High Throughput Processing of Long-Length IBAD MgO and Epi-Buffer Templates at SuperPower

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***Abstract*— SuperPower has successfully transferred from low throughput IBAD (ion beam assisted deposition) YSZ technology to high throughput IBAD MgO technology. Pilot-scale IBAD system and pilot-scale epi-buffer deposition system, each with capabilities of producing single-piece lengths over 1000 m have been established. Helix tape handling approach instead of wide tape approach is chosen due to its immense advantages over wide tape approach. High-performance IBAD MgO buffer stack and their processes have been developed together with high throughput where each layer in the buffer stack is processed at 40m/h tape speed or higher during our Phase I scale up. Both pilot systems are in routine production mode since March 2006. More than 14 km IBAD MgO buffer tapes of 12 mm width were produced for Albany cable project. 700-800m IBAD MgO tape per run is routinely produced in pilot IBAD system with single piece tape length ~ 570m. 400-550m epi-buffer tape per run is routinely produced in pilot buffer system. High throughput IBAD MgO buffer gives better texture of $YBa_2Cu_3O_7$ (YBCO) film compared with IBAD YSZ, and superior superconducting properties. Record high critical current of 557 A/cm in short tapes and a world record critical current * length value of > 70,000A-m were obtained with the high throughput IBAD MgO buffers.**

***Index Terms*— buffer, coated conductor, high throughput, IBAD MgO.**

I. Introduction

Two main factors that challenge second-generation (2G) HTS (high temperature superconductor) conductors to become commercially viable are the cost and availability in long length with high performance. Higher critical current (Ic), higher throughput, and lower manufacturing cost are three main ways to reduce the conductor cost. High throughput processing of long lengths is a key for the success of 2G development for two reasons, reducing cost and enabling long length production. Many applications of 2G conductor require the length to be several hundreds meters to more than one kilometer in a single piece [1]. Long length production of high quality 2G conductor presents a challenge because the yield of high-quality product has decreased exponentially with tape length. It places great demands on the stability of equipment and process control. Some hardware variability with process time is inevitable. Not only is high throughput processing an effective way to reduce cost, it also plays an important role in enabling the long length production. It reduces the process time which limits the drifting of hardware during the process.

From 2001 to 2005, SuperPower had been scaling up 2G conductors using IBAD (ion beam assisted deposition) YSZ type buffer technology and had demonstrated up to 200m YSZ tape with good uniform texture [2]-[4]. But IBAD YSZ buffer is a very slow process due to a growth competition texturing mechanism. Many efforts have been undertaken to increase throughput of IBAD YSZ process like optimizing process parameters to get faster texture evolution, using helix tape winding system, using sources with a faster deposition rate and employing smaller ion to atom ratio, etc. With such efforts, SuperPower was able to increase the throughput from 0.05 m/h (meter per hour) to ~ 1m/h. This throughput was still far away from that required to commercially manufacture 2G tape, and would have been a challenge for SuperPower to deliver 10 kilometers of 2G conductor to Sumitomo Electric Industries to construct a 30m cable for Albany cable project. As a result, SuperPower transitioned to the to IBAD MgO process [5] [6] with the support from LANL (Los Alamos National Laboratory). The MgO process has different texturing mechanism from IBAD YSZ type process. Texture develops during nucleation stage, and is further improved during subsequent epi-buffer depositions and $YBa_2Cu_3O_7$ (YBCO) deposition. It only requires ~ 10 nm thickness of IBAD MgO to form optimal biaxial texture, compared with ~ 1000 nm of IBAD YSZ optimal thickness we used before. So the throughput can be theoretically up to 100 times higher. Another advantage of IBAD MgO is its higher Ic performance compared with IBAD YSZ. The texture of YBCO film grown on IBAD MgO buffer template is usually ~2-3 degrees compared with ~ 5-6 degree texture of YBCO on IBAD YSZ buffer template. This kind of single crystal like film opens a way to Ic up to more than 1000A/cm. Right now, Ic of >557 A/cm of 2.1 micro meter thick YBCO has been obtained on our high throughput IBAD MgO buffer stack, across entire tape width of 12 mm.

