# Understanding Ferroelectric Polarization in Hafnium Zirconium Oxide

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**Meeting-report**

# Understanding Ferroelectric Polarization in Hafnium Zirconium Oxide

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Ferroelectric materials exhibit spontaneous electrical polarization that can be reversed by the application of an external electric field. At the atomic level, this reversal is created by the movement of atoms and their accompanying charge from one stable position inside the crystallographic unit cell to another. Because both atomic arrangements are stable and reproducible, ferroelectric materials have the potential to form the basis of an ideal non-volatile electronic memory technology: one that is fast, low-power, robust, and highly scalable. Ferroelectric hafnium zirconium oxide ($Hf_{0.5}Zr_{0.5}O_2$, HZO) is particularly attractive to the semiconductor industry, because it can be deposited with atomic layer deposition (ALD) and is 100% compatible with standard CMOS fabrication processing [1].

Unfortunately, materials problems have prevented ferroelectrics from realizing their technological promise. In the case of HZO, many non-ferroelectric crystal phases compete with the desired ferroelectric phase in the requisite thin-film form. Without an effective technique for correlating polarization response to atomic-scale structure, blindly searching the multidimensional processing parameter space to find good deposition conditions is tedious and expensive.

Scanning transmission electron microscope (STEM) electron-beam induced current (EBIC) imaging addresses this problem, in that it reveals ferroelectric polarization with good spatial resolution and high contrast. In STEM EBIC imaging, the microscope's focused electron beam is rastered over the sample while the beam-induced currents in the sample are collected and digitized [2]. Especially large currents are collected where electric fields in the sample separate electron-hole pairs created by the beam. STEM EBIC thus maps the electric fields in a sample.

We demonstrate STEM EBIC imaging's application to ferroelectric materials on custom-microfabricated 30 nm TaN/20 nm HZO/20 nm TaN capacitors that are supported by a 20-nm-thick $Si_3N_4$ membrane [3]. Before STEM EBIC imaging we apply an extended nano positive-up negative-down (PUND) sequence [4] *in situ*, both to characterize the capacitor's polarization state and to initialize it for the STEM EBIC imaging. Combining PUND, which measures the ferroelectric switching currents, and STEM EBIC imaging, which measures the in-sample electric fields, determines the sample polarization via $\boldsymbol{P} = \boldsymbol{D} - \epsilon_0 \boldsymbol{E}$. An on-membrane heater provides pulse heating capability. Thus it is possible to repeatedly switch a capacitor *in situ* while monitoring its polarization and applying various heat treatments. Coupled with STEM's usual quiver of structural characterization capabilities, this combination can provide a complete picture of the ferroelectric properties of HZO, from its transition from the amorphous to the crystalline state, to its wake-up, retention, and fatigue [5].

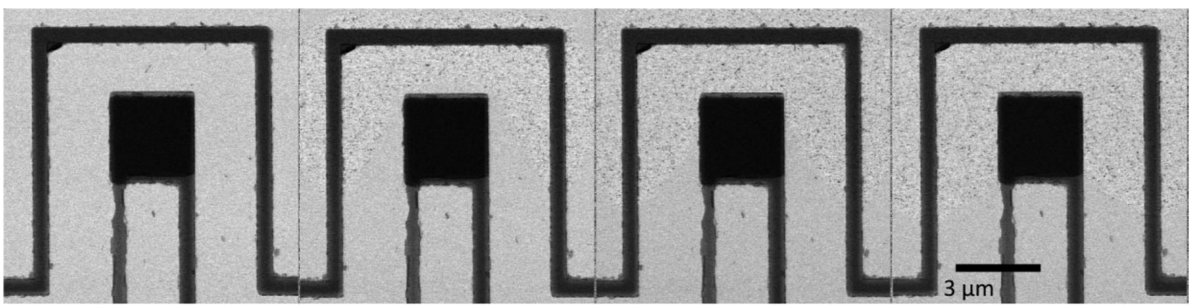


**Fig. 1.** A time series of bright field (BF) images of a TaN/HZO/TaN capacitor and the adjacent TaN heater, with time increasing from left to right. HZO and the supporting silicon nitride membrane span the entire field of view. The heater wraps around three sides of the capacitor, which is in the center of the field of view. Initially the HZO is amorphous everywhere, but as the heater power is increased a wave front of crystallization can be seen moving down to envelop the capacitor.

