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High Frequency broadband characterization of Metal/High Tc superconducting coplanar structures

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Abstract

High Tc structures have raised a great interest for microelectronics applications. We have investigated two layer coplanar structures made of an Ag layer (200nm) sputtered on YBaCuO (300nm). The typical structures are 50Ω coplanar lines and resonator bandpass filters (24 GHz) analyzed from 45MHz to 30GHz. Coplanar lines are studied in the normal and superconducting states whereas filter shows transmitted signals only in the superconducting state. We propose a phenomenologic model taking into account the two layers and their interface. At 60K and 10GHz, the Rs of our YBaCuO layer is roughly 1.5mΩ. A good consistency is observed among the different lines and resonating measurements.

1. Film deposition and characterization

A ~ 300 nm thick $YBa_2Cu_3O_7$ thin film has been *in-situ* deposited by laser ablation on a 12 x 12 mm^2 (100) MgO substrate at 750° C, under an oxygen pressure of 0.3 mbar. More details about the deposition process are given in ref [1]. The epitaxial growth of the film (i.e. alignment of the film crystal axes with those of the substrate) has been verified *in-situ* by reflection high energy electron diffraction (RHEED). Standard θ-2θ x-ray diffraction has showed the pure c-axis orientation, and θ-scan (rocking curve) around the (005) peak has a full width at half maximum (FWHM) of 0.42° confirming the good crystallization of the film.

Before patterning, narrow superconducting transition (~2K between 0 and 100%) has been observed by resistive measurements with Tc (R=0) at 86K.

The $YBa_2Cu_3O_7$ film is silver coated with a 200nm thick layer after an *in-situ* ion beam precleaning process. The silver film is then sputtered at room temperature. The resulting bilayer is then patterned using standard contact lithography and ion-milling.

2. Coplanar structures

The MgO substrate thickness is 500μm with no background metal plane. Two types of structures are patterned with a ground plane completely surrounding them: 50 Ω coplanar lines and symmetrical band-pass filters made with a n.λ/2 50Ω line resonator magnetically side coupled. Table 1 contains nominal geometrical values. Shorts and Through have been added in order to check the calibration procedure. Nominal values must be corrected for an overetching of 2-3 μm mainly due to mask processing.

Table 1. Geometrical dimensions of coplanar structures

Name	Width (μm)	Spacing (μm)	Length (mm)
L1	70	30	8.5
L2	100	45	8.5
L3	70	30	4.2
L4	70	30	2.8
L5	100	45	4.2
L6	100	45	2.8
Filt1	70	30	8.0
Filt2	100	45	8.0

All these structures can be easily probed with a 125μm pitch Ground-Signal-Ground coplanar probe. The filter's coupling coefficient allows easy measurements of the five resonances in the 8GHz-40GHz frequency range.

3.Experimental set-up and parameter extraction

Coplanar S parameters measurements have been carried out using a custom built vacuum cryogenic high frequency probe station connected to an HP 8510C network analyzer.

The present design of cryogenic on-chip microwave coplanar probe station brings improvements in several areas in order to extend the frequency range of accurate on-chip measurements up to the millimeter range: i- temperature control of the microwave probes, sample holder and calibration chips to insure long term stability of the calibrations, ii- easy and fast *in-situ* calibration at each measurement temperature, iii- vacuum chamber to prevent moisture and to provide stable temperature of microwave access cables and probes.

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The cryogenic station operates under vacuum and integrates an ultra flat helium continuous flow cryostat with a cold screen from TBT(Air Liquide) designed for operation in the range 300K-10K. The modular design allows the incorporation of rf probing heads, rf cables, temperature sensors , sample manipulation. Basically similar mechanical motions available in a Cascade type station are provided from outside the vacuum cryostat through bellows to the microwave coplanar heads.

Our cryogenic calibrations use the Cascade LRM standard substrate. The geometrical variations with temperature of Through and Short standards are negligible compared to probe position uncertainties. The impedance of the LOAD standards which have laser trimmed resistors does not vary significantly. Then, these standards are well suited for SOLT and LRM calibrations at low temperature.

The temperature range is 10K-300K with a stability of a few mK at 100K. A key feature is in-situ high accuracy HF calibration (SOLT/LRM) at each measurement temperature.

The measurement results have been compared with simulated structures on a linear microwave simulator (HP-MDS). The simulation uses a physical coplanar model with infinite metal conductance. Width and spacing are modified by the penetration depth λ_L[2] and by overetching. The losses are treated independently by cascading lossless sections with frequency dependant lossy networks (Figures 1-2)

4. Coplanar lines properties

Both transmitted (S12,S21) and reflected (S11,S22) complex scattering S parameters are measured from 45MHz to 30GHz (201 frequency points).

