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Journal of the European Ceramic Society 24 (2004) 1463–1466

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Dielectric data of ceramic substrates at high frequencies

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Abstract

The dielectric constants of standard ceramic substrates like alumina and LTCC have been determined in the frequency range from 1 to 50 GHz. For the measurements cylindrical disk resonators and printed microstrip line resonators on substrates have been prepared. The RF-data have been measured with network analyzers and suitable wafer probe stations, the calculations of the dielectric data have been done on basis of two different simulation programs. The preparation of the samples and the test conditions of both resonator methods have proven to yield reliable results over a wide frequency range.

Keywords: Al_2O_3; Dielectric properties; LTCC; RF properties; Substrates

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1. Introduction

Ceramic materials are used in the microelectronics industry as dielectric substrates, due to their high reliability, high integration potential, good dielectric properties, excellent thermal conductivity and their coefficient of thermal expansion close to silicon.[1] Alumina is the standard material for the manufacturing of hybrid circuits via thick or thin film technology and for high integrated multilayer circuits produced via co-firing of metallized green tapes. Since the mid 1990s aluminium nitride and LTCC (Low Temperature Co-fired Ceramics) have successfully entered the market. Whereas in former times the dielectric constant and loss were measured at 1 MHz, the dependence of these data on frequencies up to 100 GHz is of high interest, today, due to the dynamic development of mobile communications.[2] For an accurate determination of the dielectric properties in this frequency range, specific designs of the specimen's geometry and of the measuring circuitry have to be used.[3] To achieve reliable data, the Institute of Materials Science and the Institute of High Frequency Technology co-operate on the basis of their specific know-how and equipment.

2. Outline of experimental approach

The dielectric constants of alumina (96%, thick film quality, Rubalit 708 S, CeramTec AG, Germany) and LTCC (Green Tape 951 A2, DuPont, USA) substrates and the attenuation of microstrip lines on these materials have been determined in the frequency range from 1 to 50 GHz at room temperature. For via filling and metallization a gold conductor paste was used (5723 Au, post-firing paste, DuPont, USA).

2.1. *Preparation of specimen*

The dielectric data have been measured by using two different kinds of microwave resonators: microstrip line resonators and cylindrical disk resonators.

2.1.1. *Microstrip line resonator method*

The line width w of 50 ohm microstrip transmission lines is a function of the dielectric constant ε_r and the thickness h of the substrate (Fig. 1). To get a higher packaging density and to avoid the propagation of higher order microstrip modes the thickness of the

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doi:10.1016/S0955-2219(03)00580-6

substrate should be kept as small as possible.[4] Eq. (1) gives a good approximation for the cut-off frequency of the first higher order mode of a microstrip line by defining an equivalent “magnetic wall model”:

$$f_{c,TE_{m0}} = m \cdot \frac{c_0}{2w_{\mathrm{eff}} \cdot \sqrt{\varepsilon_{\mathrm{eff}}}} \quad m = 1, 2, \ldots \tag{1}$$

c_0: speed of light, w_{eff}: effective width of the equivalent magnetic wall model, $\varepsilon_{\mathrm{eff}}$: effective dielectric constant of the model. The effective width of the model is a function of the thickness of the substrate.

The designs of the planar line structures are shown in Fig. 1, comprising microstrip resonators (line, stub, ring), microstrip lines with a line impedance close to 50 ohms, and calibration structures. In order to allow microwave measurements by using coplanar on-wafer probes, direct access to the ground metallization by means of two vias left and right of the microstrip lines is required (Figs. 1 and 2). In the case of alumina, a sintered substrate of 0.38 mm thickness was used, the vias of 250 μm diameter were formed by laser drilling. The vias were filled with Au paste via screen printing. After drying the microstrip lines of 350 μm width and the ground plate were screen printed on the substrate, using the Au paste. After a second drying process the printed substrates had been fired at 850 °C in air with a dwell time of 10 min.

In case of the LTCC substrates, two green tapes were laminated by thermo-compression (70 °C, 25 MPa for 10 min). The vias of 250 μm in diameter were punched into the laminate. After firing at 870 °C for 20 min in air the laminate exhibited a thickness of 0.28 mm. The filling of the vias, the printing of the strip line layout, and the firing procedure was done at the same conditions like in case of the alumina resonator. In both cases the thickness of the fired conductor lines was approximately 10 μm.

