RELIABILITY OF BST THIN FILM CAPACITORS

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ABSTRACT

Thin film voltage tunable ferroelectric capacitors on various substrates show significant promise for use in high power microwave and other RF systems. The commercialization of ferroelectric components requires compliance with certain industry standards. TDDB (Time Dependent Dielectric Breakdown) is a fundamental measure of a dielectric material's aging characteristics under applied bias. Tuning is the main function of a tunable capacitor. Stability of tuning within a required temperature and voltage range is critical. This paper presents the results of a tuning degradation test. Acceleration factors and their limitations are discussed. The relationship of Mean Time to Failure (MTTF) and film grain structure is presented.

1. INTRODUCTION

Barium Strontium Titanate (BST) and other high-K ceramic oxides are important materials used in integrated passive devices, multi-chip modules (MCM), high-density interconnect (HDI), and chip-scale packaging. A variety of techniques have been employed to manufacture BST thin films, e.g.: Metal-organic decomposition (MOD), reactive sputtering, sol-gel, metal-organic chemical vapor deposition (MOCVD), ion beam assisted deposition (IBAD) and pulsed laser deposition (PLD) [1]. BST-based capacitors are currently used for decoupling purposes and have been fabricated with high yield, repeatability and high capacitance per unit area (up to 120 nF/mm^2)[2].

All plasma assisted deposition techniques result in dense polycrystalline BST layers with a pronounced vertical columnar grain structure. Such a crystalline habit maximizes capacitance and electrical tunability of these capacitors. Conversely, MOD- and Sol-Gel-derived films have randomly distributed crystals without a preferential orientation. This gives them lower tunability and capacitance density.

Utilization of BST tunable capacitors in RF modules requires tuning fields of between 40 and 80 V/um. These fields are much higher than for decoupling applications, which generally require voltages less than 5 V.

In order to commercialize BST tunable capacitor technology, reliability of the tunable capacitors should be assessed from two standpoints: standard JEDEC testing and tuning stability testing. Standard JEDEC testing includes Time Dependent Dielectric Breakdown (TDDB), Temperature Humidity Bias (THB) and Temperature Humidity No Bias (THNB). TDDB characterizes the fundamental stability of a capacitor under maximal bias with appropriate acceleration in order to get feedback on the expected lifetime. THNB tests die hermeticity and overall sensitivity to moisture. THNB shows the sensitivity of the die finish (including metalization) to storage conditions.

A standard technique for testing tuning stability under maximal bias and at rated temperature range does not exist today [3].

2. EXPERIMENTAL PROCEDURE

Single layer thin film BST capacitors were manufactured on polished polycrystalline Alumina substrates. Pre-deposition preparation of all substrates involved a multi-step oxidative cleaning and drying process. Substrates have an adhesion layer of thermally oxidized titanium [4]. Pt electrodes were deposited by DC magnetron sputtering. BST films were deposited by RF-Magnetron Reactive Sputtering and Metal Organic Decomposition (MOD) techniques. Individual mesa structure capacitors were patterned using ion milling. Individual capacitors were encapsulated using a typical interlayer dielectric (ILD) process. Vias were formed in the ILD by photolithography and reactive ion etching (RIE). Capacitors were interconnected using Aluminum based interconnect layer and finally passivated with a hermetic Silicon Nitride passivation.

Film morphology was examined with a Field Emission Scanning Electron Microscope (FE-SEM) Hitachi S-4500 at a 9 mm working distance, 3-5 kV accelerating voltage.

Low frequency dielectric measurements of capacitance, dissipation factor and C-Vs, were collected with a HP4284A LCR meter. The I-V characteristics were recorded using a Keithley 236 Source Measure Unit.

TDDB and THB were tested using a EG&G Wakefield Systems (now Despatch Industries) and Thermotron SM-16 ovens respectively. The packages (16 pin CERDIPs) were mounted onto custom made boards with individual 100kΩ external resistors to limit their current in the event of a failure (short).

3. RESULTS AND DISCUSSION

3.1 Electrical Characteristics

Low frequency (1 KHz) electrical measurements of tuning, dissipation factor, and leakage current at the rated voltage for the fully passivated BST thin film capacitors were carried out. Electrical measurements were averaged from 88 sites per wafer. Average tuning for a control voltage of 0-10V is about 3.4:1 for the BST60 columnar film and 2.9:1 for BST60 with randomly oriented grains. Leakage current and dissipation factor were tested on planar MIM capacitors (250x500 um). In general, tuning correlates with dielectric phase volume to perimeter ratio. All the capacitors used in this experiment had the same geometry and as a result the same dielectric phase volume to perimeter ratio.

