**Magnetic Properties and Irreversibility Behavior in Ag-Sheathed Bi-Based
Superconducting Wires Fabricated Using a Controlled Melt Procedure***

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MAGNETIC PROPERTIES AND IRREVERSIBILITY BEHAVIOR IN Ag-SHEATHED Bi-BASED SUPERCONDUCTING WIRES FABRICATED USING A CONTROLLED MELT PROCEDURE

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ABSTRACT

A significant enhancement of the in-field J_c of Ag-clad (Bi,Pb)-Sr-Ca-Cu-O (BPSCCO:2223) wires has been achieved using a controlled melt procedure. The greatly reduced weak linking has resulted in an extended plateau regime in the J_c -H curve. J_s of 40,000 A/cm² at 77 K (self field) and 9,000 A/cm² at 77 K (1 T) have been achieved. The improved J_c -H characteristics may be attributed to microstructures consisting of uniform grain alignment throughout the entire cross section, intimate connection between grains, impurities within the grains, and an optimal level of dispersed 2212 phase. Irreversibility line measurements using both AC susceptibility in DC fields (reported elsewhere), and magnetization measurements, have indicated that flux pinning can be enhanced in the melt-processed samples over the results of normal solid-state processing with its less-than optimal 2212-phase content. But sufficiently long annealing times during the "normal" route may achieve 2212-phase content and J_c s which are comparable to those of melt-processed samples.

KEY WORDS: Powder-in-tube wire, BSCCO:2223 wire, critical current density, melt processing, irreversibility line, flux pinning.

INTRODUCTION

Background

It is well known that numerous research-and-development programs directed towards the processing of current-carrying high- T_c superconductors (HTSCs) are under way worldwide. It is also recognized that the powder-in-silver-tube process can be counted among the most successful to date. Powder-in-tube processing (henceforth PIT processing) is being investigated in the US (several programs), in Germany (in at least two locations), and in Japan where at least seven major programs are under way. In many of these programs very high transport critical current densities have been achieved -- particularly on short lengths and mostly in the He-temperature range (4-30 K). Superconductors based on the compound Bi-Sr-Ca-Cu-O (henceforth BSCCO) have been identified as possessing outstanding potential for low-temperature high-magnetic-field applications. But numerous problems need to be solved before PIT conductors can be deemed suitable for service. Among the most pressing of them are innovative ways of introducing flux-pinning sites into BSCCO in order to raise its practical operating temperature into the liquid-N range.

The starting materials, initially powders of nominal composition $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_y$ (i.e. "2212") or $(\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ ("2223") are loaded into Ag tubes. Using standard deformation methods the packed tubes are reduced to wire of about 1-2 mm in diameter. It is then usual to flat roll the wire to ribbon, commonly 0.1-0.3 mm thick. If 2212 is being processed, the ribbon is given a final carefully controlled heat treatment to promote grain growth, connectivity, and orientation. If 2223 has been selected, the ribbon is given two or more heat treatments separated by cold rolling. Of the three known superconducting BSCCO phases -- 2201 ($T_c = 20$ K), 2212 ($T_c = 90$ K), and 2223 ($T_c = 110$ K) -- only the latter two are technically viable. Of these, 2212 is the easier to form and the more thermodynamically stable. Since 2212 is simpler to prepare initially than 2223 and requires only one final heat treatment rather than 2223's several heat treatments (separated by an intermediate cold rolling) it is the preferred material for high-field operation in the liquid-He range. But if operation in 77 K is to become a reality, the higher- T_c 2223 material (in association with due attention to flux pinning) will be necessary.

Important contributions to progress in BSCCO:2223 PIT conductor processing have been made by researchers associated with companies and institutions such as: Mitsubishi Material Corporation (MBC) [1], Interdisciplinary Research Center in Superconductivity (IRC) [2,4], Northwest Institute for Nonferrous Metal Research (NIN) [3], Toyohashi University of Technology (TTI) [4], University of Geneva (UDG) [5], Showa Electric Wire and Cable (SEW) [6], Sumitomo Electric Industries (SEI) [7-13], Kyoto University Dept. of Metallurgy (KUM) [14-16], National Research Institute for Metals (NRI) [17], Vacuumschmelze (VAC) [18-21], Argonne National Laboratory (ANL) [22,23], Intermagnetics General Corporation (IGC) [24-26], and University of New South Wales (NSW) [27-33].

