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EXPERIMENTS WITH A 31-CM HIGH-T_c SUPERCONDUCTING THIN FILM TRANSMISSION LINE

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Electrical time domain measurements and transmission response measurements were made using a 31 cm long, YBaCuO superconducting thin film microstrip line and a YBaCuO ground plane, each on separate 1 cm $LaGaO_3$ substrates, with a 125 μm sapphire substrate serving as the dielectric insulator. Degradation of the performance of the line for currents up to the critical current density and for magnetic fields moderately above the lower critical magnetic field H_{C1} were evaluated in a variety of simple measurements.

INTRODUCTION

Simple, idealized models of superconducting microstrip transmission lines suggest a nearly vanishing intrinsic dispersion and very low signal attenuation at temperatures $T \ll T_c$, T_c the transition temperature and at signal frequencies $\omega \ll \omega_g$, ω_g the gap frequency (several THz for the new high-T_c superconductors). The implication is that such superconductors may be superior to normal metal for electronic system inerconnections [1,2]. Thick-film superconductors are limited by their granular structure introducing considerable attenuation relative to the intrinsic attenuation of an ideal superconductor [3]. Thin film superconductors may show more nearly ideal behavior, limited by the quality of the dielectric rather than granular structure of the superconducting material. Indeed, early optical measurements of pulse propagation demonstrated the potentially high performance on short striplines (a few mm in length) [4,5]. Microwave cavity and resonator measurements samples are the preferred methods for evaluation of high frequency surface impedance and similar very high frequency effects [6,7], though the exposed surface rather than the superconductor/dielectric interface is typically evaluated [8]. Direct electrical measurements on long length microstrip interconnections, which directly probe the engineering issues that impact chip-to-chip and other intra-system interconnections, are described here.

We present the results of initial measurements on a 31 cm long YBaCuO superconducting thin film microstrip interconnection and a separate YBaCuO superconducting ground plane, both on lanthanum gallate substrates, with a sapphire dielectric sparating the two conductors. The specific initial results presented here are (1) signal delay measurements using a conventional, electrical time-domain reflectometer (TDR) system, (2) RF transmission measurements, (3) critical current (J_c) measurements based on transmission attenuation criteria, and (4) distortion measurements evaluating behavior at magnetic fields exceeding H_{C1}.

TEST STRUCTURE

Approximately 4000Å thick, YBaCuO thin films were deposited on lanthanum gallate substrates [10,11] using coevaporation from separate Y, Cu and BaF_2 sources with e-beam heating of the Y source and resistive heating of the Cu and BaF_2 sources as described in [9]. Patterning was obtained by liftoff, with coevaporation directly onto a patterned photoresist layer overlaying the substrate. Following liftoff of the unwanted YBaCuO film, the patterned amorphous films were annealed in a tube furnace with a flowing oxygen environment. A gold thin film for contacts was separately deposited, using a shadow mask, directly on the annealed YBaCuO film, without subsequent annealing.To minimize degradations in the microstrip performance due to unexpected dielectric effects, a sandwich structure using a sapphire substrate was used in the electrical measurements below.

Figure 1 illustrates the sandwich structure. Here, a sapphire

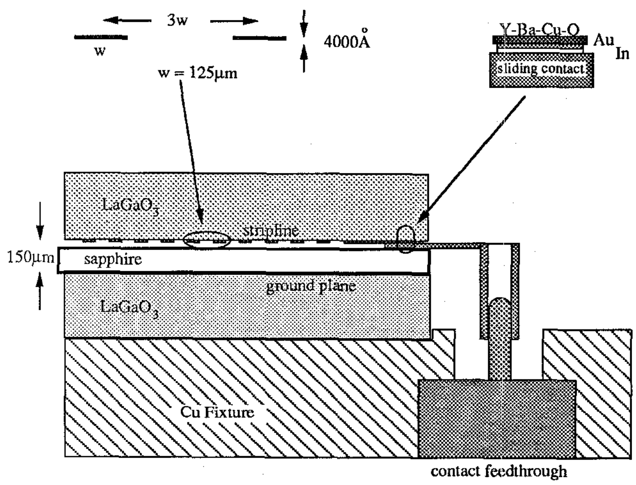

Figure 1: Sandwich of sapphire substrate and superconducting films used for microstrip test structure.

substrate provides the dielectric layer between the patterned superconducting lines and the superconducting ground plane. The penetration of electric fields into the superconductor film substrates is minimized, though not eliminated, in such a structure. Electrical connection from the rigid miniature coaxial cables' connectors to the gold film overlaying the ends of the superconductor line was obtained by pressing a thin layer of indium between the gold film and the connector pin. Completing the external electrical connections to the superconductor imposed a small ($\approx 25\mu$m) air gap between the superconducting thin film and the sapphire substrate.

