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Investigation of the Dielectric Permittivity of Anodic Aluminum Oxide Substrates for Multi-Chip Modules

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***Abstract*—The present article describes the investigations, performed in order to determine some dielectric characteristics of anodic aluminum oxide (AAO), obtained by electrochemical anodization process. The AAO layer is grown directly on aluminum substrates, considered as suitable carriers for multi-chip modules (MCM). Test samples for measurements of the dielectric permittivity and loss tangent were elaborated by anodization in 5% oxalic acid electrolyte. The chosen measurement technique is based on the ring resonator method. The values, obtained for the S21 parameter of a two-port ring resonator, were used to determine the permittivity of the board substrate.**

***Keywords*— multy-chip modules (MCM); aluminum substrate; anodic aluminum oxide (AAO); dielectric permittivity;**

I. INTRODUCTION

The tendency to reduce the size of microelectronic systems while combining many functions has led to the development of new technologies for assembly – namely the multy-chip modules (MCM) [1]. The emergence of multy-chip modules has led to a new stage in the development of modern electronic devices and evolution in design and assembly of electronic systems. At the same time the increased level of integration and density assembly raise problems in the design and manufacture of MCM: compatibility problems between different technologies for MCM, problems in multilayer switching capabilities and a parasitic resistances. Solving these problems requires deep knowledge of materials, components and technology of production. Materials used for substrates in MCM are divided into two main groups: organic and ceramic. They include - different kinds of ceramics, glass, silicon, organic materials. A modern and current guidance in this respect are the pads with metal core.

In this article, attention is drawn and investigations are made on aluminum substrate, coated with a dielectric layer of an anodic aluminum oxide (AAO) [2] as the substrate for MCM. The aluminum as a carrier of electronic circuits is used because it has a good thermal conductivity, good mechanical properties and low price. An AAO layer could be grown on the aluminum surface as a dielectric layer. It has a cell nanoporous structure, whose parameters can be sufficiently and accurately controlled through selection of electrical parameters (voltage and current) and operating conditions (temperature, type of electrolyte) during the electrochemical process [3]. These advantages justify its widespread use.

II. OBJECTIVES

This article is dedicated to the investigation of some parameters of this type substrates, in particular - measuring the dielectric permittivity of AAO. To this purpose the following tasks have been defined:

- to investigate and define a methodology for measuring the dielectric permittivity and quality factor of AAO;

- to elaborate experimental models/prototypes with the layered structure Al / Al_2O_3 and Al / Al_2O_3 / Ni / Cu;

- to design topology structure suitable for measuring the dielectric permittivity and quality factor of AAO;

- using the chosen methodology for measurement to conduct measurements of created prototypes for the evaluation of the permittivity and the quality factor of the AAO.

A. Measurement methodology

Every material has unique electrical characteristics that are dependent on the dielectric properties. Accurate measurements of these properties can provide engineers with valuable information to properly incorporate the material into its intended application. A dielectric materials measurement can provide critical design parameter information for many electronics applications. For example, the loss of a cable insulator, the impedance of a substrate, or the frequency of a dielectric resonator can be related to its dielectric properties.

As mentioned above, the dielectric property discussed in this article is the permittivity of anodic aluminum oxide film. This parameter is not constant. It can vary with temperature, frequency, pressure, orientation and molecular structure of the material.

There are different methods for measuring a dielectric constant: transmission line method, free space method, parallel plate method, ring resonator method. These methods have varying applicability depending on the physical dimensions and state of matter of the material under test [4, 5, 6].

The transmission line method needs the material to be placed inside a portion of an enclosed transmission line. The line is usually a section of rectangular waveguide or coaxial airline. The dielectric permittivity is computed from the measurement of the reflected signal (S11) and transmitted signal (S21). In this case of measurement the sample fills the fixture cross section. In order to obtain accurate results, the material should be homogenous, with smooth, flat faces and perpendicular to long axis. This method is broadband and allows anisotropic and magnetic materials to be measured in the waveguide.

The free-space method involves antennas that focus microwave energy at or through a sheet of material. This method is non-contacting and can be applied to materials to be tested under high temperatures and hostile environments. In this case large, flat, parallel-faced and homogeneous samples are needed for correct measurement. The free-space method is non-destructive, measures magnetic and anisotropic materials.