A cross-sectional schematic of a passivated capacitor is shown in Fig.1.

Leakage current at 10V of fully passivated capacitors is in the range of 1-7 nA for 250x500 um capacitors. There was no significant correlation between leakage current and BST film orientation.

3.2 Film Morphology

A surface morphology examination of $(Ba_{0.6}Sr_{0.4})TiO_3$ films was carried out using FE-SEM.

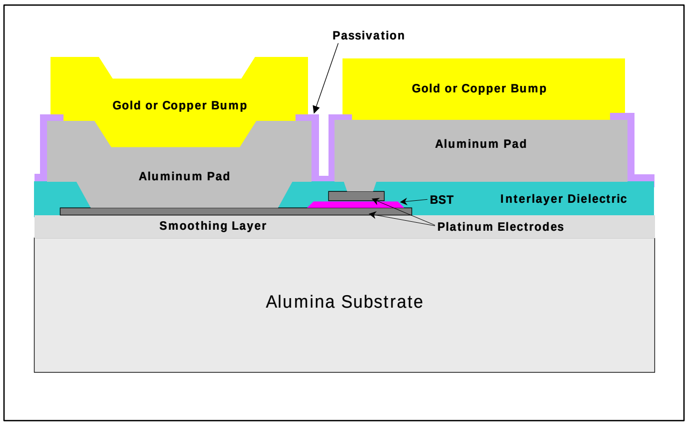

Fig. 1. Cross-sectional schematic of a passivated and interconnected BST capacitor

Figure 2 and Figure 3 show FE-SEM cross-sectional images of BST films deposited by MOD technique and by RF-Magnetron Sputtering . In both cases films were deposited on α-Al_2O_3 (99.6%) polycrystalline polished substrates.

A BST film deposited by Metal organic Decomposition shows a typical structure of randomly distributed crystallites with visible porosity [5]. Morphology of a sputtered BST film has a pronounced columnar crystalline habit with a clear orientation perpendicular to a substrate surface .

The degree of film densification and size of specific defects (i.e., pores, grain boundaries, cavities, etc.) is strongly dependent on the processing temperature and particular substrate [6]. The substrate material can influence the kinetics of film growth having different thermal conductivity**,** specific heat and emissivity [7, 8]. However, the same difference in morphology was found in the films deposited on Si/SiO2/Ti/Pt substrates.

3.4 Electrical Characteristics

Capacitance tuning versus tuning voltage and leakage current versus bias (I-V) plots are presented in Fig. 4 and Fig. 5. Electrical measurements were averaged from at least 9 sites taken from 3 identical types of samples with the same lower electrodes and identical BST deposition conditions.

It can be seen from Fig. 4 that there is a significant difference between the group of wafers with columnar crystalline habit and the group of wafers with randomly oriented grains. 0-10V tuning of 2.4 um thick films with a columnar crystal habit reaches 3.4:1 while films of the same thickness with a randomly oriented granularity show only 2.5:1 under the same bias. I-V curves of the samples of those two groups don’t show a significant difference taking in to account the fact that leakage is usually within an order of magnitude for different devices.

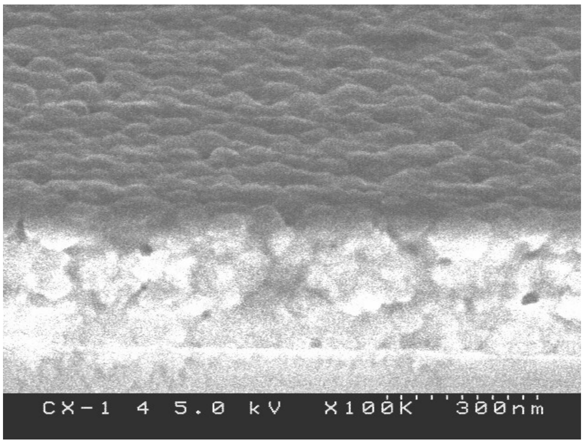

Fig. 2 . FE-SEM micrographs of 0.24 µm thick BST film with randomly distributed grains

