Supporting information:

High Performance Ferroelectric Field-effect Transistor for Large Memory-window, High-reliability, High-speed 3D verical NAND Flash Memory

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SUPPLEMENTARY FIGURES

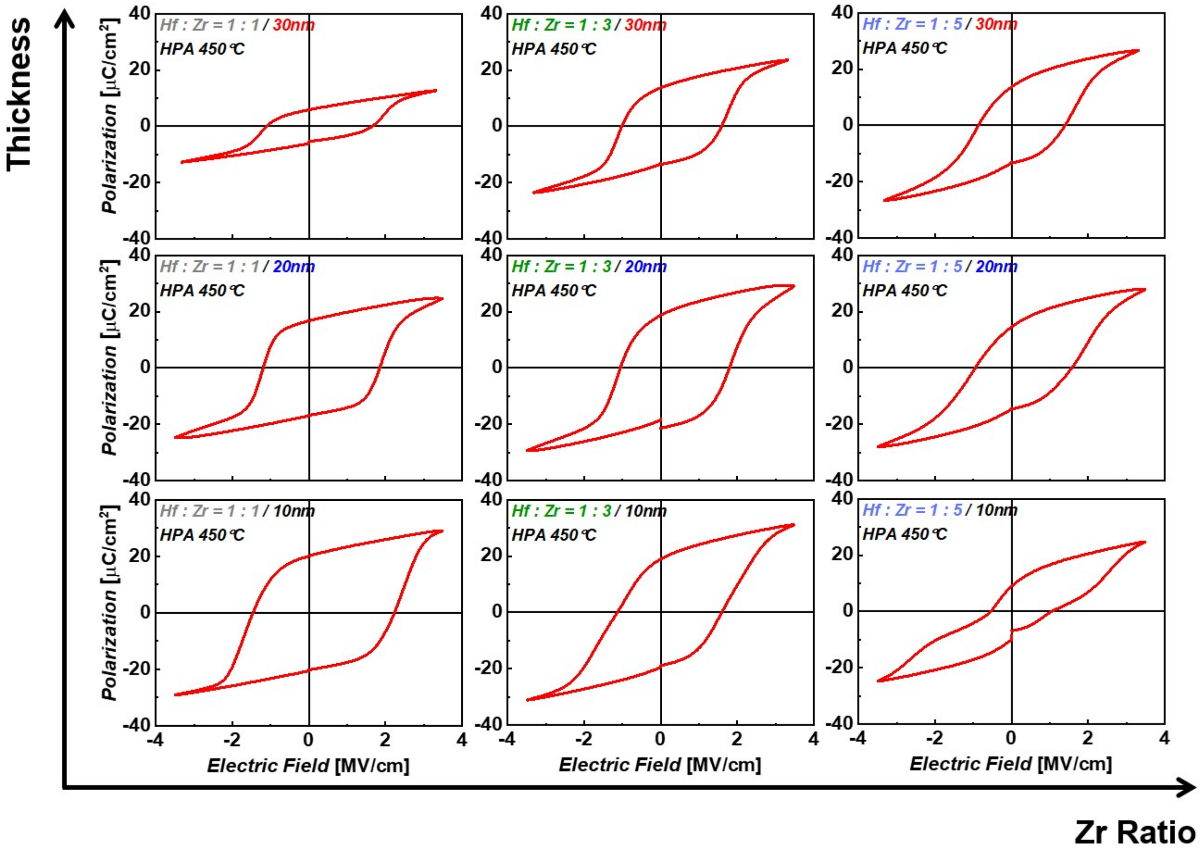


Figure S1. Polarization-electric field curves for various Zr ratios and thickness.

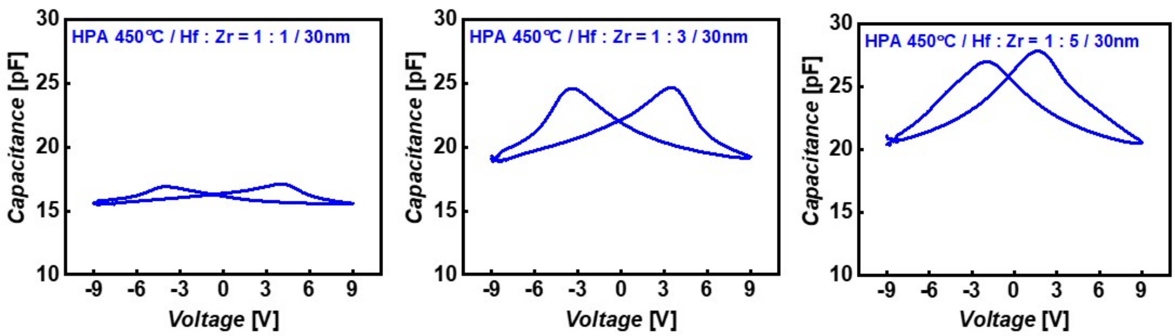


Figure S2. Capacitance-voltage curves of the HfZrO different Zr ratio with the thickness of 30 nm.

