The trade-off between tuning ratio and quality factor of $Ba_xSr_{1-x}TiO_3$ MIM capacitors on alumina substrates

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Abstract—**Barium strontium titanate with different compositions is deposited using wet-chemical processing on a glass planarization layer, on top of alumina substrates. Three samples were fabricated with $Ba_xSr_{1-x}TiO_3$ (BST) with the barium content *x* varying between 0.8 and 1. The poly-crystalline films are 530 ± 12 nm thick. The optimization in terms of permittivity and quality factor is explored for barium strontium titanate on alumina substrates. The trade-off between the permittivity and quality factor (at 1 GHz) is investigated. Our results show that wet-chemical processing on glass-planarized alumina results in a quality factor between 21–27 at 1 GHz and a tuning ratio from 1.8 to 2.0 at an electric field of 0.4 MV/cm.**

Index Terms—**ferroelectric, tunable capacitor, barium strontium titanate, high-k dielectric and alumina.**

I. INTRODUCTION

Tunable capacitors can facilitate the miniaturization of electronic circuits in mobile applications and their reconfiguration by exploiting the DC bias (V_{dc}) dependence. Tunable components integrated in microwave applications can be based on a transistor-capacitor array [1], micro-electro mechanical systems (MEMS) [2], varactor diodes (varicaps) [3] or ferroelectric capacitors [4-6]. In this work we focus on ferroelectric capacitors. Mobile applications can benefit from ferroelectrics by continuous tuning (< 50 V), small area consumption (A < 60 μm^2), low-cost, high permittivity (ε_r = 100−1000), high capacitance density (typically 1−20 nF/mm^2) and integrated decoupling.

The steps for optimizing a ferroelectric capacitor operating in the microwave frequency range (> 1 GHz) are application-specific. Preferably the capacitor has a high quality factor (1/tanδ) and a high tuning ratio ($\varepsilon_r(0\ V_{dc})/\varepsilon_r(V_{dc})$). Examples of application with ferroelectric capacitors are phase shifters [7], matching networks [8] and filters [9].

Barium strontium titanate ($Ba_xSr_{1-x}TiO_3$) with different compositions is deposited using wet chemical processing on glass-planarized alumina substrates. We optimized barium strontium titanate ($Ba_xSr_{1-x}TiO_3$) in a metal-insulator-metal (MIM) configuration by changing the barium content x varying between 0.8 and 1. Others have reported deposition of a single BST composition onto a glass planarization layer on alumina with metalorganic decomposition (MOD) [4] and onto polished alumina using RF magnetron sputtering [5,6].

The work in this paper will point out that a trade-off exists between the quality factor and the tuning ratio. This paper is subdivided in a section on the tuning ratio, on the quality factor and will end with the conclusions.

II. RF TEST STRUCTURES

The RF MIM test structures [10] were fabricated with different poly-crystalline ferroelectric compositions. We varied the barium content x in $Ba_xSr_{1-x}TiO_3$ (BST) between 0.8 and 1. Three samples of a few cm^2 in size were fabricated. The processing recipe [11] is unaltered for all wafers, except for the dielectric composition. The dielectric thickness is 530 ± 12 nm, according to results obtained from a scanning electron microscope (SEM). The dielectric varactors operate at relatively low voltages (typically <50 V).

The dielectric varactor stack is schematically shown in Fig. 1. A glass planarization layer is put on top of alumina to have a low surface roughness due to, e.g., grain boundaries. In addition, the thermal expansion mismatch coefficient of BST is closer to that of alumina than to Si [2,3].
The BST is deposited using wet-chemical processing on top of an unstructured homogeneous Pt bottom electrode. The Au/Pt top electrode is placed on top and the first and final patterning step is applied.