In the parallel plate method, a capacitor is formed by sandwiching a thin sheet of the material or liquid under test between two electrodes. Then the measured capacitance is used to calculate permittivity. This method is simple and gives best results for accurate, low frequency measurements of thin sheets or liquids. A LCR meter is needed to perform the measurements. The schematic diagram and the equivalent circuit of this method are shown on fig. 1.

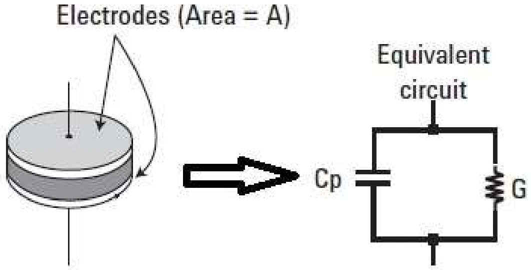

Fig. 1. Parallel plate method.

By this method permittivity and loss tangent can be calculated using the following equations:

$$\varepsilon_r = \frac{t_m.C_p}{A.\varepsilon_0} = \frac{t_m.C_p}{\pi\left(\frac{d}{2}\right)^2.\varepsilon_0} \tag{1}$$

$$\tan\delta = D \tag{2}$$

Where:

C_p: Equivalent parallel capacitance (measured value) of MUT, F;

D: Dissipation factor (measured value);

t_m: Average thickness of MUT, m;

A: Electrode's surface area, m^2;

d: Electrode's diameter, m;

ε_0: Permittivity of free space = 8.854×10^{-12}, F/m.

The ring resonator-based method [5, 6] for the measurement of complex dielectric permittivity of materials requires a ring resonator structure. Similar to the transmission line method, a measurement of the S21 parameter of a two-port ring resonator could be used to determine the permittivity of the material. More precisely, during the measurements of S21 the f_n resonant frequency can be determined, where n is the resonance number. Further, the frequency dependent effective dielectric constant $\varepsilon_{eff}(f)$ can be calculated using the following equation:

$$f_n = \frac{nC}{2\pi r\sqrt{\varepsilon_{eff}(f)}} \tag{3}$$

Where:

r: the mean resonant structure radius;

C: the speed of light in vacuum.

ε_{eff} is relied to ε_r by the next equation:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}.\frac{1}{\sqrt{1 + 12\frac{h}{w}}} \tag{4}$$

Where ε_r is the relative dielectric permittivity, h is the average material thickness and w is the width of the feed lines.

The loss tangent could be found with the following relation:

$$\tan\delta = \frac{1}{Q} \tag{5}$$

$$Q = \frac{F_0}{\Delta F} \tag{6}$$

In equation (6) $\Delta F = f_{3dB,U} - f_{3dB,L}$, where $f_{3dB,U}$ - $f_{3dB,L}$ are the F_0 upper and lower half-power frequencies, respectively.

In the current research the used measurement technique is the ring resonator method, considered as the most appropriate for AAO substrates. This method, based on perturbation of a resonant cavity will require standard of known dielectric constant and loss tangent for calibration.

B. Substrates elaboration

In order to elaborate the test substrates for the current work, initial sheets of aluminum with 99.99% of purity and 100 µm thickness where used. In order to degrease the surface before the anodization the aluminum substrate was treated in 4% of NaOH solution for 1 minute and rinsed with distilled water. Then second degreasing in acetone and rinsing with distilled water was made.

The anodic oxide layer was then obtained by electrochemical anodization process, performed in 5% oxalic acid electrolyte. The process parameters are as follows: current density – 2 A/dm^2, voltage – 40V, duration – 120 min, at room temperature with stirring. At the beginning of the anodization process it is important not to exceed the limit of the current density. For this purpose the voltage is raised smoothly with rise rate 0.5 V/s until its maximum value is reached. By these parameters a uniform dielectric aluminum oxide layer of 15 µm thickness can be achieved on the top of the substrate.

The next steps in the test substrate technological roadmap are the surface metallization and the photolithography processes for the resonant ring structuring.

