Test structures for dielectric spectroscopy of thin films at microwave frequencies

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Abstract

This work describes the application of two different test structures to execute broadband microwave measurements of the dielectric constant of ceramic thin films. Coplanar waveguide probes and vector network analyzer were used to measure the dielectric constant versus frequency of thin films of lead zirconate titanate and zirconium titanate, fabricated by sol gel methods. One-step lithography was used to produce planar metal-insulator-metal and interdigitated capacitor test patterns. The two test structures are compared for zirconium titanate films. The Metal-Insulator-Metal method has been applied also to a lead zirconate titanate film to show also the capability of computing the dielectric tunability.

Keywords: microwave, dielectric thin film, spectroscopy, ferroelectric.

1. Introduction

In recent years, the measurement of dielectric properties of ceramics at microwave frequencies has become important. The miniaturization of monolithic microwave integrated circuits (MMIC) for communications applications needs dielectric components with improved characteristics, smaller size and compatibility with other existing circuits. Paraelectric materials used for resonators and filters in microwave applications require high dielectric constant, to reduce the size, and low dielectric losses (tanδ). Data reported in literature show that zirconium titanate (ZT) has a high dielectric constant suitable for microwave devices and low losses in a frequency range up to 10 GHz [1]. Moreover ferroelectrics, as lead zirconate titanate (PZT), have been widely investigated for their tunable dielectric constant [2].

The purpose of this work is to determine the dielectric properties of ZT thin films up to 20 GHz and the tunability of ferroelectric films at frequencies up to 3-4 GHz. Metal-Insulator-Metal (MIM) and interdigitated capacitors (IDC) coplanar electrodes were prepared by a one-step lithography process to study the dielectric properties of PZT and zirconium titanate (ZT). Dielectric measurements were made using a vector network analyser and the data was analysed and the parasitic elements were de-embedded.

2. Experimental

2.1 Sample preparation

Ceramic $ZrTiO_4$ (ZT) and tetragonal ferroelectric $Pb(Zr_{0.25}Ti_{0.75})O_3$ (PZT) thin films were deposited onto silicon or alumina substrates using metal organic decomposition (MOD) preparation technique. These have been described previously [3] [4] and use methoxyethoxide precursors dissolved in methoxyethanol. The solutions were spun onto $Si/SiO_2/TiN/Pt$, for the MIM structures, and Al_2O_3 (CeramTec) for the IDC substrates and heat-treated to leave the oxide films.

Two different structures were adopted to measure the dielectric properties of the film layer: metal-insulator-metal (MIM) and interdigitated capacitors (Fig. 1). Both the structures have a simple shape and can be made using a one-step lithography process. A 120 nm Au film was evaporated to form the top electrodes. The Au patterns were defined with the lift-off technique, to match a 150 μm pitch coplanar ground-signal-ground (G-S-G) probe used for the measurements. A matrix of metal-insulator-metal (MIM) capacitors with two different diameters, 100 and 50 μm, was patterned to de-embed the capacitance due to the top-ground metallization from the results provided by the vector network analyzer (VNA) Anritsu 37347C VNA in the range 40 MHz ÷ 20 GHz [5]. Two interdigitated capacitors with 10 and 16 fingers were also tested and analysed.

2.2 Circuit modelling

Lumped element equivalent circuit of MIM structure

Considering the wavelengths of the 40 MHz – 20 GHz interval, the MIM structure is small enough to be lumped. The circuit in Fig. 2 models the measured impedance electrically. R_{cA} and R_{cB} are the contact resistances between the signal probe tip (S) and the circular patch of the device under test (DUT), and between the ground probe tips (G) and the top-ground respectively, C_d and C_{tg} are the capacitances of the circular patch and the top-ground, respectively, while R_d and R_{tg} are resistances representing the dielectric losses of the two capacitors. R_s is the resistance of the Pt ring that connects the bottom electrode of the circular capacitor with the bottom electrode of the top-ground capacitor. The impedance of this model is then:

$$Z_{AB} = R_t + \frac{R_d}{1+\omega^2 R_d{}^2 C_d{}^2} + \frac{R_{tg}}{1+\omega^2 R_{tg}{}^2 C_{tg}{}^2} - i\left(\frac{\omega R_d{}^2 C_d}{1+\omega^2 R_d{}^2 C_d{}^2} + \frac{\omega R_{tg}{}^2 C_{tg}}{1+\omega^2 R_{tg}{}^2 C_{tg}{}^2}\right) \quad (1)$$

where R_t represents the sum of R_{cA}, R_s and R_{cB}.