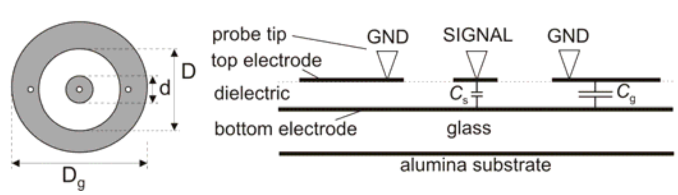

Fig. 1: A top view of a MIM capacitor is given on the left side with white coloured landing spots for three probe tips of a single ground-signal-ground (GSG) probe. A schematic cross-section is given on the right side. Starting with an alumina substrate, a glass planarization layer follows and then the MIM capacitor stack.

The ground-signal-ground (GSG) probe from the Advantest R3767CG vector network analyzer (VNA) is connected to the RF test structure. The small signal pad capacitance C_s is connected in series with the much larger ground capacitance C_g (since the ground pad diameter D_g is much larger than the signal pad diameter d). Effectively, the results of the total capacitance after a 1-port RF measurement is approximately equal to the signal pad capacitance. From the RF measurements the sheet resistance is determined. The sheet resistance of the Pt bottom electrode is $R_{s,bottom} \approx 1.4\ \Omega/\square$ and the sheet resistance of the Pt/Au top electrode is a $R_{s,top} \approx 70\ \mathrm{m}\Omega/\square$.

The quality factor at RF is obtained from the s_{11}-parameters of the VNA. The tuning ratio is assessed with a HP4194a impedance analyzer at 1 MHz at 50 mV_{ac}. Both, the quality factor and the tuning ratio are discussed in the next sections.

III. TUNING RATIO

A feature of tunable ferroelectric capacitors, which can be exploited in reconfigurable architectures, is the sensitivity of the relative permittivity to a change in DC bias. Increasing the absolute electric field between the parallel plates reduces the permittivity (see Fig. 2). A change in electric field, between the plates, causes the dipole moments in the dielectric to reorient, and the polarization to change, affecting the permittivity ε_r and tuning ratio η.

We define the tuning ratio as

$$\eta = \frac{\varepsilon_r(0\,V_{dc})}{\varepsilon_r(V_{dc})}\ . \qquad (1)$$

The numerator is often defined as the maximum permittivity of the ferroelectric. The denominator equals the permittivity at the maximum operating voltage. To extent the lifetime of the device the operating voltage typically is significantly lower than the breakdown voltage. A positive DC voltage is applied on the top electrode with the bottom electrode at 0 V. A DC voltage sweep is performed from negative to positive voltages. The measurements are performed at 1 MHz, 50 mV_{ac}, and room temperature. The measurement results are depicted in Fig. 2 for each sample.

The relation between the barium content in BST and the tuning ratio at an electric field of 0.4 MV/cm is shown in Fig. 3. More barium within the BST film increases the Curie temperature. An amount of barium $x \geq 0.8$ should result in a ferroelectric BST [12]. The increased tuning could thus mean that ferroelectric domain contribute at the higher Ba content. A higher permittivity at zero field resulting from a higher barium content results in a higher tuning ratio, since the permittivity at an electric field of 0.4 MV/cm appears to be approximately the same for a varying barium content.

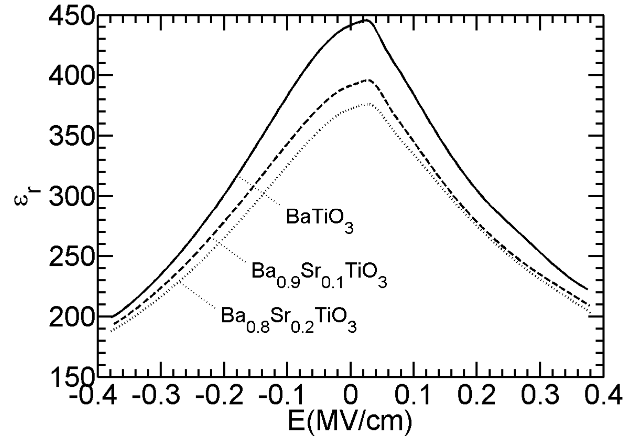

Fig. 2: The relative permittivity ε_r vs. electric field E for $Ba_xSr_{1-x}TiO_3$ compositions with a barium content x varying between 0.8 and 1.0 at 1 MHz, 50 mV_{ac} and at room temperature. The area of the test structures is 100 μm x 100 μm. A higher barium content increases the ε_r.