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However, compared with IBAD YSZ, IBAD MgO buffer stack is more complicated. In addition to IBAD MgO which forms biaxial texture, it needs anti-diffusion layer alumina, and seed layer yttria for IBAD MgO nucleation. These three layers are coated at room temperature by our Pilot IBAD system. After these three layers, it also needs two epitaxial layers --- homo-epi (homo epitaxial) MgO and $LaMnO_3$ (LMO) --- between the IBAD MgO layer and YBCO layer. These two epi-buffer layers require high temperature deposition, and are deposited in our Pilot Buffer deposition system.

II. High Throughput IBAD MgO Buffer Development

A. *Buffer Structure*

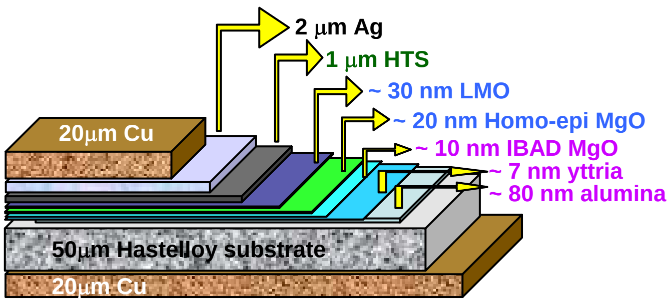

Fig.1. Layer structure of SuperPower's IBAD MgO coated conductor.

Our IBAD MgO buffer stack includes 5 layers between metal substrate and HTS layer in order to make it robust in our MOCVD HTS film deposition, as shown in Fig. 1. The first layer alumina mainly serves as diffusion layer to prevent elements of metal substrate from diffusing into other buffer layers and HTS layer during deposition. The second layer yttria serves as a seed layer to help IBAD MgO nucleation; the third layer IBAD MgO is the key layer which forms biaxial texture by ion beam assisted deposition. The fourth layer homo-epi MgO makes the IBAD MgO robust and improves the texture [7], and the fifth layer is the cap layer to provide good match with HTS layer. At beginning, we used $SrTiO_3$ (STO) as cap layer. Later we changed to LMO as cap layer because of several advantages of LMO over STO 1. LMO yields higher Ic than STO; 2. The process window of LMO is larger than that of STO, and so LMO process is more robust and reliable; 3. LMO has much higher deposition rate compared with STO with RF sputtering, 4. Sr-Ti alloy target is not available, while La-Mn alloy target is available, and so we can deposit LMO by reactive sputtering for even higher deposition rates. Buffer stack is ~ 150nm thick.

B. *Choice of wide tape and helix system*

Since we use an in-situ deposition approach, we have choices of either using wide tape or narrow tape + helix tape winding system to increase the throughput. With same deposition zone area and deposition rate, the total volume throughput using a single wide tape and helix is roughly the same, but helix system provides extra and very important advantages.

With a helix tape handling system, tape goes through the deposition zone multiple times and gets coated with very uniform thickness along tape width. Since the entire deposition zone is covered across the width of the tape, a better uniformity can be expected across the tape width compared to a single wide tape. Another benefit of helix tape handling approach is that for a given process time period, much longer (6 times for 6 wraps helix system) single piece lengths can be processed which is important for wire customers who are already used to several 100 m to 1000 m of first generation HTS tape. Alternately, much shorter (6 times for 6 wraps helix system) process time periods are required for a given piece length, which is beneficial for high process yield since there is less chance of process and hardware drifts.

C. *Scale-up high throughput IBAD MgO process in Pilot IBAD system.*

The Pilot IBAD system is equipped with two 60 x 6cm linear ion sources**.** One is used to sputter the target to deposit target material onto substrate, and the other is used as assisting ion beam bombardment on growing IBAD MgO film. The available deposition zone is 60 cm long, ~ 8.5cm wide, and 6 tape wraps are coated in the deposition zone, as shown in figure 2.

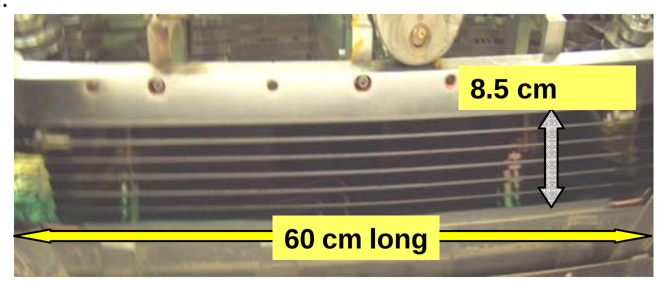

Figure 2. Helix tape wraps in pilot IBAD system deposition zone.

