

MICROWAVE DEVICES USING $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ FILMS MADE BY PULSED LASER DEPOSITION

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Abstract

High-quality oriented thin films of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ having transition temperatures > 88 K and critical current densities (at 77 K, zero magnetic field) $> 10^6$ A/cm² have been made by pulsed laser deposition on $< 100^\circ$ MgO and LaAlO_3 substrates. The microwave surface resistance (R_s) has been measured between 20 K and 120 K at 36 GHz by a copper cavity end-wall-replacement technique. R_s measurements show consistently sharp transitions having high critical temperature onsets with low residual surface resistances (< 10 m Ω at 36 GHz and 77 K). Microwave devices fabricated from films on MgO have included an X-Band modified 5-pole Chebyshev filter having an insertion loss of ~ 8 dB at 77 K. Irradiation of unpatterned films on LaAlO_3 with 2 MeV H^+ ions at a fluence increment of 10^{16} /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

$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films (~ 500 -nm thick) on $< 100^\circ$ oriented MgO were made *in situ* by pulsed laser deposition (PLD). The output from an excimer laser (Lambda Physik 315) operating on KrF was focused with a 50-cm-focal-length lens onto a rotating $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ 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 T_c and critical current density J_c were measured using a technique which requires neither electrical contact nor film patterning, thus allowing the later use of the film for surface resistance measurements and device design.¹ To measure T_c , a multi-turn pancake coil is pressed against the film and driven by a 10-kHz, 0.3-mA current. For temperatures below T_c , 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 T_c point normally observed in resistance measurements. To measure J_c , 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 J_c , the

current sheet in the film is distorted temporally and odd-harmonic components of the coil current are generated. J_c is determined by the rapid onset of the third-harmonic component of the coil current. Typically these films had T_c 's exceeding 88 K, and at 77 K, J_c 's exceeding 10^6 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.² 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 TE₀₁₁ 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 $|S_{21}|$ 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 LaAlO_3 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 R_s , 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.³ Plotted in Fig. 2 are error bars for the determination of R_s 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 f^2 and $f^{1/2}$ 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- T_c microwave devices in satellite environments, films grown on LaAlO_3 were subjected to a sequence of proton (H^+) irradiations.

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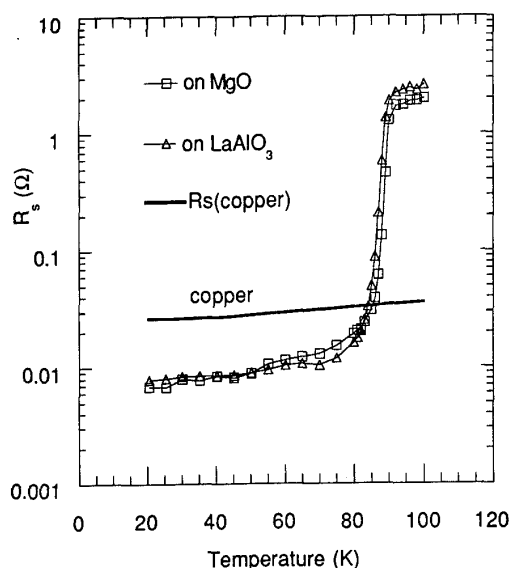


FIG.1. 36 GHz microwave surface resistance of 500 nm YBCO thin films made by pulsed laser deposition on MgO and LaAlO₃. The surface resistance of copper is shown for reference.

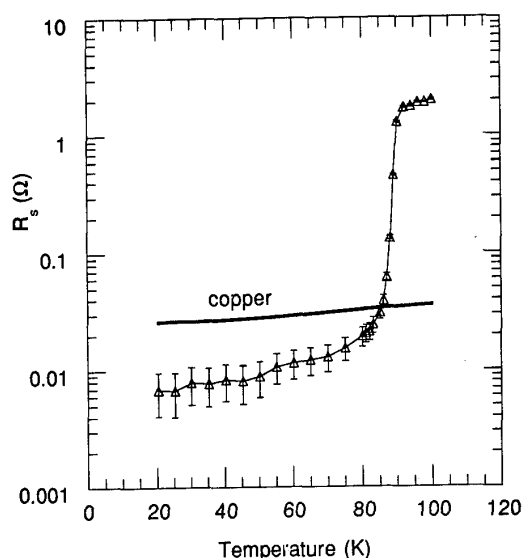


FIG 2. Plot showing the error accompanying the surface resistance measurement. The uncertainty increases as the YBCO surface resistance improves significantly over copper.

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.⁴ At a fluence of $10^{16}/\text{cm}^2$, the predicted decrease in T_c is $\sim 2\text{ K}$.⁴ It should be noted that this dose greatly exceeds the typical exposure experienced in space flight applications.

