Nanosecond Switching Dynamics in Ferroelectric Devices

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The fundamental physics of ferroelectric materials is intimately linked with the response of the stored electric polarization to applied fields. It has been difficult to quantify the creation and motion of ferroelectric polarization domains in part due to a lack of suitable microscopic probes. The key challenge for these experimental tools is to capture the behavior of domains at the appropriate time and length scales. Hard X-ray scattering has unique advantages for these studies, offering chemical, structural, and elemental specificity with excellent time and spatial resolution as well as the unique ability to look within operating devices. A one-of-a-kind tool results from the combination of existing microdiffraction and time resolved scattering techniques. We have begun to use time resolved diffraction techniques to probe piezoelectric distortion and polarization switching. An ultimate goal of these experiments is to develop x-ray scattering tools that obtain information from a single growing domain both as a probe of the fundamental mechanisms of polarization switching and as a diagnostic for emergin devices.

The response of a ferroelectric material to the abrupt application of an electric field includes phenomena at a wide range of time scales, beginning at nanoseconds and extending to slow relaxation phenomena occurring over periods of hours or even longer. The immediate response to the electric field is a linear electric polarization and piezoelectric distortion. If the field is high enough, the electric dipole energy can be reduced by switching. A simple estimate magnitude of the electric field at which switching occurs can be found from a mean field theory calculation of the energetics of homogeneous switching. In practice however, this field is never reached. Instead, polarization switching begins (Figure 1) with the nucleation of a region in which the polarization is opposite to the original polarization. The domain walls bounding the critical nucleus move into the device in two stages: growth along the direction of the applied field (i.e. the normal direction to the film) until the reversed domain bridges the two electrodes followed by lateral propagation followed by lateral growth through the extent of the extent of the film. Continuum descriptions of switching often result in a domain wall velocity on the order of the speed of sound in the film: in ferroelectrics as in most solids this is of the order of magnitude of one nanosecond per micron. Thus, the growth along the surface normal direction is brief in comparison with the time required for the lateral motion of the domain wall through the device. Depending on the linear dimensions of the device, the lateral growth of domains can take up ~ 100 ns. During the time the domain walls are in motion, a displacement current flows between the two electrodes to supply the difference in polarization between the two

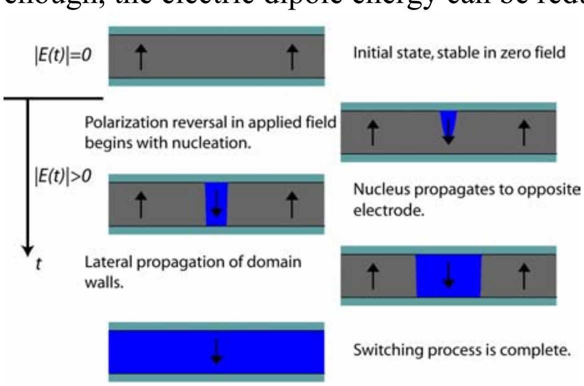

Figure 1 Domain propagation during polarization switching in a ferroelectric thin film capacitor according.

states. Most of what is presently known about the dynamics of polarization reversal has been discovered by interpreting this current

Time resolved x-ray scattering is possible because the radiation from synchrotron x-ray sources occurs in pulses with durations on the order of 100 ps. In the most common operating mode of the Advanced Photon Source there are 23 single bunch groups stored in the ring, spaced at time intervals of 153 ns. The total flux received at a detector is proportional to the counting time for long integration times, but becomes time dependent for integration times less than twice the pulse interval. The time resolution of a measurement is thus linked to the time-averaged flux for time scales longer than about a microsecond. At times shorter than this, however, the next fundamental step in time resolution is to hundreds of picoseconds; this is a huge potential benefit of synchrotron x-ray work. The rapid evolution in the past two years of timing techniques is an important technical factor in making *spatially* resolved time resolved diffraction experiments possible.

We have already used time resolved diffraction to probe polarization switching and piezoelectric distortion with 10 μs time resolution. It is already possible with this resolution to resolve the dynamics for which the natural timescale is the duration of the electrical pulse. These experiments have used an avalanche photodiode detector in a photon counting mode and simply time-resolved the diffracted beam using a multichannel scaler. This simple is useful as a new, quantitative, way to study piezoelectric distortion in thin film capacitors.

The time resolution of our experiments can be improved to the intrinsic, nanosecond, regime relevant to switching. In doing this, we hope to address some of the most important questions in ferroelectric dynamics: What is the speed of a moving domain wall? How quickly can a ferroelectric thin film capacitor switch polarization? Are there any intermediate structural states that are important to switching? Some of the transient signals that it will be possible to see in a time resolved microdiffraction experiment are shown in Figure 2.

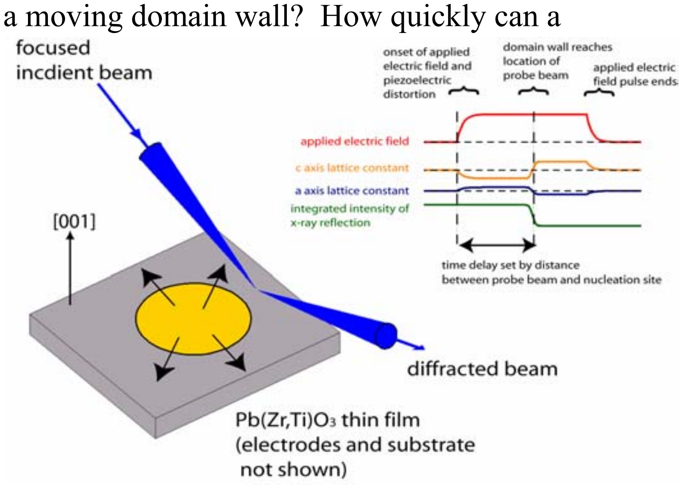

Figure 2 The transients observed in a time resolved x-ray microdiffraction experiment include an immediate distortion due to the piezoelectric response of the film and a signal due to switching that occurs when a propagating domain wall (bounding the expanding circular region in this diagram) reaches the footprint of the focused beam

The dynamics of ferroelectric polarization domains is conceptually similar to the role of dislocations in the distortion of materials and conceptually similar to inhomogeneities due to crystallography, magnetism, or electronic effects in materials including liquid crystals, ferromagnets, and even Gunn diodes. Time resolved microdiffraction techniques have a potential role in probing each of these systems at their intrinsic length- and time-scales.