Evaluation of Superconducting Tl–Ca–Ba–Cu–O Thin-Film Surface-Resistance Using a Microstrip Ring Resonator

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***Abstract*—The use of thin-film superconductors for microwave applications critically depends on the material parameters of surface resistance and penetration depth. These parameters are generally difficult to measure. A measurement technique is presented using microstrip ring resonators and contactless probing that determines these critical parameters. Analysis accounting for field penetration into the conductors is also presented. Normal metal resonators are used to calibrate/verify the measurement. The surface resistance of a Tl–Ca–Ba–Cu–O superconducting thin film measured at 8.03 GHz and 77 K was found to be about 0.5 mΩ.**

MICROSTRIP ring resonators are commonly used to study material parameters because of their low radiation loss, ease of launching, and lack of end effects [1], [2]. To date, these experiments have been done for conductors assumed to be considerably thicker than their skin/penetration depth. Ring resonator measurements typically use ordinary microstrip lines for the signal launch. In the present work, a contactless probing technique is used. The apparatus is shown schematically in Fig. 1. It allows for two-port measurements with continuously adjustable coupling.

To include the effects of field penetration in the analysis, standard microstrip loss results cannot be used (e.g., [3]). Instead, a phenomenological loss equivalence method (PEM) developed by Lee and Itoh [4] is implemented which makes no assumption about film thickness. This procedure converts the microstrip line into an equivalent transmission line that has identical external energy storage and excess internal impedance (Z_x) due to the top conductor. This excess internal impedance is due to field penetration into the metal conductor.

From Lee and Itoh [4], the equivalent strip width (W_e) is found by

$$1/W_e = \frac{1}{\mu}\sum_j (\partial L/\partial n_j) \tag{1}$$

in which the sum j is over the top conductor's boundaries, and L is the inductance per unit length of the line. Using semiempirical expressions for microstrip lines [3] and applying (1), gives

$$W_e = \frac{2\pi(32h^2 + w^2)}{32h - w^2/h + 64h^2/w - 2w} \tag{2}$$

Manuscript received December 6, 1990. This work was supported by the U.S. Department of Energy under Contract No. DE-AC04-76P00789, and by DARPA, ONR, and SDIO under Contract No. N0017390W00172.

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IEEE Log Number 9143086.

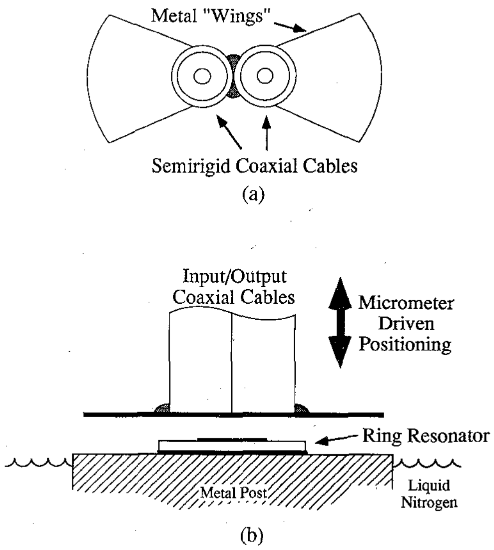

Fig. 1. Contactless probing technique for microstrip ring resonators. (a) End view of contactless probe. (b) Side view of probe positioned over ring resonator.

in which w is the width of the top conductor and h is the dielectric thickness. The equivalent strip thickness (t_e) is found by [4]

$$t_e = t(w/W_e), \tag{3}$$

where t is the thickness of the top conductor.

The excess internal impedance is given by [4]

$$Z_X = (Z_s/W_e)\coth\left[\sqrt{j\omega\mu\sigma}\, t_e\right] \tag{4}$$

where Z_s is the surface impedance and σ is the conductivity both of the top conductor. In the case of a superconductor, the surface impedance is given by [5]

$$Z_s = R_s + j\omega\mu\lambda_{\text{eff}} \approx \frac{1}{\sigma\lambda_{\text{eff}}} \tag{5}$$

where $R_s(t, \omega)$ is the surface resistance, $\lambda_{\text{eff}}(T)$ is the effective penetration depth, and σ is the conductivity. For normal conductors Z_s is simply $(1 + j)\sqrt{\omega\mu/2\sigma}$.

With the excess internal impedance known, the conductor attenuation coefficient (α_{top}) and the propagation constant (β) of the line are found from

$$\alpha_{\text{top}} + j\beta = \sqrt{(Z_x + j\omega L_{\text{ext}})(j\omega C_{\text{ext}})} \tag{6}$$

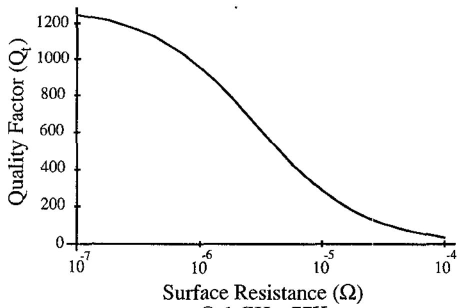

Fig. 2. Theoretical ring resonator Q_t as a function of superconductor surface resistance R_s. The effective penetration depth was fixed at 500 nm.