Conventional Processing and Typical Properties of PIT BSCCO:2223

Starting Compositions and Powder Preparation: Numerous slight variants of the nominal starting-material cation-ratio of $[(\text{Bi,Pb})]/[\text{Sr}]/[\text{Ba}]/[\text{Ca}]/[\text{Cu}] = (2)/2/2/3$ have been preferred by various groups. MBC employed a Bi-poor, Ca-rich (1.3,0.4)/2/2.2/3.1 blend. Bi-rich but otherwise close-to-nominal ratios were employed by NIN, VAC, ANL, and NSW -- e.g. in the latter case (1.83,0.35)/1.90/2.05/3.05. Ratios that were both Bi-rich and Ca-rich were employed by TTI, SEI, and IGC -- e.g. in the latter case (1.8,0.4)/2/2.5/3. Popular powder preparation routes included: (1) the milling of mixtures of oxides and carbonates followed by calcination and further milling or grinding (ANL, IGC); (2) the co-decomposition into powder of a mixed metal nitrate solution, followed by calcination, grinding, pelletization, sintering and further grinding (NSW).

Heat Treatments and Phase Stability: The PIT fabrication sequence for BSCCO:2223 ribbon is terminated by a sequence of thermomechanical processing steps consisting of two or more heat treatments separated by cold compaction. Selection of the heat treatment temperature is critically important. Between 854 and 858°C 2223 coexists with 2212, while above 859°C 2212 is the equilibrium phase. The longer the dwell time in the 2212 regime the more difficult it becomes to recover the 2223 phase during subsequent lower temperature annealing (e.g. at 834°C) [33]. For this reason, heat treatment of the PIT 2223 tapes is usually performed at about 840°C. Examples of some selected temperatures and times are: 20h/840°C (IRC), 70h/845°C (NIN), 100h/815-840°C (TTI), 24-48h/845°C (UDG), 30-100h/840-850°C (SEI), 10-100h/830-845°C (KUM), 40h/840°C (NRI), 100h/830°C (VAC), 50-100h/845°C (ANL), 48-150h/840°C (IGC). Some heat treatments are performed in air, others in mixtures of N_2 and O_2 .

Short-Sample Critical Current Densities: For BSCCO:2223, 4.2-K J_c s at 0 to several tens of teslas are frequently reported, as are 77-K J_c s at 0 (self-field), 0.1, and 1 T. The 77-K self-field J_c makes a useful benchmark number. Some typical values that have been reported in recent years are: (i) At the low end of the scale: 3.2 kA/cm² (IRC), 6.3 kA/cm² (SEW), and 9 kA/cm² (ANL). (ii) Further up the scale are: 24 kA/cm² (IGC), 33 kA/cm² (UDG, VAC), and 54 kA/cm² (SEI). Intermediate values were reported by MBC, NIN, TTI, and KUM.

The purpose of the present paper is to emphasize the improvement in properties that follow when 2212 phase is present. One route towards achieving this is to briefly heat the PIT ribbon to 860°C during three-stage thermomechanical cycling to 832-836°C.

FLUX PINNING IN PIT BSCCO:2223

Flux Pinning Microstructures

Magnetization decay (flux creep) studies have shown that the pinning potentials of defects inherent in HTSCs are comparable to those that have been developed in practical low- T_c superconductors such as Nb_3Sn [34] and presumably NbTi. However, particularly in the BSCCO HTSCs, *extra pinning* by defects and precipitates is needed to support supercurrents at temperatures above 30-40 K. Flux-pinning defects have been produced by irradiation [35] and cold deformation [27,29]. Flux pinning has also been introduced in the form of fine-scale

Fig. 1: Highly textured PFDR-process microstructure exhibiting uniformly elongated 2212 precipitates (white) less than 1 μm in thickness.

Fig. 2: TEM image taken from a PFDR-process tape showing a high density of dislocations.

Fig. 3: Influence of 2212 abundance in a PFDR-process tape on critical current density (77K, 1T).

Fig. 4: J_c versus H curves for the PFDR-process tapes A, B, C, D, and N-process tapes E, F, G.

dispersions of Ca_2PbO_4 and $(\text{Ca},\text{Sr})\text{-Cu-O}$ (SEI), and MgO and CaO precipitates (KUM). But just as α -phase in NbTi and 211-phase in YBaCuO:123 act as "naturally occurring" flux-pinning precipitates, it was predicted that 2212-phase should play a comparable role in 2223. To provide flux pinning without degrading the primary superconducting properties the 2212 phase must, however, be sufficiently fine and well dispersed. Dou and colleagues have achieved this goal using the "phase formation-decomposition-recovery process" (PFDR) in which a brief excursion into the molten regime at 860°C is inserted between several lower temperature heat treatments.

