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PARTICIPANTS:

Participant Type: Co PD/PI
Participant: Susanne Stemmer
Person Months Worked: 1.00 **Funding Support:**
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Authors: Cedric J. G. Meyers, Christopher R. Freeze, Susanne Stemmer, Robert A. York
Acknowledged Federal Support: **Y**

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Robert York
Signature Date: 8/11/21 10:35PM

Investigation of RF Losses in Tunable Dielectric Devices

Final Report

Award Information:
Contract Number: W911NF1410335
UNIVERSITY OF CALIFORNIA, SANTA BARBARA
Santa Barbara, 93106-2050, USA
Principal Investigator: Dr. York, Robert , rayork@ece.ucsb.edu, phone: 805-895-2562

1 Major Goals

The overarching goal of this research project was to investigate the fundamental limits of tunable dielectric varactors using advanced deposition and processing methods. The key enabling technology for this effort is a hybrid molecular-beam epitaxial deposition technique developed at UCSB.

2 Accomplishments

While some key advances were made during this project, including the highest-reported figure of merit for a tunable dielectric device, some new unexpected challenges and questions also arose that have not been fully explained at the conclusion of this project. This report will highlight some of the findings and will attempt to offer some conclusions relating to the stated goal above.

It should be noted that *many* advances in MBE growth and device processing were made during this project that may be useful for future work in this field. These cannot all be summarized in this final report, but all of the pertinent information is provided in the two PhD theses that were completed under this project sponsorship, by Dr. Chris Freeze [1] and Dr. Cedric Meyers [2].

2.1 The Emergence of a New Challenge

Prior to the start of the project, thin-film BST had been investigated for almost two decades by numerous researchers using a variety of growth methods, but nearly all of the work to that point had been with polycrystalline materials of varying levels of purity and stoichiometry, and the RF performance of the devices had been limited to Q-factors of 50-100 in the low GHz range [3]-[5]. Figure **1** shows a chart comparing the measured quality-factors and tunabilities of several devices gleaned from the literature prior to 2009 [1]. The premise of our project was that the performance of such devices was likely limited by the quality of the material itself, since historical data on single-crystal

$SrTiO_3$ and $BaTiO_3$ showed much lower loss tangents than had been observed with polycrystalline materials, and to some extent by interfacial effects which we attributed to a lack of attention to process cleanliness and surface treatments. New capabilities developed at UCSB for oxide MBE by the Stemmer group [6]-[9] had recently opened up the possibility of carefully exploring the impact of material quality on RF performance for the first time, and the early data on MBE-grown materials had showed dramatic improvements in both the dielectric constant (ultimately connected to the tunability) and the quality-factors as shown in Figure **2**.

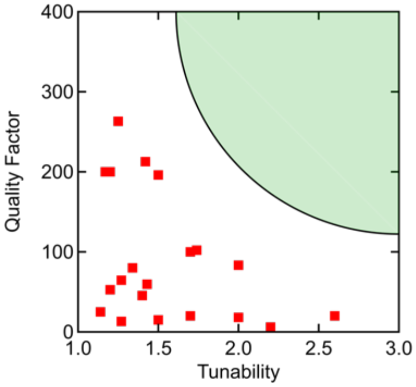


Figure 1: Comparison of some published data on BST devices [1]. Shaded region is desired for practical applications.

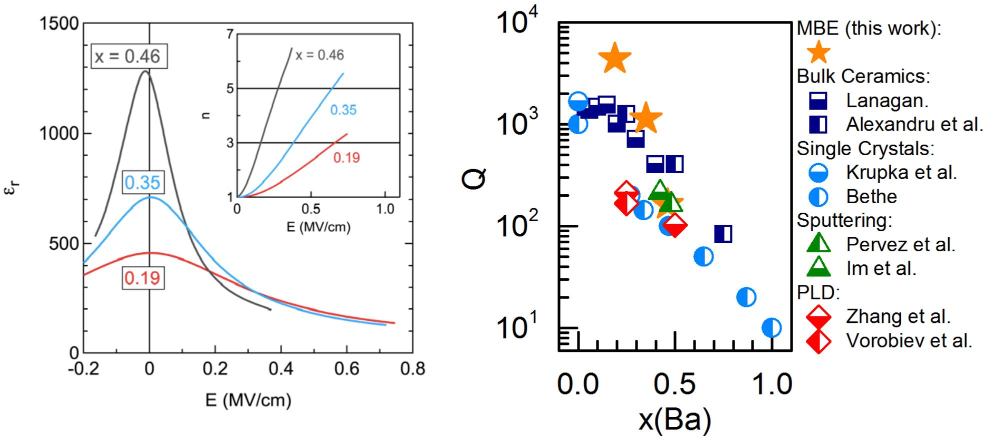


Figure 2: Dielectric constant versus field for MBE-grown BST, and quality factor (inverse loss tangent) as a function of Ba content [9]. This data was measured at 1 MHz.

Initial work on MBE growth of BST sought to minimize strain the films by growing on substrates with a close lattice match. Figure **3** shows some candidates:

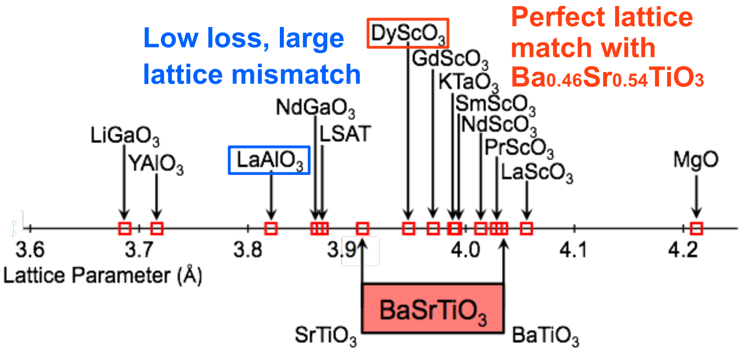


Figure 3: Possible substrates and lattice parameters in comparison to BST. This project focused on $DyScO_3$ and $LaAlO_3$ substrates.

