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A TESTBED FOR HIGH VOLTAGE, HIGH BANDWIDTH CHARACTERIZATION OF NONLINEAR DIELECTRICS

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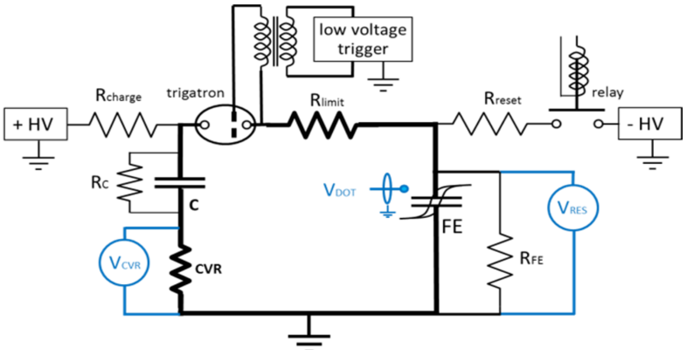
Abstract

The dielectric response of many high permittivity materials is nonlinear with both field and frequency. For example, ferroelectric materials exhibit a hysteretic polarization - electric field (P-E) response similar to the B-H curve of ferromagnetic materials. These P-E hysteresis loops are typically measured at low frequencies; the material behavior at high frequencies is less understood. To address this information gap, a test bed has been created to characterize non-linear material behavior at high frequencies and high voltages. This paper will report testbed goals in addition to design, assembly, analysis, and issues. Preliminary results will also be presented from commercially available nonlinear capacitors and in-house fabricated ferroelectric materials, including 10 nF non-linear $BaTiO_3$-based capacitors and 3 mm thick lead zirconate titanate (PZT)-based materials..

INTRODUCTION

All high permittivity materials exhibit some degree of nonlinear dielectric (NLD) response with applied electric field, and for most, this involves saturation (decrease) of the small-signal permittivity under increasing DC field. A particularly interesting and challenging case is that of ferroelectric (FE) materials. Their large permittivities make FEs the basis for the ceramic capacitor industry, and field-switchable spontaneous polarization underlies their use for nonvolatile memory (FERAM), piezoelectric, and many other applications. A complete representation of the dielectric response of such materials requires a full description of both monotonic field saturation and frequency dispersion of relevant polarization mechanisms as well as the dynamic response of the polarization reversal associated with ferroelectric switching.

Accurate description of the NLD response of high permittivity (FE) materials at high fields and high frequencies requires direct measurement. The signature P-E hysteresis loop of ferroelectrics, however, is generally measured under low-current conditions. Existing work on the exposure and response of FEs to brief high-field pulses has focused on thin films under large electric fields but low voltages [1-3], and it has been well established that the differences in chemical, interface, and strain conditions contribute to significant differences in the observed response(s) between thin films and bulk ceramics. In order to help fill the significant knowledge gap associated with the dynamic response of NLD, this paper describes the design and construction of a custom test bed for accurate measurement of this nonlinear response of high permittivity bulk ceramics in the large electric field and high frequency regimes.

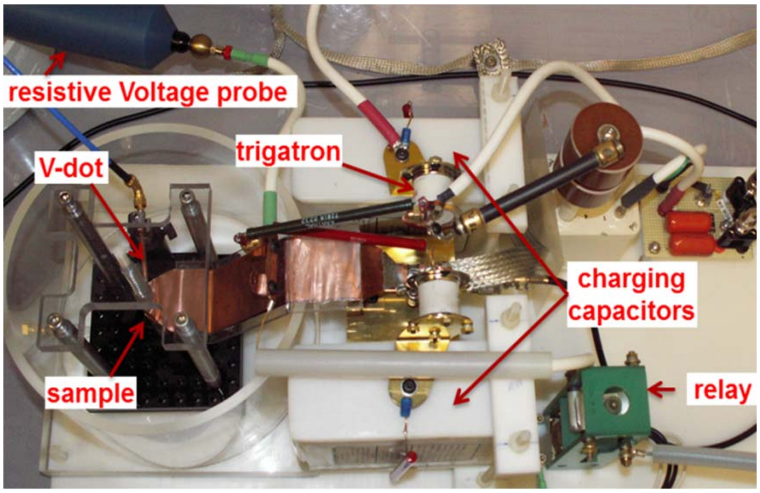


The high voltage, high bandwidth, NLD testbed schematic diagram
The "fast" (low inductance) part of the circuit has thicker lines.
Component values are below.