If $C_{tg} >> C_d$ and $R_{tg} << R_d$ then the equation (1) reduces to:

$$Z_{AB} = R_t + \frac{R_d}{1+\omega^2 R_d{}^2 C_d{}^2} - i\frac{\omega R_d{}^2 C_d}{1+\omega^2 R_d{}^2 C_d{}^2} \quad (2)$$

R_t can be evaluated from the measured data when ω tends to infinity.

After de-embedding R_t, the real part of the dielectric constant can be calculated from the measured susceptance B_m using the formula reported in Eq. 3: where t is the dielectric thickness, A_d is the electrode area of the capacitor under test and ε_0 is the vacuum dielectric constant.

$$\varepsilon'_r = \frac{B_m \cdot t}{2\pi \cdot f \cdot A_d \cdot \varepsilon_0} \quad (3)$$

The loss tangent is calculated from Eq 4:

$$\tan\delta = \frac{\varepsilon'}{\varepsilon''} = \frac{\mathrm{Re}\{Y_m\}}{\mathrm{Im}\{Y_m\}} = \frac{\mathrm{Re}\left\{ 1/Z_m \right\}}{\mathrm{Im}\left\{ 1/Z_m \right\}} \quad (4)$$

where Y_m and Z_m are the measured admittance and impedance, respectively, after de-embedding R_t.

Interdigitated Capacitors (IDC)

To a first approximation, considering the critical length of the circuit, the IDC structures here can be modelled by a lumped element circuit up to about 10 GHz. Below this frequency, a physical model based on a conformal mapping technique and developed by Gevorgian et al [6] was adopted to derive the dielectric constants of the oxide films that ignores parasitic elements of the test structure. These elements are responsible for resonances, thus, one must remain much lower than the resonance frequency to calculate the dielectric constant.

3. Results and Discussion

3.1 MIM and IDC with $ZrTiO_4$ film

The dielectric constant and loss tangent of an 825 nm thick ZT film are plotted as a function of frequency in Fig. 3. These results are obtained from a test device with a 50 μm electrode diameter having a capacitance between 1.5 to 0.6 pF in the range 40 MHz – 20 GHz. The relative dielectric constant of $ZrTiO_4$ falls from 65 to 30, which at lower frequencies is somewhat higher than reported previously [1]. The loss tangent is rather high, falling from 0.4 down to 0.1 at 1 GHz, possibly due to material defects (e.g. cracks).

Similar results were obtained from test a device with 100 μm electrode diameter.

In addition, the dielectric properties were measured using a 16 finger IDC on a similar film. Preliminary results from a reflection measurement show a first resonance at about 6 GHz, thus only the frequencies up to 600 MHz can be considered reliable. Fig. 4 shows ε′ evaluated with the model introduced by Gevorgian et al. [6]. At frequencies up to 600 MHz the mean value is similar to the MIM values. The behaviour is not monotonic, probably because of inadequate modelling and/or not-ideality introduced by the fabrication process.

3.2 MIM capacitor and $Pb(Zr_{0.25}Ti_{0.75})O_3$ film

The results obtained from the MIM structure with 50 μm DUT diameter are shown in Figures 5 and 6 for the structures with a 330 nm PZT film. Although the impedance measured in the range of 40 MHz to 20 GHz always has a negative reactance, the indirect measurement method used in this case is appropriate only up to approximately 3 GHz, since tanδ becomes negative above this frequency. The impedance values close to zero at higher frequencies introduce large errors when one evaluates the dielectric constant from the admittance; at higher frequencies the problem is ill-conditioned. Below 3 GHz, the PZT film has a dielectric constant around 130 that falls by applying a DC bias (110 with 4 V DC bias). The relative tunability ($n_r=(\varepsilon(0V)-\varepsilon(4V))/\varepsilon(0V)$) is 15 %, a small value for tunable applications [7]. The low losses are not affected by the DC biasing. The peaks that appear in tanδ applying a DC bias are probably due to the bias-Tee used, which was not considered in the calibration step of the VNA.