First, at the top of the AAO surface a Ni seed was deposited by electroless chemical process. The substrate was treated as follows:

- treatment in $SnSO_4$ solution for 2 min, T=20ºC, rinsing;
- treatment in $PdSO_4$ solution for 2 min, T=20ºC, rinsing;
- chemical electroless deposition of a nickel layer in $NiSO_4/NaH_2PO_2$ solution for 10 min, T=60ºC;

The nickel seed layer thus obtained has a thickness of up to 6 µm. This allowed to perform the next step for the test substrate elaboration - electrochemical copper layer deposition in acid type Cu electrolyte solution. The duration of this process was 90 min with direct current regime and current density of 1,5 A/dm^2. Figure 2 shows schematically the cross section structure of the elaborated test substrate.

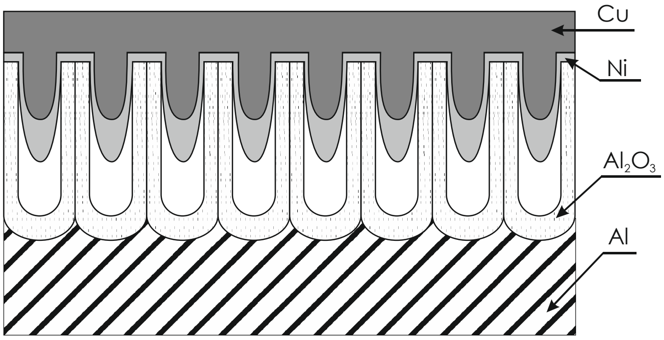

Fig. 2. Cross section structure of the elaborated test substrate.

The ring resonator and the feed lines shapes and dimensions where then obtained by standard PCB photolithography processes, using dry negative photoresist Laminar GA with 35 µm thickness. The etching solution, applied to dissolve the Cu/Ni layer, was sodium persulfate based.

III. EXPERIMENTAL RESULTS

The ring resonator device is composed of printed ring and microstrip lines on the top of the substrate. The ground plane occupies the entire lower surface of the board. The feed lines and ring resonator are printed transmission lines with a width chosen for 50 Ω characteristic impedance. A small gap Δ is included between the ring and each feed line; this gap is realized to separate the resonant behavior of the ring from the feed lines and has a dimension from 0.1 to 1.0 times the width of the feed microstrip. The ground plane occupies the entire bottom surface of the board. Two SMA connectors are used to connect the device to a network analyzer for measurement. The device structure, developed for this investigation is shown on figure 3.

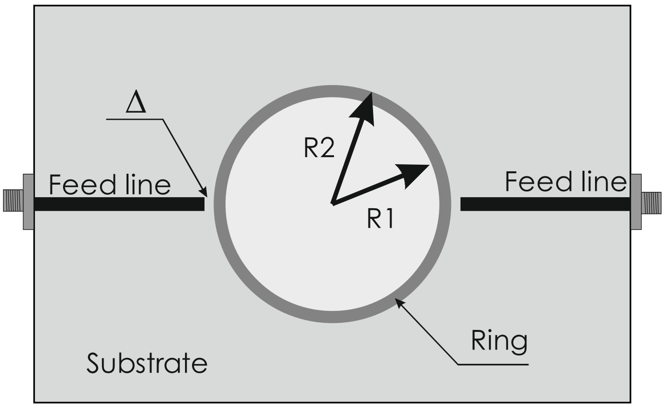

Fig. 3. Structure of the test substrate.

A. RF Measurements and Verification

In order to verify the ring resonator theory, a substrate of PCB material FR4 with 18 µm copper foil thickness, 1.5mm dielectric thickness and known dielectric parameters was used for the first measurements. The design of the ring and the feed lines dimensions on the FR4 substrate are relied to the following equation:

$$2\pi R = n\lambda_g \tag{7}$$

$$\lambda_g = \frac{C}{\sqrt{\varepsilon_{eff}} f} \tag{8}$$

Where R is the mean ring radius, n is the resonant frequency number and λ_g is the wave length.

According to (7), (8), (3) and (4) the FR4 test substrate was designed with the structure, shown at figure 3 with the following dimensions: R2 = 26.52 mm, R1 = 23.87 mm, Δ = 0.265 mm, the feed lines width is 2.65 mm. A picture of the FR4 test structure is shown on figure 4.