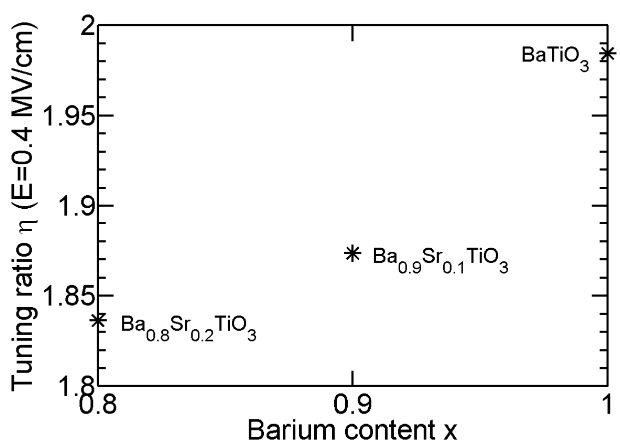

Fig. 3: The tuning ratio η (at an electric field of E = 0.4 MV/cm, 1 MHz, 50 mV_{ac} and at room temperature) related to the barium content x in BST. The area of the test structures is 100 μm x 100 μm. A higher barium content increases the tuning ratio.

IV. QUALITY FACTOR

Besides the tuning ratio, also the quality factor at microwave frequencies is important for circuit designers and the performance of the varactor.

The unloaded quality factor of a device equals

$$Q = \tan\delta^{-1}\ , \qquad (2)$$

where tanδ expresses the dielectric loss. The dielectric and the resistive electrodes result in the loss of a capacitor. Both losses can be separated at RF using test structures, as depicted in Fig. 1, with different signal pad diameters [13].

A higher energy-efficient device ensues from a higher quality factor. The quality factor Q of the dielectric at zero bias, -10 dBm RF power and at 1 GHz is illustrated for the measured dielectric compositions in Fig. 4.

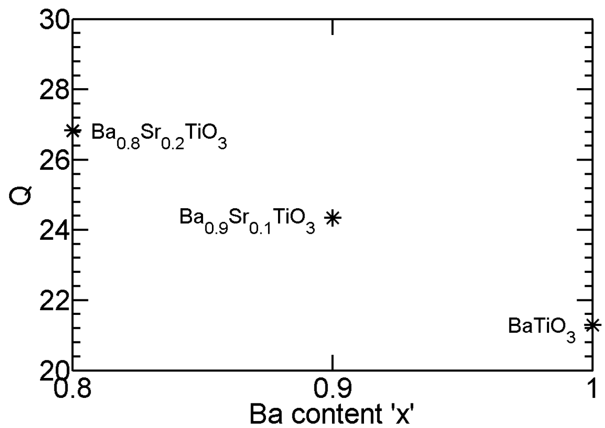

Fig. 4 The quality factor *Q* of the dielectric vs. the barium content at zero DC bias, -10 dBm RF power, at room temperature and at 1 GHz. A decrease in barium content in BST increases the *Q*.

The quality factors at 1 GHz, –10 dBm RF power and zero DC bias are closely spaced together between 21.3 and 26.8. An increase in barium content in $Ba_xSr_{1-x}TiO_3$ results in a higher dielectric loss (decreased Q).

IV. CONCLUSIONS

Barium strontium titanate with different compositions is deposited using wet-chemical processing on glass-planarized alumina substrates. Three different $Ba_xSr_{1-x}TiO_3$ solutions with x=0.8, 0.9 and 1 are fabricated and measured. A clear trade-off between the quality factor Q and tuning ratio at an electric field of 0.4 MV/cm is found. A higher barium to strontium ratio results in a higher permittivity and a higher tuning ratio, at the cost of a lower Q. The quality factor varies between 21–27 (at 1 GHz) and the tuning ratio (at an electric field of 0.4 MV/cm) between 1.8–2.0.

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