Figure 2 shows the serpentine microstrip pattern, generated as a spiral to compress as long a length as possible onto the 1 cm substrate. The lines were 125μm wide with 375μm center-to-center spacing. The sapphire substrate (C axis normal), with

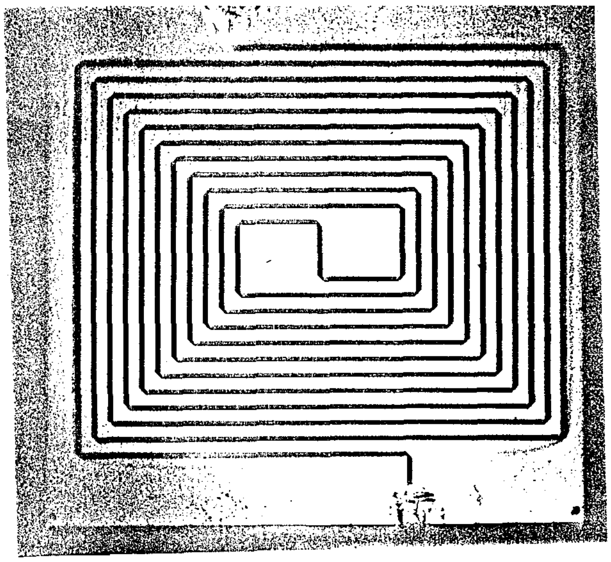

Figure 2: Serpentine microstrip pattern providing 31 cm long line on 1 cm substrate.

dielectric constant $\epsilon_r = 11.6$ in the substrate plane and $\epsilon_r = 9.4$ normal to its plane, was 125μm thick, giving an approximately 50Ω characteristic line impedance. The overall length of the microstrip line was 31 cm, allowing straightforward electrical measurements of its behavior. However, coupling between adjacent straight-line segments of the line structure gives rise to an analog filtering of signals transmitted through the line, as illustrated later. The coupling can also produce distortion of signals observed in reflection measurements.

Figure 3 shows the DC resistance as a function of temperature. The residual resistance ($< 1\Omega$ below 30°K) is the resistance of the pressure contacts between the coaxial cables and the thin-film superconductor. The transition is sharp, indicating a high quality film. The absence of a resistive tail below T_c suggests well coupled grains, without weak links dominating the transport current paths [9,12]. The small intercept of the normal state resistance at T = 0° implies good epitaxial growth with a high proportion of the crystallites oriented with c-axis normal to the substrate [9,12].

ELECTRICAL CHARACTERISTICS

In this section, initial results from various simple electrical measurements are summarized. The intent here is to clarify some

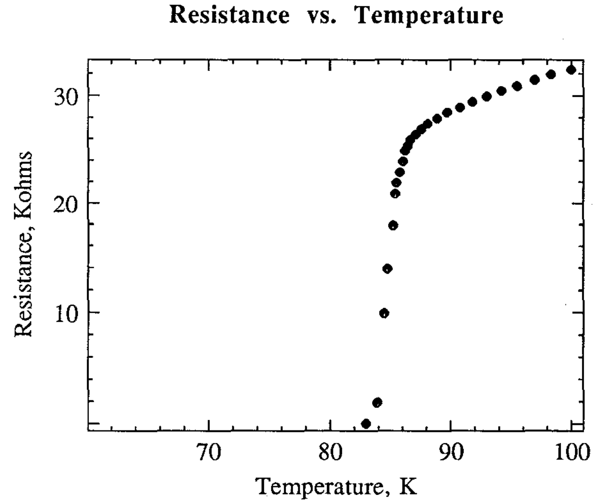

Figure 3: Two-point measured DC resistance of 31 cm line, including contact resistances.

issues that arise in the application of high-T_c superconductors to chip-to-chip interconnections and other interconnection applications within digital systems.

Signal Delay

Pulse propagation delay along the microstrip was measured using time domain reflectometry techniques, with the far end rigid coaxial cable left open. The impedance discontinuities at the contacts to the superconducting line provide convenient signatures for delay measurements. Assuming that the rigid cables merely add a constant delay, the signal delay variation with temperature through the superconducting line can be obtained from the reflection delay variation from the far end of the miniature coaxial cable. The overall delay, $\tau_{ms} \approx 6ns$, is consistent with the dielectric constant of sapphire. Using an HP 54120A digitizing oscilloscope, small delay variations were readily measured, both using TDR with step inputs and using transmission measurements of single frequency signals. The TDR delay measure-

