A Simple Parallel-Plate Resonator Technique for Microwave Characterization of Thin Resistive Films

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A parallel-plate resonator method is proposed for non-destructive characterisation of resistive films used in microwave integrated circuits. A slot made in one of the plates is used to measure surface impedance of a reference film and film under test. The surface impedance of the film under test is extract from these two measurements using a simple procedure. X-band experimental verification is given for a number of resistive films.

INTRODUCTION

High resistivity films are used in resistors and other components in hybrid and monolithic microwave integrated circuits and multichip modules (MICs, MMICs and MM). Correct specification of the surface impedance (sheet resistance) of these films in the design phase is a critical issue. Similar problem arises with the conducting strips of the interconnects of high speed ICs, where per unit length losses need to be specified in the design stage. The density of thin metal films is usually smaller, and the specific DC resistivity (Ohm m) is larger than the specific resistivity of the bulk materials. The problem is even more critical at microwave frequencies where the skin effect plays a major role. In this work we propose a simple method for non-destructive microwave characterization of the surface impedance of resistive and conductive films using a simple parallel-plate resonator technique.

Parallel-plate resonators have been widely used for surface impedance measurements of High Temperature Superconductor (HTS) films, R. C. Taber (1), A. Ya. Basovich et al (2). The accurate measurement of extremely low surface impedances of HTS films is possible if the radiation and dielectric losses are negligible. The radiation losses are inverse proportional to the thickness of the dielectric spacer between the (superconductor) plates, F. Abbas and L. E. Davis (3). For this reason the thickness of the dielectric spacer in HTS measurements is made very small (of the order 10 μm) enabling measurement of surface impedances smaller than 10 μOhm. However, the measurement resolution and accuracy becomes poor where attempts are made to use such a resonator for measurement of the surface impedance of the conductive films with resistivity is larger than 1.0 mOhm, since the Q-factor of the resonator becomes very small. Moreover, such a resonator becomes useless if the surface resistance measurement of high resistivity films in microwave LTCC circuits and advanced high-speed digital and is concerned. Additionally, the plates of the resonator have to be conformal, which puts stringent requirement on the alignment of the plates.

In the proposed method, in contrast with R. C. Taber (1), A. Ya. Basovich et al (2), a rather thick dielectric substrate (however electrically thin, i.e. its thickness is much smaller than half wavelength at the highest et al measurement frequency) is used with the plates directly deposited on both surfaces. Rectangular or circular microstrip patch resonators may be used for measurements. However, to avoid the effect of the substrate surface waves, A. K. Verma, and Nasimuddin (4), disc resonators with the dimensions of the substrate same as the plates are used in this work, Fig.1. In one of the plates a narrow slot is open along the current lines. The current lines of the lowest order resonance in a rectangular resonator are parallel to the edges. In circular resonator, they have different configuration, A. Eriksson et al (5). In this work we discuss only rectangular resonators Fig.1 a. To avoid the effect f the degenerate mode, the resonators are made rather rectangular than square. In such a resonator two lowest order modes are TM_{01} and TM_{10}. The aspect ratio is

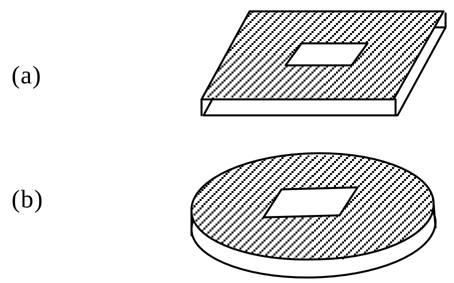

Fig.1. Rectangular (a) and circular (b) parallel-plate disc resonators with measurement slots.

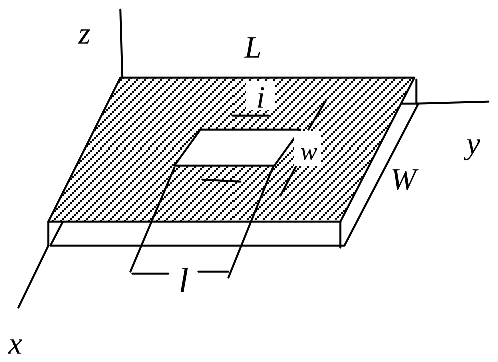

Fig.2. The model of the resonator.

chosen so that the resonance frequencies of the modes are well apart and the measurements are not affected by the presence of the other mode.