The Phase Formation-Decomposition-Recovery (PFDR) Process

A typical PFDR Process consists of three heating cycles at $832\text{-}836^\circ\text{C}$ for 50-80 h for each cycle, during which a melt treatment of 15-30 min. at 860°C is introduced as part of the initial segment of the second temperature cycle. X-ray diffraction studies have revealed that the 2223 phase formed during the first cycle decomposed into 2212 and impurity phases during the second cycle then almost fully recovers during the third heating cycle [33]. The result was a textured predominantly 2223 phase matrix containing 2212 phase as fine elongated dispersants less than $1\text{ }\mu\text{m}$ thick, Fig. 1, together with fine CaCuO and SrCaCuO precipitates. It is probable that lattice defects such as stacking faults and dislocations, Fig. 2, and the nonsuperconducting precipitates provide flux pinning over the entire temperature range of the 2223 matrix, and that the 2212 phase enhances that pinning in the higher temperature regime above its T_c . The optimal 2212-phase abundance seems to be about 7-10 percent, Fig. 3.

RESULTS AND DISCUSSION

In what follows a comparison is made between the properties of several samples of PFDR-process and solid-state reacted, N-process, tapes. Some earlier measured samples, designated A, B, C, D, were prepared by the above-mentioned PFDR process. Another set, E, F, G, were prepared by an N-process consisting, typically, of the above but without the upquench to 860°C . Two recently studied samples are: (a) Sample M1, PFDR-processed according to: $(70\text{h}/830^\circ\text{C})\text{p}(20\text{min}/862^\circ\text{C})(50\text{h}/825^\circ\text{C})\text{p}(40\text{h}/834^\circ\text{C})\text{p}(65\text{h}/834^\circ\text{C})$, and (b) Sample N1, N-processed according to: $(80\text{h}/832^\circ\text{C})\text{p}(60\text{h}/832^\circ\text{C})\text{p}(30\text{h}/833^\circ\text{C})\text{p}(50\text{h}/833^\circ\text{C})\text{p}(60\text{h}/833^\circ\text{C})$, where "p" indicates pressing between heat treatments.

Transport Critical Current Density

Figure 4 compares the field dependence of transport J_c in PFDR-process and N-process tapes at 77 K. Evidently in the low field regime, the J_c for the PFDR-process tapes drops much slower than that for the N-process tapes. At low fields ($H < 300\text{-}500\text{ Oe}$) the rapid drop in J_c is attributed to Josephson weak links at grain boundaries. The N-process tapes lose more than 75% to 80% of their zero-field J_s at 0.1 T, whereas the PFDR-process tapes lose only 25% to 43%, indicating a significant reduction in weak link behavior. At 1 T the best PFDR-process tapes retain 33% of their zero-field J_c while the N-process tapes retain only 10%. Thus at 1 T the PFDR-process tapes would be expected to show a 3- to 10-fold higher J_c than their N-process counterparts.

Summary of PFDR J_c Properties: PFDR-process tape can possess 77-K J_s of 40 kA/cm^2 at 0 T, 25 kA/cm^2 at 0.1 T, and 9 kA/cm^2 at 1 T; its J_c shows an extended plateau from 0.1 to 1 T.

Fig. 5: Magnetic $J_{cab}(5 \text{ kOe})$ versus T for the PDFR-process tape C and the N-process tape F. Inserted are $J_{cab}(5 \text{ kOe})$ data for M1 and N1.

Fig. 6: Magnetic J_{cab} versus T and H for PDFR-process tape M1 and the N-process tape N1.

Magnetic Critical Current Density

The magnetic critical current density, J_{cab} , in the ribbon plane can be calculated from the height, ΔM (emu/cm^3), of the $M(H)$ hysteresis loop with the aid of the formula $J_{cab} = \Delta M(20/W)/\{1-(W/3L)\}$, where L and W ($L > W$) are the length and width of the sample, and the field, $H_{\perp}$, is applied perpendicular to the plane of the ribbon. The magnetic J_{cab} for samples C and F (at 5 kOe) are plotted versus temperature in Fig. 5, and those for samples M1 and N1 are plotted versus field in Fig. 6. Also inserted in Fig. 5 are a set of $J_c(T)$ values for samples M1 and N1 from Fig. 6. In Fig. 5 we note that for $T > 40 \text{ K}$ $J_{cC} > J_{cF}$ in agreement with Fig. 4. From this we conclude that the flux-pinning 2212 particles have their greatest influence at elevated temperatures and fields. But in Fig. 6 we note little difference between the J_c s of the PFDR- and N-processed samples. That J_{cN} has risen towards J_{cPFDR} , and not the contrary, can be seen by the position of the M1 and N1 data in Fig. 5; in fact this N-processed sample is slightly better than the M1 melt-processed sample. This result is the first indication that 2212-like flux pinning may not be unique to the PFDR process. It seems that variations in the ostensibly normal process can also yield the beneficial 2212 precipitates. These conclusions are corroborated by the irreversibility-field results.

