Abstract

High-quality oriented thin films of YBa2Cu3O7-δ having transition temperatures > 88 K and critical current densities at 77 K, zero magnetic field > 10^6 A/cm² have been made by pulse laser deposition on <100> MgO and LaAlO₃ substrates. The microwave surface resistance (Rₛ) has been measured between 20 K and 120 K at 36 GHz by a copper cavity end-wall replacement technique. Rₛ measurements show consistently sharp transitions having high critical temperature onsets with low residual surface resistances (< 10 mΩ at 36 GHz and 77 K). Microwave devices fabricated from films on MgO have included an X-Band modified 5-pole Chebyschev filter having an insertion loss of ~ 8 dB at 77 K. Irradiation of unpatterned films on LaAlO₃ with 2 MeV H⁺ ions at a fluence increment of 10¹⁶/cm² resulted in only a small shift (~ 2 K) in the 36 GHz microwave transition temperature. No accompanying degradation in the residual surface resistance was observed within the sensitivity of our measurement.

Film Deposition

YBa₂Cu₃O₇-δ thin films (~500-nm thick) on <100> oriented MgO were made in situ by pulse laser deposition (PLD). The output from the excimer laser (Lambda Physik 315) operating on KrF was focused with a 50-cm-focal-length lens onto a rotating YBa₂Cu₃O₇-δ target, achieving an energy density of ~2 J/cm². The substrate was mounted on an electrically isolated substrate heater approximately 3 cm from the target. Films were deposited at 750 °C in 300 mTorr of oxygen and then quenched to room temperature in one atmosphere of oxygen. Films prepared this way were superconducting as deposited and required no further processing. Analysis by x-ray diffraction indicated that the films were oriented with the c-axis perpendicular to the plane of the substrate.

Film Characterization

The transition temperature Tc and critical current density Jc were measured using a technique which requires neither electrical contact nor film patterning, thus allowing the use of the film for surface resistance measurements and device design. To measure Tc, a multi-turn pancake coil is pressed against the film and driven by a 10-kHz, 0.3-mA current. For temperatures below Tc, the appearance of superconducting shielding currents in the film are detected as a drop in inductance of the coil. This drop is observed close to the zero-resistance Tc point normally observed in resistance measurements. To measure Jc, the frequency of the driving current is lowered to 1 kHz, the temperature is fixed at 77 K or 4.2 K, and the amplitude of the driving current is increased monotonically. Once the amplitude of the induced shielding current reaches Jc, the current sheet in the film is distorted temporally and odd-harmonic components of the coil current are generated. Jc is determined by the rapid onset of the third-harmonic component of the coil current. Typically these films had Tc's exceeding 88 K, and at 77 K, Jc's exceeding 10⁶ A/cm² in zero magnetic field.

Microwave Surface Resistance

Cavity Technique

The microwave surface resistance was measured as a function of temperature at 36 GHz by means of a cavity end-wall replacement technique. An oxygen-free-high-conductivity (OFHC) copper cavity was mounted on the cold stage of a closed-cycle helium refrigerator capable of being controlled between 20 K and 300 K. Coupling to the cavity was achieved by means of loop antennas formed at the ends of 2.16-mm-diameter stainless-steel coaxial cable which were press-fit into holes placed to excite the TEM₁₁ circular mode. The magnitude of the coupling was adjusted so that the insertion loss of the cavity remained below ~ 35 dB, thus achieving severe undercoupling. The transmission coefficient |S₂₁| versus frequency was measured employing an HP8510B network analyzer. Because of the severe undercoupling and consequent large insertion loss, the resonant frequency, unloaded Q, and transmission coefficient at resonance were accurately determined from the time-averaged, but still noisy transmission data by applying an orthogonal-polynomial least-squares fitting algorithm to the data. By comparing the Q of the cavity with a superconducting end wall with the Q of the cavity with a reference OFHC copper end wall, the surface resistance of the superconducting film could be determined.

Results

The surface resistance vs. temperature for typical films grown on MgO and LaAlO₃ are shown in Fig. 1. The films are ~500 nm thick, and are grown on 16-mm-square substrates. Both examples indicate comparable normal state Rₛ, steep drops at the 88 K - 90 K transitions, and relatively temperature-independent behaviour below the transition. The sharp microwave transition over a narrow temperature range to a value less than that of copper is an indication of a high degree of c-axis orientation in the films. Plotted in Fig 2 are error bars for the determination of Rₛ from the cavity Q data. It can be seen that when the surface resistance falls significantly below the copper background resistance, the uncertainty grows pronounced. By assuming an f² and f¹/² frequency dependence for the superconductor and the metal respectively, we can establish an upper bound for the X-band surface resistance for these films which is no worse than 15 times better than copper at 77 K.

