APPLICATION NOTE

Characterizing High Temperature Superconductors (HTS) Using the Model 8600 VSM

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Introduction

High temperature superconductors (HTS) were discovered in 1986 by IBM researchers Georg Bednorz and K. Alex Muller[1]. They discovered superconductivity in a lanthanum barium copper oxide (LBCO) which has a transition temperature $T_c = 35$ K. Shortly thereafter, Paul Ching-Wu Chu found that by replacing lanthanum with yttrium making yttrium barium copper oxide (YBCO) raised the transition temperature to above 90 K[2]. Bednorz and Muller won the Nobel Prize in Physics in 1987 for their landmark discovery. The most extensively studied HTS are YBCO, bismuth strontium calcium copper oxide (BSCCO)[3], and thallium barium calcium copper oxide (TBCCO)[4] with transition temperatures of ~92 K, 110 K (2223 phase), and 125 K, respectively.

The most common characterization techniques for HTS are:

- Resistance measurements as a function of temperature T, current I and magnetic field H.
- Magnetization measurements as a function of (T, H).

Both measurements enable the determination of transition temperature T_c and critical current density J_c. Resistance measurements yield a direct measurement of J_c but require the attachment of 4 leads to a sample for current excitation and voltage measurements. Magnetization measurements provide a non-contact technique for indirect measurement of J_c by application of a suitable critical state model.

In this Application Note we will present Model 8600 low temperature VSM results for a $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi2223) tape sample and a $YBa_2Cu_3O_{7-x}$ (Y123) solid sample (mass < 10 mg).

Magnetization measurements as a function of temperature:

Two measurement protocols are typically used: zero-field cooled warming (ZFCW) and field-cooled cooling (FCC). In ZFCW, a sample is cooled in zero field from above, to below T_c. A field is then applied and magnetization versus temperature M(T) is measured on warming to $T > T_c$. In FCC a sample is cooled in an applied field and M(T) data are collected while cooling from above to below T_c. ZFCW and FCC yield different information:

ZFCW:

- Shows the “ideal” magnetic behavior because the superconductor is allowed to expel the magnetic field completely (Meissner effect) as it transitions into the superconducting state.
- Below T_c, the magnetic response is typically more sensitive to the pinning of flux lines or vortices and the intrinsic properties of the superconductor. In ZFCW, the vortices can become de-pinned (flux creep) owing to thermal activation.

FCC:

- The superconductor is already in the presence of a magnetic field as it cools, so magnetic flux lines or vortices may become pinned in the material. This results in a less ideal magnetic response due to the inability to expel all the field lines (partial flux penetration).
- Below T_c, the FCC magnetization often remains smaller in magnitude compared to ZFCW due to these pinning effects.

Figure 1 shows ZFCW and FCC M(T) curves at H = 10 mT for the Bi2223 tape. In these measurements, the applied field H was oriented parallel to the tape plane, and the results are presented in terms of magnetic moment in SI units (Am^2). Figure 2 shows similar results for the Y123 sample. In both cases, the slightly different T_c’s between ZFCW and FCC curves are related to flux pinning effects.

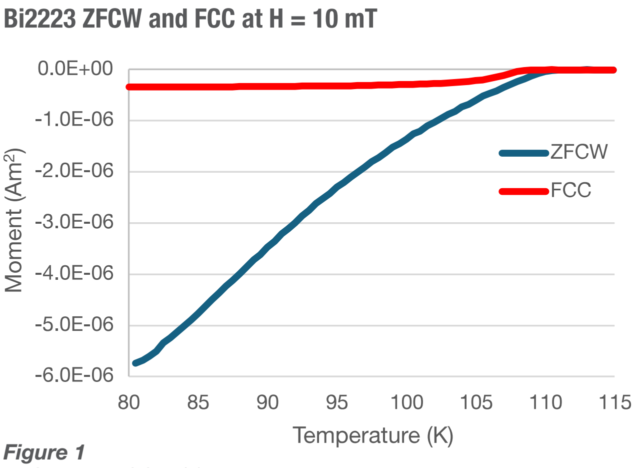

Figure 1
ZFCW and FCC M(T) curves for Bi2223 tape at 10 mT applied field.