Irreversibility Field

The $M-H$ behavior of HTSCs is generally reversible throughout a region in $H(T)$ space between $H_{c2}(T)$ and a locus $H_i(T)$, where H_i and T_i are the irreversibility fields and temperatures, respectively. Since the study by Xu and Suenaga (XS) of the temperature dependence of H_i in a series of substituted YBCO:123 compounds [36], the irreversibility parameters have become established as useful measures of flux pinning strength. An argument based on flux depinning [37] yielded an H_i temperature dependence of the form $H_i = a(1-t)^n$ where $t = T_i(H)/T_c(0)$. For substituted YBCO:123, XS demonstrated conclusively a one-to-one relationship between the prefactor "a" and a quantity proportional to the magnetic J_c at a given field. For YBCO the index "n" was claimed equal 1.5 [36], and indeed the results of numerous experiments on YBCO [36,37] and both BSCCO:2212 [38,39] and BSCCO:2223 [40] have confirmed that prediction. This is not to say that $n = 1.5$ is universally accepted. Some authors have claimed significant departures from that value, for example: $n = 4$ in BSCCO:2223 below -80 K [41], $n = 3$ in BSCCO:2223 [42] and TiBCO:2223 [43], $n = 2.19-2.99$ in BSCCO:2223 [44], and $n = 1.17-1.52$ in BSCCO:2212 [45]. But as first indicated by Yamada *et al.* [41] and later more specifically by de Rango *et al.* [40] and Shi *et al.* [46] major departures from the Yeshurun-Malozemoff power-law itself may be encountered in BSCCO:2223 (also in BSCCO:2212 [47]) as the temperature drops 30 K or so below T_c . As pointed out by Ku and Shi [46] at sufficiently high fields H_i decreases exponentially with temperature due to a gradual breakdown of interlayer proximity coupling. But this exponential temperature dependence seems to be confined to near-monocrystalline and hence very weakly pinned samples [46,47]. It turns out that fully thermomechanically processed PIT BSCCO:2223 exhibits a pure power-law dependence (albeit with $n \sim 3$) throughout the entire $H_i(T)$ range [29].

Fig. 7: Irreversibility field, $H_{r,\perp}$, versus T for the PDFR-process tape C and the N-process tape F. Inserted are $H_{r,\perp}$ data for M1 and N1.

Fig. 8: Irreversibility fields $H_{r,\parallel}$ and $H_{r,\perp}$ (in which H is $\parallel$ and $\perp$, respectively, to the ribbon plane) versus temperature.

No single reason has emerged for the variability of n , nevertheless the prefactor a , or position of the irreversibility line in $H(T)$ space, still remains a valid measure of relative pinning strength within a given class of materials.

The results of static magnetization measurements of irreversibility field in samples C and F are shown in Fig. 7. A corresponding set of AC-susceptibility results are to be found elsewhere (for D and E in [29] and C, D, and G in [28]). At temperatures above ~ 10 K sample C, with about 10% 2212 phase shows stronger pinning than the precipitate-free counterpart. Figures 7 and 5 contain qualitatively similar pinning-strength information; in both cases the curves cross over at low temperatures. The irreversibility fields for samples M1 and N1 are given in Fig. 8. Just as in Fig. 6, we note little difference between the pinning strengths of those samples. Indeed the response of H_r to change of field orientation is greater than its response to change of sample. Sets of $H_{r,\perp}$ data for samples M1 and N1 are plotted in Fig. 7. As before we note that N1 has risen in pinning strength towards M1 rather than otherwise. For this reason we deduced that the particular variant of the normal process that produced sample N1 must have resulted in 2212 phase precipitation. Subsequently, x-ray diffraction indicated that N1 contained 8-9% of 2212, and a member of the M1 batch was found to contain 5-8% of the precipitate.