R_{charge}	R_{limit}	R_{reset}	R_{FE}	R_C	R_{CVR}	C
50 kΩ	10-1000 Ω	100 kΩ	1 GΩ	100 MΩ	50.5 mΩ	75 nF

REFERENCES

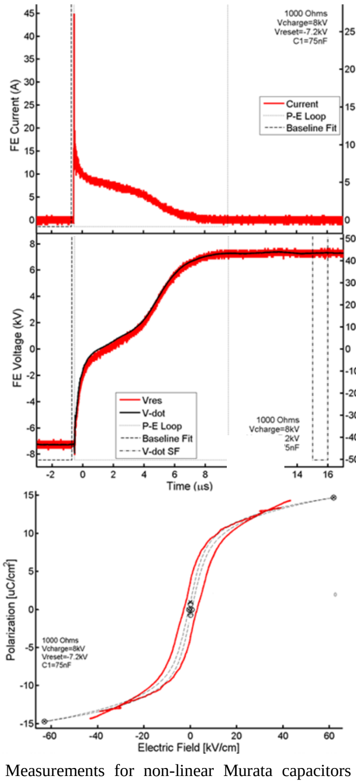
1. J. Li, B. Nagaraj, H. Liang, W. Cao, Chi. H. Lee, and R. Ramesh, "Ultrafast polarization switching in thin-film ferroelectrics," *Appl. Phys. Lett.*, 84[7] 1174-6 (2004).
2. A. Grigoriev, D.-H. Do, D.M. Kim, C.-B. Eom, B. Adams, E.M. Dufresne, and P.G. Evans, "Nanosecond Domain Wall Dynamics in Ferroelectric Pb(Zr,Ti)O_3 Thin Films," *Phys. Rev. Lett.*, 96, 187601 (2006).
3. I.K. Bdikin, A.L. Kholkin, A.N. Morozovska, S.V. Svechnikov, S.–H. Kim, and S.V. Kalinin, "Domain dynamics in piezoresponse force spectroscopy: Quantitative deconvolution and hysteresis loop fine structure," *Appl. Phys. Lett.*, 92 182909 (2008



The NLD testbed and critical components

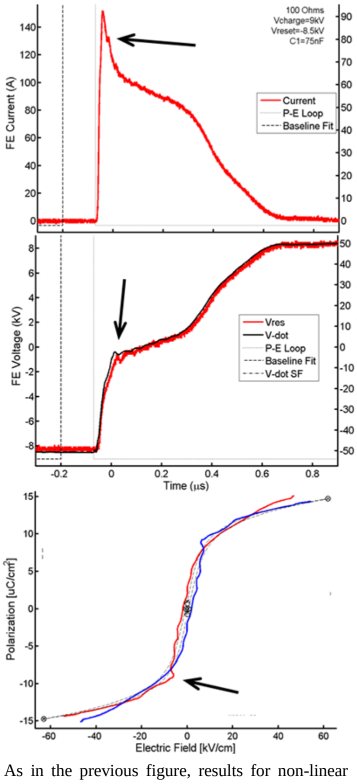
$BaTiO_3$ Capacitors

1 kΩ



Measurements for non-linear Murata capacitors with current limited by 1 kΩ are shown: (top) current and current density, (middle) voltage and electric field, (bottom) high BW P-E loop based on V-dot monitor and CVR (red curve and low BW P-E loop (black dashed). The upper left leg of the P-E loop is the symmetric reflection of the lower right leg.

100 Ω



As in the previous figure, results for non-linear Murata capacitors are shown. In this case, the current was limited by 100 Ω. A faster increase in electric field in the FE sample and a distortion at the knee of the P-E curve (bottom red curve) appear in these higher BW measurements. The blue curve, the symmetric reflection of the red curve, emphasizes the issues in the P-E loop width that are caused by this distortion.

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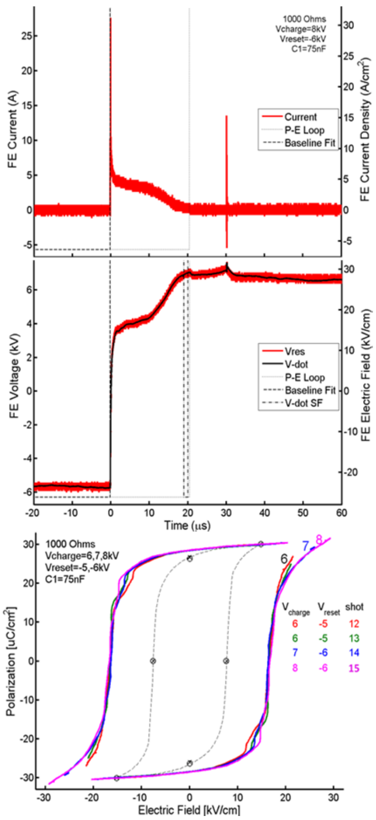
A TESTBED FOR HIGH VOLTAGE, HIGH BANDWIDTH CHARACTERIZATION OF NONLINEAR DIELECTRICS (continued)

