Center for 3D Ferroelectric Microelectronics (3DFeM)
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Lead Institution: Penn State
Class: 2020 – 2024

Mission Statement*: To develop three-dimensional, low-power, non-volatile ferroelectric memories that can be integrated reliably and densely interconnected with logic to enable low-power, 3D non-von Neumann circuits and systems*

The Center for Three-Dimensional Ferroelectric Microelectronics (3DFeM) is addressing fundamental scientific challenges required to enable beyond von-Neumann computing by densely interconnecting non-volatile memory with logic processors. The resulting step change in the connectivity of memory and logic will significantly reduce both the latency and energy cost associated with computation. To accomplish this, 3DFeM is probing the underlying mechanisms for emerging ferroelectric responses and tying the characteristic properties to the energy cost of computation, thereby addressing a significant US need by pursuing integrable, low-power on-chip memory. Ferroelectricity is attractive for low-power memories, as it allows access times <10 ns, retention exceeding 10 years, low power writing, high noise margins, and high endurance. While ferroelectric random-access memories have been commercialized by companies such as Texas Instruments, Cypress, Rohm, Panasonic, and Fujitsu, the available materials are limited in either thickness or coercive field scaling; this limits the scalability and density of memories that can be achieved. Moreover, the high processing temperature is an additional barrier for integration at the back-end-of-the-line (BEOL) in a semiconductor process, hindering 3D integration. However, recent developments in new ferroelectric materials point to the potential for a paradigm change. Exploring these defines the mission, goals, and research strategy of the center.

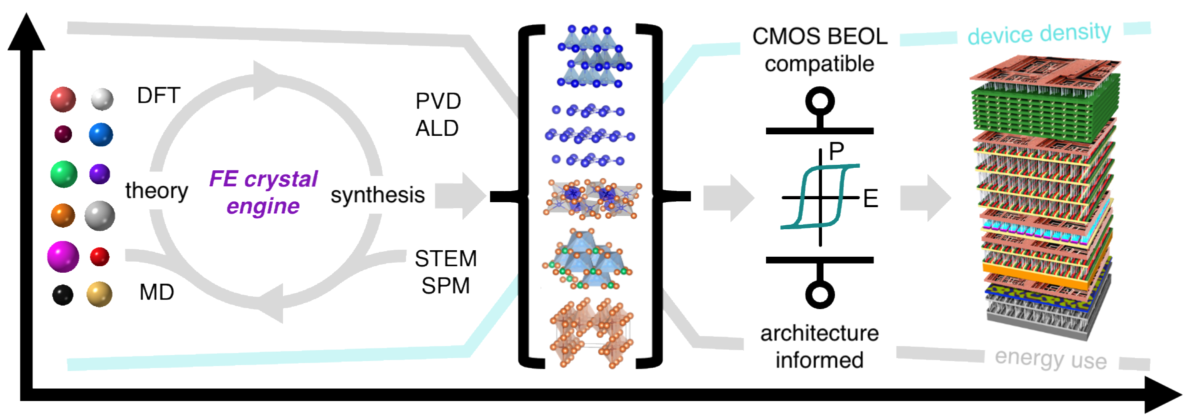

Fig. 1: The 3DFeM vision leverages fundamental understanding of emergent ferroelectricity created via nanoscale inhomogeneity to create memory devices densely interconnected with logic to enable low-power, 3D non-von Neumann computation

GOALS: 3DFeM will: (i) design ferroelectricity in new host crystal structures, (ii) tailor coercive voltages through engineering emergent nanoscale inhomogeneity in scaled ultra-thin films, (iii) deposit ferroelectric materials with ancillary electronics at low temperatures at wafer scale, (iv) characterize materials at previously inaccessible time and length scales, and (v) demonstrate device functionality.

RESEARCH STRATEGIES: 3DFeM is pursuing development of new ferroelectric materials that can be prepared at temperatures compatible with back-end-of-the-line processing, with tailored coercive fields, and robust reliability in memory applications. The goal, as shown in Figure 1 is to enable a significant increase in the connectivity between memory and logic that enables a significant reduction in energy usage. Computing accounts for 5 – 15% of worldwide energy consumption. While efficiency gains in hardware have partially mitigated the rising energy cost of computing, major gains are achievable in a paradigm shift to 3D computing systems. *3DFeM will reduce the energy cost of data movement while simultaneously manipulating data closer to where it is stored. This is now a critical need.*

3DFEM has built a synergistic team aligned towards accomplishing the center goals. The research in the center is organized around 2 Thrusts: *Designer Ferroelectrics for 3D Microelectronics* and *Integration and Reliability of 3D Ferroelectrics*. These two thrusts are closely intertwined, so that new understanding of basic mechanisms underpinning ferroelectricity and switching pathways can be developed, while simultaneously validating device functionality. Center-wide activities have developed common terminology, established healthy team dynamics, and prioritized tasks to accelerate research.

Thrust 1 serves as the designer ferroelectrics engine enabling 3D-integration of ferroelectric memory with processors. First, Thrust 1 seeks to identify "rules" for designing ferroelectricity by exploring the role of synthesis in stabilizing ferroelectricity in host structures normally considered to be only polar or centric. Second, the mechanisms responsible for polarization reversal in these new materials, including the switching pathways, will be identified. These efforts will culminate in the third goal of establishing new structure-property relationships governing ferroelectricity.

Thrust 2 integrates new ferroelectric materials into devices to assess their functionality and reliability as memory elements. For $Hf_{1-x}Zr_xO_2$ (HZO) and similar ferroelectric films, 3DFeM is enhancing our community's understanding of ferroelectricity and exploring opportunities for 3D integration. Nanoscale piezoresponse force microscopy (PFM) measurements have quantitatively demonstrated the role of oxygen stoichiometry on the phase assemblage, and hence the ferroelectric phase fraction and the wake-up characteristics for the first time. The collective domain dynamics also produce collective device responses. The proposed hardware-algorithm co-design utilizing the FeFET dynamics requires 1/3 fewer training samples (and hence 1/3 less energy) to converge compared to standard STDP.

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