$H_{r,\perp}(T)$ data for samples M1 and N1, fitted to the function $a(1-t)^n$ ($T_c = 108.3$ and 107.6 K respectively) yielded $n = 2.97$ (for N1) and 2.89 (for M1) -- values very close to the reported $n = 3$ for BSCCO:2223 [29][42].

CONCLUSION

We have measured the pinning strengths of BSCCO wires fabricated via several routes using measurements of magnetic J_c and irreversibility field, H_r . The latter follows a $(1-t)^n$ power law throughout the entire field range of 0-14 kOe with indexes n mostly close to 3. We find that a fine dispersion of 2212 phase is an effective flux-pinning addition to PIT BSCCO:2223, seemingly regardless of the route used to obtain it. A recommended procedure for introducing the precipitates includes a brief exposure to 860°C (during which the conversion $2223 \rightarrow 2212$ takes place) followed by anneals at 832 - 836°C (during which partial reversion of $2212 \rightarrow 2223$ occurs). It seems that this process has significant potential for optimization in terms of precipitate size and distribution, processing time, and number of thermomechanical process steps.

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REFERENCES

- [1] M. Suzuki, T. Kimura, and T. Takeshita, Paper presented at the 4th Int. Symp. on Superconductivity, Tokyo, Japan, Oct. 14-17, 1991.
- [2] W. Lo and B. A. Glowacki, *Adv. Cryo. Eng. Materials* **38**, 1065-1072 (1992).
- [3] Z. Xi, L. Zhou, C. Ji, S. Wu, and Z. Cheng, *Adv. Cryo. Eng. Materials* **38**, 1057-1063 (1992).
- [4] K. Ohba, T. Horio, K. Iwasaki, and A. Oota, *Supercond. Sci. Technol.* **5**, S312-315 (1992).
- [5] R. Flukiger, A. Jeremie, B. Hensel, E. Seibt, J. Xu, and Y. Yamada, *Adv. Cryo. Eng. Materials* **38**, 1073-1080 (1992).
- [6] T. Kitamura, T. Hasegawa, F. Takeshita, K. Yamamoto, S. Murase, and H. Ogiwara, Paper presented at the 4th Int. Symp. on Superconductivity, Tokyo, Japan, Oct. 14-17, 1991.
- [7] T. Hikata, M. Ueyama, H. Mukai, *et al.*, *Cryogenics* **30**, 924-929 (1990).
- [8] K. Sato, N. Shibuta, T. Hikata, T. Masuda, M. Uyama, T. Kato, and J. Fujikami, Paper presented at the 4th Int. Symp. on Superconductivity, Tokyo, Japan, Oct. 14-17, 1991.
- [9] K. Sato, N. Shibuta, H. Mukai, T. Hikata, M. Ueyama, and T. Kato, *J. Appl. Phys.* **70**, 6484 (1991).
- [10] M. Ueyama, T. Hikata, T. Kato, and K. Sato, *Jpn. J. Appl. Phys.* **30** L1384 (1991).
- [11] K. Sato, T. Hikata, H. Mukai, M. Ueyama, N. Shibuta, T. Kato, T. Matsuda, M. Nagata, K. Iwata, and T. Mitsui, *IEEE Trans. Magn.* **27** 1231 (1991).
- [12] K. Sato, T. Hikata, M. Ueyama, H. Mukai, N. Shibuta, *et al.*, *Cryogenics* **31**, 687 (1991).
- [13] N. Shibuta, M. Ueyama, H. Mukai, and K. Sato, *Jpn. J. Appl. Phys.* **30**, L2084 (1991).
- [14] K. Osamura, S. S. Oh, and S. Ochiai, *Supercond. Sci. Technol.* **3**, 143-147 (1990).
- [15] K. Osamura, S.S. Oh, and S. Ochiai, Paper presented at the 4th Int. Symp. on Superconductivity, Tokyo, Japan, Oct. 14-17, 1991.
- [16] S. Ochiai, K. Hayashi, and K. Osamura, *Cryogenics* **31**, 954 (1991).
- [17] T. Kuroda, M. Yuyama, K. Itoh, and H. Wada, *Adv. Cryo. Eng. Materials* **38**, 1045-1051 (1992).
