W BAND SILICON DIELECTRIC RESONATOR FOR SEMI CONDUCTOR SUBSTRATE CHARACTERIZATION

P. BLONDY* - D. CROS* - P. GUILLON*
F. BALLERAS - C. MASSIT****

**I.R.C.O.M. - Faculté des Sciences - UMR CNRS 6615 - 123 Av. A. Thomas - 87060 LIMOGES Cédex - FRANCE*
***LETI-CEA - 17 rue des Martyrs - 38054 GRENOBLE Cédex 9 - France*

ABSTRACT

This paper is about the use of planar millimeter wave whispering gallery dielectric resonator modes for material characterization. Experimental results and theoretical ones obtained with finite element method permit to determine electromagnetic characteristics of a material like silicon. The results on loss factor are compared to basic electromagnetic theory. It is shown that high resistivity silicon dielectric resonators could be used to build high Q millimeter wave resonators.

INTRODUCTION

A lot of material characterization methods have been developed these last years to determine complex electric permittivity in the microwave frequency range. These methods are classified as resonant or reflexion-transmission method. The first ones are more interesting to characterize low loss material that are used in many microwave applications. These techniques are based on cavity measurements or dielectric resonators excited on TE or TM modes and Fabry Perot structures.

Unfortunately, these methods are not adapted at high frequency or are difficult to set up. A solution to complete a quick and reliable material characterization at millimeter wave frequencies is to use a dielectric resonator operating on whispering gallery modes. These modes offer advantages such as large dimensions and high unloaded Q factors and have already permitted to realize a large number of microwaves devices [1][2][4].

For material characterization, we take significant advantages from low radiation loss since the energy is confined within the dielectric resonator. Indeed, resonance frequencies of these modes and unloaded Q factor are essentially imposed by resonator dimensions and the material used to machine it. Using finite element method to simulate the experimental structure, the electromagnetic properties of material can be determined by fitting theoretical results to experimental ones [2].

We have applied this method of characterization to silicon material that is used in many millimeter waves devices and subsystems [3]. Basic electromagnetic theory allows to predict loss factor variations as a function of frequency. Then experimental results obtained using whispering gallery dielectric resonator modes are compared to theoretical results.

BASIC THEORY

In dielectric material, the complex permittivity is defined as :

$$\varepsilon_r = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\,tg\delta) \quad (1)$$

In semi conductor samples conductivity σ or resistivity $\rho\left(\sigma = \frac{1}{\rho}\right)$ must be taken into account in Maxwell equations, to define the electromagnetic parameters of the material.

$$\vec{rot}\,\vec{H} = \vec{J} + j\omega\varepsilon_0\,\varepsilon_r\,\vec{E} \quad (2)$$

with : $\vec{J} = \sigma\vec{E}$ (3)

$$\vec{rot}\,\vec{H} = \left(\sigma + j\omega\varepsilon_0\,\varepsilon_r\right)\vec{E} \quad (4)$$

Next, let ε* be the equivalent electric permittivity, so that we can write :

$$\vec{rot}\,\vec{H} = j\omega\varepsilon_0\,\varepsilon^*\vec{E} \quad (5)$$

Equations (4) and (5) are compared and we obtain :

$$\varepsilon^* = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0} \quad (6)$$

Using equation (1) the equivalent permittivity ε* becomes :

$$\varepsilon^* = \varepsilon^{*\prime} - j\varepsilon^{*\prime\prime} = \varepsilon' - j\left(\varepsilon'' + \frac{\sigma}{\omega\varepsilon_0}\right) \quad (7)$$

and the loss tangent factor is given by :

$$tg\delta^* = \frac{\varepsilon'' + \frac{\sigma}{\omega\varepsilon_0}}{\varepsilon'} = \frac{\varepsilon^{*\prime\prime}}{\varepsilon'^*} \quad (8)$$

The imaginary part of the equivalent electric permittivity ε* depends on the dielectric properties (ε'') and on the conductor parameter (σ). In semi conductor material at room temperature dielectric effects are negligible and loss tangent factor can be approximated by :

$$tg\delta^* = \frac{\sigma}{\omega\varepsilon_0\,\varepsilon'} = \frac{18\sigma}{\varepsilon' f(\mathrm{GHz})} \quad (9)$$

In this expression, ε' is the real part of the permittivity that can be determined by microwave measurement and σ is the conductivity of the semiconductor sample, given by static measurement. It is important to note that the imaginary part of permittivity decreases as frequency increases. It means that high resistivity silicon can be a decent dielectric material at high frequency although it is a high loss material at low frequencies.

