) in a field lower than B^*, B_0=0.13 T and 0.9 T at 77 K and 60 K, respectively. l is given by $l=1/[2\pi(B_0/\phi_0)^{1/2}]$. Hence, l (T=77 K)=20 nm and l (T=60 K)=7.6 nm. The estimated l value yields J_b=15 MA/cm^2 for J_d=80 MA/cm^2, ξ=2.9 nm and l=20 nm at 77 K. The estimated J_b value is much larger than J_{cgb} in a self-field (=0.8 MA/cm^2), showing that J_{cgb} at a self-field was determined by depinning.

Figure 4(a) shows the temperature dependencies of a^* and l. l is proportional to $(1-T/T_c)^{-1.1}$, which is consistent with Gurevich's result.[7] The temperature dependence of a^* is similar to that of l. Figure 4(a) shows $a^*\approx 4.4l$. The solution of NJE for the periodic AJ vortices is given by

$$\varphi = \pi + 2\mathrm{Tan}^{-1}\left(M\tan\frac{\pi}{a}x\right), \tag{2}$$

where $M=(1+1/h)^{1/2}+(1/h)^{1/2}$, $h=(2\pi l/a)^2$, and x denotes the position along the GB.[6,7] The behavior of $\varphi(x/a)$ only depends on l/a since M is expressed as a function of l/a. Equation (2) shows that the next AJ vortex appears when x/a changes by 1. The intervortex behavior shown by $\varphi(x/a)$ only depends on l/a, which indicates that the intervortex behavior is identical for the same l/a. When neighboring vortices approach each other, the J cores in the AJ vortices overlap. Then the intervortex behavior should determine the overlapping field of the J cores in AJ vortices. Regardless of the temperature and field, $l/a^*=1/4.4$, suggesting that the magnetic-field-induced JJ behavior can be explained based on the overlapping J cores in AJ vortices.

A vortices, however, may also induce the magnetic-field-induced crossover from FF to JJ behavior, so that its possibility should be discussed. It was predicted that the crossover from FF to JJ behavior occurs due to the disappearance of A vortex core in a weak link when its length or width are decreased to be smaller than the critical length and the critical width.[21] Since the critical length($=3.5\xi$) for YBCO is comparable with the length of the region where the superconductivity is degraded by LAGBs,[2] it is difficult to compare the experimental results with the diagram in Ref. 21. Then, the comparative study of the length scale may not give the sufficient conclusion when the A vortices in a weak link determine the magnetic-field-induced crossover from FF to JJ behavior. Before discussing the experimental results based on A vortices, the condition for the existence of A vortices in the LAGB should be considered. Because it is crucial to the vortex structure whether the LAGB was SNS or SS'S junction, we should make that clear. It was suggested that the size of the normal regions around the edge dislocations start to overlap at 3–6° when the tilt angle of the LAGB is increased.[6,22] This suggests that the 5° tilt LAGB may consist of the normal region. The temperature dependence of l in Fig. 4(a) also indicates that the LAGB was SNS junction where J_b is proportional to $(1-T/T_c)^2$.[7] In SNS junction, A vortices cannot exist regardless of its size.[21] Moreover, the temperature dependence of a^* was well described by $l\sim(1-T/T_c)^{-1}$ (AJ vortices), not by $\xi\sim(1-T/T_c)^{-1/2}$ (A vortices). Therefore, it is concluded that the magnetic-field-induced JJ behavior resulted from overlapping J cores in AJ vortices.

Figure 4(b) is a phase diagram, which shows the temperature dependence of B^* and indicates the J_{cgb} and J-V curve mechanism. In a field lower than B^*, the phase variation is localized as shown at the bottom of Fig. 4(b). In this case, the GB vortices behave like A vortices. When the field is higher than B^*, the phase variation begins to spread along the GB as shown at the top of Fig. 4(b). Equation (2) suggests that $\varphi\to\pi+(2\pi/a)x$ as $B\to\infty$, since $M\to 1$ as $B\to\infty$. In this case, the GB can be regarded as JJ.

The intervortex spacing at B^* provides the diameter of the J core in an AJ vortex. $a^*\approx 4.4l$ indicates that the J core diameter of the AJ vortex is $4.4l$. The solution of the NJE for a single AJ vortex is given by $\varphi=\pi+2\,\mathrm{Tan}(x/l)$ where x denotes the position along the GB.[6] As x changes from $-l$ to l, the phase increases by π. Since one vortex corresponds to 2π phase shift along GB, the diameter of AJ vortices is larger than $2l$. The tunnel current in usual JJs is saturated at $L=4\lambda_J$ when the junction length, L, increases.[23] This suggests that the tunnel current and the phase variation spread out in the length range of $4\lambda_J$ for the usual JJs. A factor of 4.4 for the AJ vortices in our study may be obtained in a similar manner since l and λ_J are on similar length scales.

In conclusion, the anomalous change of curvatures in J-V characteristics (magnetic-field-induced JJ behavior) was observed at B^* in YBCO prepared on a 5° tilt bicrystal STO substrate. The analysis of J-V curves showed that AJ vortices exist in the LAGB, and the characteristic length of the AJ vortices, l, was obtained. Both JJ and FF behaviors were observed in a single LAGB depending on the temperature and magnetic field. Regardless of temperature, $a^*=4.4l$, indicating that the crossover from FF to JJ behavior arose from the spread of the phase variation along the LAGB when the cores of AJ vortices overlapped at $B^*=\phi_0/(4.4l)^2$.

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