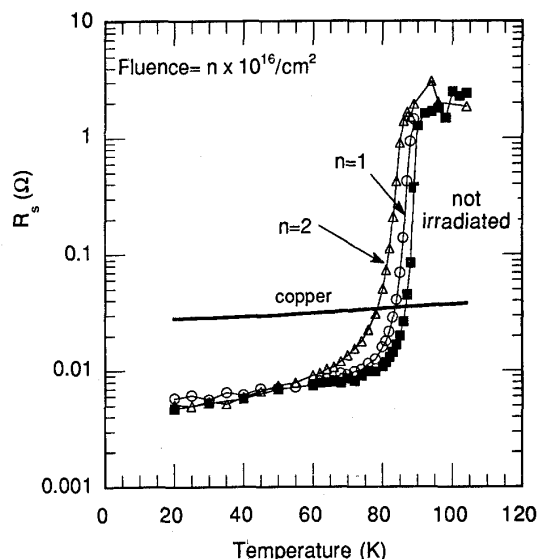


Fig. 3 Effects of 2 MeV proton irradiation on the 36 GHz surface resistance of PLD YBCO on LaAlO₃

Fig. 3 contains a plot of the 36 GHz surface resistance vs. temperature for one irradiated film, for fluences of $1 \times 10^{16}/\text{cm}^2$ and $2 \times 10^{16}/\text{cm}^2$. It can be seen that the effect of irradiation is to produce a decrement in the transition temperature measured at microwave frequencies, similar to that observed in the earlier dc measurements. The sharpness of the transition remains unchanged. Of note here is the relative indifference of the residual surface resistance to radiation damage, for these fluence levels.⁵ The measurements show that for high-quality films, there should be little change in microwave device performance at temperatures below $\sim 0.8 T_c$.

5-pole Modified Chebyshev Filter

The demonstration device chosen was a 5-pole microstrip parallel-coupled-line Chebyshev bandpass filter on MgO. Two filters were made, one having a designed center frequency of $f_0=10\text{ GHz}$ and a bandwidth of 400 MHz, the other having a designed center frequency of $f_0=9.1\text{ GHz}$ and a bandwidth of 300 MHz. The filters were arranged to fit on $16\text{ mm} \times 16\text{ mm} \times .254\text{ mm}$ 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 YBa₂Cu₃O_{7- δ} film was etched in a warm (50 C) saturated solution of EDTA.⁶ The backside of the substrate was cleaned of the residual silver paste which remained from the deposition process by lapping with $0.3\text{ }\mu\text{m}$ alumina

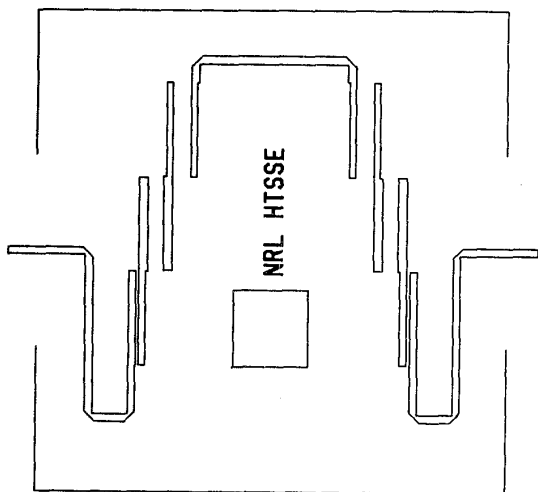


Fig. 4 Mask design for the $f_0=9.1$ GHz bandpass filter. The center half-wavelength section allows the filter to comfortably fit on a 16 mm x 16 mm substrate.

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 Ω 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.

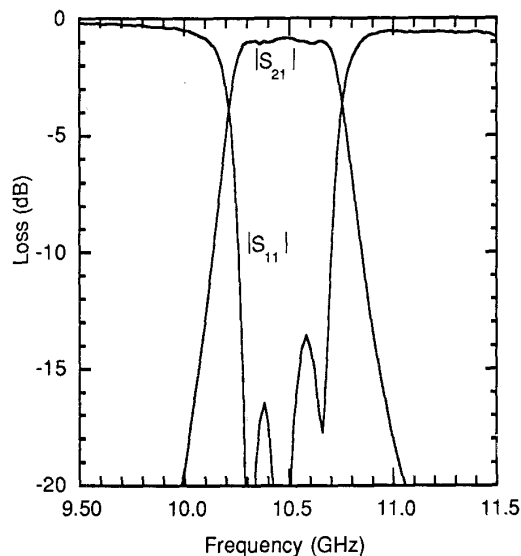


Fig. 5. Insertion loss and return loss at 77 K for the superconducting filter whose ground plane comprises the top surface of the OFHC copper test fixture.

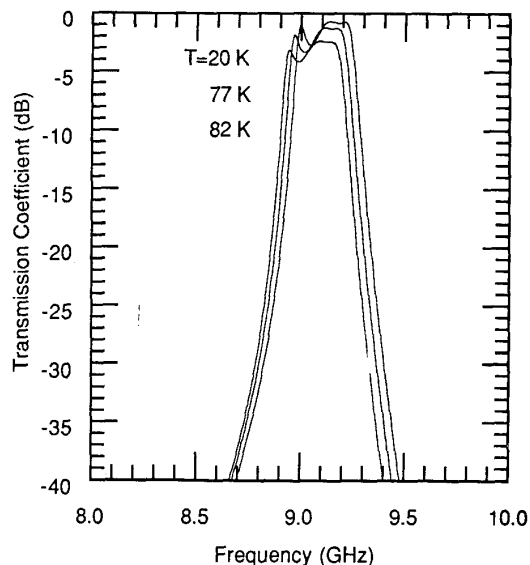


Fig. 6 Superconducting filter insertion loss at 20 K, 77 K, and 82 K. The ground plane is a 3000 nm copper film evaporated on the substrate.

Summary

Superconducting thin films made by pulsed laser deposition have been shown to produce high quality films on $\langle 100 \rangle$ MgO and LaAlO_3 having high T_c 's and J_c '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 $10^{16}/\text{cm}^2$ 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 ~ 8 dB at 77 K.

Acknowledgement

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