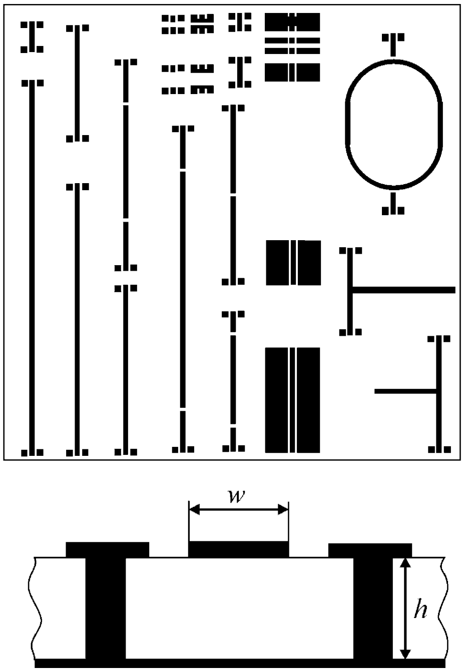

Fig. 1. Top: layout of the microstrip resonators and transmission lines (1 inch×1 inch). Bottom: geometry of microstrip lines including vias (w: 350 μm, h: 260 μm).

2.1.2. Cylindrical disk resonator method

For this measurement method, cylindrical disk resonators from alumina with 50 mm diameter and 1 mm height were manufactured by laser cutting of a sintered, 1 mm thick alumina substrate. A silver paste was applied on the entire surface of the disc by a brush to eliminate gaps between substrate and the conducting resonator cavity. A blank spot of 1.0 mm in diameter on both sides in the center of the disc was prepared by means of a PC controlled milling machine. The blank spot disturbs the ideal resonance mode, but it is needed as a coupling aperture for the resonator cavity. Its diameter was optimised for a moderate coupling.

Cylindrical disk resonators made from LTCC were fabricated by lamination of four blank green tapes of 165 μm thickness. The green laminate was mechanically milled to form a disc of 57 mm in diameter. After binder burnout and sintering at 870 °C for 20 min the laminate exhibited a diameter of 49.4 and a height of 0.56 mm. The silver paste was applied on the entire surface of the disc by a brush. The blank spots on both sides in the center of the disc with a diameter of 1.0 and 2.5 mm were achieved by means of a PC controlled milling machine.

2.2. RF measurements

The transmission and reflection coefficients of the microstrip structures have been measured with a vector network analyzer (VNA, HP 8510C, Agilent Technologies, USA) and a wafer probe station (Cascade Microtech, USA) in the frequency range from 45 MHz to 50 GHz to determine the dielectric constant and attenuation.

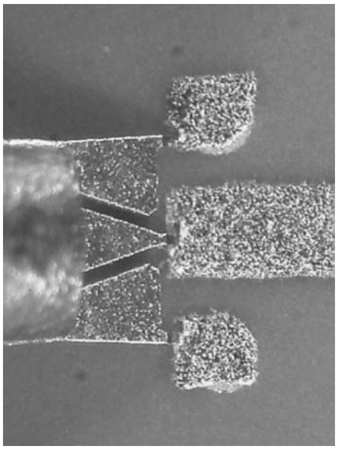

Fig. 2. Contact of wafer probe tips with microstrip line and vias on LTCC substrate.

To determine the dielectric constant from these experiments, two simulation programs (Advanced Design Systems (ADS) and Momentum, Agilent Technologies, USA) had been used. By the variation of ε_r, the calculated curves were fitted to the measured ones. In case of a perfect fit, ε_r of the material under investigation is obtained. The ADS program is based on analytical models which describe the electrical performance of microstrip lines and discontinuities. The accuracy of this program is limited by the restrictions of the models. The Momentum simulator is a 2-dimensional field solver using the method of moments for calculation. As this program is based on a full-wave solution of Maxwell's equations, it is independent of any analytical approximations. Therefore the obtained data are more reliable.

The attenuation of the microstrip lines was determined using the same experimental set-up. The transmission coefficients of the straight microstrip lines (see Fig. 1) were measured. In order to eliminate the influence of the transitions between the probes and the microstrip line, the difference of the transmission coefficients of two lines with different lengths was used for calculations.