High yield is the critical for long length production. Great efforts were spent on monitoring process parameter drifts and keeping hardware in good shape to reduce such drifts. Since drifts are inevitable, a large process window is needed for a reliable process. Good uniformity of critical process parameters like deposition rate and assisting beam density helps to enlarge the process window. We are able to get good uniformity of deposition rate and assisting beam density over 42 cm deposition zone as shown in Figure 3 and Figure 4. So we use only 42 cm out of total 60cm deposition zone for IBAD MgO process. Reflection High Energy Electron Diffraction (RHEED) is used for in-situ monitoring of the IBAD MgO texture pattern. The RHEED beam can be positioned on any of 6 wraps. The deposition rate is in-situ monitored by quartz crystal monitor (QCM), and assisting ion beam density is monitored by a Faraday cup. Ion source parameters, tape length/speed, tape tensions, spool diameters, gas flows, Ar, O2 partial pressures, cooling block temperature, etc, are all monitored and recorded automatically by process control software.

We have optimized our IBAD MgO at speeds of 65m/h, 80m/h, and 100m/h of 12 mm wide tape. Ic > 250A/cm have been in 0.7um thick HTS film deposited by metal organic chemical vapor deposition (MOCVD) on IBAD MgO templates produced at all these speeds. We chose 65m/h condition as our routine IBAD MgO production condition since it had a relatively larger process window and 65m/h is good enough for overnight (~12 hours) run of ~ 800 m tape. The speed of yttria layer is 100m/h and the alumina coating speed is 40m/h. The pilot IBAD system now is routinely producing 700-820m tapes with good quality and uniformity. Figure 6 gives example of RHEED patterns taken during one 800m IBAD MgO run. Uniform RHEED pattern was obtained throughout the run (figure 5). Processed tape composes of 2 single piece tapes spot-weld together. The longest single piece is ~ 570m limited by availability of metal substrate.

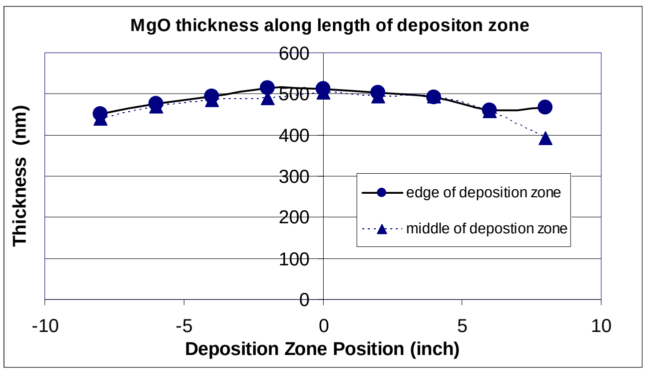

Figure 3. +/- 5% deposition rate deviation over 42 cm deposition zone. Last two data points on left side are not very reliable due to tape deformation on left side

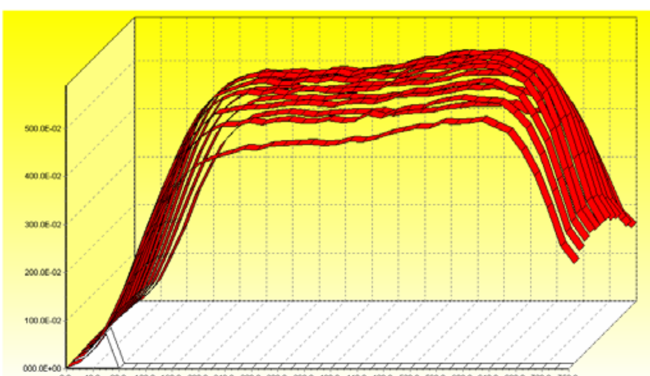

Figure 4. 3D assisting ion beam density, +/-5% deviation over 42cm deposition zone.

During tape production for the Albany Cable Project, 25 runs yielded 14,660 meter of 12 mm wide IBAD MgO tapes, in 5.5 months – equivalent to 43,980 meter of 4 mm wide tape. As seen in the figure, most of runs since April yielded lengths of 700-800 m.

