

Nanostructure characterization of resistive oxides

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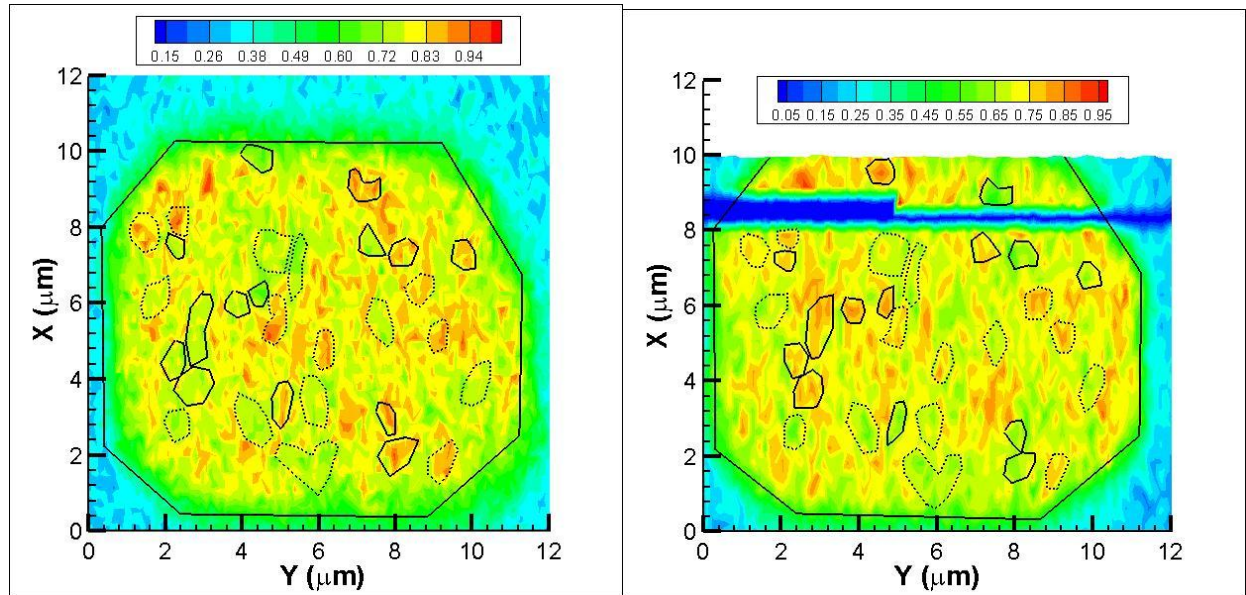
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Research Achievement

Ti-doped nickel oxide (Ti:NiO) is one material being considered for resistive random access memory applications. It has previously been demonstrated [1,2] that RRAM structures consisting of Pt/Ti:NiO/Pt can be switched between a high-resistance non-metallic state and a low-resistance metallic state with Ohmic conductance by applying unipolar voltage pulses in the range of a few volts. As deposited, a device is usually in a high-resistance state and has to be set into an initial low-resistance state by applying a moderately high voltage pulse of about 5 V (depending on the oxide layer thickness), a process called electroforming. A central question pertaining to this electroforming and switching mechanisms is whether or not ionic species (e.g. Ni vacancies or oxygen ions) or defects are actively migrating during electroforming and switching[3-6]. Such migration is certainly consistent with several of the proposed mechanisms, such as the formation of metallic filaments via oxidation and reduction of Ni.

There are a few possible mechanisms that relate the observed electronic response of these structures to microstructural changes of the constituent lattice. We have investigated changes in the NiO (111) diffraction intensity over a $10\ \mu\text{m} \times 10\ \mu\text{m}$ Pt/Ti:NiO/Pt patterned structure, between the as-deposited and electroformed states using the Hard X-ray Nanoprobe beamline (HXN) facility and $\sim 50\text{nm}$ spatial resolution. The HXN is part of the Center for Nanoscale Materials at the Advanced Photon Source at Argonne National Laboratory. We have correlated the change in resistance with structural changes.

The central result of our work is shown in the figure below, which displays the two-dimensional plots of the diffracted intensity (normalized to beam current) at the NiO(111) peak across the same Pt/Ti:NiO/Pt structure in the as-deposited state (left panel) and in the electroformed state (right panel). The solid-line (changed) regions are larger than the step size or the projected spot size, indicating that the regions in which structural changes have occurred are at least 400 nm in size, with several regions being considerably larger. This is also much larger than the grains size, which is about 15 nm as determined from TEM images. These changes in diffraction intensity are consistent with migration of ionic species or defects during electroforming. The structural changes that follow electroforming are rather subtle in that we observed changes in the NiO (111) diffraction amplitude, but we did not observe any complete loss of diffraction amplitude. Therefore, if metallic filaments are formed during electroforming, they are either much smaller than the resolution in the HXN, or consist of subtle structural changes over a larger region with a concomitant change in electronic structure. The former seems unlikely, since the observation of contiguous regions of the order of one micron implies that there would have to be many such filaments in one such contiguous region.



Normalized diffraction intensity in the as-deposited state (left panel) and electroformed state (right panel). In the figures are demarcated some of the regions that in which the diffraction intensity remained high or low after electroforming (dashed lines), as well as some of the regions in which the diffraction intensity changed from low to high, or from high to low upon electroforming. The color scales are indicated by the scale bars in the panels. The blue streak in the right panel is due to the beam current outage during the scan.

Future work

We plan to refine and expand the X-ray microscopy to include both as-deposited, electroformed, set and re-set devices. In addition, we plan to include rocking curves at selected locations of some devices to better quantify local stresses and lattice expansion/contractions. Finally, we intend to perform conducting AFM measurements to correlate local conductivity changes with local structural changes.

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Publications

“Correlating structural and resistive changes in Ti:NiO resistive memory elements”, O. Heinonen, M. Siegert, A. Roelofs, A.K. Petford-Long, and M. Holt (to be submitted, Applied Physics Letters).