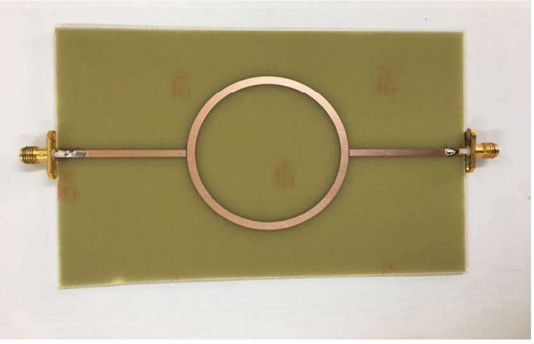

Fig. 4. Picture of the FR4 test structure.

A measurement of the S21 parameter of a two-port ring resonator was used to determine the permittivity of the board substrate. The S21 parameter measurements where performed on a vector network analyzer E5072A of Agilent Technologies. It allows measurements in the frequency range up to 8.5 GHZ.The results showed a dielectric constant value in the range from 4.62 to 4.9, which corresponds to the values given in the manufacturer's technical certificate. This fact proved the measurement method applicability.

Next, test substrates with AAO layer where subjected to measurements. The substrates where elaborated as described in section II.B of the paper. The anodization process was performed only on the top side, while the bottom side was protected and leaved un-anodized. This was made in order this side to stay conductive and to be used as a ground plane during the measurements. Two samples were obtained by this manner. The dimensions of the feed lines, the ring radiuses R1 and R2 and the gap Δ between the ring and the feed lines are the same as those to the FR4 structure. A picture of the first sample is shown on figure 5.

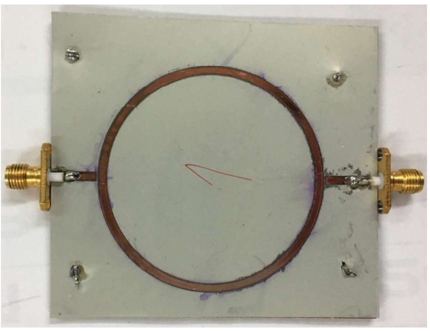

Fig. 5. Picture of the FR4 test structure.

The results, obtained after the measurements are shown in table 1. As the two measured AAO substrates demonstrated nearly the same characteristics, only the data of the first one is presented.

TABLE I
MEASUREMENT RESULTS

F, GHz	0.722	1.40	1.91	2.81	3.19	3.99	4.63	4.97
ε_r	6.62	7.03	8.51	7.03	8.51	7.81	7.90	8.95
tan δ	0.067	0.104	0.122	0.044	0.028	0.069	0.042	0.013

The dielectric permittivity results of the AAO substrate, calculated after the measurements, are shown on figure 6.

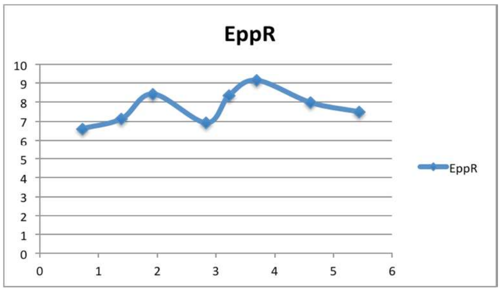

Fig. 6. Results of the measured dielectric permittivity of the AAO substrate.

The loss tangent results of the AAO substrate, calculated after the measurements, are shown on figure 7.

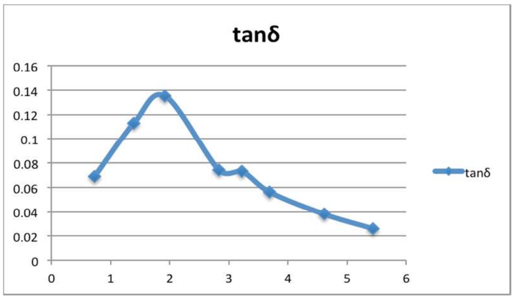

Fig. 7. Results for the loss tangent of the AAO substrate.

IV. CONCLUSION

The ring resonator method, proposed in this work, could be estimated as very convenient for the dielectric permittivity measurement of thin AAO layers. The results obtained in the measurement show that the dielectric constant of measurements varied in a range from 6.6 to 9. These values were expected, considering the dielectric permittivity of a High Temperature Ceramic (HTCC) substrate, made mostly of aluminum oxide material and having dielectric permittivity value about 9.

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