$DyScO_3$ has the advantage of close lattice match with BST so this was used in the early stages of the project, but the loss tangent of $DyScO_3$ is typically larger than or similar to that of the MBE BST ($\tan\delta = 0.001$), so in later work we switched to $LaAlO_3$ which has a much lower loss tangent of $\tan\delta = 6\times10^{-5}$, though this introduced some compressive strain in the films.

Direct growth of BST on an insulating substrate favored the use of rather simple interdigital capacitor structures for the RF devices, which require blocking contacts only on the top film surface. In Year 1 of this program, fabrication of these devices confirmed a significant improvement in the RF loss of MBE-based devices relatively to historical work with polycrystalline devices. Representative data is shown in Figure **4**, demonstrating Q-factors of over 200 at <1GHz. This figure also shows the impact of electrode resistance on the high-frequency properties of the device. The roll-off in Q at higher frequencies is due almost entirely to this electrode resistance, so moving to high conductivity materials (like Au) and increasing the thickness of the electrodes leads to marked improvements in Q-factor (note that the resonant dip at ~40GHz is due to a small series inductance in the device, and is not a limitation of the material).

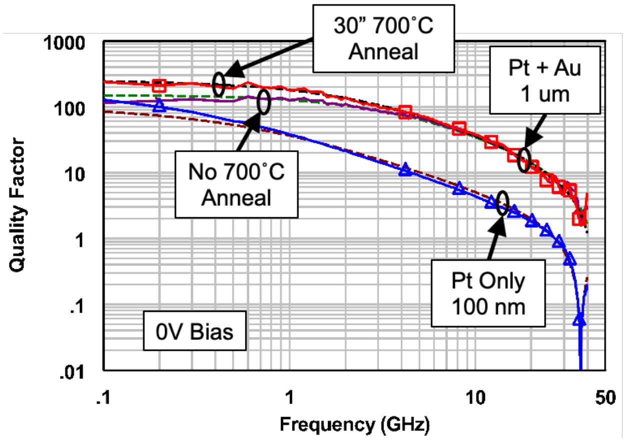


Figure 4: Measured RF quality-factor at 0 V bias, showing influence of electrode thickness and post-deposition anneal.

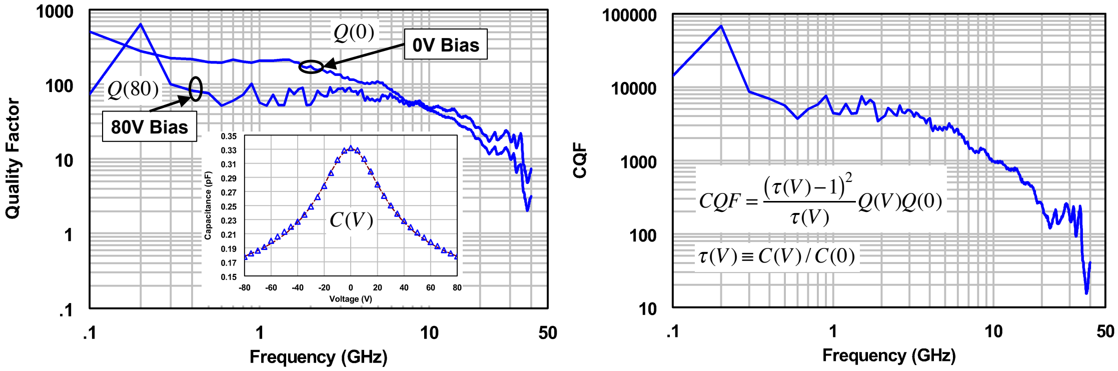


Figure 5 – Experimental data for 29% Ba films, 290nm thick, on LAO substrates. Top curve shows the frequency-dependent q-factor at zero bias and maximum bias points, with the inset showing the measured capacitance tuning curve. Bottom chart shows the commutation quality factor (CQF) computed from the data using the formula shown. The CQF of >6000 in the 1-2GHz range is the best reported value in this frequency range [10].

However, it was also quickly discovered that the new devices all failed under bias, due to excessively large leakage currents. This problem seemed surprising and somewhat counter-intuitive given the clear improvement in the underlying material quality, and our previous work with sputtered films had never shown such high levels of leakage. Subsequent investigation uncovered significant levels of organic surface contamination which led us to focus on several process improvements that would avoid exposing the pristine MBE-grown BST surface to any contaminants or other source of damage. The first of these improvements were reported in Year 2, and some representative data for devices using new processes is shown in Figure 5. As reported in [10], this device represented a new record for commutation quality factor (CQF), a useful figure of merit that takes into account the measured losses at the extremes of the bias range.

The data in Figure 5 also illustrates a problem that eventually became the #1 surprise and challenge for the remainder of the project: a significant broadband decrease in quality factor under bias in the 1-6GHz range. This had never been an issue with polycrystalline materials in the past, indeed the opposite trend (increasing Q under bias) was more commonly observed. It should be emphasized that a degradation in loss in a certain band of frequencies *cannot* be attributed to DC leakage currents, which has its own signature frequency dependence (a linearly-increasing Q vs. frequency).

