Nucleation and Growth Dynamics at the Nanoscale

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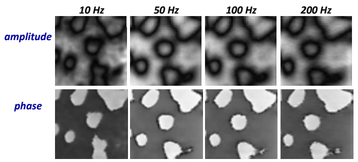
Introduction

The speed, reliability, energy consumption, and underlying switching mechanisms for data storage devices are controlled by composition, processing, design, and operating conditions. Given the continually diminishing size of individual memory elements, a fundamental understanding of nanoscale switching dynamics is therefore important for future high density data storage systems. This international effort focuses on chalcogenide-based phase change films, leveraging past experience with ferroelectrics, acoustic, optical, and thermal capabilities at UConn and Lancaster.

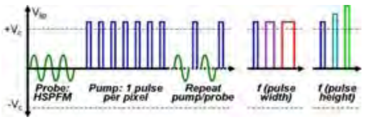
High Speed Scanning Property Mapping

'HSSPM' combines atomic force microscopy and acoustic concepts to acquire property maps at scanning rates hundreds of times faster than standard AFM. For example, with High Speed Piezo Force Microscopy (HSPFM) ferroelectric domain orientations can rapidly be mapped at the nanoscale based on phase signals. Electric fields, mechanical compliance, or current can also be mapped.

HSSPM is performed with Asylum Research Cypher and MFP-3d AFM systems, commercial cantilevers, (NTMDT DCP11), and test and measurement hardware from Agilent, NI, SRS, ZI, PPL, and Tektronix units.

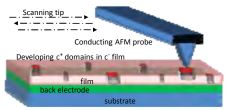


Movies of Switching Dynamics

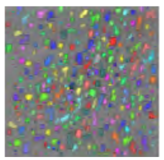


Following each successive HSSPM image to 'probe' a specimen, voltage pulses are applied to progressively 'pump' the switching process between data states. Pulse amplitude, offset, polarity, width, shape, and location are controllable.

For specimens without a top electrode, only the region beneath the scanning tip is directly biased. The evolution of film properties (i.e. bit development) can thus be efficiently mapped, frame by frame, with nm and nsec resolution.



As switching progresses, nucleation and growth can be monitored and mapped by tracking distinct features from frame to frame. Their locations, pulsing time to appearance, spatially resolved growth rates, etc. can then be quantified. Local and ensemble statistics can finally be collected and mapped as a function of pulsing conditions, specimen composition, processing, local defects, external stress, temperature, optical excitation, etc.



Acknowledgements

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• *PZT specimens: Y.H. Chu and R. Ramesh, UC Berkeley.*
• *BFO specimen: I. Takeuchi, U. Maryland.*
• *GT specimen: M. Libera, Stevens S.I.T.*

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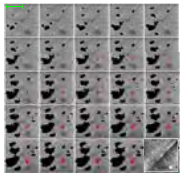
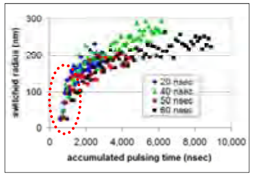
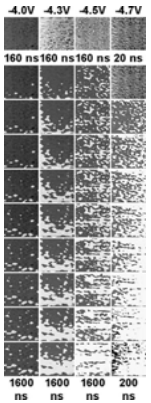
Ferroelectrics

Tracking the size of a single PZT domain (red) based on repeated HSPFM switching movies with pulses down to 20 nsec reveals enhanced growth rates for nascent domains followed by slower linear average growth.