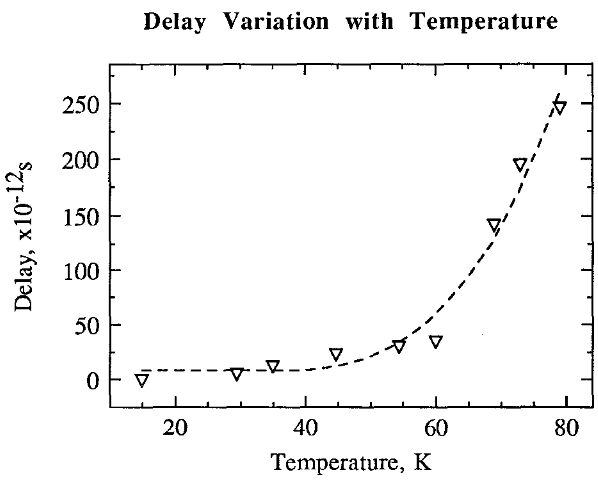

Figure 4: TDR measured delay variation with temperature.

ments would have been difficult had there been any significant change in the waveform (or its amplitude) of the reflected signal with variation of temperature below $T = T_c$. However, no significant change in the reflected waveform, aside from the change in delay, was observed below $0.6T_c$.

The temperature dependence of the signal delay depends on the dimensions and geometry of the transmission line. Figure 4 shows the experimental variation of signal delay with temperature for the 31 cm microstrip line used here (the dashed line merely illustrates the results and is not a theoretical fit). Dykaar et al [5], using optical techniques and a coplanar structure, also present delay variation with temperature. Our results show a delay variation of less than 0.3% between 15°K and 60°K. The increasing delay as $T \to T_c$ is a result of the changing interrelationship between the real and imaginary parts of the surface impedance, as discussed in [5]. Numerical evaluations of the surface impedance using the Mattis-Bardeen formulation are necessary to model this regime and the simplified analysis in [1] does not hold near $T = T_c$. Since superconducting interconnection applications would operate at temperatures well below T_c, the behavior near T_c is of interest only for special applications, e.g. providing a precise signal delay function as discussed by Hatamian et al [13].

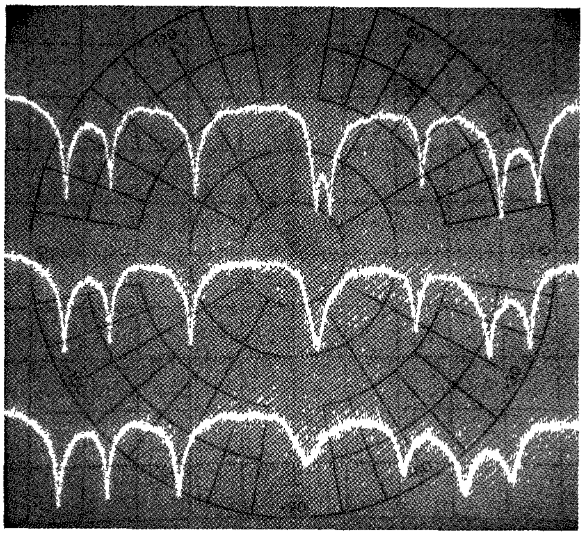

Figure 5: Transmission amplitude response of 31 cm microstrip line (scale is 20dB per grid line) from 0 to 1.2 GHz. Top trace - 76.4K (with little change at temperatures below 76.4K). Middle trace - 80.6K showing dampening of response zeroes. Lower trace - 83.6K showing increased dampening of response zeroes.

RF Transmission Results

As noted earlier, the serpentine structure of the superconducting microstrip line leads to coupling between adjacent lines and the imposition of a filter response function on the transmission results. Indeed, superconducting films offer several major advantages for analog signal processing applications [14]. Figure 5 shows the transmission-mode amplitude and phase response of the line, measured with an HP 8505A network analyzer. For temperatures below about 76K, the spectral response exhibits no significant dependence on temperature and has the behavior shown in the upper trace of Figure 5. As $T \to T_c$ from below, the contribution of the normal state resistance becomes large relative to the kinetic inductance of the paired electrons, leading to an increasing "dampening" of the response zeros as T approaches T_c, as seen in the middle and lower traces in Figure 5. At $T > T_c$, the line's attenuation increases strongly due to the line resistance (about 30kΩ). Evaluation of the expected response for the specific microstrip structure used here is in progress and depends on the electromagnetic coupling between lines. For purposes here, the distinctive transmission response provides a signature against which various non-linear effects and changes in line characteristics can be evaluated. No significant dependence of the transmission response on temperature was observed below $0.8T_c$.