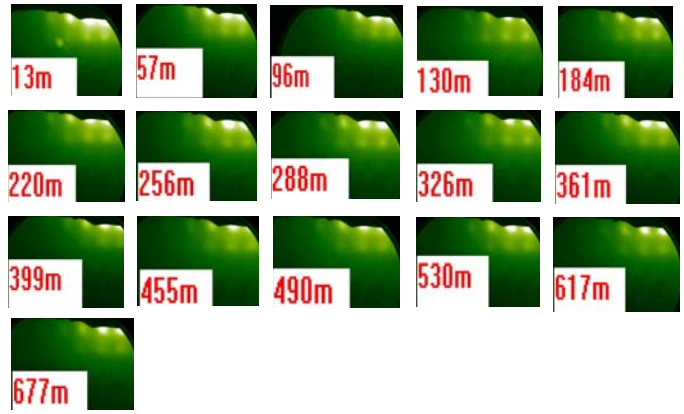

Figure 5. Uniform RHEED pattern was obtained over 800m IBAD MgO run.

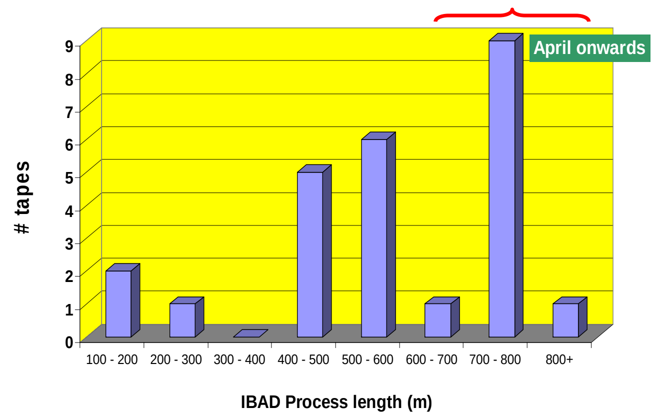

Figure 6. Number of processed IBAD MgO tapes vs. tape length in pilot IBAD MgO system during tape production for Albany Cable Project.

D. Scale up of high throughput epi- buffers in Pilot Buffer system.

The homo-epi MgO layer and LMO layer are epitaxial growth layers which require high deposition temperature. We built and tuned a Pilot Buffer system for long length, high throughput process of these two epi-buffer layers. This Pilot Buffer system comprises of two tape spool chambers which are able to handle more than 1 km long tape; two buffer deposition chamber for sequential deposition of homo-epi MgO and LMO on IBAD MgO template. Reactive MF magnetron sputtering is used for homo-epi MgO coating; RF sputtering is used for LMO deposition. The deposition zone is about 33cm x 25cm in each process chamber. The system is designed to have 12 wraps helix tape handling system in each process chamber for high throughput. During our Phase I scale up, only 6 wraps of the helix system are used.

Reactive sputtering of home-epi MgO was optimized at speed of 40m/h and 80m/h with 6 wraps helix with good and uniform texture. 40m/h condition was used for routine buffer tape production of Albany Cable Project. The 80m/h condition was not used due to a minor hardware issue. RF sputtering of LMO has also been optimized at speed of 40m/h and 80m/h with good and uniform texture and Ic. 40m/h condition is used for routine buffer tape production for delivery for the Albany

Cable Project. The 80m/h condition was not used because in some runs Ic with YBCO deposited on LMO at 80m/h was found to be 10-15% lower than the Ic of YBCO deposited on LMO at 40m/h. Both homo-epi MgO and LMO have been optimized with large process windows in our Pilot Buffer system. 250m to 570m epi-buffer tape are routinely produced in Pilot Buffer with uniform texture and good Ic. Figure 7 gives in-plane LMO textures of our buffer stacks of several runs during tape production for Albany Cable Project. It can be seen from the figure that an in-plane texture of approximately 7 degrees has been obtained in lengths of 100 to 543 m.

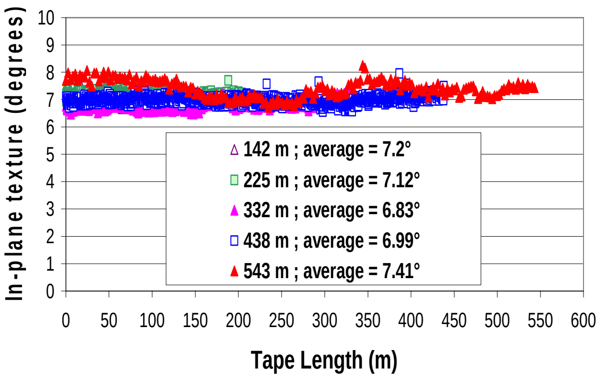

Figure 7. In-plane textures of LMO on home-epi MgO on IBAD MgO tape of several production runs.