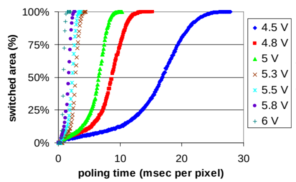


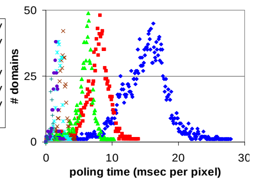


Switching Statistics



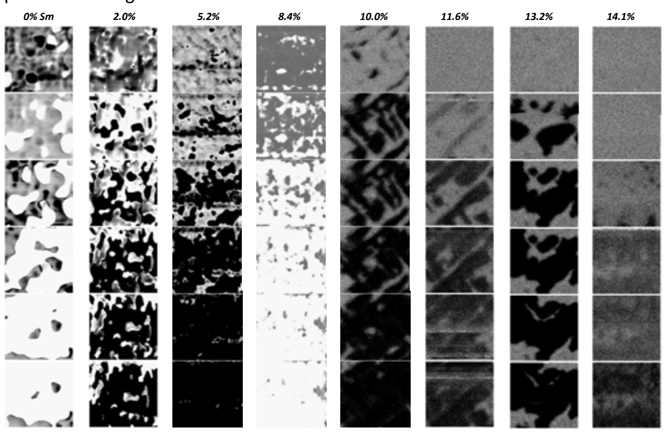
Polarization reversal in ferroelectrics is a strong function of applied bias, as shown in switching movies acquired with increasing voltages (columns) for a single area (time between frames and for entire movies noted). From a different data set, areal switching exhibits s-curve behaviour as in macroscopic measurements. Domain statistics link the switched area to the number of isolated domains. All domains participating in low-V switching contribute to high-V switching; high biases also activate additional nucleation sites.





Switching vs. Composition

Movies of switching for ferroelectric $BiFeO_3$ doped with increasing Sm (columns, concentrations as noted) indicates profoundly different switching mechanisms as a function of composition. Domain wall energies are clearly influenced by Sm substitution throughout this single phase region. Curvature is allowed for low Sm doping, but domain wall alignment along crystallographic directions is strongly preferred for higher Sm concentrations.



Phase Change Materials

Two chalcogenide PCM samples are evaluated in this study:

1. In-house fabricated $Ge_2Sb_2Te_5$ (GST) film (150 nm).
2. $Ge_{55}Te_{45}$ (GT) film provided by Libera (120 nm).

As deposited the GST films have a high percentage of amorphous phase. Subsequently, they were annealed to convert to a crystalline phase. The GT films are studied in the amorphous phase.

Optically switched bits

Arrays of amorphous and crystalline marks were next optically prepared in the crystalline and amorphous films, respectively. The specimens were mounted on a micro-positioning stage allowing translation in x and y. Stage motion was then integrated with optical shuttering to allow illumination and phase transformations for distinct locations. Typically features were prepared approximately 5 um apart, with a focal size of <2 um. Laser conditions for this optical switching follows:

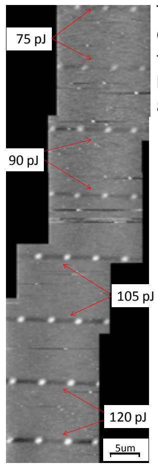
1. GST (crystalline): 100 pJ in 30 psec (pulsed Nd:YAG 532 nm laser).
2. GT (amorphous): 200 nJ in 200 usec (continuous Ar blue laser).

A range of focal conditions was also considered using a combinatorial approach based on linearly adjusting the focal point while preparing rows of features.

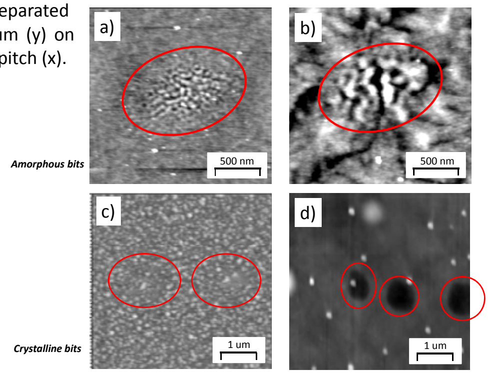
AFM of switched bits

Images of optically switched bits were acquired with AFM AC 'tapping' mode. The height and area of written marks are directly proportional to the optical power. The morphology also varies significantly with composition and fabrication parameters, Next steps include:

- Electrically induced switching based on voltage pulsing.
- Beam exit x-section polishing for depth profiling of switched regions.
- Imaging as a function of previous switching events (cycling sensitivity).



Topographic AFM images of amorphous bits in a crystalline GST film. Bits written using various powers as labeled, with tracks separated by 10 um (y) on a 5 um pitch (x).



AFM topography of a) amorphous bits in GST, b) amorphous bits in GT, c) crystalline bits in GST, d) crystalline bits in GT.

Conclusions

HSSPM reveals nanometer and nanosecond switching dynamics in ferroelectric films. Applying HSSPM to phase change materials provides opportunities for novel studies of their fundamental switching mechanisms as well. Future work requires films with integrated electrodes to incorporate local conductivity measurements.