THEORY

A simplified theory enabling evaluation of the surface impedance from measured Q-factors is based on magnetic wall approximation along the edges of the resonator, i.e. at plans $x=0$, $x=W$, $y=0$, $y=L$, Fig. 2. The dimensions of the resonator and slot are shown in Fig.2. For the TM_{01} mode the field components are given as:

$$E = E_0 \cos\left(\frac{py}{L}\right)\hat{a}_z \tag{1}$$

$$H = \hat{a}_x\left(\frac{-1}{jwm_0}\frac{\partial E_z}{\partial y}\right) = \frac{E_0}{jwm_0}\frac{p}{L}\sin\left(\frac{py}{L}\right) \tag{2}$$

The overall quality factor, Q_{tot}, of the resonator is:

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{self}} + \frac{1}{Q_{insert}} \tag{3}$$

The Q-factors of unperturbed (no slot), Q_{self}, and perturbed (slot with a film under test), Q_{insert}, ignoring the radiation and dielectric losses, are given as:

$$Q_{self} = \frac{2wW_E}{P_{plate}} \tag{4}$$

$$Q_{insert} = \frac{2wW_E}{P_{insert}} \tag{5}$$

Conserved in the resonator energy W_E, the losses in the plates of the resonator, P_{plate} and in the film under test P_{insert}, are easily evaluated using field distribution between the plates (1) and (2).

Energy stored in the electric field in the resonator without slot:

$$W_E = \frac{e_0 e_r}{4}\int_0^L\int_0^W\int_0^d E_0^2 \cos\left(\frac{py}{L}\right)^2 dzdxdy$$

$$= \frac{e_0 e_r E_0^2 Wd}{4}\int_0^L \cos\left(\frac{py}{L}\right)^2 dy$$

$$W_E = \frac{e_0 e_r E_0^2 WLd}{8} \tag{6}$$

Conductor losses in the upper and lower copper electrodes without slot:

$$P_{plate} = 2\frac{R_s^{plate}}{2}\int_0^L\int_0^W H_x^2 dxdy$$

$$= \frac{E_0^2}{(wm_0)^2}R_s^{plate}\left(\frac{p}{L}\right)^2 W\int_0^L \sin\left(\frac{py}{L}\right)^2 dy$$

$$P_{plate} = \frac{E_0^2}{(wm_0)^2}R_s^{plate}\left(\frac{p}{L}\right)^2 W\frac{L}{2} \tag{7}$$

Conductor losses due to the extra resistance over the slot region (i.e. in the film under test):

$$P_{insert} = \frac{R_s^{insert} - R_s^{plate}}{2}\int_{\left(\frac{L}{2}-\frac{l}{2}\right)}^{\left(\frac{L}{2}+\frac{l}{2}\right)}\int_{\left(\frac{W}{2}-\frac{w}{2}\right)}^{\left(\frac{W}{2}+\frac{w}{2}\right)} H_x^2 dxdy$$

$$= \frac{E_0^2}{(wm_0)^2}\frac{\left(R_s^{insert} - R_s^{plate}\right)w}{2}\left(\frac{p}{L}\right)^2\int_{\left(\frac{L}{2}-\frac{l}{2}\right)}^{\left(\frac{L}{2}+\frac{l}{2}\right)} \sin\left(\frac{py}{L}\right)^2 dy$$

$$P_{insert} = \frac{E_0^2}{(wm_0)^2}\frac{\left(R_s^{insert} - R_s^{plate}\right)w}{2} \tag{8}$$

$$\cdot\left(\frac{p}{L}\right)^2\left(\frac{l}{2} + \frac{L}{2p}\sin\left(\frac{pl}{L}\right)\right)$$