4.1 reflected signals

The line impedances are typically close to 53 Ω, so the reflected signals are very small. They are affected by an impedance change with temperature which is due to a change δl in the London penetration depth $\lambda_L(T)$. The London penetration depth increases by a few microns below Tc and decreases again at low temperature. However the reflected signals are affected by probe positioning and a quantitative interpretation is difficult due to the presence of the silver top layer.

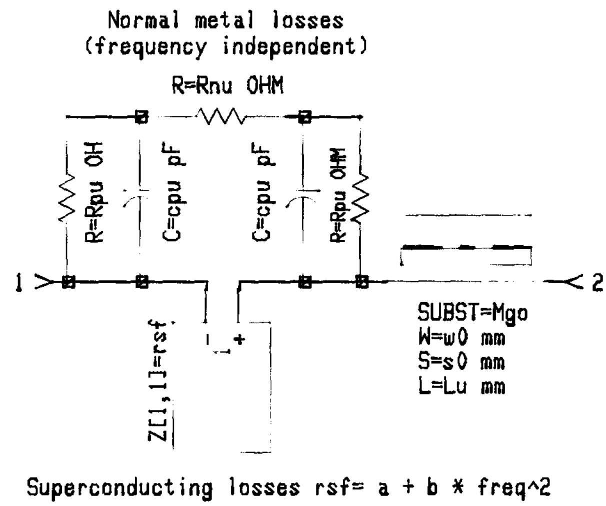

Figure 1. Losses modeling of a superconducting line section. W, S and L are defined in Table 1

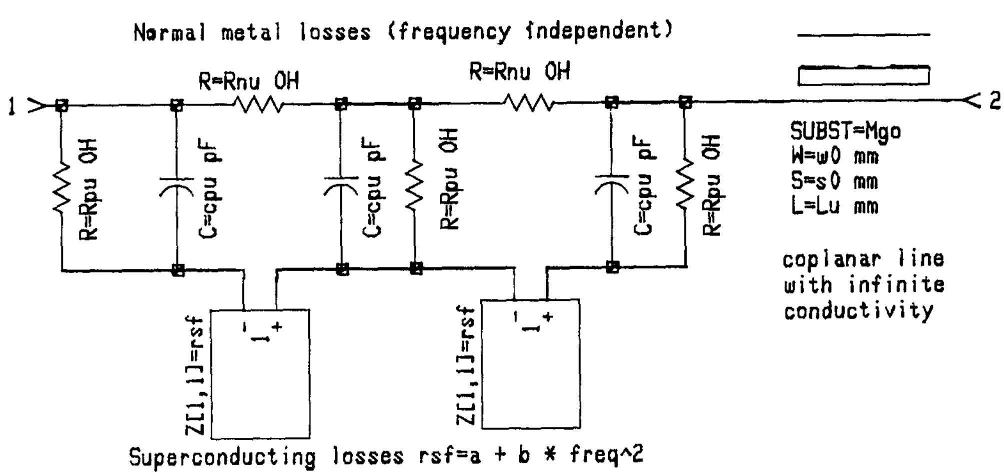

Figure 2. Modeling of the HF injection current from the probe to the superconducting layer through the normal layer

4.2 transmitted signals

The transmitted signals give directly the propagation constant. Above Tc, the signal attenuation is due to normal losses in the silver line. The observed skin effect above 25 GHz is in a good agreement with the layer thickness. A somewhat low value of 1.8 $10^7\ \Omega^{-1}.m^{-1}$ is found for the line conductivity at 100K from HF measurements whereas a value of 3.7 $10^7\ \Omega^{-1}.m^{-1}$ is found from DC measurements. This discrepancy may indicate some extra losses on the imperfect edges of the lines.