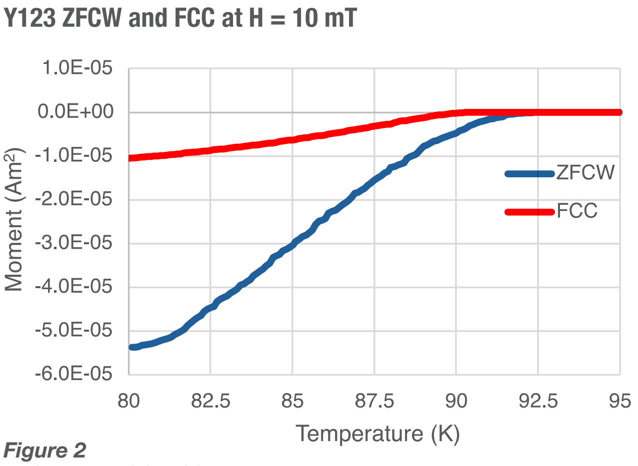

Figure 2
ZFCW and FCC M(T) curves for Y123 at 10 mT applied field.

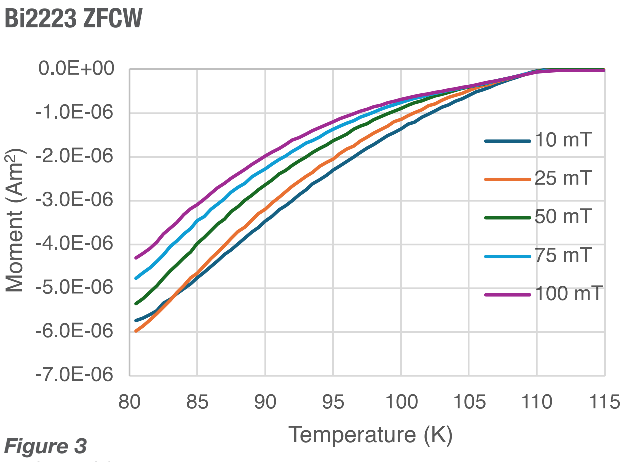

Figure 3
ZFCW M(T) at different applied fields for Bi2223 tape.

Figures 3 and 4 show ZFCW and FCC M(T) curves, respectively, for the Bi2223 tape at applied fields of 10, 25, 50, 75, and 100 mT. And Figures 5 and 6 show ZFCW and FCC M(T) curves, respectively, for the Y123 sample at applied fields 2, 3, 4, 5, 6, 8 and 10 mT. Clearly T_c and the magnitude of the magnetization are strongly field dependent in both samples.

Magnetization measurements as a function of magnetic field:

HTS are type II superconductors and hence are characterized with lower H_{c1} and upper H_{c2} critical fields, as well as the irreversibility line $H_{irr}(T)$. Below H_{c1} the superconductor is type I (Meissner state). Above H_{c1} magnetic flux penetrates the superconductor (type II mixed state), and at H_{c2} the material transitions from a superconducting to a normal state. The usable field-temperature (H-T) space for applications of type II superconductors lies between H_{c1} and H_{c2} and for applications requiring finite critical currents it also lies below $H_{irr}(T)$. H_{c1} is determined from the magnetization versus field curve (i.e., major hysteresis loop – MHL) as the point where the magnetic field begins to penetrate the superconductor, breaking the linear relationship between the applied field and the induced diamagnetic moment. To determine H_{c2} in HTS very high magnetic fields (~100 T at very low temperatures) are required. The irreversibility line corresponds to the divergence in ZFCW and FCC M(T) at a particular applied field H and also to the divergence (or equivalently the convergence) of the ascending and descending branches of the MHL at a particular temperature T.

Application of Bean's critical state model[5] also enables critical current density J_c determinations from MHL measurements. J_c is proportional to the width ΔM of the MHL: $J_c = \Delta M/a$ where a = half thickness of a slab with the applied field oriented parallel to the slab surface.[6]

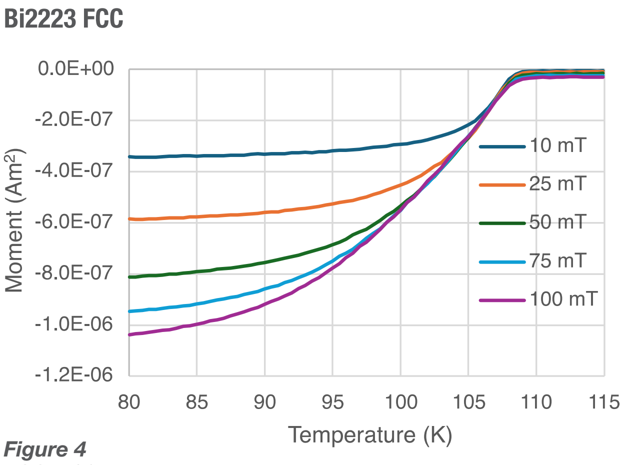

Figure 4
FCC M(T) at different applied fields for Bi2223 tape.

