Supplementary Information: Differential charge boost in hysteretic ferroelectric-dielectric heterostructure capacitors at the steady state

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I. EXPERIMENTAL DETAILS

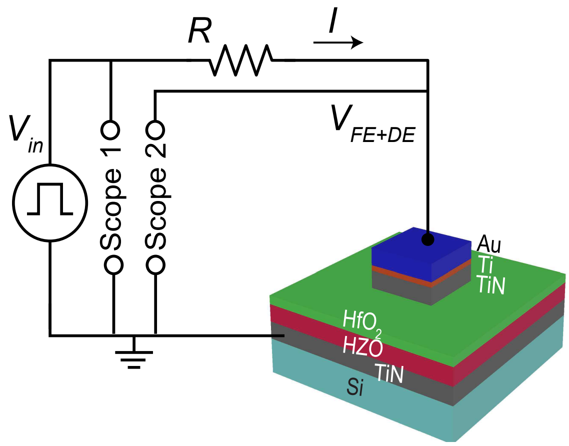

FIG. S1. (a) Schematic of the experimental setup of the pulse measurement. $V_{in}(t)$ and $V_{FE+DE}(t)$ waveforms are captured by an oscilloscope.

A resistor R=1 kΩ in series with the device under test (DUT) was connected to a pulse generator shown in fig S1. An oscilloscope was used to measure voltages across the pulse generator and the DUT.

The electrical measurements were done using a Cascade Microtech Summit 1200K semi-automated probe station. The pulse measurements on the MIFM heterostructure were performed using a Keysight 81150A Pulse Function Arbitrary Noise Generator and a Keysight DSOS104A Oscilloscope. An FE tester aixACCT TF-3000 ferroelectric parameter analyzer at 1 kHz was used to measure the polarization versus electric field curves (black dotted curves in Fig. 2(b)). The dielectric constant of HfO_2 was extracted from the capacitance versus electric field curves measured by a Keysight E4990A impedance analyzer (Supplementary Fig. S3).

II. TIME PLOTS FOR MFM CAPACITOR

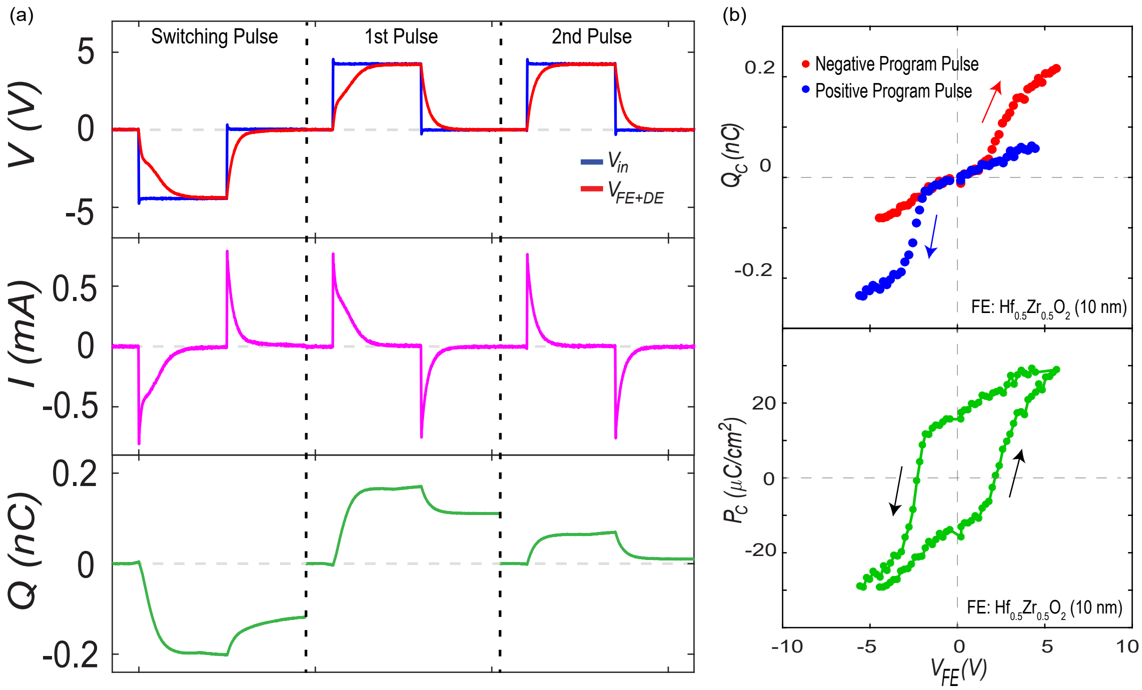

FIG. S2. (a) The source voltage V_{in}, FE voltage V_{FE}, the current through R, the charge supplied by the source, Q plotted as a function of time for $V_{prog} = -4.4$V and subsequent measurement pulses of +4.2V. The program pulse is applied before every measurement. The first measurement pulse captures Q_{SW} and Q_{DE} while the second captures only Q_{DE}. (b) $Q-V$ curve and $P-V$ curve for 10 nm $Hf_{0.5}Zr_{0.5}O_2$ measured using the modified PUND method.

Both charge, Q_C and polarization, P_C(=Q_C/Area of the capacitor) are plotted as functions of maximum voltage $V_{max}(= V_{FE})$ across the MFM capacitor, shown in Fig. 2(b). It should be noted here that the $P-V$ loops of the MFM capacitor does not show a negative slope because the NC characteristic is not stable in a simple ferroelectric capacitor.

