# Ferroelectric Hafnium Oxide and its Applications in Non-Volatile Memories, Negative Capacitance Elements, and Neuromorphic Networks

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In the last 10 years, the interest in $HfO_2$ or $ZrO_2$ based ferroelectric films for novel semiconductor applications steadily increased. Lead-free CMOS compatible ferroelectric layers even below 10 nm film thickness enable scalable devices like high aspect ratio ferroelectric capacitors (FeCap) and field-effect transistors (FeFET) in 2x nm technology nodes [1][2]. But also further applications like ferroelectric tunnel junctions, negative capacitance FETs (NCFET), neuromorphic, piezo, and pyro electric devices are in discussion [3],[4]. Ferroelectric properties are caused by a polar orthorhombic $Pca2_1$ structure in polycrystalline films with a grain size of typically 20-30 nm. TEM and PFM studies are revealing multiple phases within one grain in the pristine case leading to larger (> 100 nm) domains after field cycling [5][6]. By placing a doped $HfO_2$ layer with a small number of grains within the gate-stack of a nanoscale FeFET structure having the channel length of 30 nm, a detailed analysis of the switching behavior of these single grains is possible [7]. Nucleation limited switching is observed with slightly different coercive fields for different single grains. Multiple excitation pulses, each of which is insufficient for polarization reversal, induce an accumulative effect, which eventually leads to ferroelectric switching [8]. In addition, such an accumulative switching can be exploited to mimic the integrate-and-fire activity of biological neurons [9], which, together with FeFET-based synapses [10], might allow for building fundamental computing blocks of brain-inspired neural networks. Recently, it is shown that ferroelectrics can possess a negative capacitance [4], which could improve the energy-efficiency of conventional CMOS transistors beyond fundamental limits. For this purpose, a ferroelectric $HfO_2$ layer is incorporated into a capacitor together with a dielectric layer to prevent the initial screening of polarization charges during switching. The results are giving an inside view on the fundamental physics of ferroelectricity which indicate the energy barrier in a doped $HfO_2$ double well potential as the origin of negative capacitance [11]. Here, the fast and hysteresis-free ferroelectric switching behavior of a negative capacitance device can be confirmed, which is critical for future applications.

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