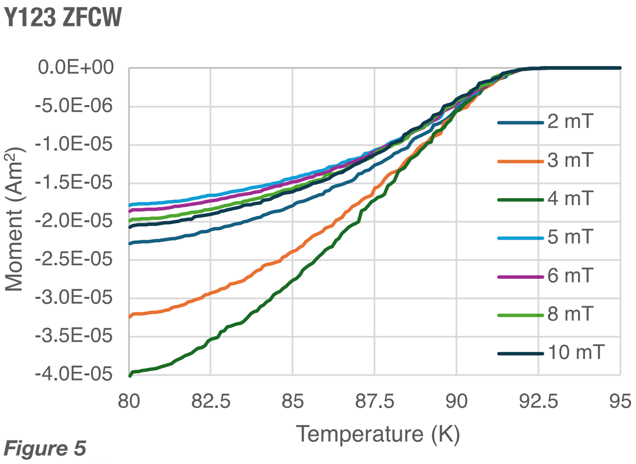

Figure 5
ZFCW M(T) at different applied fields for Y123.

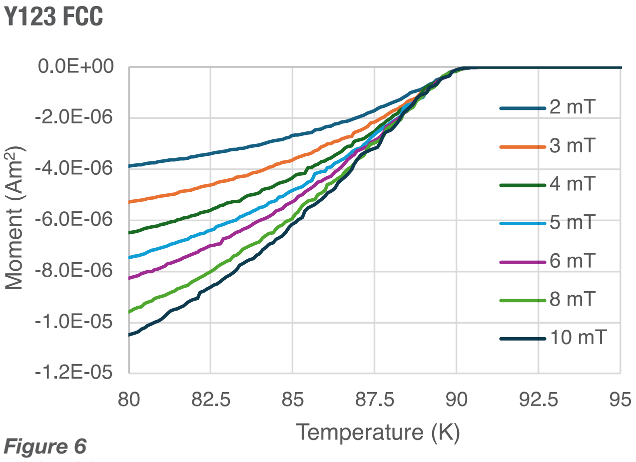

Figure 6
FCC M(T) at different applied fields for Y123.

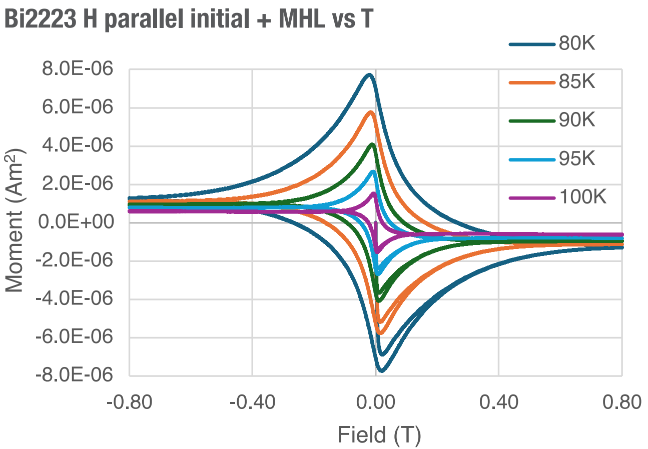

Figure 7
Initial and MHLs for Bi2223 tape.

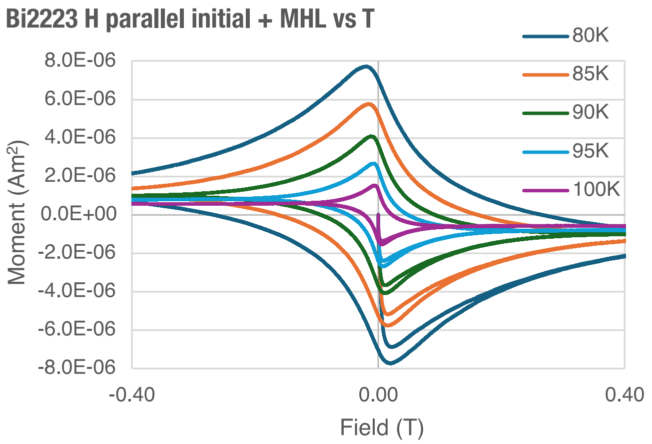

Figure 8
Expanded plot of low field region.