Radiation Effects

To explore the film's response to high-energy particle radiation, and thus demonstrate the feasibility of operating high-Tc microwave devices in satellite environments, films grown on LaAlO₃ were subjected to a sequence of proton (H⁺) irradiations.
The particle energy was 2 MeV, which is sufficient to produce uniform damage throughout the 500 nm film thickness. Previously, it had been shown that the depression of $T_c$ caused by the interaction of energetic particles with high-temperature superconductors is directly proportional to the non-ionizing energy loss of the incident particle. At a fluence of $10^{16}$/cm$^2$, the predicted decrease in $T_c$ is ~2 K. It should be noted that this dose greatly exceeds the typical exposure experienced in space flight applications.

The demonstration device chosen was a 5-pole microstrip parallel-coupled-line Chebyschev bandpass filter on MgO. Two filters were made, one having a designed center frequency of $f_0=10$ GHz and a bandwidth of 400 MHz, the other having a designed center frequency of $f_0=9.1$ GHz and a bandwidth of 300 MHz. The filters were arranged to fit on 16 mm x 16 mm x 0.254 mm MgO substrates. Because of the length of the basic filter topology and the need to have the input and output ports accommodated by the package and cryogenic test platform, the classic parallel-coupled-line design was bent around the perimeter of the substrate by the insertion of a half-wavelength microstrip line into the center of the filter. This doubled the length of the center resonator, and added narrow-band transmission maxima at $f_0/2$ and $3f_0/2$. The filter designs were then optimized using commercial CAD software (Touchstone). The mask used is depicted in Fig. 4.

Patterning was accomplished by standard photolithography, using Shipley AZ1350J resist. The YBa$_2$Cu$_3$O$_7$-δ film was etched in a warm (50 C) saturated solution of EDTA. The backside of the substrate was cleaned of the residual silver paste which remained from the deposition process by lapping with 0.3 μm alumina.
polishing grit in isopropyl alcohol. The ground plane was applied to the filter either by clamping the substrate tightly to the microwave test fixture, or by first evaporating 10 nm of chromium, 3000 nm of copper, and 200 nm of gold onto the backside and then clamping to the package. Standard wirebonds were then made from microwave connectors on the package to silver-epoxy contact pads placed on the input- and output-port microstrip lines.

Measurement Results

Calibration of the HP8510B network analyzer was carried out by employing HP's calibration standards, at 300 K, at the planes of device insertion on the same cold stage as used for the $R_S$ measurements. To measure the change in insertion loss experienced by the short lengths of 50 $\Omega$ stainless-steel coaxial cable which entered the cryostat (approximately 10 cm of 3.58 mm diameter at each port), a through connection mounted on the cold stage was measured as a function of temperature. It was thus determined that the magnitude of the error in $|S_{21}|$ due to cooling a portion of the room-temperature-calibrated test cables was about 0.1 dB in the filter bandwidth.

Plots of the transmission coefficient for each filter as a function of temperature are displayed in Figs. 5 and 6. The return loss of the first filter is shown in Fig. 5. For the $f_0=10$ GHz filter which uses the OFHC copper test fixture for the ground plane, there existed a small gap separating the bottom of the bare substrate from the top of the ground plane, thus lowering the effective dielectric constant and shifting the center frequency upward by approximately 450 MHz. The return loss for this filter is nevertheless better than 14 dB. The second filter, with an evaporated copper film for a ground plane, was mounted in a fixture using spring pressure contacts to effect a ground connection to the package ground. The integrity of this connection is somewhat variable, leading to a resonance in the passband. Fig. 6 shows the insertion loss for the second filter at temperatures of 20 K, 77 K and 82 K.

![Fig. 4 Mask design for the $f_0=9.1$ GHz bandpass filter. The center half-wavelength section allows the filter to comfortably fit on a 16 mm x 16 mm substrate.](image)

![Fig. 5 Insertion loss and return loss at 77 K for the superconducting filter whose ground plane comprises the top surface of the OFHC copper test fixture.](image)

![Fig. 6 Superconducting filter insertion loss at 20 K, 77 K, and 82 K. The ground plane is a 3000 nm copper film evaporated on the substrate.](image)
Summary

Superconducting thin films made by pulsed laser deposition have been shown to produce high quality films on <100> MgO and LaAlO3 having high Tc's and Jc's. The films' surface resistance has been measured at 36 GHz versus temperature and found to be significantly better than copper at 9 GHz and 77 K. Irradiation of these films with 2 MeV H+ ions at a fluence of 10^{16} cm^{-2} resulted in only a ~ 2 K in the 36 GHz microwave transition temperature, with no accompanying degradation in the residual surface resistance. Microstrip parallel-coupled-line bandpass X-band filters have been fabricated from films deposited on MgO. The best results indicate an insertion loss minimum of ~ 0.8 dB at 77 K.

Acknowledgement

The authors would like to thank D. C. Webb, M. Nisenoff, C. Rauscher, and H. E. Heddings for their contributions to this work. Support for this project was provided in part by the NRL High Temperature Superconducting Space Experiment program.

References