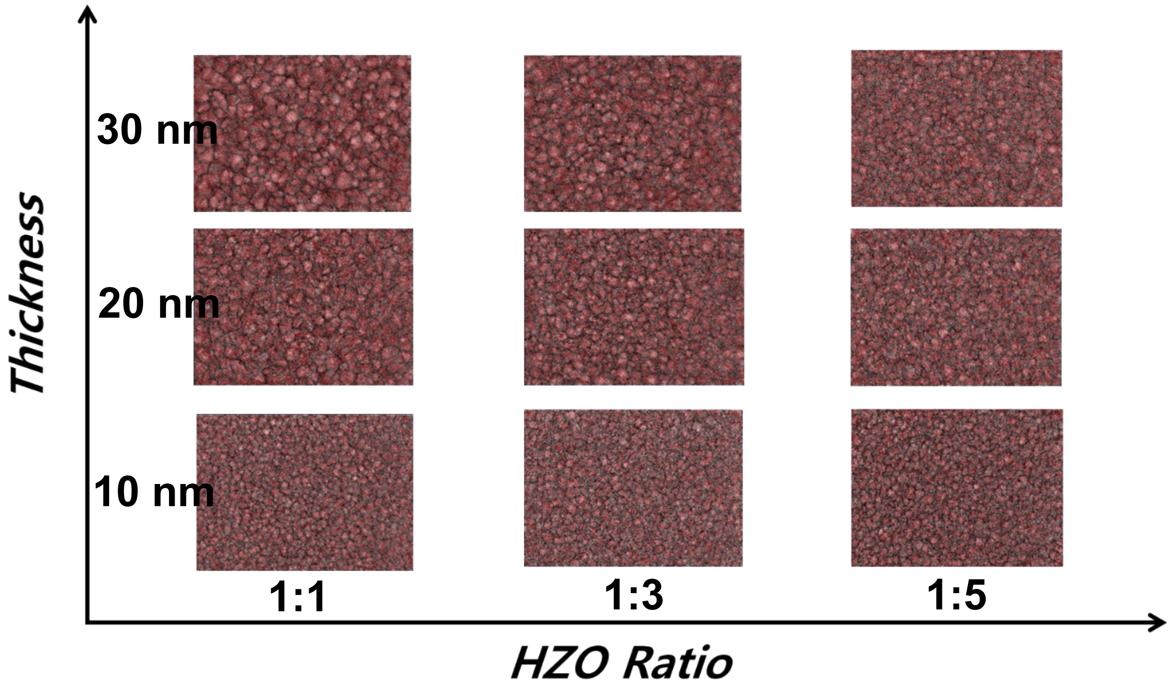


Figure S3. The result of SEM analysis according to the different Hf:Zr doping ratio and thickness.