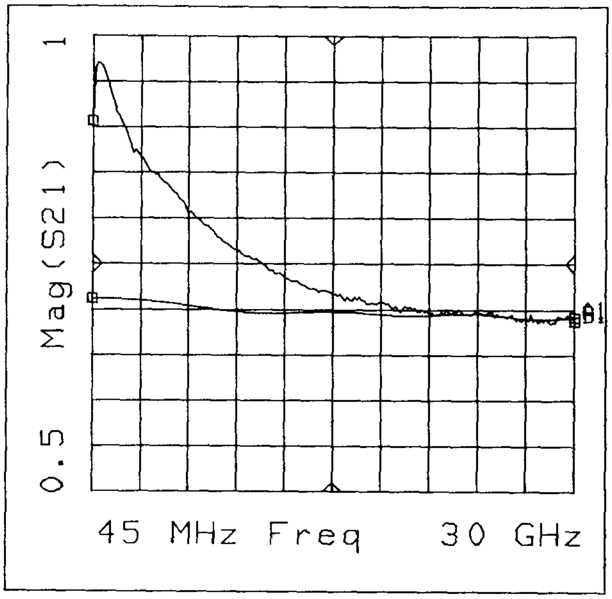

Figure 3. Transmission vs Frequency of a long coplanar line at T=84K

Figure 3 shows the magnitude of the transmitted signal (coplanar line L1) versus frequency just below the superconducting transition (84K). The bottom line takes solely into account the losses of the silver layer. The measured losses decrease strongly at 84K for frequencies between 1GHz and 15GHz as the HF current flows mainly in the superconducting layer. Above 20GHz, the superconductive losses are high and the HF current flows mainly in the silver layer. Below 1GHz, the losses increase slightly. This is opposite to a standard superconducting behavior. This can be explained assuming contact resistance between the two metal layers. At higher frequencies, this resistance is shunted by capacitive effects.

In order to emphasize the frequency behavior the transmitted signal is presented in dB versus frequency on a logarithmic scale (Figure 4 and 5). Figure 4 represents the same measurements as Figure 3, while Figure 4 corresponds to measurements of the same coplanar line at 20K. The simulation uses the model of Figure 1.

A similar agreement is observed over all the lines in the whole temperature range (20K-85K). Three regions are

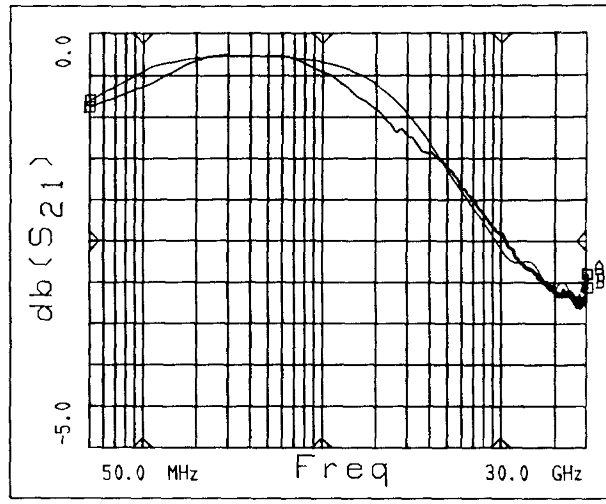

Figure 4. Transmission vs Frequency (logarithmic scale) of a long coplanar line at T=84K

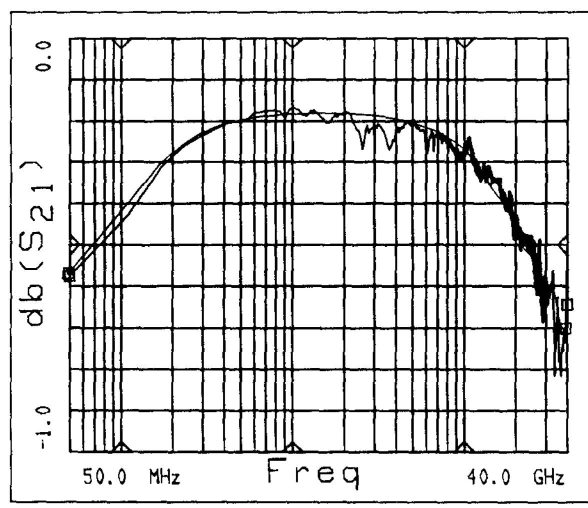

Figure 5. Transmission vs Frequency (logarithmic scale) of a long coplanar line at T=20K

visible. The lower frequency part is governed by the interface. A unique set of values is found: Cp= 9nF/mm^2, Rp=1.4 Ω.mm^2. The high capacitance value indicates that only a few atomic layers are implied. The center part corresponds to superconducting losses independent of frequency. The high frequency region exhibits the usual superconducting f^{-2} roll-off.

All the results on the longer lines (L1 and L2) are summarized in Figure 6 which presents the change in surface resistance Rs versus temperature for three frequencies. At the lower frequencies (0.1 GHz), Rs corresponds to residual losses and exhibits an exponential variation (full line) versus temperature. The values extracted from the two lines correlate generally well. The discrepancy observed at 75K is due to a poor probe contacting on the L2 lines which has not been