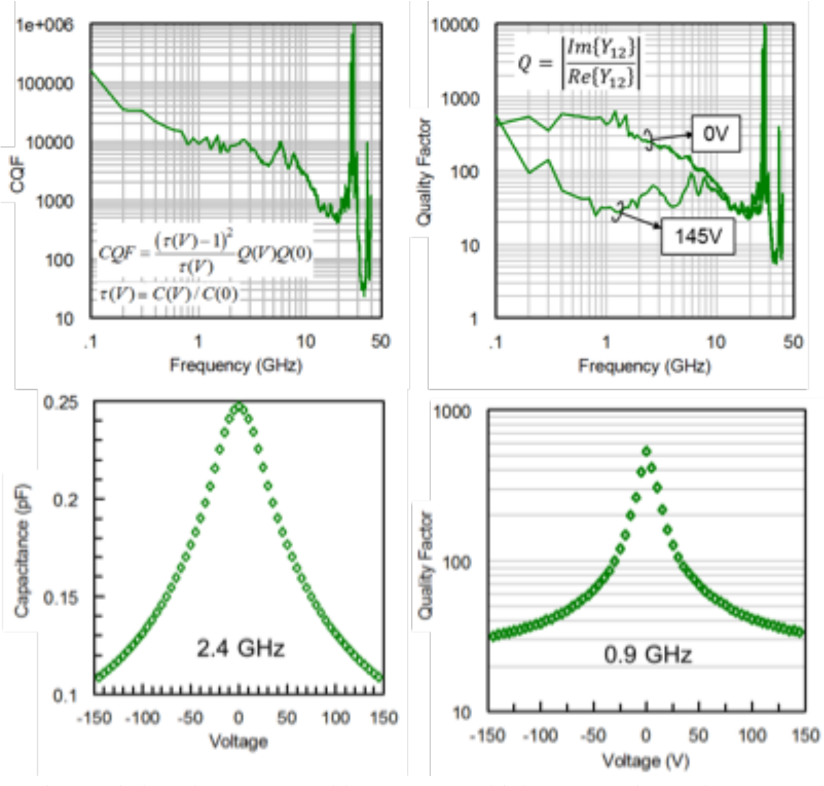


Figure 6 – Experimental data for 28% Ba films, 450nm thick, on LaAlO$_3$ substrates, with a ZrO$_2$ passivation deposited by ALD. (a) Shows the frequency-dependent q-factor at zero bias and maximum bias points, (b) shows the commutation quality factor (CQF), and (c) shows the measured capacitance-voltage tuning curve.

Based on the assumption that these losses were attributable to some defect in the material or processing or device design, several approaches were undertaken to resolve this problem, including: adjusting the material composition and stoichiometry, modifying the device processing to eliminate steps that may lead to degradation in the material, changing the design of the device to manipulate or suppress possible piezoelectric resonances, exploring the influence of periphery to area ratio, and contrasting interdigital and parallel-plate structures which apply the bias field in the film in orthogonal polarizations. Unfortunately, none of the several different avenues of exploration described below completely identified or solved this problem, and in fact any improvements in one characteristic seemed to come at the expense of another. By the end of Year 3, for example, we had nearly doubled the breakdown voltage of our IDCs, the zero-bias Q-factor at 1 GHz more than doubled from 200 to over 500, the tunability increase to 2.5:1, and the CQF increased to 10,000 at 1 GHz (Figure 6). However, the broadband decrease in Q under bias actually got significantly worse! At one point the question arose as to whether this degradation under bias was a measurement artifact, but we arranged to have our devices tested at an independent laboratory facility (Northrop-Grumman Corp. in El Segundo) but the results were the same.

Some additional detail on specific experiments that were done to understand and resolve the problem are given below. We conclude with some speculation on the origins of the mystery loss mechanism and a summary of what is known about losses in BST. It should be noted that in the narrative below, some of the commentary regarding certain experiments has been added with the benefit of some hindsight that was clear at the time.

2.2 Stoichiometric Influences

Figure 7 shows a comparison of low-frequency (1 MHz) quality factor for BST films grown by the hybrid MBE process [11] versus some historical data from UCSB by sputtering [3]. Clearly the stoichiometric BST shows impressive zero-field Q-factors. However these films do not demonstrate the strong local minimum in quality factor at zero-bias that is ubiquitously observed in literature. In fact the Q has a local minimum at zero bias only for the samples that are B-site (Ti) deficient (those with flux ratios of 28 and 32).