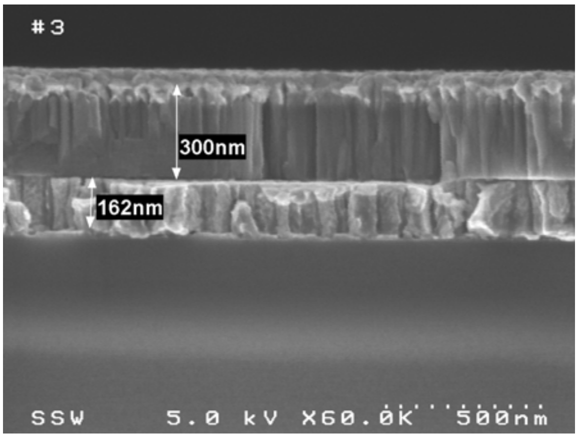

Fig.3. FE-SEM micrographs of 0.24 µm and 0.3 µm thick BST film with a columnar crystalline habit oriented perpendicular to a substrate .

I-V curves of the BST capacitors deposited by different methods are shown in Fig. 5. The knee voltage on the I-V curves of the samples with randomly distributed grains is lower (2.2V vs. 4.1V). This significant difference for the films of the same stoichiometry and thickness is probably due to lower physical density of the films with randomly oriented granularity. Films with modified columnarity have the same tuning as columnar films.

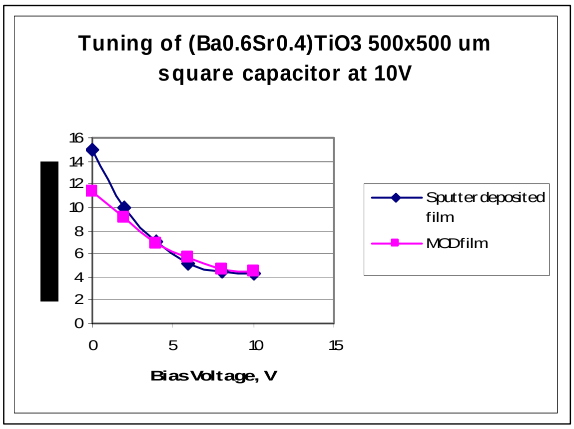

Fig.4. 1-10V tuning of BST caps (250x500 µm^2). There are 2 groups by crystal morphology, 3 wafers per group (averaged from 88 sites). Each dot represents the mean.

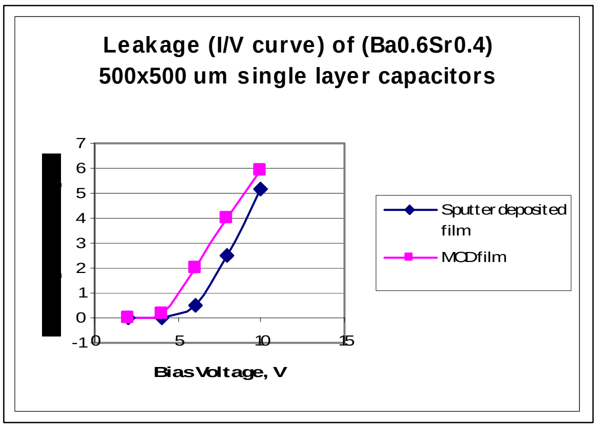

Fig. 5. Leakage current of BST caps (250x500 µm^2) at a maximal voltage (10V) . There are 2 groups by crystal morphology, 3 wafers per group (averaged from 88 sites).

3.5 Reliability testing

Temperature Humidity Bias (THB) test is an adequate indication of reliability. It shows both chip hermeticity and a dielectric degradation under working conditions as well. Diced packaged devices under went THB testing in a climatic chamber at the maximal operating voltage of 10V. Test conditions were 85^0 C @85% relative humidity. As seen in Fig.8, samples with a columnar crystalline habit showed higher knee voltages of the I-V curves. It was expected that they would demonstrate higher life times. Surprisingly, they demonstrated not only failures, but also a significant amount of early failures that could be considered as infant mortalities. The group of samples with randomly oriented granularity passed the 1000 hr test (JEDEC standard) with no failures. All process monitors demonstrated identical defect density. Hence, the THB failure of columnar samples could not be attributed to a higher density of optically detected defects.

It was confirmed with XRD analysis that films have identical cubic crystalline modification and lattice constants.

A difference in a crystalline morphology is the only significant difference that might result in a different reliability behavior.

A hermeticity check by "pressure cooker" was passed by all samples with no failures. Therefore the columnar samples failed for TDDB. Failure in TDDB testing is usually defined as the moment the leakage current reaches a certain value or changes by a pre-determined amount [9]. Failure of a device in this experiment was defined as having an increase in leakage current of 100 times from the initial value. Also a group of the randomly-oriented samples passed a 1000Hr test with no failures.