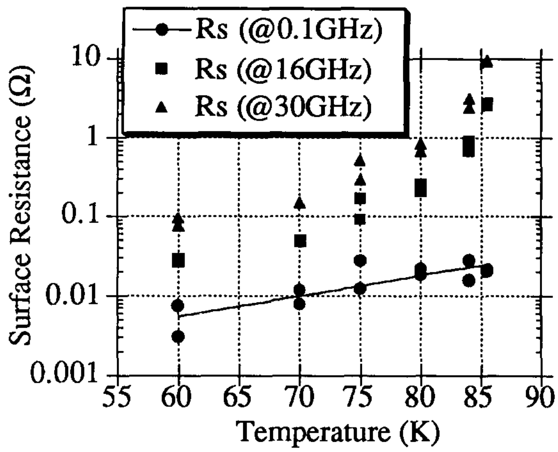

Figure 6. HF surface resistance vs temperature

detected during measurements. Bad probe positioning or contacting lead always to an apparent increase of Rs. The very low residual Rs found at 60K (L2 line) corresponds to an attenuation below 0.1 dB and can be explained by measurement uncertainties. The Rs values at 20K are slightly higher than 60K values.

5. Coupled lines filter properties

Due to the precision, low values of Rs are difficult to extract through simple line measurements. This has led us to characterize a coupled lines resonator in order to obtain these low values. The resonator used is $3\lambda/2$ long at 24GHz, and is approximately -20dB coupled via $\lambda/4$ sections. From 8 to 40 GHz, Fig 7 shows the expected 5 resonant lines of the transmission modulus.

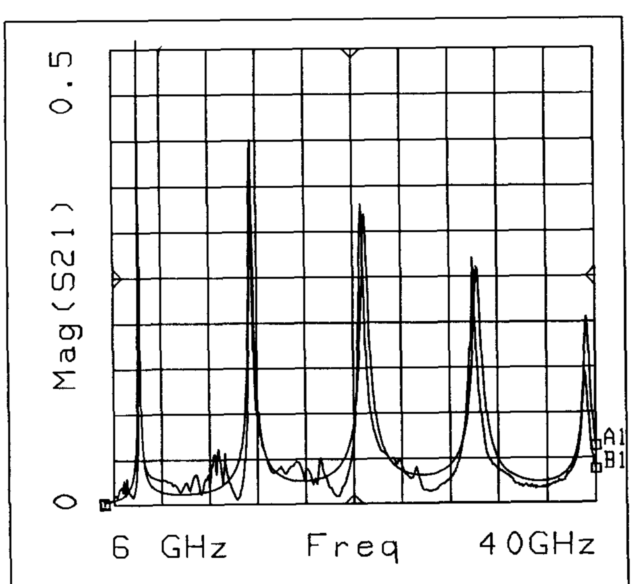

Figure 7. Transmission magnitude vs frequency of the coplanar resonator (Filt1)

A simulation has been done using the models of Figures 1, 2 where the former is used for the resonator and the latter for the access lines. This has been found necessary since the HF signal is injected by the probe in the silver layer and on the contrary is magnetically coupled to the superconducting layer of the resonator. The simulation which uses coplanar line data fits satisfactorily the measured complex reflexion (Figure 8). The Rs value may be obtained as an optimization result or from a Q factor determination.

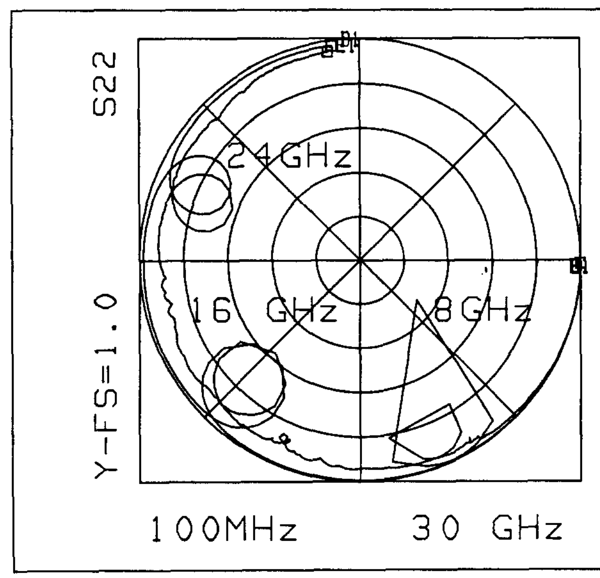

Figure 8. Amplitude and phase of the filter reflection (polar representation)

6. Conclusion

High precision broadband HF measurements on non resonant coplanar lines allow superconducting surface resistance determination versus frequency and temperature down to a few mΩ. Lower values (0.1mΩ) are accessible if narrower coplanar lines (≈ 10μm) are used. For lower values (Rs <0.1mΩ) resonant structures are mandatory. Residual losses and frequency dependent losses decrease strongly with temperature until 70K. Cooling down 70K appears usefull on our films only when working at high frequency (F>20 GHz).

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