In the case of the cylindrical disc resonator method, the transmission coefficients were measured versus frequency, using a cylindrical test fixture. This type of resonator is called an E_{ono}-resonator, which characterises the field distribution inside the resonance cavity. For this type of resonator, the dielectric constant can be calculated using Eq. (2):[5]

$$f_0 = \frac{c_0 \cdot x_{0i}}{2\pi \cdot r \cdot \sqrt{\varepsilon_r}} \tag{2}$$

ε_r: dielectric constant, c_0: speed of light, r: radius of disc, x_{0i}: ith zero of the Bessel function of 0- order, f_0: resonance frequency.

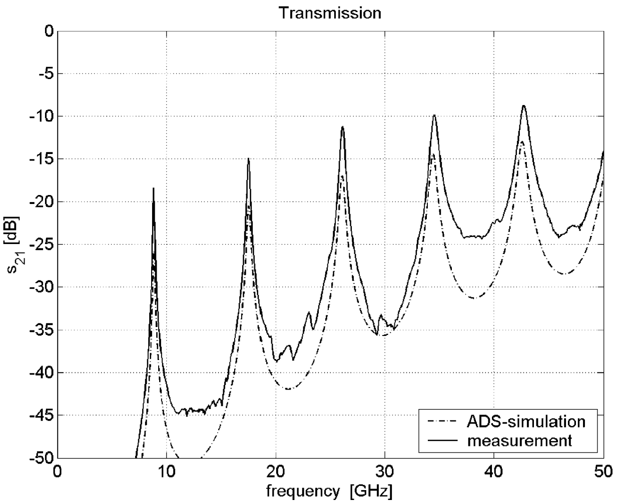

Fig. 3. Transmission coefficient versus frequency for $n \cdot \lambda/2$-line resonator on LTCC (ADS simulation based on $\varepsilon_r = 7.8$).

3. Results and discussion

The results of the RF investigations of these specimen are shown in Figs. 3–5. Fig. 3 shows the transmission coefficient versus frequency for the $n \cdot \lambda/2$-line resonator circuitry on **LTCC**. With the ADS simulation a good fit is achieved for $\varepsilon_r = 7.8$ in the frequency range 1–20 GHz. In the frequency range 41–44 GHz the Momentum calculation results in $\varepsilon_r = 7.75$. If the ADS curve was calculated with this ε_r-value, the difference in the position of the peak is 0.11 GHz, i.e. for this microstrip design both calculation programs result in nearly identical ε_r-data. There is no significant frequency dependence of ε_r, which is confirmed by the ε_r-data (Momentum) for different frequencies.

The ADS calculations of the measurement for the open stub microstrip resonator on LTCC results in a

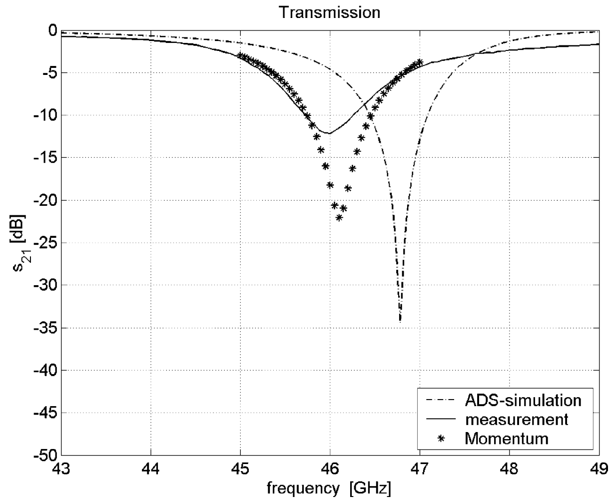

Fig. 4. Transmission coefficient at 43–49 GHz for the open stub resonator configuration on LTCC (ADS and Momentum simulation based on $\varepsilon_r = 7.6$).

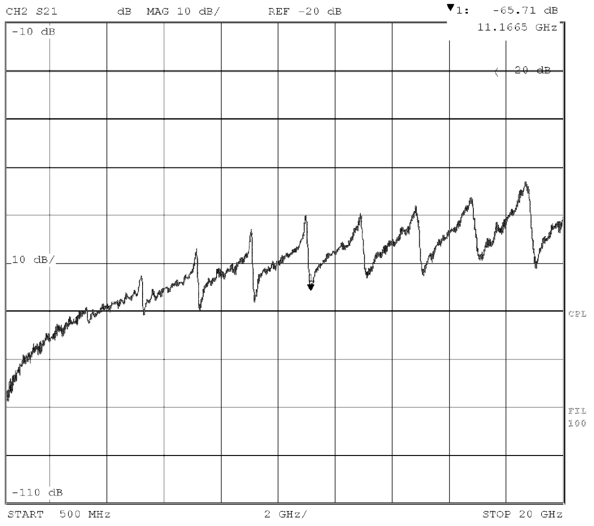

Fig. 5. Transmission coefficient versus frequency for disc resonator on alumina.

