Development of low AC loss Bi2223 tapes with interfilamentary oxide barriers

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This paper presents our recent progress in development of low AC loss Bi2223 tapes with interfilamentary oxide barriers. To suppress the secondary effect on Bi2223 phase formation in the filaments during sintering, $SrZrO_3$ was selected as barrier materials. In addition, small amount of Bi2212 was mixed with $SrZrO_3$ to improve its ductility for cold working. Both controlling barrier thickness and reducing a final tape width down to 2.7 mm, critical current densities J_c at 77 K and in self-field attained to 26.8 kA/cm^2 for a non-twisted barrier tape, and 16.5-23.6 kA/cm^2 for twisted one with twist lengths L_t = 4-9 mm. For the tape with the shortest L_t = 4 mm, coupling frequency f_c exceeded 250 Hz in an AC transverse field in perpendicular to the broader face of a tape. To our best knowledge, this f_c is the highest one for Bi2223 tapes with self-field J_c > 15 kA/cm^2. By addressing these achievements, noticeable loss reduction under a perpendicular field was successfully confirmed around 50 Hz.

INTRODUCTION

Although Ag-sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi2223) tapes with high and uniform critical current I_c above 200 A (77 K, self-field) and the length above 1 km are commercially available at present [1], their AC losses under an AC external magnetic field are still too large for the realization of AC power devices such as cables, motors and transformers. Since Bi2223 tape has anisotropic cross sectional geometry with its aspect ratio of 15-20, loss properties are strongly influenced by the direction of an external field against the broader face of a tape. Suppression of electromagnetic coupling among the Bi2223 superconducting filaments embedded in Ag matrix should be necessary for reducing losses under an AC external field, but the conditions for filament decoupling in perpendicular transverse field becomes more restrictive than in parallel transverse field case [2,3].

In order to achieve noticeable loss reduction under an AC perpendicular field, it is necessary – in addition to twisting the filaments with a suitable pitch length – to increase the matrix resistivity by introducing oxide layers among the filaments as resistive barriers [4-8]. To date, Bi2223 tapes with $BaZrO_3$, $SrZrO_3$ as interfilamentary barriers were fabricated and their positive effect for AC loss reduction under perpendicular field around 50 Hz were demonstrated [4-7]. However, critical current density J_c of those barrier tapes were much lower than 10 kA/cm^2 at 77 K and in self-field. Oxide barrier introduction causes not only the reduction of the oxygen diffusion paths for Bi2223 filaments [8] but also the serious degradation of filament flatness due to the degradation for composite workability [4-7]. Therefore, precise control in barrier thickness, tape geometries and deforming parameters during twisting and rolling process should be indispensable for barrier tape with high J_c.

This paper presents our recent progress in development of low AC loss Bi2223 tapes with interfilamentary oxide barriers. We have succeeded in achieving both J_c > 15 kA/cm^2 in self-field and significant loss reduction in an AC perpendicular field at 77 K around 50 Hz simultaneously, by controlling the thickness of $SrZrO_3$ barriers and geometrical parameters such as tape widths and twist lengths.

EXPERIMENTAL

Bi2223 tapes with oxide barriers among twisted and non-twisted filaments were prepared by a conventional powder-in-tube (PIT) method. $SrZrO_3$ (SZO) with a mean grain size below 1 μm was used as barrier materials for its compatibility with Bi2223 superconductor. Moreover, an additional $Bi_2Sr_2CaCu_2O_x$ (Bi2212) powder corresponding to 15wt% was mixed with SZO to improve its ductility for cold working [7]. The precursor powders with a composition of $Bi_{1.76}Pb_{0.34}Sr_{1.93}Ca_{2.02}Cu_{3.1}O_x$ were packed into a pure Ag tube with an outer diameter of 9.6 mm and a wall thickness of 0.8 mm. Then, the composite was deformed into a hexagonal cross-sectional shape by drawing, with its diagonal length of 1.8 mm. The outside surface of the monocore wire was coated by SZO + Bi2212 pastes. To obtain the sufficient workability of the composite, coating thickness of the paste was set to 70-80 μm, which was 30-40% thinner than our previous work [7,8]. 19-pieces of coated monocore wire were stacked and packed into an Ag-Mg alloy tube with an outer diameter of 15.7 mm and wall thickness of 0.85 mm. The composite was drawn to a diameter of 1.3 mm, cut into several pieces and twisted carefully with various twist lengths. Finally, the twisted round wires were formed into tape shape by flat rolling, and sintered at 830–840°C for 200 h with an intermediate rolling process. In fully reacted tapes, the cross sectional size was 2.7 mm × 0.25 mm and the volume fraction of filaments was approximately 20%. Twist lengths L_t were measured after removing the sheath parts from final tapes by etching and confirmed to be ranged from 4 to 9 mm. Transverse cross-sectional view for our twisted barrier tape with the shortest L_t = 4 mm is shown in Figure 1. Each filament is confirmed to be partitioned by SZO barrier layers even in tightly twisted sample. From the XRD measurements, we confirmed that the fraction of Bi2223 phase inside filaments attained to 95% in all tapes with SZO barriers.