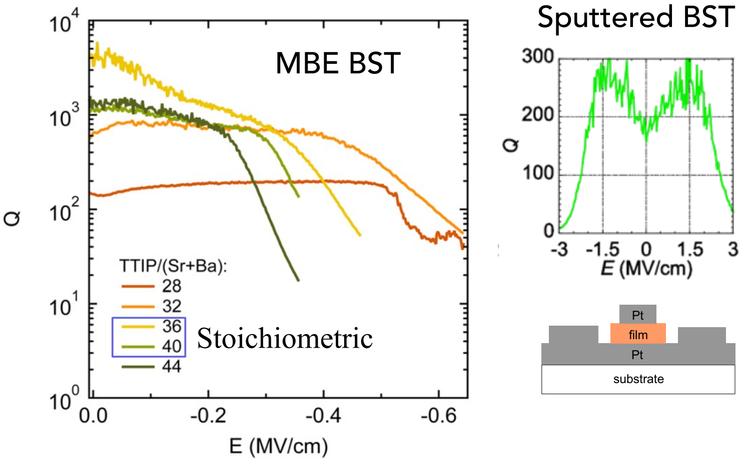
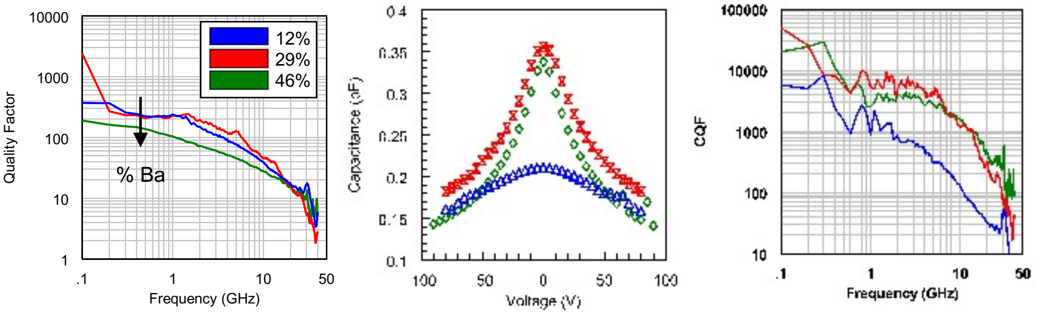


Figure 7 – Quality factor as a function of applied DC electric field for BST parallel plate capacitors for different BST growth conditions by MBE and sputtering. Relative A:B site stoichiometry for MBE samples is indicated by the ratio of TTIP (titanium source) flux to the sum of the strontium and barium fluxes, as measured by an ion gauge prior to growth. Data for both used the same device geometry shown.

There is a noteworthy attribute in the data associated with the horizontal scale in Figure 7. Note that the devices with sputtered films could support much higher applied fields before the Q-factor begins to degrade, nearly 3-5 times higher in comparison to the MBE data. The point at which the Q-factors begins to decline is associated with the onset of significant conduction (leakage currents) in the device. Note that conduction through the films is mediated by the Pt-BST Schottky contacts, which are normally very good blocking contacts owing to the high work function of Pt. There are two possible explanations for the discrepancy here. The first is the possibility that the Pt-BST contacts in the MBE grown devices had a much lower Schottky barrier than the devices using sputtered films. However, we discount that possibility because the processing steps and surface treatments were identical, and indeed other batches of devices using MBE and sputtered materials showed similar behavior. The second possibility is that the dominant conduction path is not through the film, but along the outer surface, in which case the difference between the two can be explained by very different surface conductivities in MBE films versus sputtered films. Other evidence that implicates these surfaces will be described below.

2.3 Influence of Ba Content

Given the strange behavior just noted, the study in Figure 8 was helpful in confirming that other historical trends that are more intrinsically connected with the bulk film properties could be reproduced with MBE materials. Here the Barium content of the films was changed, confirming that higher Ba content increases the tunability but decreases the Q-factor. These trends are widely reported in the literature across many different growth techniques. Based on this series a material with ~30% Barium content is optimal for the figure of merit.



% Ba on LAO	12%	29%	46%
Q-Factor (1 GHz)	220	210	100
Q-Factor (10 GHz)	40	45	27
CQF (1 GHz)	2000	5000	3500
CQF (10 GHz)	150	1200	1500
Tunability, 1:n	1.3	1.9	2.4
Max E Field (V/um)	53.3	53.3	72

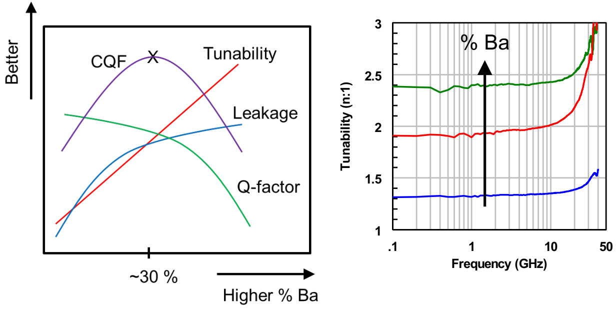


Figure 8 – Influence of Ba content on device properties..

2.4 Influence of Surface Passivation

The importance of the BST surface and associated interfaces is especially apparent in the data shown in Figure **9**. This data shows DC leakage current measurements for an interdigital capacitor (IDC) fabricated on the top surface of the BST. Following deposition of the Pt Schottky contacts, two types of dielectric were then deposited to encapsulate the device. This layer protects the BST surface from damage in subsequent processing steps. The data contrasts the leakage currents measured before the dielectric layer was deposited (the "No passivation" curves) with leakage currents for two different dielectric materials deposited by different methods: SiN_x deposited by plasma-enhanced chemical vapor deposition (PECVD), and SiO_2 deposited by Ion-Beam Deposition (IBD). This was another unexpected surprise, because PECVD SiN had been the workhorse passivation for decades of work in thin-film sputtered BST and used in commercial products without any such problems. Evidently the MBE-grown BST surface is much more sensitive to the reducing environment of PECVD deposition, resulting in a 6 order of magnitude increase in leakage currents! This is again attributed to surface conduction. Following this experiment we switched to SiO_2 and later to ZrO_2 deposited by ALD. Note also the interesting observation that the BST films are photosensitive, this was also a new discovery!

