STEM EBIC imaging for characterizing ferroelectric HZO

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In bulk form hafnium zirconium oxide (HZO) is a dielectric, but in thin films it can assume a non-centrosymmetric $Pca2_1$ phase that is ferroelectric. This ferroelectric phase might form the basis of a next-generation memory technology. However, real devices operate under challenging conditions. The large electric fields required to switch the polarization drive charge injection and atomic motion. Maintaining device reliability over the requisite number of switching cycles is an unsolved problem [1].

We are developing a comprehensive metrology technique capable of providing detailed diagnostic information from inside operating, highly scaled ferroelectric devices [2]. The technique combines scanning transmission electron microscopy (STEM) electron beam-induced current (EBIC) imaging, standard STEM, *in situ* transport measurements, and custom microfabrication. On electron-transparent silicon nitride membranes we fabricate individual devices that are encircled by resistive heaters. These devices might be ferroelectric capacitors or ferroelectric field-effect transistors (FeFETs). Using the resistive heater we can quickly heat and cool the device, limited only by the thermal time constant of the membrane ($\lesssim 40\ \mu s$). Thus we can crystallize the HZO and quench to room temperature *in situ*. Once the HZO has been annealed, we can apply arbitrary thermal treatments, either steady-state or pulsed, to study depolarization, imprint, wake-up, and fatigue as a function of temperature.

The combination of STEM and *in situ* transport allows us to observe the device as it operates and over the course of its lifetime. A customizable pulse or pulse sequence measures the device function and sets its state. Standard STEM imaging techniques, such as bright field (BF), annular dark field (ADF), or 4D STEM, map the atomic positions, providing information about crystal phase, defects, and grain structure. STEM EBIC imaging maps the ferroelectric properties, including remanent depolarization fields and coercive fields, revealing domain structure and switching characteristics. The ability to directly correlate crystalline grain structure and ferroelectric domain structure with high spatial resolution in live devices constitutes the realization of a long-standing dream, and will allow us to systematically address the pressing problems impeding the widespread implementation of ferroelectric memory technologies.

References

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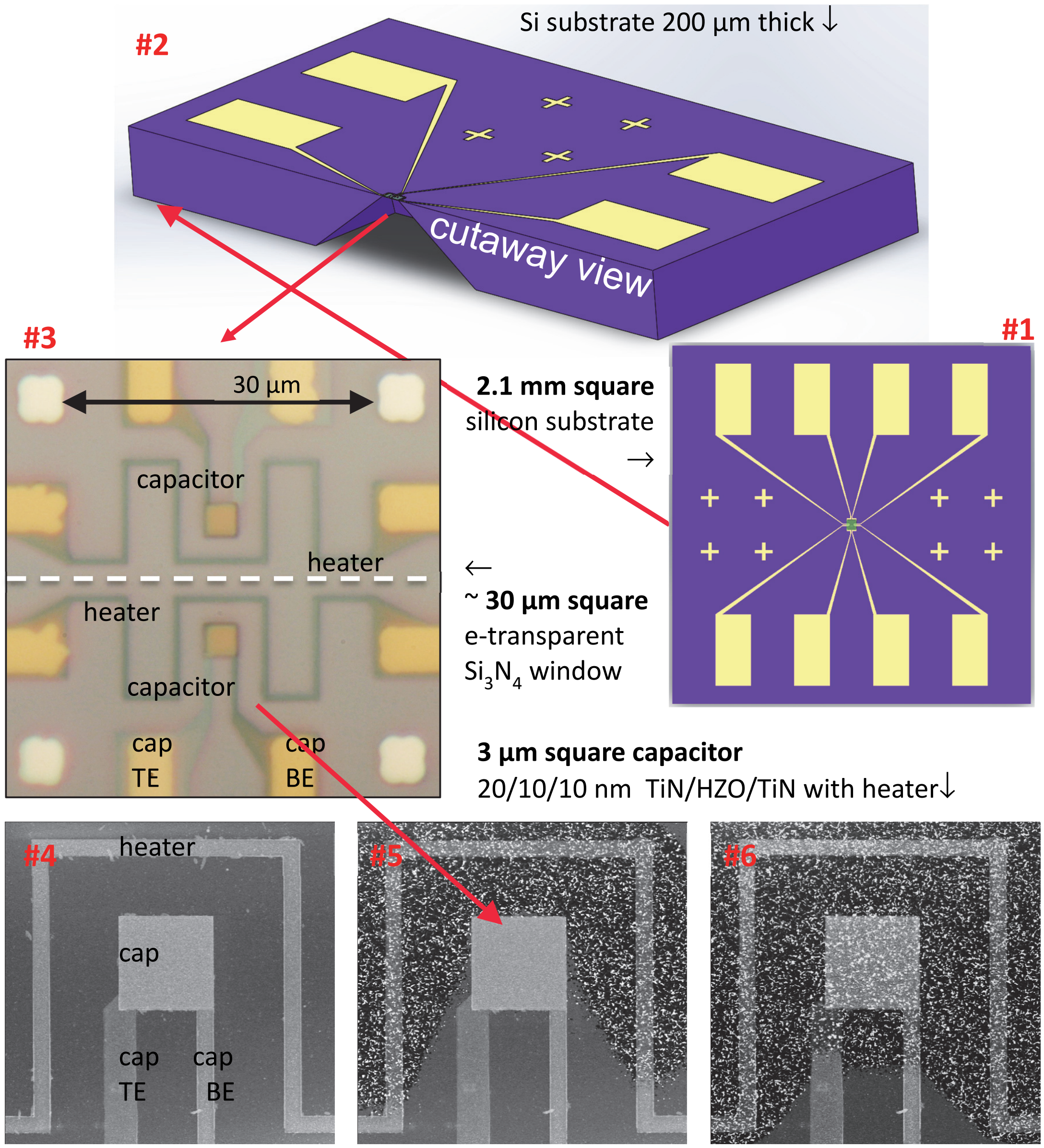

Figure: Plan view device architecture. Frames (**1-2**) show the silicon substrate, (**3**) gives an overview of the electron transparent window, and (**4-6**) form an ADF STEM time series showing the *in situ* crystallization of a ferroelectric HZO capacitor. The 25 nm Si_3N_4 membrane and everything it supports has a ~40 µs thermal time constant. Thus the capacitor can be crystallized, annealed, and thermally depolarized while, with ns-scale synchronization, E-fields are applied across the capacitor and currents from the capacitor are measured.

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