EXPERIMENTAL AND THEORETICAL CHARACTERIZATION OF THICK AND THIN FILMS FOR MICROWAVE USES ON 99.6% ALUMINA SUBSTRATES

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In a previous paper,[1] we showed, with a microwave quality factor (Q) measurement, that in the X band and with alumina substrates, thick film losses are not worse than thin film losses when the inks are screened then etched, and when they have copper oxide as adhesive layer and gold or copper as metal powder.

Here, we extend this study to show that, our experimental results being in good agreement with theory, a simple D.C. resistivity measurement is sufficient to characterize these MIC'S metallizations and is as suitable as a microwave Q measurement. We also show that the nature of the ground plane cannot be neglected.

1. INTRODUCTION

A large part of MIC technology is concerned with materials: the properties of metallizations, as well as substrates, are of particular importance.

The classical method used to characterize these metallizations is to determine their losses by a microwave quality factor (Q) measurement. This method is relatively complex and tedious, so we have worked out an easier method which gives good agreement with the theory.

2. CHARACTERIZATION METHODS

As we give some formulas in this section, we define here the symbols which will be used.

λ_g, λ_0:	guided and free space wavelength	Q:	unloaded quality factor
F, C:	frequency and light velocity	α_0:	free space losses
ϵ:	substrate dielectric constant	α_D:	dielectric substrate losses
ϵ_{eff}:	substrate effective dielectric constant	α_G, α_L:	ground plane and line losses
Tan δ:	substrate loss tangent	R_G, R_L:	ground plane and line skin resistance
μ_0, ϵ_0:	free space permeability and permittivity	ρ_G, ρ_L:	ground plane and line resistivity
q:	dielectric filling factor	w, t:	width and thickness line
Z_0:	free space impedance	h:	dielectric substrate thickness

2.1 *Classical characterization method.* The design of MIC's requires the measurements of losses by the mean of an unloaded Q' measurement. This method has been described

in an earlier paper.[1] Q is related to the losses by the following equation:

$$Q = \pi/\alpha \cdot \lambda_g \qquad [1]$$

with

$$\lambda_g = \lambda_0/(\epsilon_{eff})^{1/2} = C/F_0(\epsilon_{eff})^{1/2} \qquad [2]$$

This method is complex (requiring sophisticated equipment) and tedious (it requires a photo etching of the pattern,[1] and we have instabilities during the measurements at high frequencies).

2.2 An easier characterization method.

Because of the disadvantages of the microwave Q' measurements, we have developed an easier method which is based upon a D.C. resistivity measurement.

2.2 a. *Theory.* The losses in MIC'S are generally divided into two parts: 1) the dielectric losses, and 2) the ohmic losses, which are themselves divided in two parts: the ground plane and line losses.

2.2.a.1. *Dielectric losses:* α_D. As formulated by PUCEL,[2] we can define α_D as:

$$\alpha_D = 27.3 \ (q\epsilon/\epsilon_e) \tan \delta/\lambda_g \ db/cm \qquad [3]$$

with $\epsilon_e = 1 + q(\epsilon-1)$, q being the dielectric filling factor defined by WHEELER.[3]

2.2.a.2. *Ohmic losses:* $\alpha_G + \alpha_L \cdot \alpha_G$ can be written as:

$$\alpha_G = \alpha_0 (\epsilon_{eff})^{1/2} \qquad [4]$$

$$=> \alpha_G = (\epsilon_0 \ \epsilon_{eff}/\mu_0)^{1/2} \ (R_G/2 \ Z_0) \ \partial \ Z_0/\partial h \qquad [5]$$

with

$$R_G = (\pi \cdot \mu_0 \cdot F \cdot \rho_G)^{1/2} \qquad [6]$$

The partial derivative $\partial \ Z_0/\partial h$, valid for $w/h \leqslant 1$, is given by SCHNEIDER,[4]:

$$\partial \ Z_0/\partial h = -(W/h^2)\partial \ Z_0/\partial \ (w/h) \qquad [7]$$

We have,[4]:

$$Z_0 = 60 \ Ln(8 \ h/w + w/4 \ h) \qquad [8]$$

so,

$$\partial Z_0/\partial \ (w/h) = 60(2 \ w/h/[32 + (w/h)^2] - h/w) \qquad [9]$$

and we obtain:

$$\alpha_G = -30 \frac{(\pi \cdot \epsilon_0 \cdot F \cdot \epsilon_{eff} \cdot \rho_G)^{1/2}}{Z_0} \left(\frac{2\,w^2/h_3}{32 + (w/h)^2} - 1/h \right) \tag{10}$$