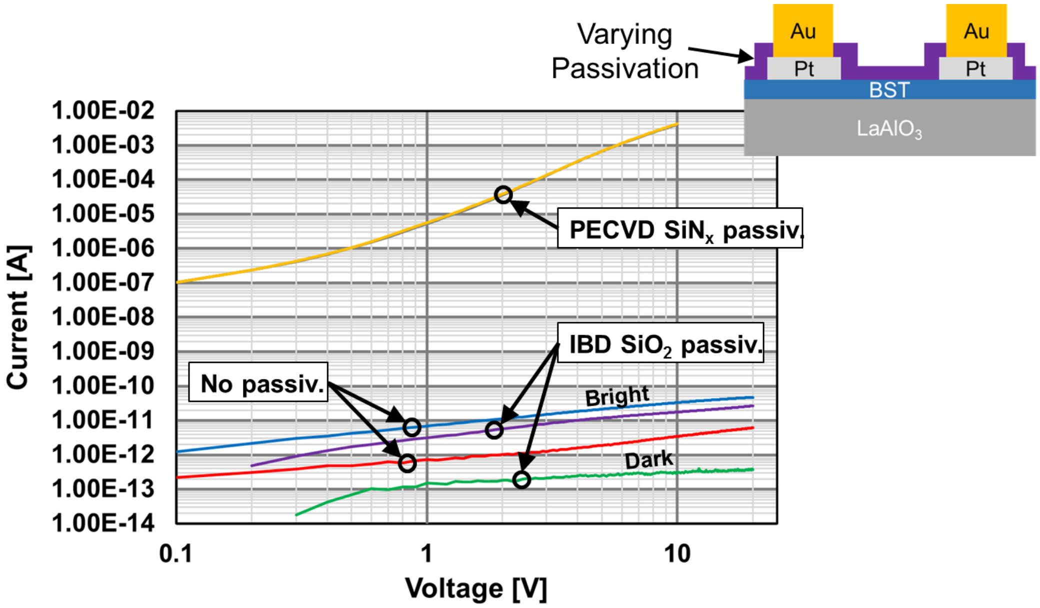


Figure 9: Leakage currents for IDC structure on an MBE-grown BST films for two different passivation schemes: PECVD-grown SiN and Ion-Beam Deposition of SiO2. Also shown for the IBD SiO2 data is a comparison of leakage currents with the room lights on and off, indicating the material is photosensitive.

Note that the IBD SiO_2 passivation actually *lowers* the leakage currents, indicating that it indeed is acting to passivate the surface in some sense, and further evidence of this is found in Figure **10** which showed that the addition of the SiO_2 allowed for larger tuning voltages to be applied before breakdown. This increased the tunability of the device and hence the figure of merit. Again, the strong influence of surfaces was somewhat surprising based on prior experience with sputtered films.

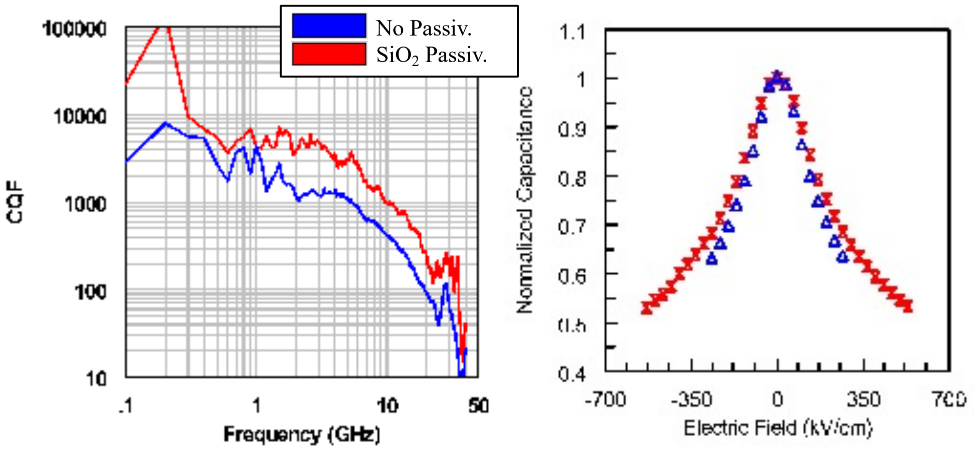


Figure 10: Influence of the SiO_2 passivation layer, which increases the breakdown voltage of the device and hence the tunability and CQF..

2.5 Impact of Device Design

Based on the possibility that interfaces near the electrodes might be playing a role in the losses under bias, some experiments were performed using interdigital capacitors with varying finger spacing, shown in **Figure 11**. While the *zero-bias* Q-factor seems greatly improved—with record high Q's in the low GHZ range—the degradation under bias appears worse in the band from 300 MHz to 8 GHz. Bias sweeps at 2.7 GHz suggest some dependence of the Q(V) response on finger spacing. While inconclusive, these observations suggest a potential link to the interfacial region *closest* to the electrodes.