4. Conclusions

The dielectric properties of $ZrTiO_4$ thin films were investigated over the microwave frequency range using MIM measurement technique. An equivalent electrical model was adopted to compute dielectric constant and losses. While the permittivity is high (65 to 30 in the 40 MHz ÷ 20 GHz range), the losses are very large. Preliminary results obtained using IDC test structure also reveal a high permittivity but the method must be improved with better modelling and processing.

A MIM microwave characterization shows that the $Pb(Zr_{0.25}Ti_{0.75})O_3$ thin film has a low tanδ in the in the 40 MHz ÷ 3 GHz range and a dielectric constant is approximately 130. The relative tunability is around 15%.

References

[1] Kim Y, Oh J, Kim TG, Park B: Influence of the microstructures on the dielectric properties of $ZrTiO_4$ thin films at microwave-frequency range. Jpn J Appl Phys 2001: 40; 4599-603.

[2] Larson III JD, Gilbert SR, Xu B: PZT Material properties at UHF and microwave frequencies derived from FBAR measurements. Proc IEEE Ultrasonics Symp 2004: 1; 173-7.

[3] Watts BE, Leccabue F, Guerri S, Severi M, Fanciulli M, Ferrari S, et al.: A comparison of Ti/Pt and TiN/Pt electrodes used with ferroelectric $SrBi_2Ta_2O_9$ films. Thin Solid Films 2002: 406; 23-9.

[4] Chiorboli G, Leccabue F, Watts BE, Di Cristoforo A, Mengucci P, Majni G: The crystallisation behaviour of $Pb(ZrTi)O_3$ sol-gel films on platinum electrodes. Mat Sci Eng B 1997: 47; 263-8.

[5] Ma Z, Becker AJ, Polakos P, Huggins H, Pastalan J, Wu H, et al.: RF measurement technique for characterizing thin dielectric films. IEEE Trans Electron Dev 1998: 45; 1811-6.

[6] Gevorgian SS, Martinsson T, Linner PLJ, Kollberg EL: CAD models for multilayered substrate interdigital capacitors. IEEE Trans on Microwave Theory and Techniques 1996: 44; 896-904.

[7] Tagantsev AK, Sherman VO, Astafiev KF, Venkatesh J, Setter N: Ferroelectric materials for microwave tunable applications. Journal of Electroceram 2003: 11; 5-66.