MEASUREMENT SETUP

The modelled resonant structure under experimental analysis is presented on figure 1. The dielectric resonator on whispering gallery modes is excited by two microstrip lines at W band. The structure is excited at port 1 and response is obtain at port 2 while ports 3 and 4 are terminated with a matched load. Due to azimuthal directivity of the propagation around the dielectric resonator on WGM, we obtain a band pass response at port 2.

To minimize radiation losses, we choose WGM with high azimuthal number, so that the electromagnetic field is confined in the dielectric resonator and unloaded Q factor depends only on the complex permittivity of the resonator. This can be explain by considering the unloaded Q_0 factor in detail, given by the following expression :

$$Q_0^{-1} = p_e\,\mathrm{tang}\delta^* + Q_r^{-1} + p_{es}\,tg\delta s \quad (10)$$

For high azimuthal mode number, the ratio p_e of the electric energy stored in the dielectric resonator is close to unity and p_{es}, that denotes the electric energy filling factor of substrate, can be neglected.

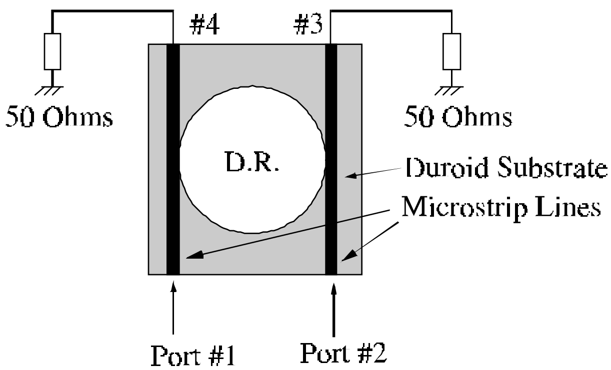

Fig. 1 Layout of the experimental setup

For the same reason, radiation loss Q_r factor that increases with azimuthal mode number doesn't disturb the unloaded Q_0 factor.

To minimize the influence of coupling with microstrip lines, the resonator is placed on a dielectric support. In this configuration the loaded Q factor, Q_L is close to unloaded Q factor, Q_0. So that we can write :

$$Q_L \# Q_0 \# \frac{1}{tg\delta^*} \qquad (11)$$

For the computation of the resonance frequencies, finite element method has been used. To apply this numerical method, the structure is enclosed in a metallic cavity (figure 2). With this method, resonance frequencies are computed as a function of real part of the permittivity.

RESULTS

We investigated WG modes in a silicon dielectric resonator at W band using a Hewlett Packard 8510 network analyzer. We used a silicon disk 15 mm in diameter and 350 µm in height. The resonator is acting on WGE modes with azimuthal mode number between 23 and 39. The resonance frequencies of these modes are located between 78 GHz and 110 GHz. An example of electric field cartography obtained by finite element method for the $WGE_{25,0,0}$ mode is given on figure 3. We can notice that most of the energy is confined at the periphery of the dielectric resonator.

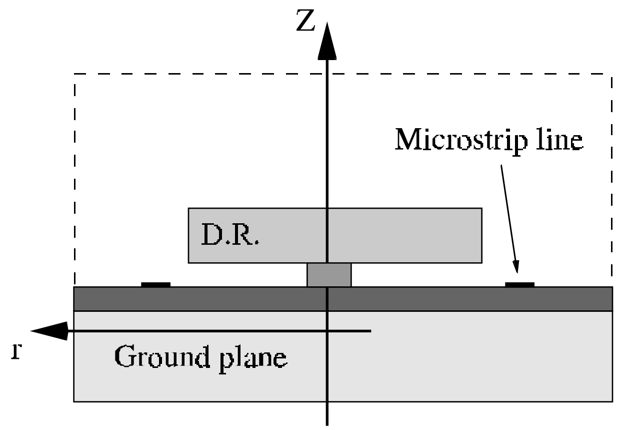

Fig. 2 Transverse section of the experimental setup

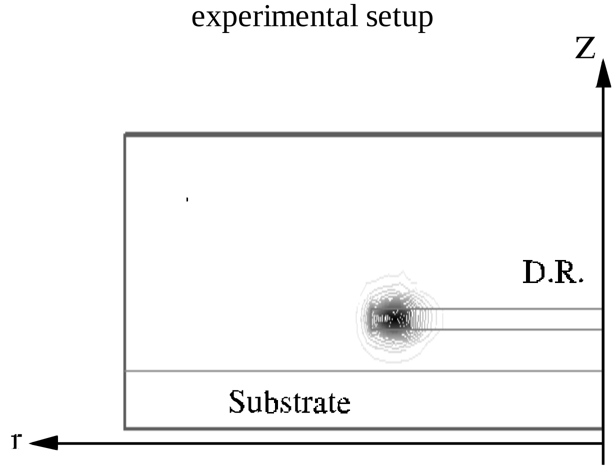

Fig. 3 Plot of the electric field intensity

The first step is to find the real part of complex permittivity by fitting the computed resonance frequencies to the measured ones. For silicon material we have found that the value is close to 11.55. On table 1, we give the experimental and theoretical results for 4 $WGE_{n,0,0}$ modes resonance frequencies.