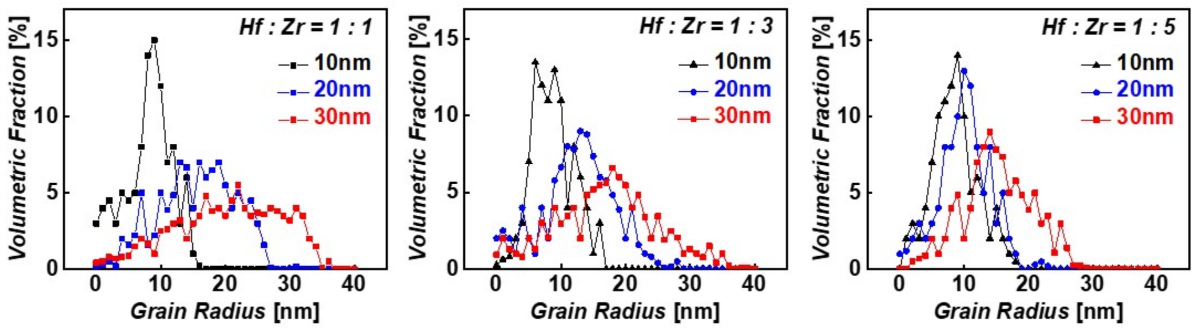
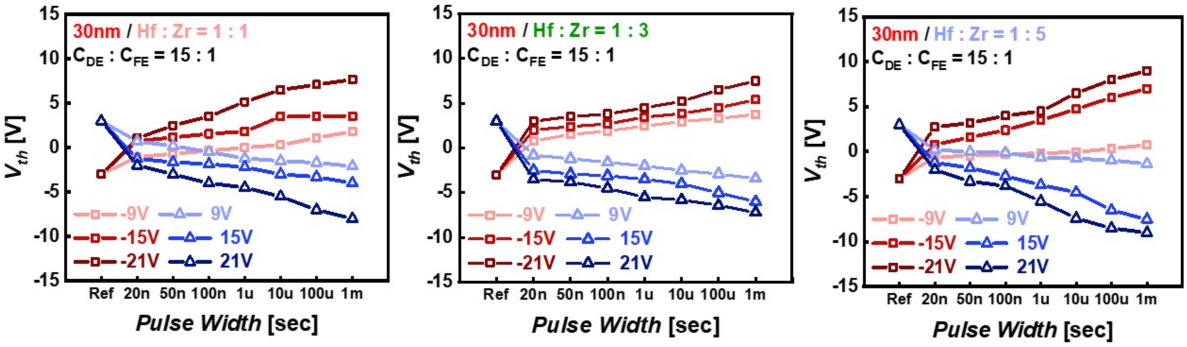


Figure S4. Extracted grain size distributions based on the SEM analysis data. A grain size distribution analysis was conducted using the watershed method implemented in the Gwyddion software.

Figure S5. The GIXRD data of 30-nm-thick HZO film with various Zr contents.



ratio varied ferroelectric films.

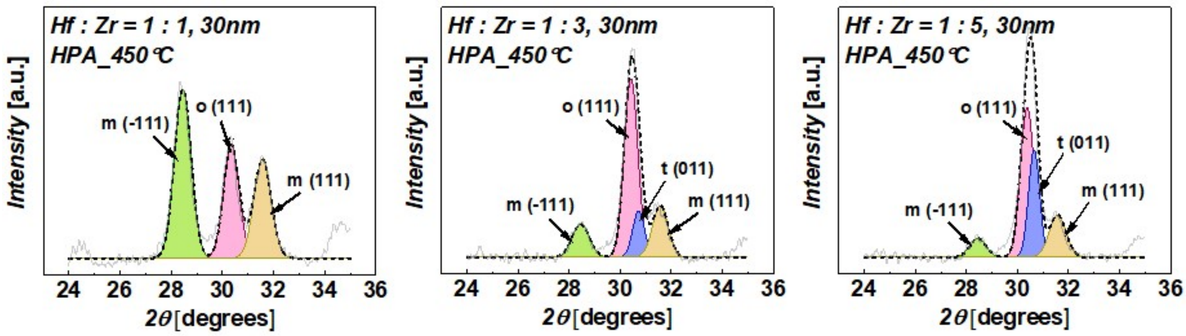
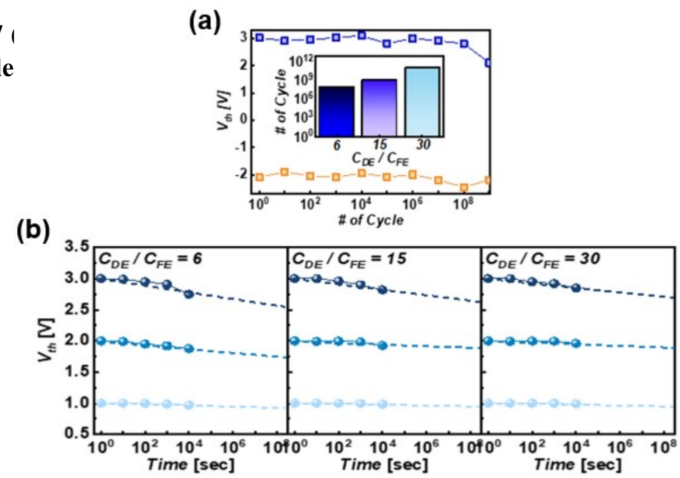


Figure S7. Figure S7 (**= 15. Inset shows the number of endurable** **nparison of retention**



Methodology

Simulation method

In this study, Synopsys TCAD Sentaurus was used for the simulation of 3D ferroelectric NAND structure. In addition, 2D based structure employed as the virtual gate all (GAA) structure during device simulation through the cylindrical command of the Sentaurus tool as shown in fig.S1. Through this process, a complete 3D ferroelectric NAND flash was simulated.