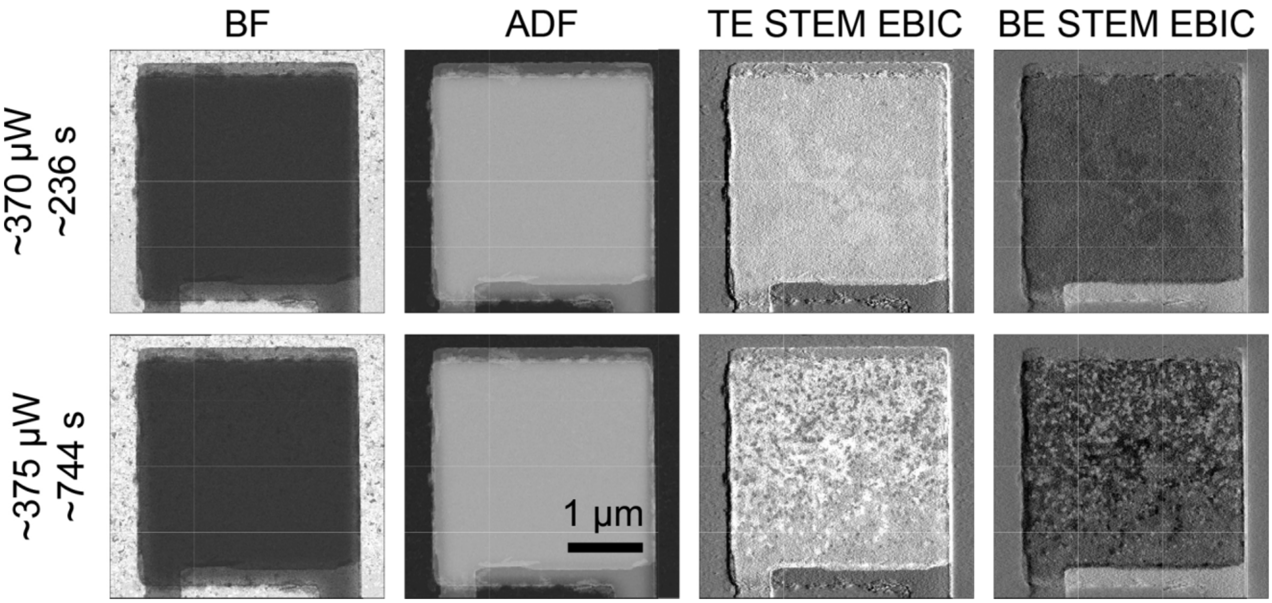


**Fig. 2.** Bright field (BF), annular dark field (ADF), top electrode (TE) STEM EBIC, and bottom electrode (BE) STEM EBIC images of a TaN/HZO/TaN capacitor. The four images in each row are acquired simultaneously, and before each row is acquired the capacitor is initialized with a PUND voltage sequence. After the first heat treatment (first row), the HZO outside the capacitor has crystallized. However, only after the second heat treatment (second row) does a strong differential EBIC signal between the TE and the BE provide evidence of remanent (ferroelectric) electric fields inside the capacitor.

## References

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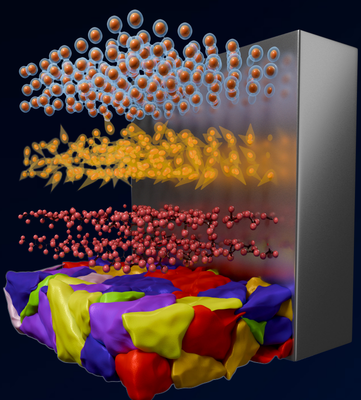

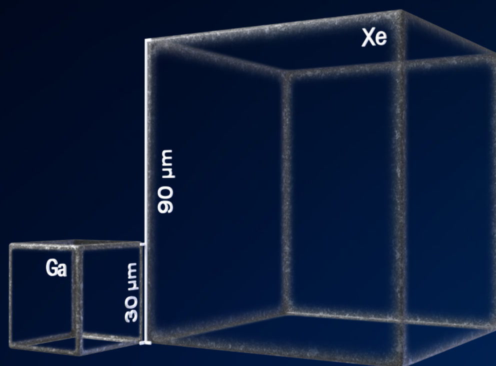


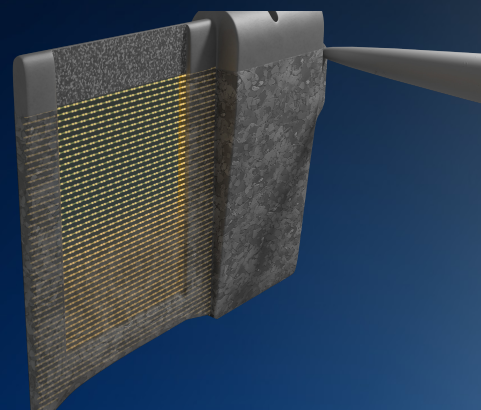

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