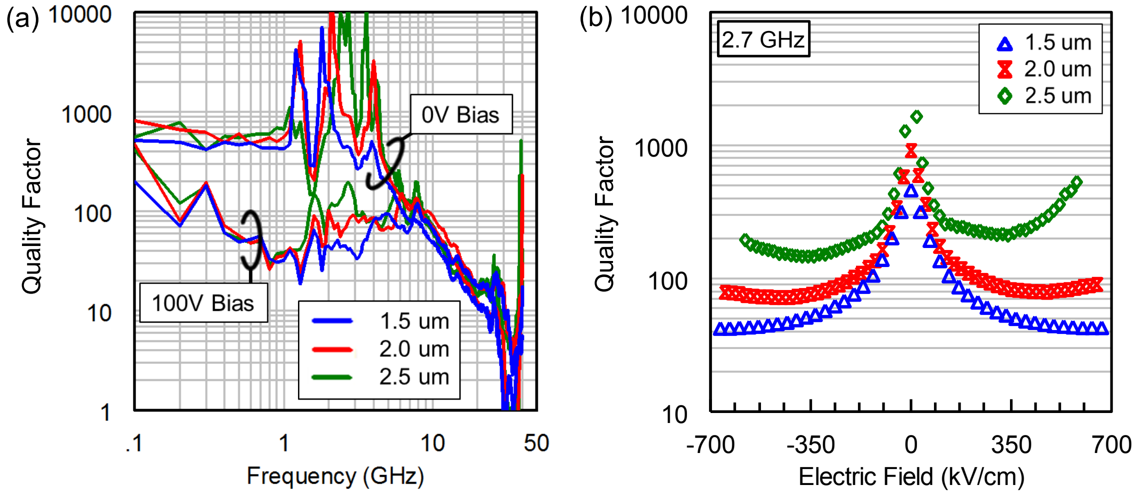


Figure 11: (a) Frequency dependence of Q for interdigitated BST capacitors with varying spacing between fingers. Bias sweeps shown at (b) 1.5 GHz and (c) 2.7 GHz, normalizing voltage by maximum field across the finger gap.

BST is known to become piezoelectric under bias, but some related experiments to trace the bias-dependent loss to a parasitically-excited surface acoustic wave were unsuccessful (reported in the final Interim Progress report), though this leaves open possibility that the loss could be related to some off-diagonal coupling to a bulk-acoustic mode.

Further evidence to implicate surfaces around the electrodes is shown in **Figure 12**, which shows how the Q-factor varies with the peripheral-to-area ratio of some devices. [11]. This was previously observed with sputtered films [12], but, since the Q-factor of those devices in the RF range was already strongly limited by other loss mechanisms, this geometry-dependent issue was largely ignored. However, given the extremely high starting values of Q-factor for MBE-grown materials, this geometry dependence becomes a serious limitation for devices in the RF frequency range which tend to have relatively small sizes and hence large P/A ratios.

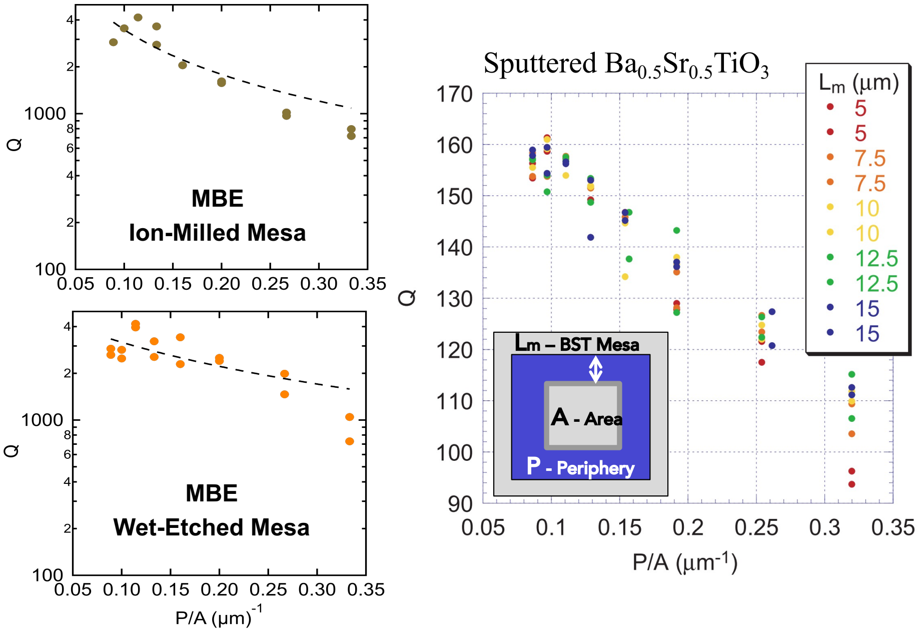


Figure 12: Variation of Q-factor with the periphery-to-area ratio of parallel-plate devices at 1 MHz. Similar behavior is observed for both MBE films and sputtered films.

2.6 Possible Origin of Observed Losses

It seems clear from our work on this project that the new loss mechanisms uncovered in this project present the most serious and unresolved limitation to high-performance tunable dielectrics using MBE materials. These are (a) clearly induced by an applied field, and (b) seem heavily influenced by interfaces between the film and other materials. The fact that the losses appear over a certain specific range of frequencies also suggest that a time-delay is involved in

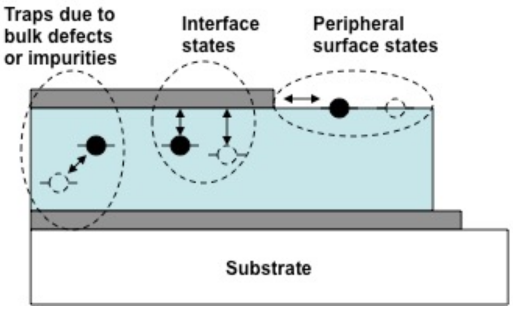


Figure 13: – Cartoon of possible loss mechanisms associated with charge trapping.

whatever process is contributing to the loss. A possible mechanism that can explain these observations is charge-trapping, most likely near the interfaces, as depicted in **Figure 13**. Similar mechanisms have been used to explain unexpectedly high gate resistance in FETs [13]-[14]. Charge trapping can be modelled by adding a small RC time-constant circuit in parallel with the device. Figure **14** shows that such a model is capable of reproducing the observed degradation in Q-factor in the low GHz range.