Then, considering the value of the real part of permittivity, we can compute the loss tangent of silicon using equation (9). The resistivity value obtained by static measurement is ρ=68 Ωm for silicon sample investigated. On table 2, results on measurement and theoretical loss tangent are given for differents modes.

We observe a low difference between theoretical and experimental results. It can be explained by small radiation losses in experiment and by dielectric effects that are neglected in the computation of the theoretical loss tangent. To improve the characterization method, we have determined the electromagnetic parameters of silicon with cavity method at low frequencies. By this method, the real part of complex permittivity and the loss tangent have been measured from 8 GHz to 40 GHz. The global results for both parameters using these methods of characterization are given on figure 4. We can notice that real part of complex permittivity is close to 11.6 from 8 GHz to 110 GHz and that the loss tangent decreases as a function of frequency in the same way as predicted by theory.

CONCLUSION

In this paper we have performed material characterization of high resistivity silicon at millimeter wave frequencies, using silicon as dielectric resonator material. The low value of losses, the low cost of this material, suggest that it can be used at millimeter wave frequencies to build dielectric resonators based devices. In this case, fabrication can take advantage of microelectronic fabrication techniques such as RIE to machine dielectric resonators in a collective and low cost process.

This work has been supported by the French Army (DGA) under contract n°93.311.00.022.

Modes	fo (GHz) exp.	fo (GHz) the.	ε '
WGE $_{29,0,0}$	90.10	90.09	11.55
WGE $_{30,0,0}$	91.85	92.07	11.55
WGE $_{31,0,0}$	93.98	94.04	11.55
WGE $_{32,0,0}$	96.04	96.00	11.55

Table 1

Modes	Q_L	tg δ* exp.	tg δ* the.	fo (GHz)
WGE $_{39,0,0}$	3010	3.32 10^{-4}	2.09 10^{-4}	110
WGE $_{34,0,0}$	3020	3.31 10^{-4}	2.30 10^{-4}	100
WGE $_{29,0,0}$	2750	3.64 10^{-4}	2.55 10^{-4}	90
WGE $_{23,0,0}$	2590	3.85 10^{-4}	2.95 10^{-4}	78

Table 2

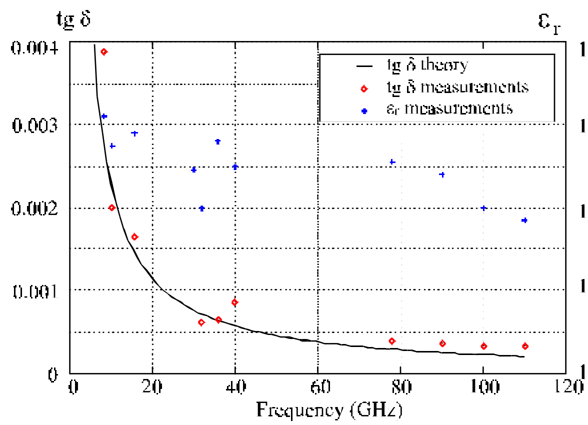

Fig. 4 Complex permittivity versus frequency

REFERENCES

[1] **D. Cros, P. Guillon** "Whispering gallery dielectric mode for W band devices" *IEEE Transactions on MTT, vol.38, n°11, pp.1667-1674, November 1990*

[2] **J. Krupka, P. Blondy, D. Cros, P. Guillon, R.G. Geyer** "Whispering gallery modes and permeability tensor measurements in magnetized ferrite resonators" *IEEE Transactions on MTT, vol.44, n°7, pp.1097-1103, July 1996*

[3] **S. Raman, G.M. Rebeiz** "Single and dual polarized millimeter wave slot ring antennas" *IEEE Transactions on Antennas and Propagation, vol.44, n°11, November 1996*

[4] **A.N. Luiten, A.G. Mann, D.G. Blair,** "Ultra high Q factor cryogenic sapphire resonator", *Electronics Letters, vol.29, n°10, pp.879-881*