Similarly, we can formulate α_L as:

$$\alpha_L = (\epsilon_0 \cdot \epsilon_{eff}/\mu_0)^{1/2}\ (RL/2\,Z_0)\ (\partial Z_0/\partial h - 2\,\partial Z_0/\partial w - 2\,\partial Z_0/\partial t) \tag{11}$$

with

$$R_L = (\pi \cdot \mu_0 \cdot F \cdot \rho_L)^{1/2} \tag{12}$$

The partial derivatives can be formulated as:

$$\partial Z_0/\partial w = (1/h)\ \partial Z_0/\partial(w/h) \tag{13}$$

and

$$\partial Z_0/\partial t = (\partial Z_0/\partial w)\ (\partial w/\partial t) = (1/h)\ (\partial Z_0/\partial\,(w/h))\ (1/\pi)\ \mathrm{Ln}(2\,h/t) \tag{14}$$

for $w/h \geqslant 1/2\,\pi$.[4] Arranging [11], [12], [13], [14] and [7], we have:

$$\alpha_L = -30 \frac{(\pi \cdot \epsilon_0 \cdot F \cdot \epsilon_{eff} \cdot \rho_L)^{1/2}}{Z_0} \left(\frac{2\,w/h}{32 + (w/h)^2} - h/w \right) [w/h^2 + 2/h + (2/h\pi)\mathrm{Ln}(2\,h/t)] \tag{15}$$

2.2.b. *Theoretical and experimental results.*   To compare with experimental results at 10 GHz, we take a microstrip line 0.0635 cm width and 0.001 cm thick; the substrate is 0.0635 cm thick. With α in Np/cm, F in Hertz, ρ_L and ρ_G in Ω.cm, w, h and t in cm, $\epsilon_0 = 8.85.10^{-14}$ Farad/cm, $\epsilon_{eff} = 6.8$ and $C = 3.10^{10}$ cm/s, we have theoretically: $Q = 2.73/(\alpha_G + \alpha_L)$ from equation [1]; $Z_0 = 126.6\ \Omega$ from equation [8]; $\alpha_G = 0.482$ $(\rho_G)^{1/2}$ from equation [10]; $\alpha_L = 2.933\ (\rho_L)^{1/2}$ from equation [15]. Theoretical ohmic losses, measured and theoretical Q, are computed in table 1 and plotted in figure 1, for the resistivities of the thick and thin films used.

3.   DISCUSSION

From equations [10] and [15], tables I and II, and figure 1, it can be seen theoretically and experimentally that: 1) the losses are dependent upon the resistivity, and 2) the ground plane resistivity cannot be neglected.

3.1 *Evaluation and characterization of MIC'S by a resistivity measurement.*

It is of great interest to know if this simple method permits not only a comparison between different metallizations (evaluation), but also constitutes a characterization method, and consequently a means of determining the absolute value of losses, such as the Q measurement.

We have seen that, with figure 1, we give the theoretical and experimental curves $Q = f(\rho)$. If we take into account the only ohmic losses (table I), we can see that there is a divergence between theoretical and experimental Q; this difference increases when the resistivity decreases.
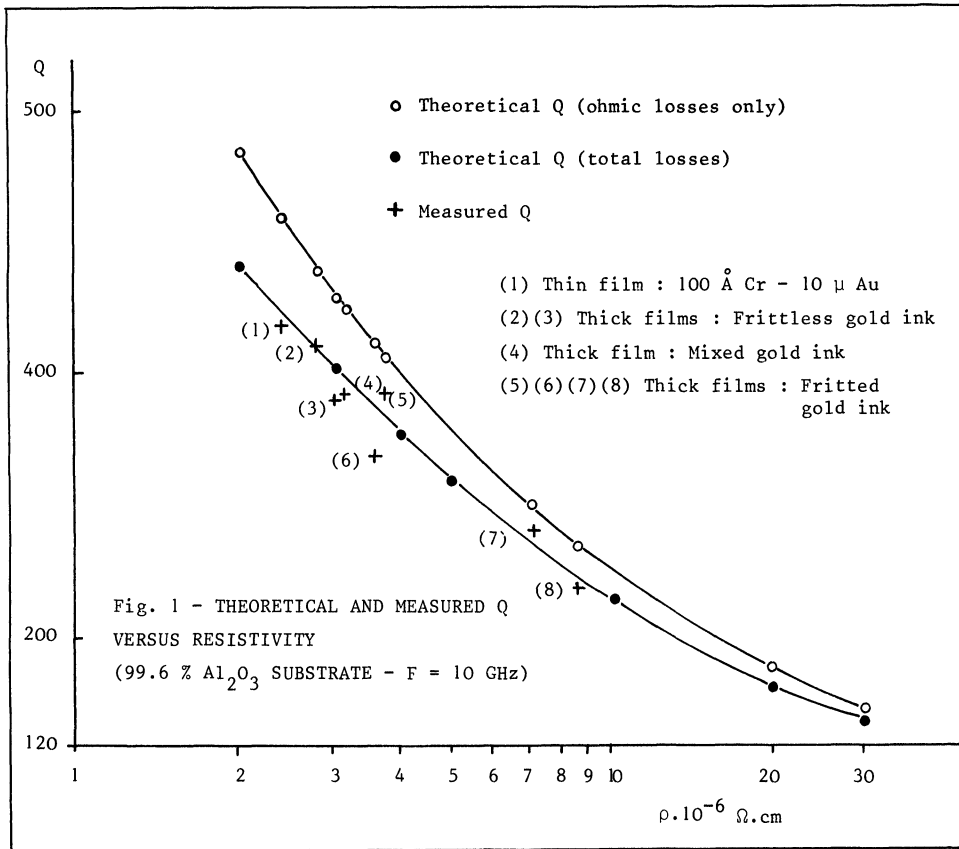
Fig. 1 - THEORETICAL AND MEASURED Q VERSUS RESISTIVITY (99.6 % Al_2O_3 SUBSTRATE - F = 10 GHz)