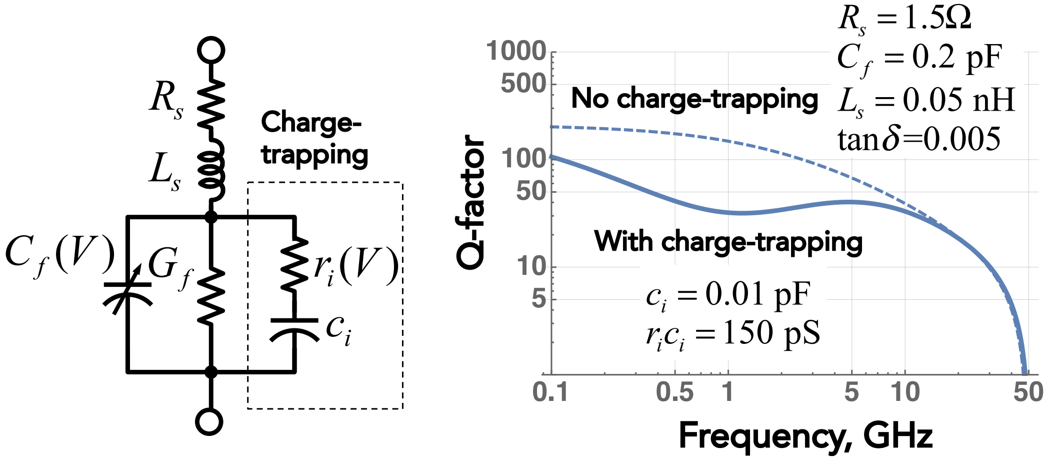


Figure 14: Adding a small RC time-constant to the equivalent circuit model of a BST capacitor can reproduce the observed degradation in Q-factor in the low GHz region.

The possibility of charge-trapping as a loss mechanism in BST devices is not a new idea, and indeed this was anticipated in our original proposal, and provided the motivation for exploring alternative passivation methods and surface treatments during the project. However, if this is in fact the mechanism responsible for the observed loss degradation our devices, the somewhat surprising conclusion is that we seem to have made the problem *worse* using high quality MBE-grown materials and processes that reduce surface roughness and contamination. What we see as a signature dip in the Q-factor near 1 GHz was never previously observed with sputtered films. With reference to Figure **14**, it may be that previous generations of BST devices had more readily accessible states near the contacts such that the interfacial resistance term r_i was much smaller, and therefore the dip would have been obscured by the natural rolloff in Q-factor at higher frequencies, *i.e.* by other loss mechanisms. In retrospect, this may in fact explain why historical attempts to improve the device Q-factor by lowering the electrode resistance also never seemed to work as expected in the low GHz range.

If the problem of charge-trapping could be resolved, perhaps by exploring other surface passivation methods or surface treatments, other aspects of the MBE films seem quite promising, and the remaining bulk loss mechanisms seem reasonably well understood at present. Many of these have been described in [4],[15]-[17], but the recent data on MBE films has added to our understanding.

3 Participants

During this reporting period the following participants were involved in this study

- PI Prof. Robert York, UCSB: administrative oversight of the project, and technical oversight of the device and circuit development (unchanged from previous reporting period). Nearest whole person-month on project: July 2019. Resident of California.
- Co-PI Prof. Susanne Stemmer, UCSB: technical oversight of the MBE materials development (unchanged from previous reporting period). Nearest whole person-month on project: July 2019. Resident of California.
- Graduate Student Researcher, Cedric Meyers, UCSB: device design, fabrication, and modeling (unchanged from previous reporting period). Nearest whole person-month on project: July 2019. Resident of California.
- Graduate Student Researcher, Christopher Freeze, UCSB: MBE materials development and characterization (unchanged from previous reporting period). Nearest whole person-month on project: March 2019. Resident of California.

4 Products

Conference Publications/Abstracts

- C.J.G. Meyers, C. R. Freeze, S. Stemmer, and R.A. York’, “Two-Port Tunable Interdigital Capacitors Fabricated on Low-Loss MBE-Grown Ba$_{0.29}$Sr$_{0.71}$TiO$_3$”, Materials Research Symposium, Phoenix, AZ, March 2016.
- C.J.G. Meyers, *C.* Freeze, S. Stemmer, X. Lan, L. Chau, and R. A. York, “Two-Port Tunable Interdigital Capacitors Fabricated on Low-Loss MBE-Grown Ba0.29Sr0.71TiO3”, IEEE International microwave Symposium (IMS), San Francisco, May 2016.
- C. J. G. Meyers, C. R. Freeze, S. Stemmer, and R. A. York, “Tunable Interdigital Capacitors Fabricated on Low-Loss Ba0.29Sr0.71TiO3 Grown by Hybrid MBE “, International Symposium on Applications of Ferroelectrics (ISAF), Darstadt, Germany, August 2016
- C. J. G. Meyers, C. R. Freeze, S. Stemmer, and R. A. York, “Tunable Interdigital Capacitors and Phase Shift Unit Cell Fabricated on Ba0.29Sr0.71TiO3 Grown by Hybrid MBE.” International Symposium on Applications of Ferroelectrics (ISAF), Atlanta, May 2017
- C. J. G. Meyers, C. R. Freeze, S. Stemmer, and R. A. York, “Voltage-Tunable Parallel-Plate Capacitors Fabricated on Low-Loss MBE-Grown BST”, International Symposium on Applications of Ferroelectrics (ISAF), Hiroshima, Japan,
- C.J.G. Meyers, C. Freeze, S. Stemmer, and R. A. York, “Voltage-Tunable Parallel-Plate Capacitors Fabricated on Low-Loss MBE-Grown BST”, IEEE International microwave Symposium (IMS), Philadelphia, May 2018.

