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Domain Structures in Nano-Toroids and Ultra-Thin Single Crystals[1]

MARTY GREGG, Queen's University Belfast

Rationalisation of the formation of domain structures, in ferroics of limited dimensions, has been a topic of interest since the 1940's [1], with early work, specifically in ferroelectrics, in the 1950's [2]. Experimental studies at that time primarily involved domain investigations using optical microscopy, on samples down to the order of hundreds of microns. More modern studies, extending domain research into the thin and ultrathin film regime [3], suggest that our understanding of certain aspects of domain behaviour remain relatively unchanged, despite the intervening decades. This might imply that reduction of scales into the nanometre range will not reveal anything new or interesting in ferroelectric domain research. In this talk, we hope to illustrate that this is not the case. We describe results from two recent research programmes on the characterisation of ferroelectric domain structures in single crystal $BaTiO_3$ (BTO) using Scanning Transmission Electron Microscopy. In both studies sample preparation was performed using a Focused Ion Beam Microscope (FIB). In the first study, the domain periodicity has been measured as a function of thickness of parallel-walled BTO slabs from several hundred nanometres down to ~50nm. Early work [2] suggested that the domain width should vary as the square root of slab thickness, and this is consistent with our data. However, we find, in plotting data from several works on different ferroelectric materials, with differing surface boundary conditions, across six decades in thickness, that all data lie on the *same* parent function, with the *same* constants of proportionality. This is totally unexpected, as the proportionality constants should be material and surface boundary state dependent. We suspect that this reveals fundamental aspects in the physics of ferroelectric domain formation that will be discussed. The second study was motivated by modelling done in 1994 by Gorbatsevich and Kopaev [4] and more recently by Fu and Bellaiche [5] and Naumov, Bellaiche and Fu [6]. Here, the influence of depolarization fields at ferroelectric surfaces were found to create polarization vortex structures when the ferroelectrics were sufficiently small. In toroidal shapes, Gorbatsevich and Kopaev even envisioned ordering of the vortices to produce nanoscale ferroelectric 'solenoids'. We have used the FIB to make toroidal structures and have characterized their domain morphologies. At the time of writing, only conventional domain behaviour has been observed down to scales of the order of ~100nm. However, results on smaller scales to be performed over the next few months will be described, as well as the novel imaging techniques we intend to use to probe for the ferroelectric vortices. [1] C. Kittel, Physical Review, **70**, 965 (1946) [2] T. Mitsui and J. Furuichi, Physical Review, **90**, 193 (1953) [3] S. K. Streiffer *et al.* Phys. Rev Lett. **89**, 067601 (2002) [4] A. A. Gorbatsevich & Yu V. Kopaev, Ferroelectrics **161**, 321 (1994) [5] I. Naumov *et al.* Nature **432**, 737 (2004) [6] H. Fu and L. Bellaiche, Physical Review Letters, **91**, 257601 (2003)

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