Critical current I_c was measured in all tapes with DC four-probe method at 77 K and in self-field, with an electric field criterion of 1 μV/cm. The critical current density J_c was determined from I_c and transverse cross-sectional area of Bi2223 filaments. The AC losses Q_m at 77 K in a perpendicular transverse field were measured by a pick-up coil method [9]. For the loss measurements, the lengths of tapes were fixed to 80 mm.

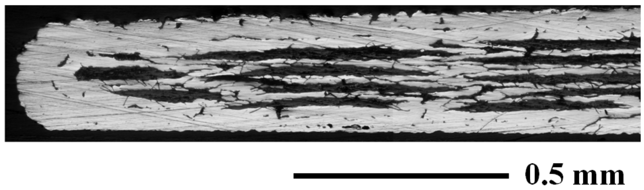

Figure 1 Cross-sectional view of twisted Bi2223 tape (L_t = 4 mm) with SZO barrier.

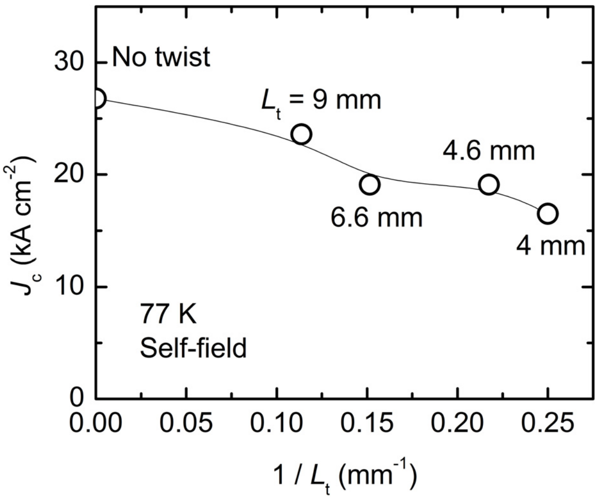

Figure 2 Self-field J_c at 77 K for Bi2223 tapes with SZO barriers plotted against inverse of twist lengths L_t

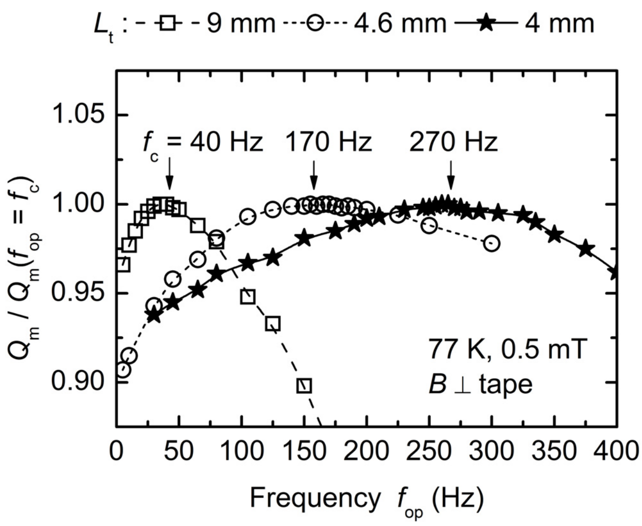

Figure 3 Frequency dependence of losses Q_m normalized to the value at $f_{op} = f_c$ at 77 K and 0.5 mT for twisted Bi2223 tapes in AC perpendicular field

