Fabrication of nanoscale $BiFeO_3$ thin film-based capacitors using combined electron-beam and focused ion-beam lithography

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ABSTRACT

$BiFeO_3$ (BFO) is considered as one of the strong candidates for future nanoscale ferroelectric capacitors for high-density ferroelectric random access memories (FeRAMS), due to its high polarization (over 100 $\mu C/cm^2$) and high ferroelectric transition temperature (1100 K) [1]. For high-density FeRAMs, however, it is imperative to pattern thin film BFO into nanoscale capacitors without losing polarization and thermal stability. It is observed that as the lateral sizes shrink, the in-plane shape of the capacitors can play an important role in both the electric- and strain-field distributions due to symmetry and edge effects [2]. In addition to achieving nanoscale size and optimized shape, another main challenge in patterning is the minimization of crystal damage that is incorporated into the devices during fabrication.

Our group studied polarization domains and dynamics in nanoscale BFO capacitors using a unique combination of X-ray diffraction with the X-ray nanoprobe beam at the Advanced Photon Source at Argonne National Laboratory, and characterization of ferroelectric domains via piezoresponse force microscopy (PFM) [3]. The fabrication of BFO nanocapacitors involved the following steps: 1) growth of epitaxial BFO/SRO bi-layer thin films on single crystal $SrTiO_3$ (STO) substrates, using RF magnetron sputter deposition; and 2) patterning of nanocapacitors, with dimensions in the range 50–2000 nm, using focused ion beam (FIB) direct-write lithography. We investigated the dependence of domain configuration and behavior on the capacitor shape (square vs. circular) before and after oxygen annealing. Our results reveal mono-domain and multi-domain configurations dependent on the shape of the BFO nanostructures in the as-fabricated state. Further details about the ferroelectric properties of the capacitors are published elsewhere [3].

In this presentation we will show that the 30kV Ga^+ FIB-based fabrication, if done directly on the BFO layer, creates irrecoverable damage to the nanocapacitors, producing deleterious effects on the domain configuration and dynamics. In order to reduce FIB damage and improve device performance we have modified the fabrication process involving e-beam lithography and lift-off of 100 nm thick tungsten hard mask that is followed by FIB direct milling around the pattern of the mask. The tungsten is removed subsequently by wet chemical etch in hydrogen peroxide. Because of the BFO layer is protected by the hard mask from Ga ion impacts during FIB patterning, the new process yields nearly damage-free capacitors as evidenced by the PFM image in Figure 1b. Details of the fabrication steps and further comparison of the original and the improved fabrication methods will be given in the presentation.

References

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2. J. Seidel et al., “Conduction at domain walls in oxide multiferroics,” Nature Materials **8**, 229 - 234 (2009)
3. S. Hong et al., “Nanoscale Piezoresponse Studies of Ferroelectric Domains in Epitaxial $BiFeO_3$ nanostructures,” *J. Appl. Phys.* **105**, 061619 (2009) [Cover Page]

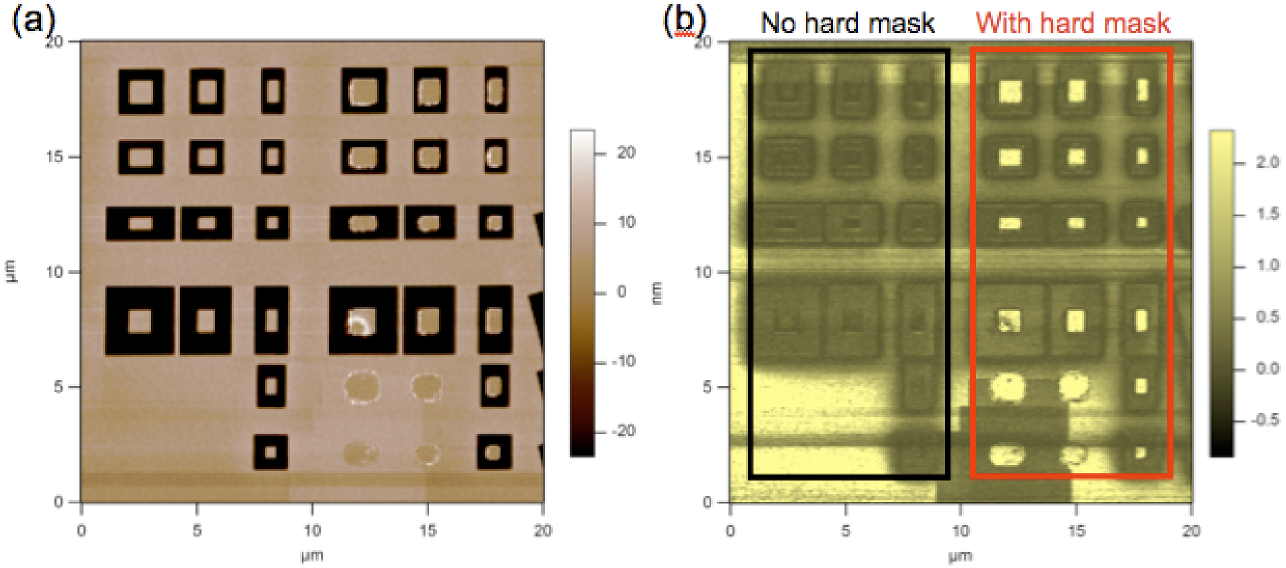

Figure 1. (a) Topography and (b) PFM amplitude images of rectangular and circular shaped BFO capacitors of various aspect ratios fabricated with and without hard mask. The PFM amplitude image clearly shows that the capacitors patterned with hard mask survived the FIB patterning exhibiting bright contrast similar to the surrounding continuous film, whereas those without hard mask lost their ferroelectricity.