Legend:
- o Theoretical Q (ohmic losses only)
- ● Theoretical Q (total losses)
- + Measured Q

(1) Thin film : 100 Å Cr - 10 μ Au
(2)(3) Thick films : Frittless gold ink
(4) Thick film : Mixed gold ink
(5)(6)(7)(8) Thick films : Fritted gold ink

TABLE I

Theoretical ohmic losses, measured and theoretical Q for thick and thin films used

Pattern technology	Measured ρ 10^{-6} Ω.cm	Theoretical ohmic losses 10^{-3} Np/cm		Theoretical Q F = 10 GHz	Measured Q F = 10 GHz
		α_G	α_L		
Thin film	2.4	0.747	4.544	516	436
Thick film (etched pattern)	2.79	0.805	4.899	479	419
	3.05	0.842	5.122	458	380
	3.15	0.855	5.206	450	384
	3.6	0.915	5.565	421	338
	3.75	0.933	5.680	413	385
	7.1	1.284	7.815	300	281
	8.74	1.425	8.671	270	237

The influence of the ground plane resistivity on the measured and theoretical Q is displayed in table II.

TABLE II

Ground plane resistivity influence on measured and theoretical Q. The line pattern is etched; 2.79. 10^{-6} Ω.cm is a frittless gold ink resistivity; $32.4.10^{-6}$ Ω.cm is a fritted silver-palladium ink resistivity

Measured ρ	10^{-6} Ω.cm	Theoretical ohmic losses 10^{-3} Np/cm		Theoretical Q F = 10 GHz	Measured Q F = 10 GHz
Ground plane	Line	α_G	α_L		
2.79	2.79	0.805	4.899	479	419
32.4	2.79	2.744	4.899	357	354

To obtain a good agreement, we must introduce the dielectric losses α_D, and a correcting factor K which takes into account the surface roughness of the substrate. At 10 GHz, with tan δ = 2.10^{-4}, and $q\epsilon/\epsilon e \simeq 0.9375$,[2] we have: α_D = $0.513.10^{-3}$ Np/cm from equation [3], and K $\simeq 1.05$.[5]

The table III presents the total theoretical losses (α_D, α_G, α_L, and surface roughness losses) and Q for different resistivities.

From table III, we can see that the dielectric losses cannot be neglected for the lower resistivities, but the greater the resistivity is, the more α_D can be neglected. This explains the divergence between theoretical (if only computed with ohmic losses) and experimental Q (see figure 1).

If we take into account the total losses, we can see from figure 1, that there is a very good agreement between theory and practice, and that consequently the resistivity measurement is a characterization method of MIC's as suitable as the Q measurement.

3.2 Influence of the ground plane.

For a lower cost, it would be attractive to use a ground plane metallization such as silver-palladium which is about ten to fifteen times less expensive than gold. Unfortunately, the results show that the ohmic losses are very much higher than when we have gold as ground plane and conductor line. So, if we compute α_G versus α_L with equations [10] and [15] for the experimental resistivities used (see table II), we have $\alpha_G \simeq 0.16 \alpha_L$ for a 2.79 $\mu\Omega$.cm frittless gold conductor line and ground plane, and $\alpha_G \simeq 0.56 \alpha_L$ when the gold ground plane is substituted by silver-palladium. As we can see in table IV, we have a good agreement between theory and measurements if we take into account the total losses (α_D, α_G, α_L and surface roughness losses).

TABLE III

Total theoretical losses and Q for some resistivities

ρ 10^{-6} Ω.cm	α_D 10^{-3} Np/cm	α_G 10^{-3} Np/cm	α_L 10^{-3} Np/cm	Total losses 10^{-3} Np/cm K($\alpha_D+\alpha_G+\alpha_L$)	Theoretical Q F = 10 GHz
2	0.513	0.682	4.148	5.610	487
3	0.513	0.835	5.080	6.749	404
4	0.513	0.964	5.866	7.710	354
5	0.513	1.078	6.558	8.556	319
10	0.513	1.524	9.275	11.878	230
20	0.513	2.156	13.117	16.575	165
30	0.513	2.640	16.065	20.179	135

TABLE IV

Theoretical and experimental effect of ground plane metallization on Q. For α_D, α_G and α_L values, see tables II and III; K = 1.05.[5]

ρ 10^{-6} Ω.cm		Theoretical Q $Q = 2.73/K(\alpha_D + \alpha_G + \alpha_L)$ F = 10 GHz	Measured Q F = 10 GHz
Ground plane	Line		
2.79	2.79	418	419
32.4	2.79	318	354

4. CONCLUSION

Because we have a good agreement between theory and practice, we have shown that a simple D.C. resistivity measurment is as suitable as a more complex microwave Q' measurement, in order to characterize the MIC'S metallizations.

We have also showed that the nature of the ground plane cannot be neglected.

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