Figure 7 shows initial magnetization curves and major hysteresis loops (MHLs) for the Bi2223 tape at temperatures of 80, 85, 90, 95 and 100 K. Figure 8 is an expanded plot of the low field region. Figure 9 shows similar measurement results for Y123 at temperatures of 80, 82, 84, 86, and 88 K, and Figure 10 is an expanded plot of the low field region. These measurements were performed using the protocol:

- Cool the sample from above T_c to $T_1 < T_c$ in zero field.
- Record initial + MHL at T_1.
- Heat the sample above T_c and cool to T_2 ($T_2 > T_1$) $< T_c$ in zero field.
- Record initial + MHL at T_2.
- Etc.

Conclusions:

In this application note we have presented 8600 low temperature VSM results for HTS Bi2223 tape and Y123 sold samples. ZFCW and FCC M(T) curves at various applied fields H and M(H) curves at various $T < T_c$ have been presented for both samples. Extraction of important HTS parameters from both M(T) and M(H) such as H_{c1}, H_{c2}, the irreversibility line $H_{irr}(T)$, and critical current density J_c have been discussed.

References

[1] *J. G. Bednorz, K. A. Muller, Possible High T_c Superconductivity in the Ba-La-Cu-O System, Phys. B Condensed Matter, 64, 189, 1986.*

[2] *C. W. Chu, Superconductivity Above 90 K, Proceeding of the National Academy of Sciences, 84, 14, 1987.*

[3] *H. Maeda, Y. Tanaka, M. Fukutumi, T. Asano, A New High T_c without a Rare-Earth Element, Jap. J. Appl. Phys, 27, 2, 1988.*

[4] *Z. Z. Sheng, A. M. Hermann, Bulk Superconductivity at 120 K in the Tl-Ca/Ba-Cu-O System,. Nature, 332 (6160), 1988.*

[5] *C. P. Bean, Rev. Mod. Phys., 36:31, 1964.*

[6] *B. C. Dodrill, Critical Current Determinations for high T_c Superconductors: Magnetic Measurements and Bean's Model, Lake Shore Application Note, 1992.*

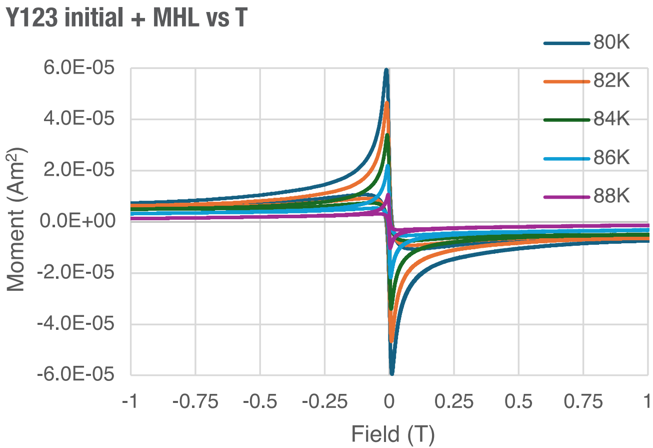

Figure 9
Initial and MHLs for Y123.

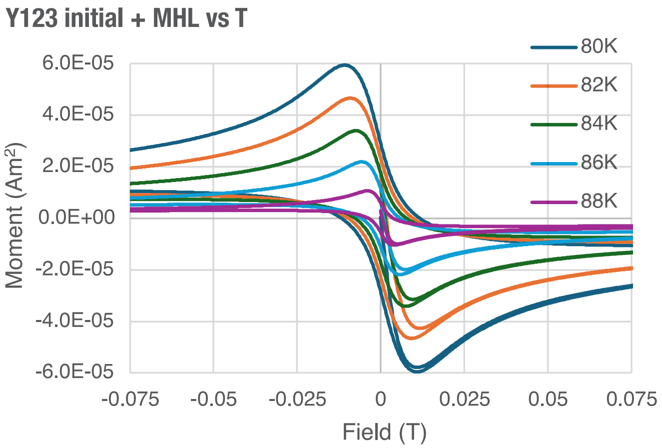

Figure 10
Expanded plot of low field region.