Modeling Single-Event-Effects on FeRAM

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The advent of ferroelectricity in doped HfO_2-based dielectrics has made ferroelectric random-access memories (FeRAMs) (Fig. 1A) scalable to advanced logic nodes, making them ideal for embedded nonvolatile memory (NVM) applications and compatible with standalone DRAM processes [1]. Thus, the shift from traditional charge-based storage to encoding memory by the metastability of polarization states offer exception performance in terms of speed, density, and power; however, radiation-induced effects and data corruption mechanisms remain to be reliability concerns that hinder broader deployment, in radiation-prone environments. While total ionizing dose (TID) effects have been extensively studied in PZT [2] and doped HfO_2 based ferroelectric capacitors, the impact of direct ionization from single-event effects (SEEs) in FeRAM has received less attention. To the best of our knowledge, this is the first work to investigate the impact of SEEs on hafnia-based FeRAM.

In this work, we investigate SEE-induced transients in FeRAM cells with varying access transistor geometries using TCAD-based mixed mode (Fig. 1D) and device-level simulations—focusing primarily on bulk planar FeRAM with dimensions and polarization-voltage characteristics shown (Fig. 1A-C). Our results show that bulk access transistors are asymmetrically susceptible to SEEs in the Data 1 state (Fig. 3) as a function of ion energy. As a heavy ion with linear energy transfer (LET) on the order of 10 to 100 $\mathrm{MeV} \cdot \mathrm{cm}^2 \cdot \mathrm{mg}^{-1}$ traverses the semiconductor medium, it loses energy via ionization, producing dense trails of electron-hole pairs on the order of $10^{22}\ \mathrm{cm}^{-3}$. Drift transport dominates near the track axis within the first few picoseconds with electric fields on the order of $10^6 \frac{\mathrm{V}}{\mathrm{cm}}$, with carriers later diffusing radially beyond 10 ps, forming a charge funnel—a transient, quasi-plasmatic isotropic region that locally alters electrostatics. In bulk semiconductors, lateral diffusion is unconstrained, thus the ionization track expands isotopically forming a radial concentration—and thus potential—gradient, per Poisson's equation ($-\nabla^2\phi = \frac{\rho}{\epsilon}$). However, this dissipates through recombination, drift, and diffusion. Data 1 experiences a reduction of polarization from 57% to 86% relative to the baseline, whereas Data 0 state remains largely unaffected (Fig. 2A). In this state, polarization vectors point radially inward with cations closely packed near the storage node. With PL at 0 V, any polarization shift reflects changes in the storage node potential, governed by $V_{PL} - V_{SN}$, where $V_{SN} \sim V_{BL}$. The unidirectional response and absence of comparable change in Data 0 suggests that electron—not hole—transport drives the observed polarization change, as seen in the band diagram time evolution around +1 ns in the bandgap diagram (Fig 2B).

In conclusion, these findings contribute to the design of high-density radiation-hardened FeRAM suitable for aerospace and other reliability-critical memories and applications. Future work will extend on the access transistor type to SOI and vertical-FET and sense amplifier response. **Acknowledgements:** The authors acknowledge the support from the Purdue Center for Secure Microelectronics Ecosystem—CSME #210205.

References

[1] S. Martin et al., 2024 IEDM, San Francisco, CA, USA: IEEE, Dec. 2024, pp. 1–4.

[2] D. N. Nguyen and L. Z. Scheick, NSREC, Vancouver, BC, Canada: IEEE, 2001, pp. 57–61.

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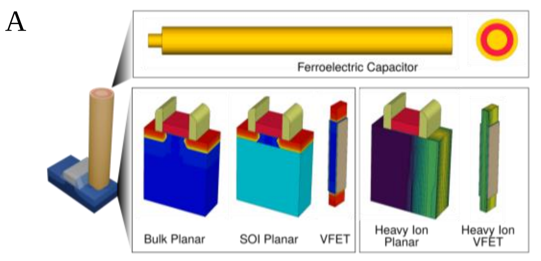
Figure 1: FeRAM Structure and Configuration



Symbol	Quantity	Value
L_{planar}	Planar Channel Length	28 nm
W_{planar}	Planar Device Width	28 nm
t_{SiO_2}	SiO_2 Thickness	0.5 nm
t_{HfO_2}	HfO_2 Thickness	10 nm
x_j	Source/Drain Junction Depth	10 nm
N_A	Body Doping	$10^{17} cm^{-3}$
N_D	Source/Drain N-Type	$10^{20} cm^{-3}$
t_{FE}	Ferroelectric Thickness	5.7 nm
P_r	Remnant Polarization	32 $\frac{\mu C}{cm^2}$
P_s	Saturation Polarization	44 $\frac{\mu C}{cm^2}$
E_c	Coercive Field	1.23 $\frac{MV}{cm}$
τ_{FE}	Polarization Relaxation Time	325 ps