Sputter-deposited samples (having a columnar crystalline habit) showed higher knee voltages on the I-V curves than MOD-deposited samples (having randomly oriented crystals) . It was expected that they would have higher lifetimes. Surprisingly, they showed both a shorter lifetime and a significant number of early failures that could be characterized as infant mortality.

4. MODIFIED COLUMNARITY

A hybrid technology was developed (Patent pending, [10] in order to combine the enhanced tuning of columnar-oriented BST films with the TDDB robustness of the randomly-oriented BST films.

Interposing a randomly-oriented film between two sputtered layers was shown to modify the columnarity of overall film. As is shown in the SEM image in Fig. 6, this hybrid film does not exhibit continuous columnar crystals between the bottom and top electrodes.

The grain structure of a film can be modified in several ways: using a super lattice structure from films having difference in composition and thus different lattice constants, or using a super lattice structure with films of the same composition having different grain morphology.

All process monitors demonstrated an identical defect density. Therefore TDDB failures in the columnar-oriented samples could not be attributed to a higher defect density. Therefore we conclude that the difference in crystalline habit is the only cause of the difference in the TDDB performance of sputter-deposited and MOD-deposited samples.

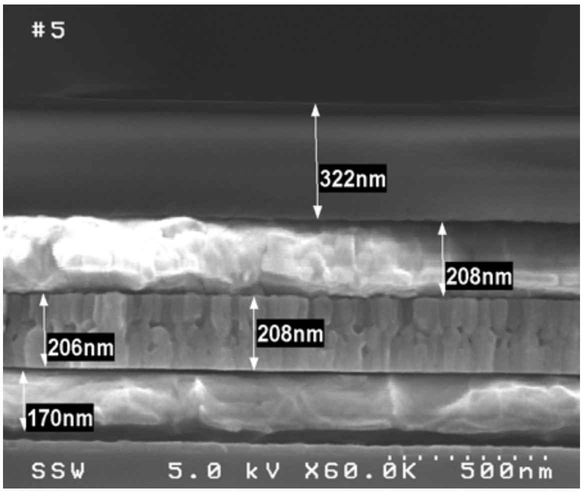

Fig. 6 FE-SEM cross-section of a film with a modified columnarity by introduction of a super lattice with a random grain orientation in the middle of the film.

As shown in Fig. 7 and Fig.8, films with the modified columnarity had similar electrical characteristics to those of purely sputter-deposited films. Tuning at 1-10V bias is 3.5:1 for sputter-deposited film and 3.32:1 for hybrid film. Leakage is identical at the same bias. This shows a similar film quality resulting from the two methods.

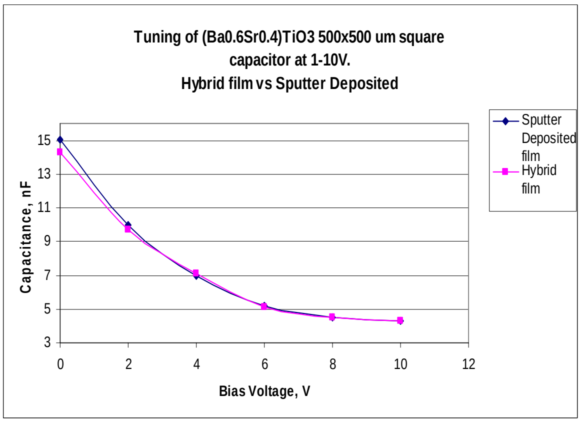

Fig 7. Tuning of the film with modified columnarity at 1-10V bias

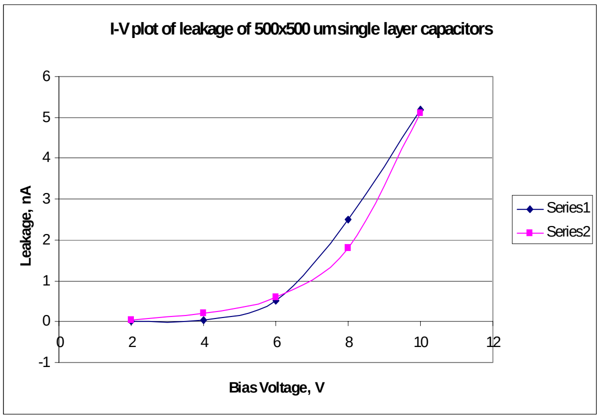

Fig. 8 Leakage of the film with modified columnarity at 1-10V bias

All hybrid samples passed standard THB test (1000 Hr) with no failures, similar to samples with randomly oriented grains. An accelerated TDDB test was performed at 125^{0}C. A failure rate plot (Weibull plot) is given in Fig. 9. Films with modified columnarity show approximately 15-25% higher MTTF. TDDB testing of columnar and hybrid samples was performed in order to assess stability of the tuning during High Temperature Operational Life test (HTOL).

