Technical Memorandum

Ambature TM # 2020-02

To: Ron Kelly, CEO, Ambature Inc.

Cc: Davis Hartman, Michael Lebby

From: Mitchell Robson

Date: 02/14/2020

Re: **A-axis formation of YBCO**

Ron,

There are two main keys to producing a-axis YBCO instead of c-axis:

- Substrate temperature
- Substrate material and orientation

Temperature

Temperature is the most important parameter for controlling the crystal orientation in YBCO growth. The reason temperature can affect the crystal orientation is related to the underlying physics of MBE growth. In MBE, material atoms (Yttrium, Barium, etc) are evaporated toward a heated substrate and stick to the substrate upon contact. Although they are stuck on the substrate, they are still free to move along its surface. Atoms move across the substrate until they find a suitable place to stick permanently. Usually they stick together in clusters that expand into thin film layers as more atoms arrive and add on to the cluster. In c-axis growth of YBCO the clusters expand into flat 2-dimensional layers. Once one layer is complete, the next layer begins growing on top until they form a stack, like sheets of paper. In a-axis growth, those flat sheets are rotated so that the layers stand vertically on the substrate (see step 3 in Fig. 1). You can think of a-axis growth as a series of 3-dimensional walls that are growing side by side. The walls start as small clusters and grow tall over time, but they can grow taller at different rates, which is why a-axis films tend to be rougher than c-axis.

Temperature affects two major parts of the film growth process. The movement of atoms on the surface of a substrate, and the shape of the clusters. The distance an atom can travel on the substrate is related to temperature. As temperature increases the atoms can travel further and conversely, when the temperature is decreased, atoms travel shorter distances before sticking permanently into clusters. c-axis YBCO requires a higher temperature to form because atoms need to travel large distances to the edges of expanding clusters as they expand to a full 2D layer. At lower temperatures the atoms form clusters on top of clusters which begins forming the 3D walls of a-axis growth (see step 1 Fig. 1). The shape of the cluster also depends on temperature, which is related to the thermodynamics of the cluster. A cluster of a-axis YBCO requires a different amount of energy to form than a cluster of c-axis YBCO. The cluster that ultimately forms is the one that takes the least amount of energy. At low temperatures, the a-axis cluster takes less energy to form than the c-axis cluster, and at high temperatures it is the opposite. The cross over temperature between 'high' and 'low' for YBCO is about 650°C [1]–[3].

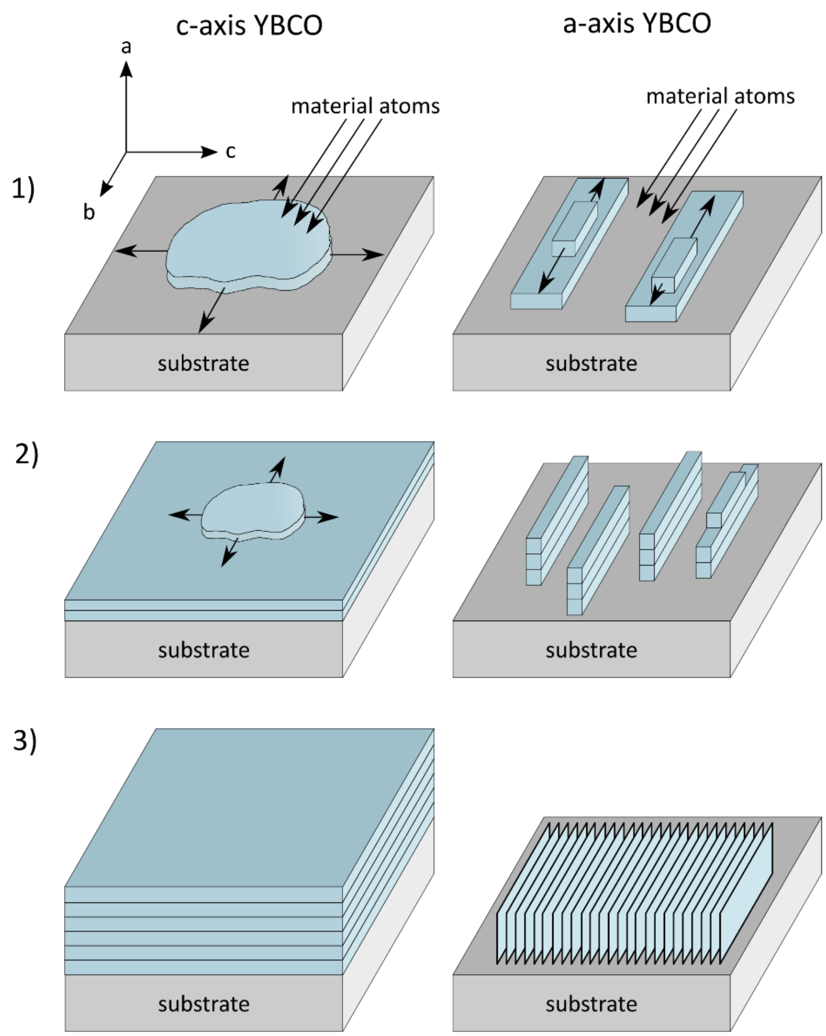

Fig. 1. C-axis and a-axis YBCO formation in MBE broken down into three steps. 1) Cluster formation, 2) Layering, 3) Completed film. Arrows in step 1 indicate the direction of cluster growth or incoming material atoms. The a-axis film in step 3 is shown as a series of vertical copper oxygen planes to emphasize the wall-like structure.

Material and Orientation

The substrate material and orientation are less important than the temperature. In general, you can achieve a-axis or c-axis YBCO on any of the commonly used substrates (MgO, LAO, LSGO, STO, YSZ) but growing high quality a-axis can be made easier with the right choice of substrate. This is related to the spacing between atoms (lattice constant) of the substrate compared to the YBCO. For a-axis YBCO it is 3.82 angstroms, c-axis is 3.89 angstroms, and our LAO substrates are 3.79 angstroms. Films with a smaller mismatch between lattice constants are easier to form thermodynamically. Therefore, it can be easier to form a-axis YBCO on LAO than c-axis.

Mitchell Robson

References

[1] S. Misat, P. . King, D. Fuchs, J. . Villégier, R. . Campion, and P. . Czerwinka, “Investigation of the electrical dissipation properties of in-plane aligned a-axis YBCO films grown on (100) LaSrGaO4 substrates,” *Phys. C Supercond.*, vol. 331, no. 3–4, pp. 241–253, May 2000.

[2] Q. Zhong, P. C. Chou, Q. L. Li, G. S. Taraldsen, and A. Ignatiev, “High-rate growth of purely a-axis oriented YBCO high-Tc thin films by photo-assisted MOCVD,” *Phys. C Supercond. its Appl.*, vol. 246, no. 3–4, pp. 288–296, 1995.

[3] Y. Q. Li, J. Zhao, C. S. Chern, B. Gallois, P. Norris, and B. Kear, “Effects of substrate temperature on growth orientation and superconducting properties of YBa2Cu3O7-x films prepared by metalorganic chemical vapor deposition,” *J. Appl. Phys.*, vol. 71, no. 5, pp. 2472–2474, 1992.