Critical Current Measurements

The YBaCuO films have high critical current densities J_c, corresponding to effective pinning of vortices at defect sites. The relatively wide microstrip lines made critical current measurements difficult since relatively large absolute current levels are required (i.e. 0.5 amps to obtain current densities of 10^6 A/cm^2 for the 4000Å thick and 125μm wide lines). However, it was possible to obtain a measure of critical current densities at $T > 68^oK$ by observing the onset of attenuation of a single frequency signal transmitted through the line. Superimposing a DC current on a small 20 MHz AC signal, the critical current was defined as that DC current producing a 1 dB attenuation of the 20 MHz fundamental, as measured using an HP 8559A spectrum analyzer. Figure 6 shows the measured critical current densities, using the microstrip's physical cross sectional area to normalize the applied current. The critical currents here ($J_c(H = 0) \approx 10^5 A/cm^2$) are similar to the high critical current densities reported by others, e.g. [12].

The critical current in the case discussed above arises from magnetic fields exceeding H_{C1} being induced by the current flow in the microstrip line. Although H_{C1} has not been well established for the specific film used here, similar films have $H_{C1} \approx 10 \to 100$ Gauss. Since the flux lines are driven by the current (i.e. by the Lorentz force $\mathbf{J} \times \mathbf{B}$), several of the measurements investigating the effect of $H > H_{C1}$ on line characteristics used both line current induced magnetic fields and externally applied magnetic fields. In particular, a permanent magnet inducing a field of about 400 Gauss normal to or parallel to the plane of the superconducting microstrip lines was used to roughly check the effect of a higher vortex density. No significant change in the critical current densities were observed below about $0.8T_c$ with

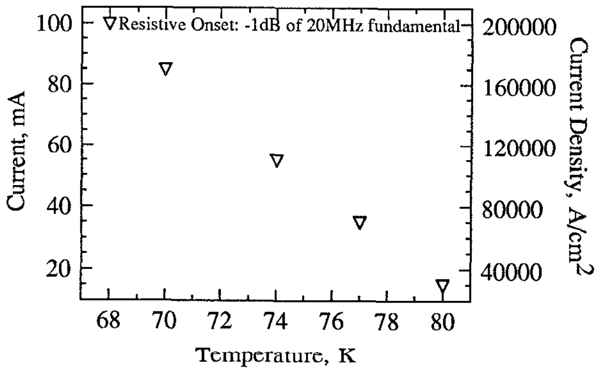

Figure 6: Critical current density from transmission response measurement.

the 400 Gauss external field[1].

Nonlinear Effects

For magnetic fields less than the lower critical field H_{C1}, the Type II YBaCuO superconductor is expected to exhibit the behavior of a typical, classical superconductor, i.e. expulsion of external magnetic fields. Most applications-oriented analyses of loss and attenuation in superconducting microstrip interconnections assume fields below H_{C1}. However, above H_{C1}, magnetic field penetrates the superconductor. Depending on the response of these vortices, one might expect the microstrip's behavior to change when moving from the flux-expulsion state below H_{C1} into the mixed state above H_{C1}.

Non-linear behavior of the line at fields exceeding H_{C1} was investigated by monitoring the harmonics of sinusoids under various conditions. In particular, the following results were observed.

A: With zero DC current and at temperatures well below T_c, no significant change in the first two harmonics (higher order harmonics were not resolvable) of the fundamental were observed in transmission as the amplitude of the fundamental was varied between -40 dBm and +10 dBm at fundamental frequencies of about 50 MHz. Application of the external, normal magnetic field as discussed earlier did not produce a significant change in the first two harmonics under these amplitude variations.

B: With the sinusoid superimposed on a DC current and temperatures well below T_c, no discernible change in the amplitude of the fundamental or of the harmonics was observed until current levels approaching the critical current. Again, application of the external magnetic field did not change these results.

C: No significant change in the magnitude and phase response of the line in transmission was observed, at temperatures well below T_c and currents well below the critical current, in response to changes in the signal amplitude and/or an external magnetic field.

These observations suggest that current near or exceeding the critical current density, and not magnetic fields exceeding H_{C1}, is the major factor degrading the performance of the superconducting microstrip line. Most single frequency measurements were made with 50 MHz sinusoids while spectral measurements were limited to 1.2 GHz by the network analyzer used. Higher frequency effects are therefore not excluded here. Extension of the measurements to higher frequencies, to higher external magnetic fields and to direct measurements of pulse distortion are clearly warranted before high-T_c microstrip interconnections can be adequately evaluated. However, the results here suggest that there are no major changes in the basic characteristics of the line until currents approach the critical current or the temperature approaches the transition temperature.

[1]Note that this does not imply the absence of high magnetic field effects but rather that magnetic fields likely to be encountered in interconnection applications do not appear to have a significant effect on the line's behavior. Much higher magnetic fields (above 1 tesla) are typically used to observe high magnetic field effects.

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