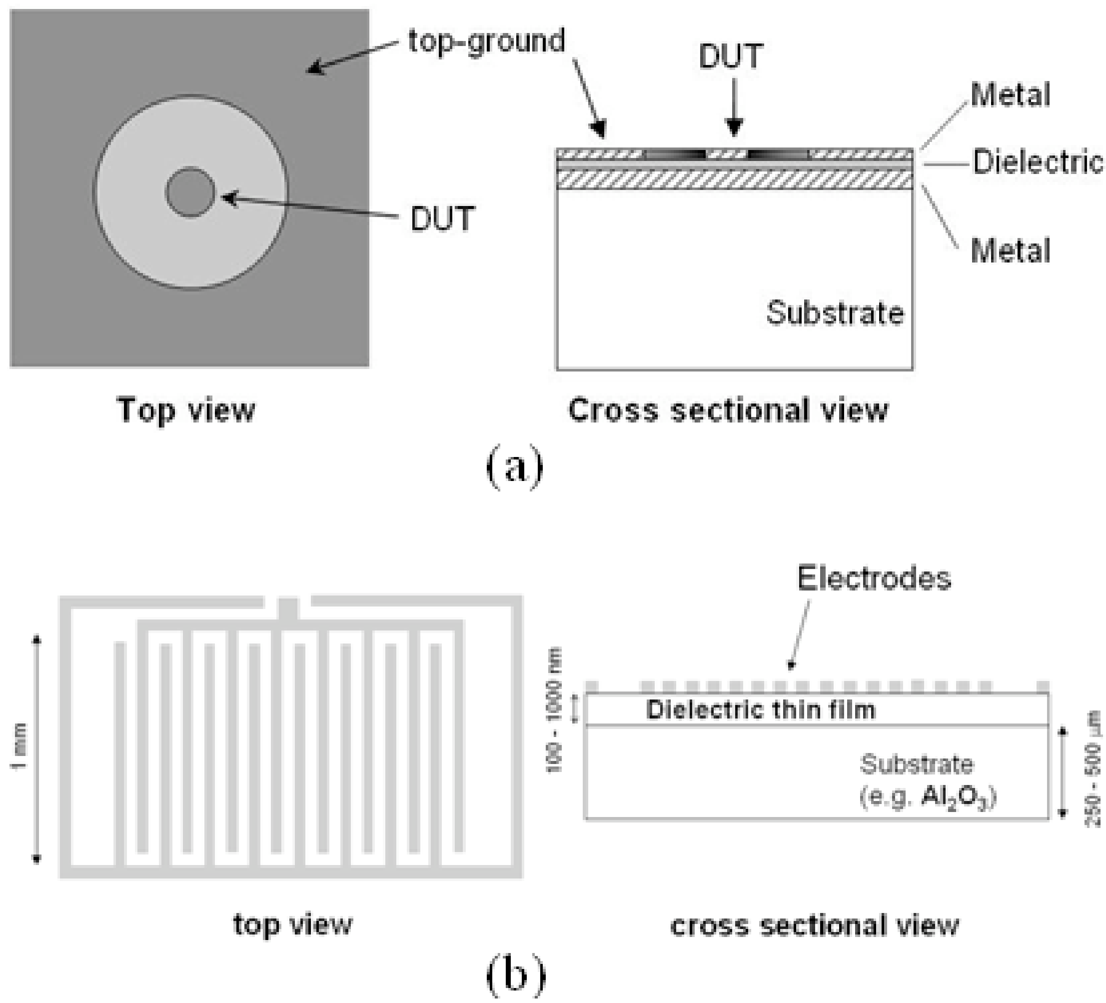

Fig. 1. Top and cross-sectional view of the test structures (not to scale): (a) MIM structure; (b) interdigitated structure.

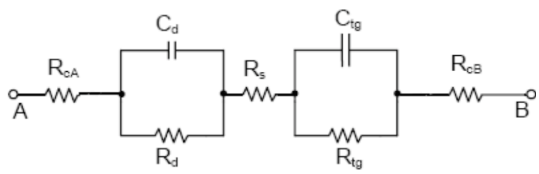

Fig. 2. Lumped element equivalent circuit of the MIM test structure.