An HTOL parametric plot for tuning is given in Fig. 10. It was found that BST films of both columnar and hybrid morphology show a reduction in C@0V of 2 - 3% after 100 hrs of testing at 1250C.

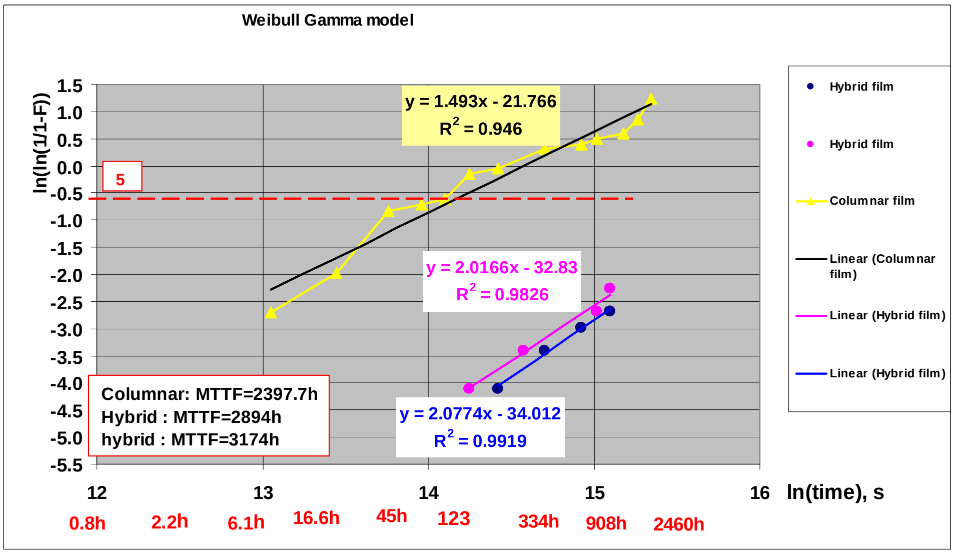

Fig.9. Failure rate plot versus time.

Even taking into account that a change in C@0V is affecting tuning, this small a change can be tolerated since there is no further degradation after the first 100 hrs.

Tuning is calculated as a ratio of the change in capacitance at applied bias to an initial capacitance value. As it is shown in Fig. 10, the capacitance value at applied bias does not change. However, the capacitance value at zero Volt bias is changing following the same pattern as tuning evolution.

That is pointing to a space charge phenomena as a mechanism for the evolution of tuning of the BST capacitors under constant voltage stress

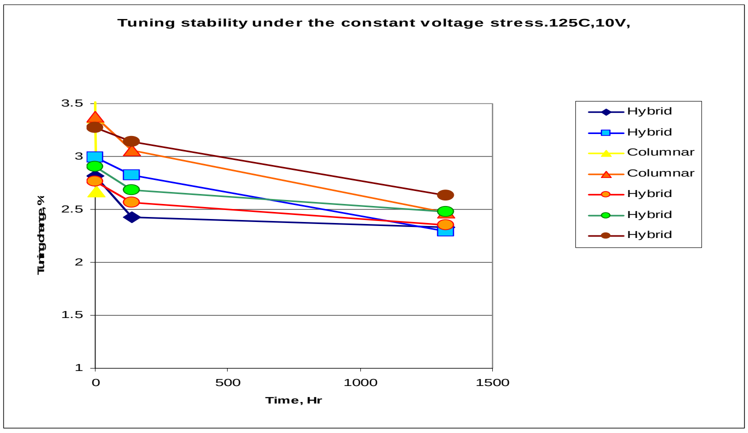

Fig. 10. HTOL parametric plot (Tuning)

CONCLUSIONS

BST capacitors are qualified for tunable application for the tuning electric field up to 50 V/µm. The corresponding tuning value is 3.5:1.

Films with modified columnar crystal morphology show 25% higher MTTF.

Evolution of the tuning under a constant leakage stress should be taken in account while designing BST tunable components.

A wafer scale burn in could be done in order to stabilize tuning of the thin film BST tunable capacitors.

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