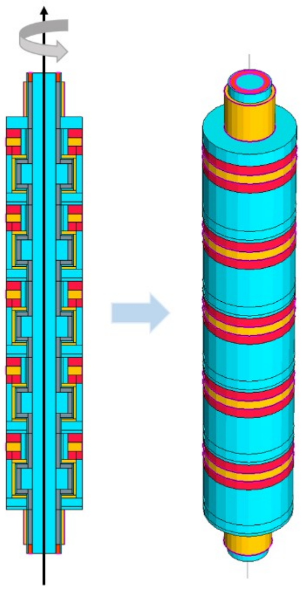


Figure S8. The simulation methodology for implementation of 3D ferroelectric NAND flash memory.

The following models were used for more accurate simulation: the doping concentration dependence, high field saturation, trap scattering mobility and trap-assist-tunnel (TAT), Shockley-Read-Hall, Auger, Schenk band-to-band recombination, and band-to-band-tunneling (BTBT) model. The trap parameters related with the poly-silicon channel is listed below.

Table S1. The simulation parameters used for the tunneling model.

Parameters	Value
Trap concentration (cm^{-3})	28
Energy level (eV)	0.1 (electron) - 0.1 (hole)

In order to reflect the characteristics of the fabricated ferroelectric film and its multi-domain based characteristics, Preisach model was employed with the parameters below.

Table S2. The simulation parameters for the preisach model.

Parameters	Value
Saturation polarization (P_s, $\mu C/cm^2$)	28
Remanent polarization (P_r, $\mu C/cm^2$)	15
Coercive field (E_c, MV/cm)	1.2

The figure below shows the calibration result of the ferroelectric film using the parameters mentioned above. (doping ratio of Hf:Zr=1:3, thickness = 30 nm, HPA 450℃ 200 atm 30 min) The P-V curve was extracted from the MFM capacitor. Fig.S2 shows the simulated P-V curve vs measured P-V curve which are well matched. Right shows that the polarization switching of the ferroelectric film is well calibrated even with in the time domain.

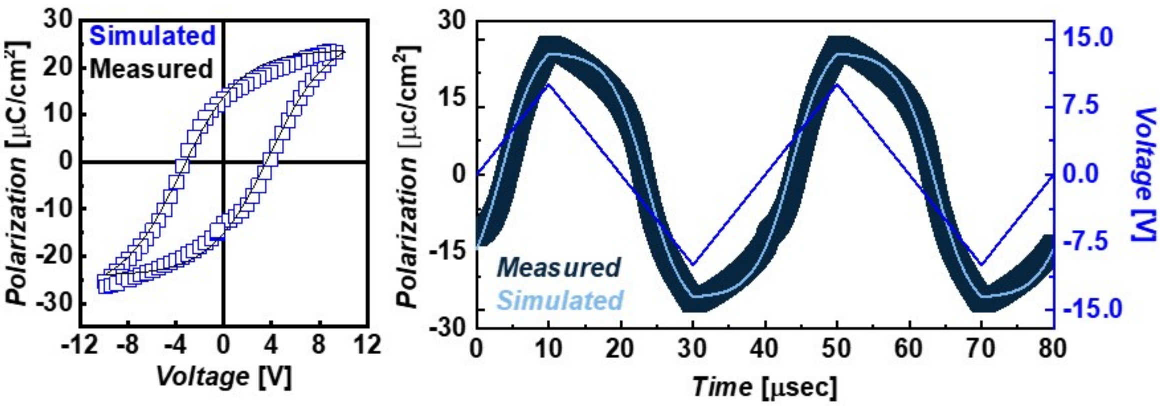


Figure S9. Calibrated polarization-voltage curve and its polarization response according to the applied pulse.

Figure below shows the calibration of the FeFET's (ferro thickness = 30 nm) transfer curves.Sharp line means the measured data while the smoothed line means the simulation data. Even with the different capacitance ratio, all the simulation results are well matched to the measured ones.

