Technical Memorandum

Ambature TM # 2014 - 04

To: Ron Kelly, CEO, Ambature Corp.

Cc: Ketan Patel, Richard Tucker

From: Davis H. Hartman

Date: 10/28/2014

Re: **Theoretical Limits on magnetic field tolerance of optimally doped YBCO.**

Ron;

To complement and guide our experimental efforts at measuring the magnetic field expulsion capability of optimally doped YBCO, we offer some rudimentary estimates of magnetic field tolerance for these materials. Using the Ginsburg-Landau model, we show that bulk YBCO have a critical magnetic field H_{c2} of 82 Tesla. Defect-free YBCO films must accommodate the substantial penetration depth of 120 nm at every surface, limiting the critical current density at given magnetic field and resulting in degraded Meissner field expulsion. Simple geometric arguments imply that a film with thickness exceeding 500 nm could expel fields up to ~ 40 Tesla, but the critical current density is likely to suffer. It is for this reason that I_c must be measured at each applied magnetic field value, and that a variety of field strengths should be measured. Only in this way can we understand the H-field tolerance (H_{2c}) and the critical current I_c, both of which are concurrent marketing requirements of our customer

YBCO characterization

It is known that optimally doped bulk YBCO can tolerate high magnetic fields. Measurements of H_{c2} in bulk YBCO as high as 100 Tesla have been reported[1,2]. When films are grown on compatible host substrates, optimally doped YBCO should exhibit Meissner-like magnetic field expulsion typical of a type II superconductor. However, the film thickness τ is an important factor determining its efficacy as a superconductor, especially when τ is comparable to the penetration depth λ or the coherence length ξ.

[1] T. Sekitani, Y. H. Matsuda, S. Ikeda, K. Uchida, F. Herlach, N. Miura, K. Nakao, T. Izumi, S. Tajima, M. Murakami, S. Hoshi, T. Koyama and Y. Shiohara: Physica C 392 (2003) 116.
[2] Shoji TANAKA, "Superconductivity Research" Japanese Journal of Applied Physics Vol. 45, No. 12, 2006.

High Tc cuprates like YBCO have a coherence length ξ much shorter than their penetration depth λ. The ab in-plane coherence length ξ_{ab} of optimally doped YBCO is about 2 nm, while the penetration depth is from 120 nm to 160 nm (c.f., Table 1). Along the c-axis, the coherence length ξ_c is about 0.4 nm, while the corresponding c-axis penetration depth λ_c is 800 nm. The ratio of penetration depth to coherence length ($\kappa=\lambda/\xi$) is a known measure of Meissner effect in the Ginzburg-Landau model. When κ exceeds 0.707 ($\kappa > 1/\sqrt{2}$), the material's tendency is toward type II superconductivity. The greater k is, the greater the tendency to Type II SC behavior. For optimally doped YBCO, κ is ~ 60 in ab plane and 200 along the c-axis. These materials are labeled "extreme Type II superconductors". Theoretical bounds for H_{c1} and H_{c2} in the extreme Type II limit can be approximated in terms of κ, λ and ξ as,[3]

$$H_{c1} \approx \frac{\Phi_0 \ln(\kappa)}{4\pi\lambda^2} \qquad H_{c2} \approx \frac{\Phi_0^2}{2\pi\xi^2} \quad , \tag{1}$$

where $\Phi_o = h/2e = 2.07 \times 10^{-15}$ Webers.

As shown in Table 2, the theoretical limit for crystal YBCO along the ab-plane is 82 Tesla. Therefore, if high quality defect-free material is a-axis grown to thickness well exceeding λ_{ab} (120 nm; see the table), and it is well-aligned crystal growth, it is feasible that H_{c2} well exceeding the marketing requirement of 10 Tesla can be achieved.

	coherence length		penetration depth		SC type indicator					
	ξ		λ		κ		$H_{c1} \approx \frac{\Phi_0 \ln(\kappa)}{4\pi\lambda^2}$		$H_{c2} \approx \frac{\Phi_0}{2\pi\xi^2}$	
ab plane YBCO	**2.00E-09**	**m**	**1.20E-07**	**m**	**60**	**ratio**	**4.68E-02**	**T**	**8.24E+01**	T
c-axis YBCO	**4.00E-10**	**m**	**8.00E-07**	**m**	**2000**	**ratio**	**1.96E-03**	**T**	**2.06E+03**	T
Flux quantum = Φ_o = h/2e = 2.07031E-15 Wb										
Coherence length ξ : 2 nm in the *ab* plane, 0.4 nm along the *c* axis										
Penetration depth λ : 120 nm in the *ab* plane, 800 nm along the *c* axis										

Table 2: Applying Ginzburg-Landau modal of SC types indicates that optimally doped YBCO is an "extreme Type II" superconductor with high H_{c2} in the bulk state.

[3] C. P. Slicter, "Magnetic Resonance Studies of High Temperature Superconductors", Handbook of High Temperature Superconductivity (J. R. Schrieffer and J. S. Brooks editors), 2007, pg. 62.

We can estimate the value of H_{c2} we might expect for films grown with thickness in the range of the customer's stated requirement of 430 nm (flexible). A 500 nm film with penetration depth of 120 nm, on top and bottom, can be expected to have its remaining material (270 nm) in the superconducting mode. The reduced area for current flow decreases the critical current (assuming the critical current density does not decrease), resulting in a diminished tolerance of applied magnetic field. A reduction of 50% of the current carrying capacity could result in a 50% reduction of Hc2 from 80 Tesla to 40 Tesla. In general, the thinner the film (in relation to ξ and λ), the more the sample will exhibit mixed mode conduction, which we observe.

Further degradation relating to imperfect growth (defects, misaligned growth etc.) can and will occur; but there appears to be margin to meet the required 10 Tesla field tolerance, as long as critical current capacity is sufficient.

Summary

A rudimentary set of calculations using the Ginzburg-Landau model indicate that there is sufficient margin to grow high quality a-axis films of optimally doped YBCO on SLGO substrates with H_{2c} well exceeding the customer's marketing requirement of 10 Tesla. Film thickness should be of high quality and at least 500 nm thick. This thickness can be challenging to grow with low defect density and immunity to threading defects; but there appears to be considerable margin to grow these films and still meet the H_{2c} (> 10 T) and J_c (>10^6 A/cm^2) requirements.

Davis H. Hartman

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