RESULTS AND DISCUSSION

Transport J_c at 77 K and in self-field for Bi2223 tapes with SZO barriers are shown in Figure 2(a), as a function of inverse of L_t. By optimizing SZO barrier thickness, tape geometry and deformation method, self-field J_c attained to 26.8 kA/cm^2 for a non-twisted barrier tape and 16.5-23.6 kA/cm^2 for twisted ones with L_t = 4-9 mm, respectively. Although these J_c values are still lower than those for commercially available Bi2223 tapes, it is worth to note that the value for our non-twisted barrier tape of 26.8 kA/cm^2 is nearly the same level as tapes without barriers prepared in our laboratory. In addition, the degradation property of J_c with reducing L_t for our barrier tapes is nearly the same as the data for non-barrier tapes with twisted filaments and similar tape widths w_{tape} = 2.4 mm [8], indicating that introduction of interfilamentary SZO layer with suitable thickness among the filaments hardly affects on wire deformability.

In next, we examined the coupling frequency f_c for twisted barrier tapes under an AC perpendicular transverse field. f_c is related with coupling time constant τ_c of multifilamentary superconducting wires with normal metal matrix as the expression of $f_c = 1/2\pi\tau_c$, and determines the AC operating condition for filament decoupling. To achieve a significant loss reduction by decoupling the filaments, f_c should at least be higher than operating frequency f_{op} [4-7]. Figure 3 shows the frequency dependence of losses Q_m per-cycle for twisted barrier tape with different L_t at 77 K and in fixed field amplitude B_0 = 0.5 mT. As can be seen, Q_m data shows the maximum at different frequencies among the tapes with different L_t. These specific frequencies correspond to f_c at which coupling loss Q_c per-cycle included in total Q_m shows the maximum for each tape. f_c increases monotonically with decreasing L_t and attains to 270 Hz for the tape with the shortest L_t = 4 mm. Although the achievement for higher f_c of 400-500 Hz in barrier tapes was already demonstrated [6,7], transport J_cs of these barrier tapes were much lower than 10 kA/cm^2. To our best knowledge, this is the first achievement for both J_c > 15 kA/cm^2 in self-field and f_c > 250 Hz in an AC perpendcular field in a single Bi2223 tape.

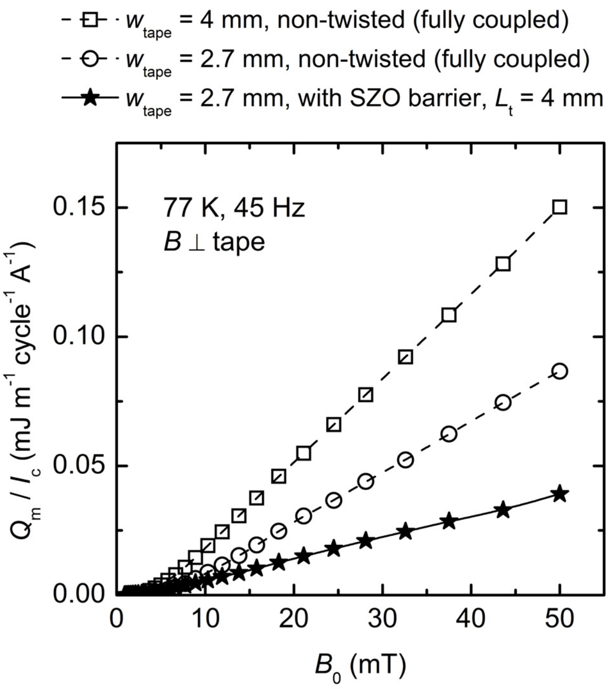

Figure 4 Normalized AC losses Q_m/I_c at 77 K and 45 Hz for twisted barrier tape with L_t = 4 mm. The data for non-twisted tapes with tape width of 4 mm and 2.7 mm are also plotted as the references