The resonant condition is given by

$$k_{0n}\sqrt{e_r} = p \;/\; l$$

where d is distance between planes, e_r is the dielectric constant, k_o=w/c_o =$2pf/c_o$, f is frequency, c_o is free space light velocity. By using (6), (7) and (8) in (3), (4) and (5) we arrive at:

$$R_s^{isert} = R_s^{plate} + \frac{Q_{self} - Q_{total}}{Q_{self}Q_{total}} \frac{wm_0 dLW}{w\left[l + \frac{L}{p}sin\left(\frac{pd}{L}\right)\right]} \qquad (9)$$

Not that this formula is valid also in the limit cases w or $l \to 0$ (i.e. $Q_{tot} \to Q_{self}$). In this analysis the losses in the dielectric are ignored assuming use of low loss substrates (e.g. Al_2O_3 or $LaAlO_3$).

EXPERIMENTAL PROCEDURE

The measurement procedure is simple. First, Q_{self} of a resonator without slot is measured followed by measurement of Q-factor, Q_{tot}, of resonator with a resistive film inserted in the slot. The surface impedance, R^{insert}, of the resistive film is computed from (9). The measurement of Q_{self} is carried out with a conducting film (same as the plate of the resonator) in the slot.

The plates of the resonator are made of conductive films (e.g. Cu, Au) with thickness at least three times larger than the skin depth. The sizes of the slot and its location on the plate depend on the sizes and range of the surface impedance of the film under test. Resistive films tend to reduce the Q-factor of the loaded resonator drastically, while conductor films introduce only slight changes. For high resistivity films the slot need to be rather narrow and short if it is symmetrically located in the middle (current maximum) of the plate. In this case the Q-factor of the loaded resonator is not affected strongly and its measurement is carried out correctly. It is understood that the slot for extremely resistive films may be located in the areas of the film where the current density is low and the Q-factor is measurable with a reasonable accuracy.

For conducting films, as the films used in MMICs, the slot may stretch across all plate of the resonator to ensure measurable changes in the Q-factor.

The currents for the selected mode are along the slot, Fig. 2, i.e. there are no current across the films under test covering the slot. Hence contact resistance between the plate and the film on top of it does not affect the measurement. However, there are small contact areas (resistance) at the ends of the slot, where the currents flow between the plate and film under test. The resistance of these contacts are “calibrated” out from the measurement results if the gap contact between the film under test and the plate is the same as the gap between the plate and conductive film used for “shorting” the slot while measuring the unperturbed resonator.

Table I

FILM	DC R_S, W /□	MICROWAVE R_S, W /□
$SrRuO_3$	54	59.5
$SrRuO_3$	58.5	90.5
$SrRuO_3$	67.5	110
$SrRuO_3$	135	180
Nb	0.38	1.9
Nb	0.42	3.6
Au	0.22	1.16

In our measurements we use 0.5 mm thick 5x5 mm^2 supphier substrate with 100 μm thick Cu plates. The slot sizes are 0.5x3.4 mm^2. The resonator is enclosed in a special package with coaxial connectors and microstrip probes for in/out coupling, similar to that used in R. C. Taber (1). The resonant frequency and Q-factor of unperturbed resonator are 12 GHz and 480. Table 1 compares the results of microwave measurements with the DC four probe measurements for a number of films. The films are fabricated on different substrates using different deposition technologies and have different thicknesses. Note that for these films the thickness is much smaller than the skin depth and R_s=r/t, r being the specific DC resistance of a bulk material, i.e. one expects similar results from the microwave and DC measurements. Extra losses at microwave frequencies appear due to the grain boundaries.

Additionally, the observed discrepancy between DC and microwave results may be explained by the reflections of the microwave signals in the substrates supporting the films (Fig.2 in N. Klein et al (6), and P. Harteman (7)).

CONCLUSION

The proposed method may be used both for resistive and conductive films, including resistivities of highly doped epitaxial layers. However, as it follows from (6) in case of conducting films the measurement uncertainty may be high if the surface impedance of the film under test is close to the surface impedance of the plate. In the case of high resistivity films, the fundamental limit of the highest resistivity possible to measure is given by Maxwell relaxation frequency. The films under test need to support conductive currents, i.e. the conduction currents need to be more than the displacement currents.

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