Journal Publications

- Meyers, C. J.G., Freeze, C. R., Stemmer, S., & York, R. A. (2016). "(Ba, Sr) TiO3 tunable capacitors with RF commutation quality factors exceeding 6000." Applied Physics Letters, 109(11), 112902.
- Freeze, C. R., & Stemmer, S. (2016). "Role of film stoichiometry and interface quality in the performance of (Ba, Sr) TiO3 tunable capacitors with high figures of merit." Applied Physics Letters, 109(19), 192904.
- Meyers, C. J.G., Freeze, C. R., Stemmer, S., & York, R. A. (2017). "Effect of BST Film Thickness on the Performance of Tunable Interdigital Capacitors Grown by MBE" Applied Physics Letters, 111 (26), 262903
- Z Gu, S Pandya, A Samanta, S Liu, G Xiao, CJG Meyers, AR Damodaran, et al "Resonant domain-wall-enhanced tunable microwave ferroelectrics." *Nature* vol. 560 (7720), August 2018, pp 622-628

5 References Cited

[1] C.R. Freeze, *Molecular beam epitaxy of wide-band gap perovskite oxides: (Ba, Sr)TiO$_3$ and BaSnO$_3$* , PhD Thesis, UC Santa Barbara, 2019.

[2] C.J.G. Meyers, *Voltage-Tunable RF Capacitors Fabricated on Low-Loss (Ba,Sr)TiO$_3$, PhD Thesis*, UC Santa Barbara, 2019.

[3] N.K. Pervez, P.J. Hansen, and R.A. York, "High tunability barium strontium Titanate thin films for RF circuit applications," *Applied Physics Lett.*, vol. 85, no. 19, pp. 4451-4453, 8 Nov 2004.

[4] R.A. York, "Tunable Dielectrics for RF Circuits", Chapter 4 of *Multifunctional Adaptive Microwave Circuits and Systems*, M. Steer, W. D. Palmer (Editors), SciTech Publishing, Jan 2009.

[5] Baki Acikel, *High Performance barium strontium titanate Varactor Technology for Low Cost Circuit Applications*, Ph.D. Thesis, University of California Santa Barbara, 2002.

[6] B. Jalan, R. Engel-Herbert, N. J. Wright, S. Stemmer, Growth of high-quality SrTiO3 films using a hybrid molecular beam epitaxy approach, J. Vac. Sci. Technol. A 27, 461– 464 (2009).

[7] B. Jalan, P. Moetakef, S. Stemmer, Molecular beam epitaxy of SrTiO3 with a growth window, Appl. Phys. Lett. 95, 032906 (2009).

[8] J. Son, P. Moetakef, B. Jalan, O. Bierwagen, N. J. Wright, R. Engel-Herbert, S. Stemmer, Epitaxial SrTiO3 films with electron mobilities exceeding 30,000 cm2V-1s-1, Nature Mater. 9, 482 – 484 (2010).

[9] E. Mikheev, A. P. Kajdos, A. J. Hauser, and S. Stemmer, Electric field-tunable BaxSr1-xTiO3 films with high figures of merit grown by molecular beam epitaxy, Appl. Phys. Lett. 101, 252906 (2012).

[10] C. Meyers, C. Freeze, S. Stemmer, and R. York, "(Ba,Sr)TiO3 tunable capacitors with RF commutation quality factors exceeding 6000", Applied Physics Letters, to appear Sept 13, 2016.

[11] Freeze, C. R., & Stemmer, S. (2016). "Role of film stoichiometry and interface quality in the performance of (Ba, Sr) TiO3 tunable capacitors with high figures of merit." Applied Physics Letters, 109(19), 192904.

[12] N. Pervez, and R A. York, "Geometry-Dependent Quality Factors in Ba0.5Sr0.5TiO3 Parallel-Plate Capacitors", IEEE Trans. Microwave Theory and Tech., vol. 55, pp. 410-417, Feb 2007

[13] H. Rohdin, N. Moll, C-yi Su, G. S. Lee, "Interfacial Gate Resistance in Schottky-Barrier-Gate Field-Effect Transistors", IEEE Trans. Electron Devices, Vol. 45, No. 12, December 1998, pp. 2407-2416

[14] H. Rohdin, N. Moll, A. M. Bratkovsky, and C.-Y. Su, "Dispersion and tunneling analysis of the interfacial gate resistance in Schottky barriers", Phys. Rev. B, vol. 59, no. 20, 15 May 1999

[15] A.K. Jonscher, “Dielectric Relaxation in Solids”, *J. Phys.D*: *Appl. Phys*. 32, R57 (1999).

[16] A.K. Tagantsev, V.O. Sherman, K.F. Astafiev, J. Venkatesh, and N. Setter, “Ferroelectric Materials for Microwave Tunable Applications”, *J. Electroceramics* 11, 5 (2003).

[17] N. Pervez, *Investigation of Loss Mechanisms in Thin Film Barium Strontium Titanate Capacitors,* Ph.D. Thesis, University of California Santa Barbara, 2006