- [18] J. Tenbrink, K. Heine, and H. Krauth, *Cryogenics* **30**, 422 (1990).
- [19] K. Heine, J. Tenbrink, H. Krauth, and M. Wilhelm, Paper presented at Euromat 91, Cambridge, July 22-27, 1991.
- [20] J. Tenbrink, M. Wilhelm, K. Heine, and H. Krauth, *IEEE Trans. Magn.* **27**, 1239 (1991).
- [21] K. Heine, J. Tenbrink, H. Krauth, and M. Wilhelm, *Adv. Cryo. Eng. Materials* **38**, 1033-1040 (1992).
- [22] D. Y. Kaufman, M. T. Lanagan, S. E. Dorris, J. T. Dawley, *et al.*, *Applied Supercond.* **1**, 81-91 (1993).
- [23] J. S. Luo, N. Merchant, A. V. Moroni, D. M. Gruen, *et al.*, *Applied Supercond.* **1**, 101-107 (1993).
- [24] L. R. Motowidlo, E. Gregory, P. Haldar, J. A. Rice, *et al.*, *Appl. Phys. Lett.* **59**, 736-738 (1991).
- [25] P. Haldar, J. G. Hoehn, Jr., J. A. Rice, and L. R. Motowidlo, *Appl. Phys. Lett.* **60**, 495-497 (1992).
- [26] P. Haldar and L. Motowidlo, *JOM*, pp. 54-58, October 1992.
- [27] S. X. Dou, H. K. Liu, Y. C. Guo, and P. Munroe, *Physics C* **190**, 157-159 (1991).
- [28] S. X. Dou, H. K. Liu, Y. C. Guo, J. Wang, X. J. Jin, and Q. Y. Hu, *Proc. 3rd World Congr. Superconductivity*, 14-18 Sept., 1992, Munich, Germany.
- [29] S. X. Dou, Y. C. Guo, and H. K. Liu, *Physica C* **194**, 343-350 (1992).
- [30] S. X. Dou, H. K. Liu, Y. C. Guo, and C. C. Sorrell, *Supercond. Sci. Technol.* **5**, S471 (1992).
- [31] S. X. Dou, H. K. Liu, Y. C. Guo, *Appl. Phys. Lett.* **60** 2929 (1992).
- [32] Y. C. Guo, H. K. Liu, and S. X. Dou, *Applied Superconductivity* **1**, 25-31 (1993).
- [33] Y. C. Guo, H. K. Liu, and S. X. Dou, *Physica C* **200**, 147 (1992).
- [34] S. Sengupta, Donglu Shi, S. Salem-Sugui, Jr., Z. Wang, *et al.*, *J. Appl. Phys.* **72**, 592-595 (1992).
- [35] H. W. Weber, in *Critical Current Limitations in High Temperature Superconductors*, M. Baran *et al.*, eds. (World Scientific, Singapore, 1992) pp. 3-16, 239-245.
- [36] Y. Xu and M. Suenaga, *Phys. Rev. B* **43**, 5516-5525 (1991).
- [37] Y. Yeshurun and A. P. Malozemoff, *Phys. Rev. Lett.* **60**, 2202-2205 (1988).
- [38] B. D. Biggs, M. N. Kunchur, J. J. Lin, *et al.*, *Phys. Rev. B* **39**, 7309-7312 (1989).
- [39] C. Quitmann, U. Ebels, P. C. Splittgerber-Hünnekes, *et al.*, *Physica B* **165&166**, 1143-1144 (1990).
- [40] P. de Rango, B. Giordanengo, J. L. Genicon, *et al.*, *Physica B* **165&166**, 1141-1142 (1990).
- [41] Y. Yamada, S. Murase, K. Yamamoto, and Y. Kamisada, *Cryogenics* **30**, 581-585 (1990).
- [42] A. Nishada and K. Horai, *Solid State Comm.* **74**, 947-950 (1990).
- [43] Y. Wolfus, Y. Yeshurun, and I. Felner, *Phys. Rev. B* **39**, 11, 690-11,694 (1989).
- [44] J. B. Shi, P. L. Kuo, B. S. Chiou, and H. C. Ku, *Physica C* **185-189** 2143-2144 (1991).
- [45] L. W. Lombardo, D. B. Mitzl, A. Kapitulnik, and A. Leone, *Phys. rev. B* **46**, 5615-5620 (1992).
- [46] H. C. Ku and J. B. Shi, in *Superconductivity and its Applications*, Y. H. Kao *et al.*, eds. (Amer. Inst. Phys., NY, 1992) pp. 467-476.
- [47] E. W. Collings, M. D. Sumption, Y. Higashida, and K. Michishita, paper on BSCCO:2212 in this proceedings.

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