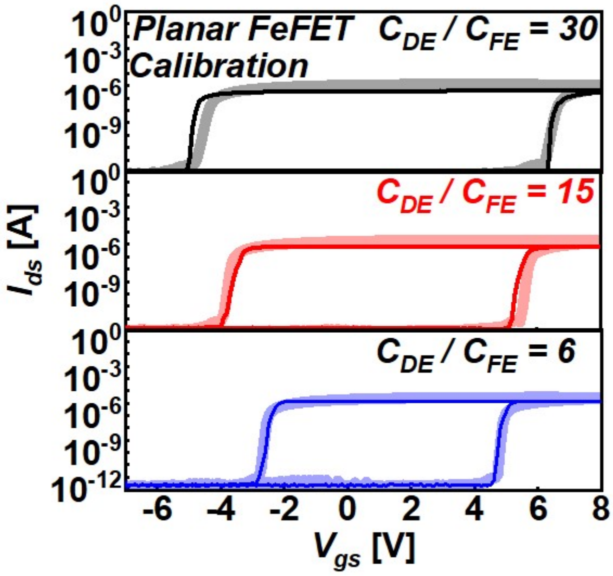


Figure S10. Calibrated transfer curves of the FeFETs according to its capacitance ratios.

Ref [6]	DRAM	NAND Flash (cell)	ReRAM	PCM	STT-MRAM	This Work
MLC	No	Yes	Yes	Yes	No	Yes
Operation Speed	< 10 ns	≈ 100 μs	100 ns	150 ns	20 ns	20 ns
R_{ON}/ R_{OFF} ratio	N/A	> 10^4	10 - 100	10 - 100	< 10	> 10^6
Endurance	10^{16}	10^4 - 10^6	10^5 - 10^7	10^5 - 10^7	10^6 - 10^7	10^9
Retention	< 1sec	10 yrs	10 yrs	10 yrs	10 yrs	10 yrs
Cell Size	40 F^2	60 F^2	60 F^2	60 F^2	50 F^2	60 F^2
Density	Good	Excellent	Excellent	Excellent	Excellent	Excellent

Table S3. Benchmark of performance of various memory devices.

Reference paper	MW value	Endurance
[27] (MFIS FeFET)	0.9V	10^5 cycles
[28] (MFIS FeFET)	2.8 V	No data

[29] (MFIS FeFET)	1.28 V	10^4 cycles
[30] (MFIS FeFET)	1.2 V	10^4 cycles
Our work (MFMIS FeFET)	5 V	> 10^9 cycles

Device fabrication

Table S4. Comparison of memory characteristics and reliability characteristics with existing works based on MFIS FeFET

[Fabrication and measurement of MFM capacitor]

MFM (TiN/HfZrO/TiN) capacitors are fabricated for this study using different doping ratio of Hf and Zr (1:1, 1:3, and 1:5) and different thickness (10 nm, 20 nm, 30 nm). The top and bottom TiN electrodes were deposited using DC sputtering technique whereas the HfZrO films were deposited using plasma enhanced atomic layer deposition (PEALD). For the crystallization of the HfZrO films and to compare the ferroelectric characteristics according to the annealing method, both RTA and HPA were conducted. In the case of RTA, MFM capacitors were post-metallization annealed at the condition of 600 ℃, 10 sec in N_2 atmosphere. In the case of HPA, MFM capacitors were annealed at the condition of 450 ℃, 30 min and 200 atm in forming gas atmosphere.

For the SEM and GIXRD analysis, the top electrodes of MFM capacitors were wet-etched after the crystallization of the ferroelectric film.

The electrical properties such as polarization-electric field curve, capacitance-voltage curve, endurance were measured with Keithley 4200 parameter analyzer. The thickness and crystal structure HfZrO flim were measured using ellipsometer (Nano View, SE MG-1000) and grazing incidence X-ray diffraction (GIXRD, Rigaku, SmartLab), respectively.

[Fabrication and measurement of FeFET]

The MFMIS FeFET is fabricated using the typical gate first process. The gate stack is composed of P-type silicon substrate, SiO2 (5 nm), TiN (50 nm), Hf0.5Zr0.5O2 (30 nm), and TiN (50 nm). After MOSFET fabrication, the MFM capacitor is sequentially stacked following the fabrication process of MFM capacitor. The capacitance ratio of the gate insulator and ferroelectric film was fine-tuned by reducing the relative area of the MFM compared with MOSFET. For the crystallization of the ferroelectric film, HPA was also performed at the condition of 450 ℃, 200 atm. The Transfer curve (I_d-V_g), Incremental step pulse program (ISPP), endurance and retention of MFMIS FeFET with different C_{DE}/C_{FE} and A_{FE}/A_{DE} were measured using Keithley 4200 parameter analyzer and semiconductor device parameter analyzer (Keysight, B1500).