III. DIELECTRIC CONSTANT OF HfO_2 CAPACITOR

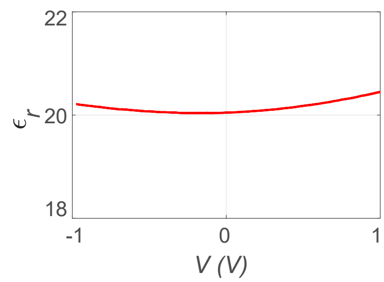

FIG. S3. Dielectric constant ϵ_r vs Voltage (V) of 10nm HfO_2. Hafnia's dilectric constant is approximately 20.

The dielectric constant of HfO_2 was extracted from the capacitance versus electric field curves measured by a Keysight E4990A impedance analyzer with a small-signal amplitude of 50 mV and a frequency of 100 kHz. From the figure, the dielectric constant of HfO_2 is $\sim$ 20 which is used to extract $P_C - V_{FE}$ loop from the $P_C - V_{FE+DE}$ data.

IV. P_C VS V_{FE} LOOP EXTRACTED FROM FIG 2B

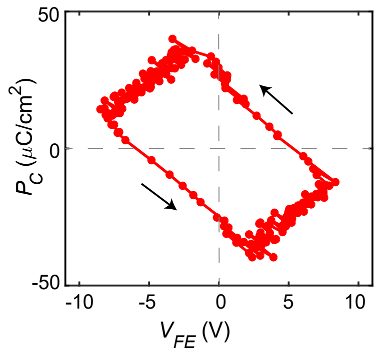

FIG. S4. $P_C - V_{FE}$ curve extracted from the $P_C - V_{FE+DE}$ curve obtained from the modified PUND method.

Under the assumption that the capacitance of HfO_2 is constant and the negative capacitance phenomenon is stabilized in an FE-DE capacitor, we extracted voltage across the ferroelectric layer V_{FE} and plotted the $P - V_{FE}$ characteristics.

V. PLOTS FOR 1.5 μS.

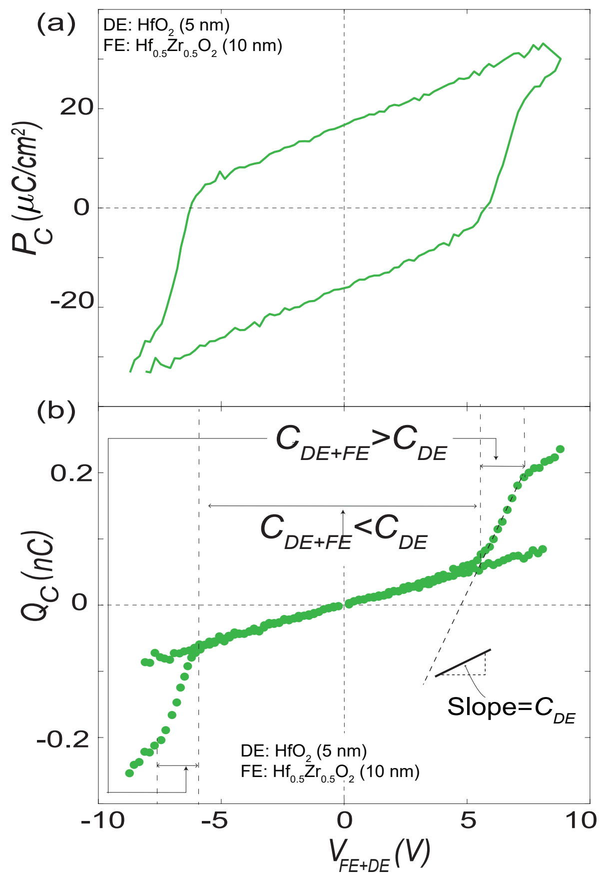

FIG. S5. (a) $P-V$ curve from modified PUND method (green cruve) for 10 nm $Hf_{0.5}Zr_{0.5}O_2$ with 5 nm HfO_2 for pulse width=1.5 μs. (b) Differential NC based capacitance enhancement is shown using modified PUND method.

The modified PUND method was also applied on the DUT with pulse width = 1.5 μs and Fig. S5(a) shows the resulting P_C vs V_{FE+DE} plot. The P_C vs V_{FE+DE} curves are shown is Fig. S5(b) demonstrating the capacitance enhancement due to negative capacitance of the ferroelectric layer.

VI. SIMULATION MODEL

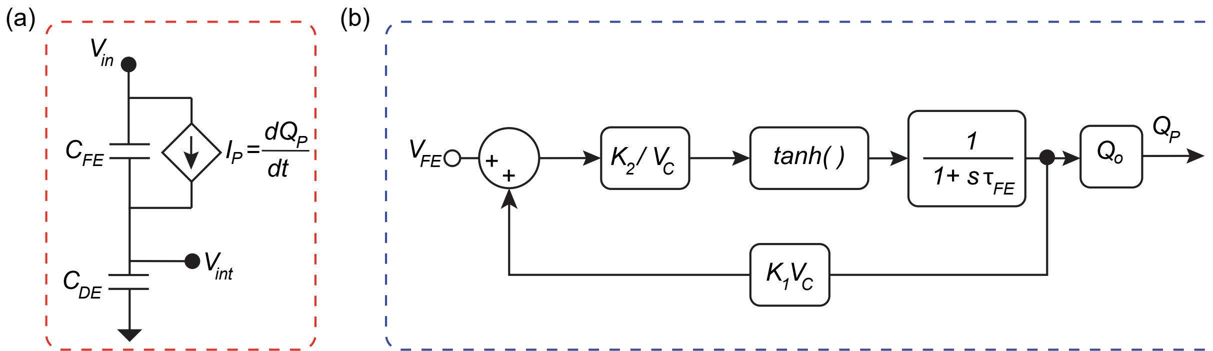

FIG. S6. (a) SPICE circuit model of the FE-DE interaction for a single domain, (b) SPICE implementation of dynamics of charge switching based on positive feedback-loop.