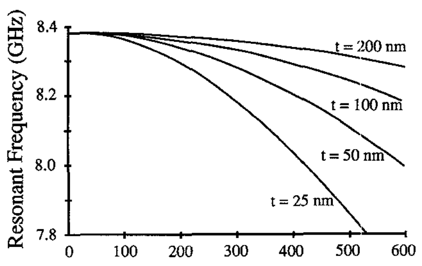

Fig. 3. Theoretical ring resonator resonant frequency (f_o) as a function of superconductor effective penetration depth λ_{eff} for several different top conductor thicknesses (t).

where L_{ext} and C_{ext} are the inductance and capacitance per unit length for the ideal line (no penetration) that can be computed from standard microstrip formulae [3].

Bending effects are ignored since the rings' radii are much greater than their width. This assumption is justified since the resonant frequency of a normal metal resonator was found to be within 0.1% of that predicted assuming no bending effects. Radiation losses are ignored since the radiation quality factor (Q_r) is expected to exceed 10,000 [6], which greatly exceeds the rings' total quality factor ($Q_t < 350$). The gold ground plane and dielectric ($LaAlO_3$) of the resonator also contribute to total loss. These loss mechanisms are accounted for by the loss term α_p, which is determined experimentally with a resonator having a gold top conductor. This loss correction is not very critical since the loss contribution by the top conductor α_{top} was found experimentally to be at least 2.6 α_p for the resonator with the superconducting top conductor. Q of the resonator is approximately

$$Q_t \approx \frac{\beta}{2(\alpha_p + \alpha_{\text{top}})}. \tag{7}$$

Fig. 2 shows a theoretical plot of Q_t vs. surface resistance (R_s) of the superconducting top conductor at the resonant frequency (8.03 GHz). In the calculation, the superconducting top conductor has a thickness of 40 nm and an effective penetration depth of 500 nm. The loss term α_p was the 77 K experimental value given next. One can see that Q_t has good sensitivity to R_s even for very good superconductors.

The effective penetration depth λ_{eff} is measurable due to the frequency shift Δf_o introduced by the kinetic inductance of the superconductor. Fig. 3 shows a theoretical plot of f_o vs. λ_{eff} for film thicknesses of 25, 50, 100, and 200 nm to illustrate measurement sensitivity. Note the reduction of sensitivity as the film thickness increases. The superconductor's thickness must be significantly less than λ for this technique to be accurate.

The rings used in the experiment were designed with a 50 Ω characteristic impedance on $LaAlO_3$ substrates of nominal thickness 520 μm. The rings' mean diameter was 3 mm and the line width was 125μm. Probing was done with the contactless system shown in Fig. 1. The metal "wings" on the probe allow for capacitive coupling to the ground plane in order to achieve efficient rf coupling. The probe was positioned high enough above the test rings (> 1 mm) to allow for the direct measurement of the rings' unloaded Q.

Microstrip rings were constructed with gold ground planes and either gold or aluminum top conductors to calibrate and verify the method. The ground planes were 1 μm thick and the top conducto s were 300 nm thick. For the gold top conductors, 4-point DC measurements gave conductivities of 0.38×10^8 S/m (300 K) and 2.5×10^8 S/m (77 K). These correspond well with the expected theoretical values of 0.41×10^8 S/m and 3.7×10^8 S/m, respectively. Using the measured conductivities, the strip loss α_{top} was computed. From this and the measured ring's Q_T's (45@300 K and 267@77 K), the loss contribution of the gold ground plane and dielectric were found to be $\alpha_p(300 \text{ K}) = 0.92$ Np/m and $\alpha_p(77 \text{ K}) = 0.26$ Np/m. Using these values for α_p, the conductivity of the aluminum verification ring was measured at 300 K to be 0.28×10^8 S/m compared to 0.31×10^8 S/m by DC measurements and 0.37×10^8 S/m theoretical. At 77 K, the aluminum ring's conductivity was found to be 1.5×10^8 S/m compared to 1.7×10^8 S/m by DC measurements and 3.3×10^8 S/m theoretical. The deviations from theoretical are probably due to shorter mean-free paths in the actual films [7].

The Tl–Ca–Ba–Cu–O ring resonators were fabricated on $LaAlO_3$ substrates using gold ground planes as previously described. The superconductor's thickness was about 35–45 nm where the uncertainty is largely due to substrate roughness. The Tl films were made by electron-beam evaporation with subsequent anneal in a procedure described elsewhere [8]. The films had a zero resistance T_c of 102 K with a zero-field J_c of about 250 kA/cm^2 (77 K). Patterning was done with a 2% solution of Br in isopropanol. Measurements performed on two superconducting rings gave Q_t's of 353 and 351 with $f_o = 8.03$ GHz (77 K). This gives a surface resistance of 0.55 ± 0.05 mΩ and an effective penetration depth of 506 ± 32 nm where the error range is due to the film thickness uncertainty. The measured effective penetration depth is somewhat larger than expected. With the very thin films used here, the mean free path is very short and hence the effective penetration depth is large [5].

In conclusion, a technique has been demonstrated for measuring the surface resistance and penetration depth of thin superconducting films using a fast and simple contactless probing technique. Films of Tl–Ca–Ba–Cu–O showed a surface resistance about a factor of 16 less than that of gold at 8 GHz and 77 K.

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