Table 1
Dielectric constant of the alumina disc resonator versus frequency

Frequency in GHz	3.36	5.27	7.21	9.14	11.08	13.00	14.96	16.90	18.87
ε_r	9.93	9.89	9.85	9.77	9.81	9.78	9.74	9.69	9.67

good fit for $\varepsilon_r = 7.78$ at frequencies between 1 and 25 GHz, at 26 GHz the ADS simulation results in $\varepsilon_r = 7.90$. Between 3 and 7 GHz, the Momentum simulation gives a good fit for $\varepsilon_r = 7.65$ and shows only a small difference of the resonance frequency in comparison with the ADS results. At higher frequencies between 43 and 49 GHz the Momentum program results in $\varepsilon_r = 7.6$ (Fig. 4). Feeding the ADS program with this value, the fit was insufficient and showed a significant shift of 0.8 GHz. An ε_r-value of 8.0 would give a good fit for the ADS program. This difference is caused by the microstrip T-junction and the open end, which are not described accurate enough by the models. Due to the full-wave electro-magnetic field solution, the data of the Momentum program are more realistic.

In the case of the microstrip lines ($n \cdot \lambda/2$-resonator) on **ALUMINA**, the same method was applied. ε_r was 9.7 in the range of 1–45 GHz using the Momentum program. No frequency dependence was observed. In the case of the open stub microstrip resonator on alumina, $\varepsilon_r = 9.65$ was achieved with the Momentum program in the range from 1 to 41 GHz.

The measured resonance frequencies of the cylindrical disk resonator, filled with an **ALUMINA** sample, are shown in Fig. 5. From the resonance frequencies, ε_r was calculated (Table 1) using Eq. (2). The values for ε_r decrease from 9.93 at 3.4 GHz to 9.67 at 18.9 GHz. This frequency dependence seems to be caused by the non-ideal coupling aperture of the disc resonator. With increasing frequencies the perturbation of the ideal resonator fields by the aperture is more significant.

In the case of the LTCC resonator, the aperture of the resonator could not be optimised. The resonator with the aperture of 1 mm resulted in an insufficient coupling, no clear resonance peaks were obtained. In case of the aperture of 2.5 mm the coupling is too strong, and the perturbation of the resonator by the measurement system is too high. Therefore the resonance peaks resulted in very low values for ε_r of 7.2.

The results of the attenuation measurement of the microstrip lines on the LTCC substrate and are in the range of the attenuation data measured by other authors.

4. Conclusions

The values of the measured dielectric data show that the installed equipment and specimen design is suitable to characterise the dielectric data of ceramic materials in the GHz range. In case of the cylindrical disk resonator method the entire volume contributes to the signal response. Therefore data of the pure dielectric material concerning ε_r and in principle also for dielectric losses are obtained. In the case of the microstrip lines it is possible to determine ε_r, but not the dielectric losses due to the superposition of the substrate materials' dielectric losses and the conductor losses of the microstrip lines. Nevertheless, the attenuation of a microstrip line is a very important parameter for microstrip circuit designs on specific substrates.

As shown in this paper and also in the literature,[6] the calculation of ε_r at high frequencies by using simple analytical approximations for the microstrip discontinuities exhibits considerable tolerances. On the other hand, the use of field solvers is very time consuming (appr. factor 15.000 on a modern PC). For standard accuracy requirements the fast modelling in ADS is sufficient for elementary structures. Since the Momentum simulation is based on Maxwell's equations, the results are more reliable but may imply also errors, if the geometrical representation used for the field simulation deviates from the real structure.

The disc resonator has the advantage of precise analytical descriptions and therefore the potential for a high accuracy at a minimum of computation time. A topic of future investigations is the optimisation of the coupling aperture, which caused deviations of the measured ε_r-values at higher frequencies.

Acknowledgements

The authors would like to thank the Bavarian State Ministry of Science, Research and Arts for the financial support within the program "New Materials", and Dr. Ruska, CeramTec AG, Germany and Dr. Schwanke, Micro Systems Engineering GmbH, Germany for technical support.

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