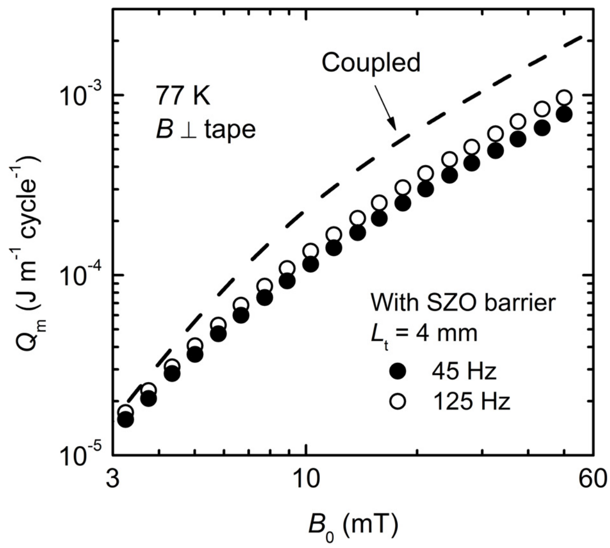

Figure 5 AC losses Q_m per-cycle at 45 Hz and 125 Hz for twisted tape with SZO barriers (Lt = 4 mm), plotted against perpendicular field amplitude B_0. A dashed line represents a predition for a tape with fully coupled filaments.

In order to confirm perpendicular field loss reduction around 50 Hz for twisted barrier tape with L_t = 4 mm and f_c = 270 Hz, field amplitude B_0 dependence of losses Q_m at 77 K and 45 Hz are shown in Figure 4. As the references, the data for non-twisted tapes with their tape widths (w_{tape}) of 4 mm and 2.7 mm are also plotted. These two reference tapes have no barrier layers so that all filaments are electromagnetically coupled among them under an AC perpendicular field at 45 Hz. In Figure 4, Q_m for each tape is normalized by its self-field I_c at 77 K for direct comparison among the tapes with different properties. As can be seen, losses for twisted barrier tape with L_t = 4 mm are reduced by 35–40% at B_0 between 10 and 50 mT, compared with the reference tape with same w_{tape} = 2.7 mm and fully coupled filaments. Such remarkable loss reduction around 50 Hz is attributed to simultaneous achievement for f_c > 250 Hz and J_c > 15 kA/cm^2. Furthermore, due to the difference in tape widths, losses for our twisted barrier tape with w_{tape} = 2.7 mm are estimated to be 70-80% lower than those for the reference tape with wider w_{tape} = 4 mm.

Figure 5 shows the losses Q_m per-cycle at 45 Hz and 125 Hz as a function of perpendicular field amplitude B_0 for the tape with L_t = 4 mm. As shown in Figure 5, the losses Q_m per-cycle are increased monotonically with increasing operating frequency f_{op} from 45 Hz to 125 Hz in whole measured B_0 range, but the increase with frequency seems to be small. Losses at 125 Hz are still much lower than a semi-analytical prediction for a fully-coupled tape [10]. This suggests that around power-grid frequency, the contribution of coupling loss Q_c to total loss Q_m is not so large for our twisted barrier tape with L_t = 4 mm. If we can reduce the individual filament width in twisted barrier tapes with maintaing high J_c and f_c, perpendicular field losses Q_m around 50 Hz will be further reduced because the hysteresis loss Q_h in decoupled superconducting filaments can be reduced with reducing individual filament width.

SUMMARY

Low AC loss Bi2223 tapes with interfilamentary $SrZrO_3$ barriers were successfully fabricated through powder-in-tube method. By controlling barrier thickness and reducing a final tape width down to 2.7 mm, transport critical current densities J_c at 77 K and in self-field attained to 16-20 kA/cm^2 for twisted barrier tapes with twist lengths L_t of 4 to 7 mm. For the tape with the shortest L_t = 4 mm, coupling frequency f_c attained to 270 Hz in an AC transverse field in perpendicular to the broader face of a tape. To our best knowledge, f_c = 270 Hz is the highest one for Bi2223 tapes with self-field J_c > 15 kA/cm^2. According to these achievements, perpendicular field losses around 50 Hz for our twisted barrier tape with L_t = 4 mm were 70-80% lower than those for conventional 4 mm width tape. Further loss reduction under a perpendicular field will be possible by reducing individual filament width, together with maintaining both high J_c and f_c.

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