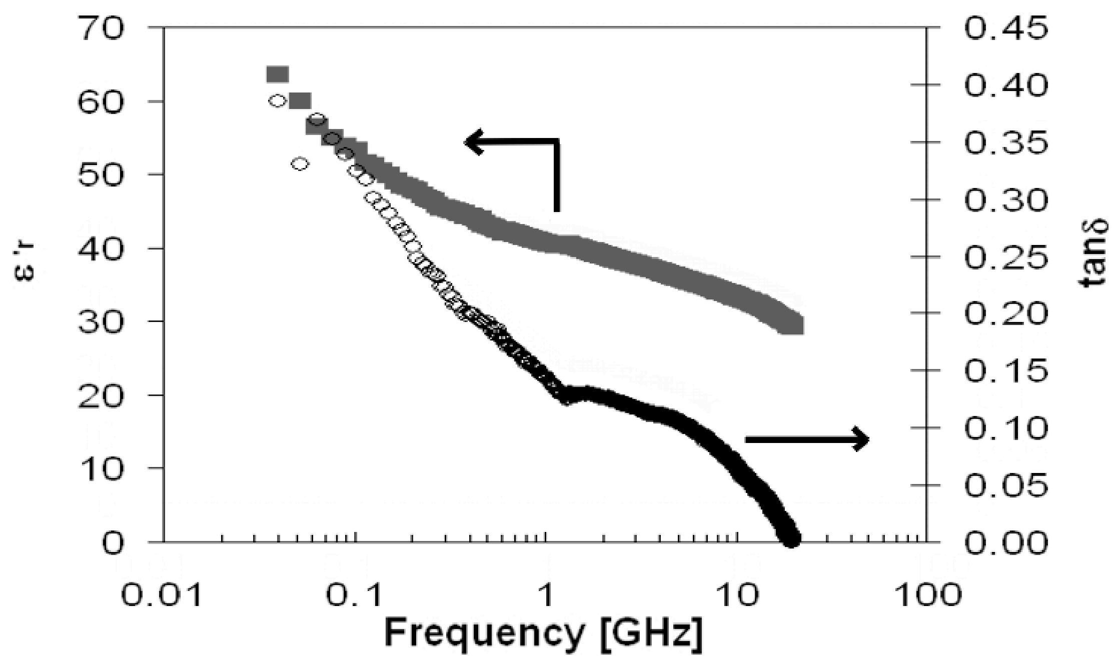

Fig. 3. MIM structures with 825 nm ZT film: real part of dielectric constant and loss tangent as a function of frequency.

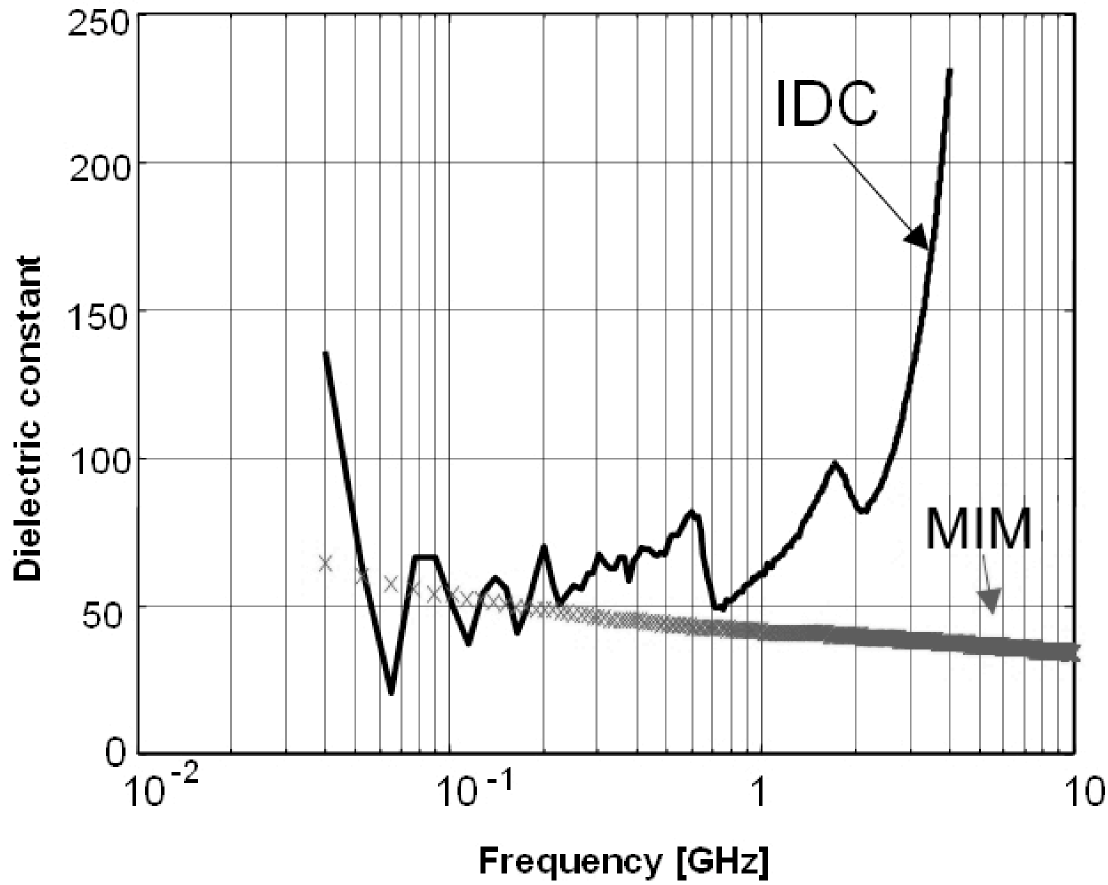

Fig. 4. Comparison between dielectric constant of 825 nm ZT film calculated with interdigitated capacitor (IDC) and a MIM capacitor.