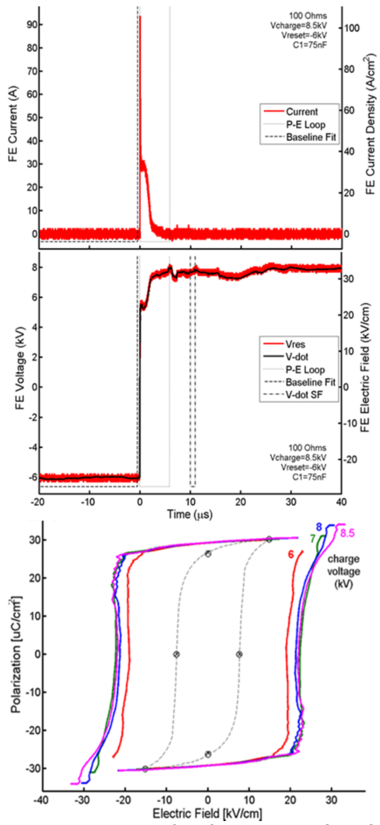
PLZT

1 kΩ



These measurements were obtained from PLZT with the current limited by 1 kΩ. The bottom plot displays the P-E curves from 4 shots (12-15), whereas the current (top) and voltage (middle) are displayed only for shot 15. The upper-left legs of the P-E loops are the symmetric reflections of the lower right legs.

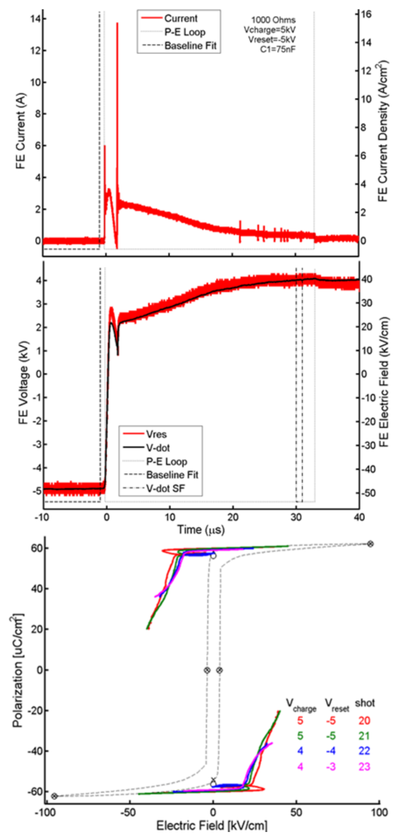
100 Ω



PLZT measurements when the current was limited with 100Ω are shown above. Faster charging produces sharper corners and noisier knees. P-E loops are shown for 4 shots, whereas the current (top) and voltage (middle) are displayed only for the shot charged to 8.5 kV. In this case, all shots had the same reset voltage (-6 kV).

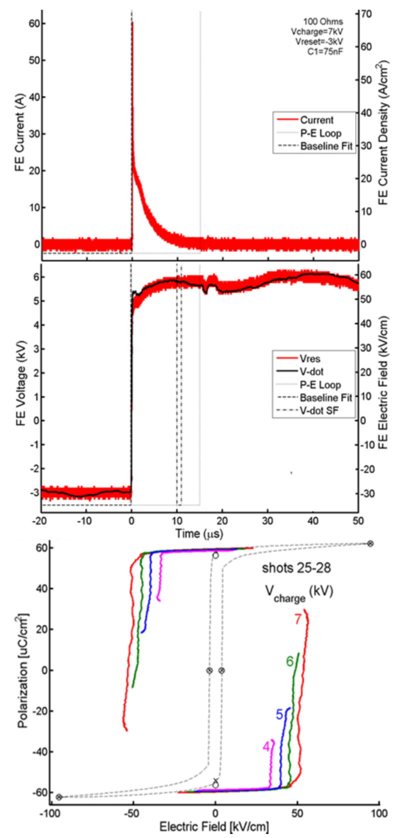
$LiTaO_3$

1 kΩ



These measurements from $LiTaO_3$ had the current limited by 1 kΩ. The bottom plot displays the P-E curves from 4 shots (20-23). The current (top) and voltage (middle) are displayed only for shot 21. The upper-left legs of the P-E loops are the symmetric reflections of the lower right legs.

100 Ω



$LiTaO_3$ measurements when the current was limited with 100Ω are plotted above. Faster charging produces nearly right angle corners and smoother knees. P-E loops are shown for 4 shots, whereas the current (top) and voltage (middle) are displayed only for the shot charged to & 7 kV. In this case, all shots had the same reset voltage (-6 kV).

CONCLUSIONS

The testbed for non-linear dielectrics has demonstrated low inductance, high bandwidth operation. The measurements made on ferroelectric materials in this test bed compared to low bandwidth measurements illustrate the importance of high voltage, high bandwidth measurements in characterizing their response. Models to explain these materials and models to simulate their operation in high voltage, high speed circuits will be validated with this information.

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