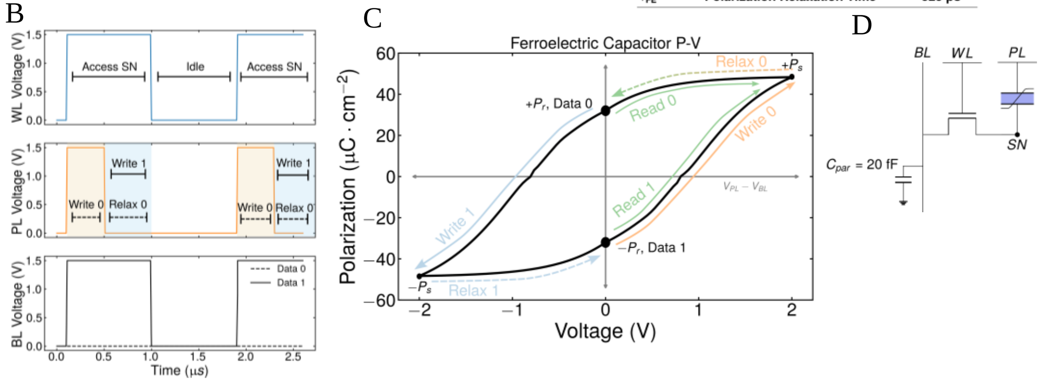
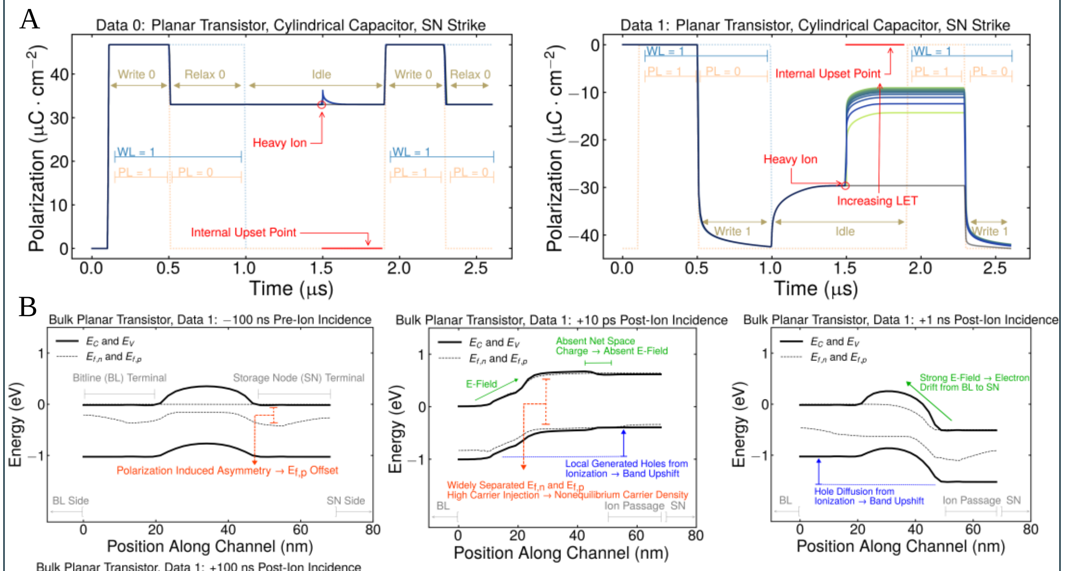


Figure 1. (A) Structure of FeRAM cell with table of dimensions. (B) Timing diagram of the FeRAM cell performing two write operations in a Mixed-Mode simulation. (C) Polarization–Voltage characteristic of the simulated ferroelectric capacitor, showing a $2P_r$ value of 65 $\frac{\mu C}{cm^2}$. (D) FeRAM memory cell schematic in TCAD mixed mode simulation.

Figure 2: FeRAM Polarization and Energetic Response



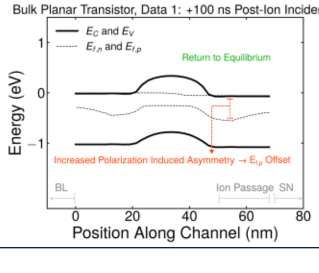


Figure 2. (A) Temporal polarization response of FeRAM using waveforms of Fig. 1B with heavy ion occurring at 1.5 μs. (B) Simulated energy band diagram of bulk planar access transistor structure under Data 1 condition, showing the access transistor channel, at various instances of heavy ion passage (-100 ns, +10 ps, +1 ns, and +100 ns) and the resulting band bending across the storage-node-bulk junction incited by the heavy ion.