Figure 8 shows the performance of a 322 m long 2G conductor with good and uniform Ic produced by our Pilot MOCVD system on our high throughput IBAD buffer stack during tape production for Albany cable project. A minimum was measured corresponding to a Ic * Length value of 70,520 A-m

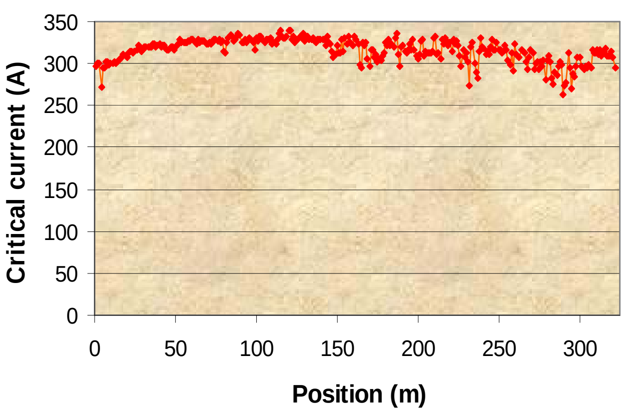

Figure 8. Critical current over 300m of coated conductor by Pilot MOCVD on IBAD MgO buffer tape produced by pilot IBAD system and Pilot Buffer system at speed of 40m/h. min Ic =263A=219A/cm over 322 m. YBCO thickness is ~ 1.2um.

The homo-epi MgO and LMO buffer processes developed in Pilot Buffer are very robust processes. Process parameters have never been changed or re-optimized since they were optimized in end of March 2006. In the manufacturing campaign for Albany Cable Project, 37 production runs yielding 12,520 m of 12 mm wide epi-buffer tape equivalent to 37,560 m of 4 mm wide tape was produced in four months. A histogram of epi-buffer tapes produced in this campaign is shown in figure 9. As shown in the figure, most of the runs yielded 400-500 m long epi-buffered IBAD MgO tapes.

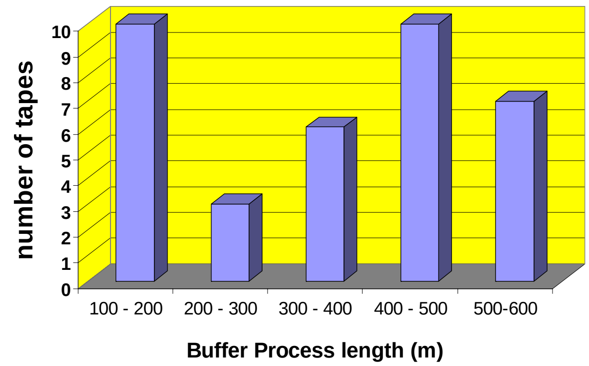

Figure 9. Number of processed epi buffer (LMO/homo-epi MgO) tapes vs. tape length in Pilot Buffer system during tape production for Albany Cable Project.

III. Conclusion

SuperPower has successfully transitioned from low-throughput IBAD YSZ process to high-throughput IBAD MgO. Pilot-scale IBAD and Buffer deposition systems, each with capabilities of producing single-piece lengths over 1000 m have been established. High performances IBAD MgO buffer stack and their processes have been developed in pilot scale IBAD and Buffer systems together with high throughput > 40m/h in all steps during phase I scale up. 700-800m tape is routinely produced in Pilot IBAD system per run with single piece tape ~ 570m. 400-500m home-epi MgO and LMO buffer tape is routinely produced in Pilot Buffer system per run. IBAD MgO buffer gives better texture of YBCO film compared with IBAD YSZ buffer, and better Ic performance. Critical currents up to of 557 A/cm in short samples (measured across entire 12 tape width) and word record Ic * Length value of greater than 70,000A-m in long lengths were obtained using the high throughput IBAD MgO buffer. The leap in both throughput and Ic performance suggests a promising future for 2G conductor manufacturing.

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References

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