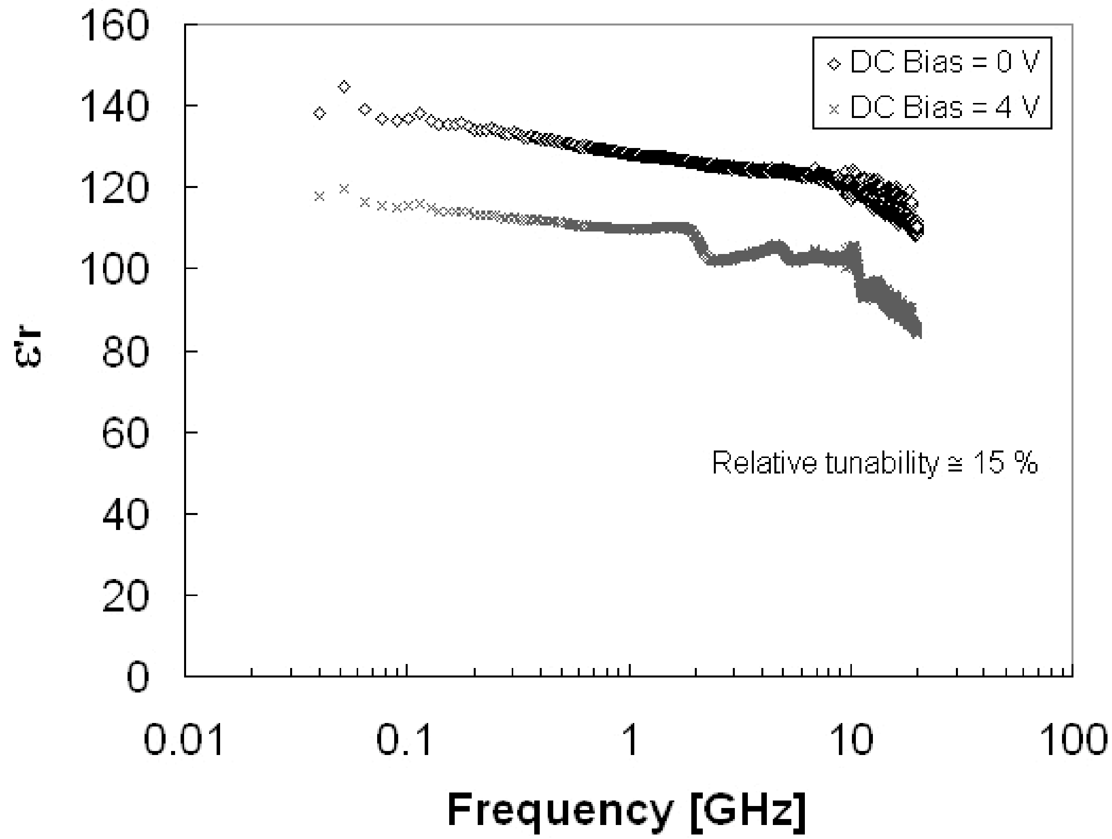

Fig. 5. MIM structures with 330 nm PZT film: real part of dielectric constant as a function of frequency.

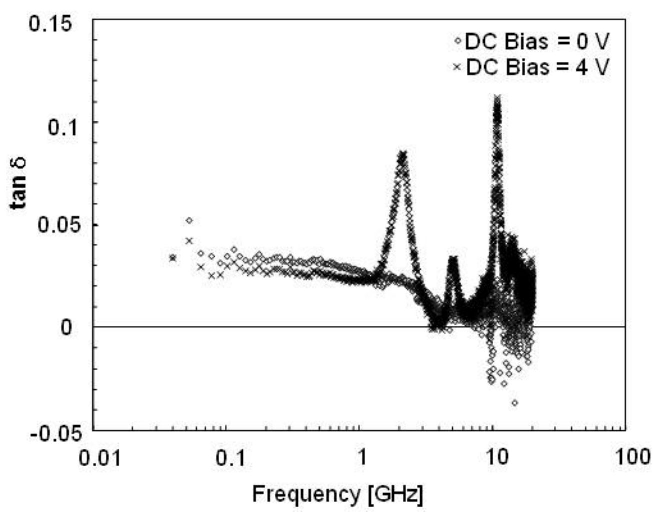

Fig. 6. MIM structures with 330 nm PZT film: loss tangent as a function of frequency.