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Supporting Information

Improvements in Synaptic Operations of Ferroelectric Field-Effect Transistors Using $Hf_{0.5}Zr_{0.5}O_2$ Thin Films Controlled by Oxygen Partial Pressures during Sputtering Deposition Process

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In a previous study, we investigated the effect of HZO film thickness for optimizing the nonvolatile memory characteristics for the ferroelectric field-effect transistors (FeFETs) with MFMIS gate-stack structures. We provided the obtained memory device operations and the detailed descriptions on the effects of HZO film thickness and area ratio between the capacitors of the MFMIS gate stack on the device characteristics of the fabricated FeFETs as supporting information.

1. Retention characteristics of the Pt/HZO/TiN/SiO_2/Si capacitors with variations in S_I/S_F

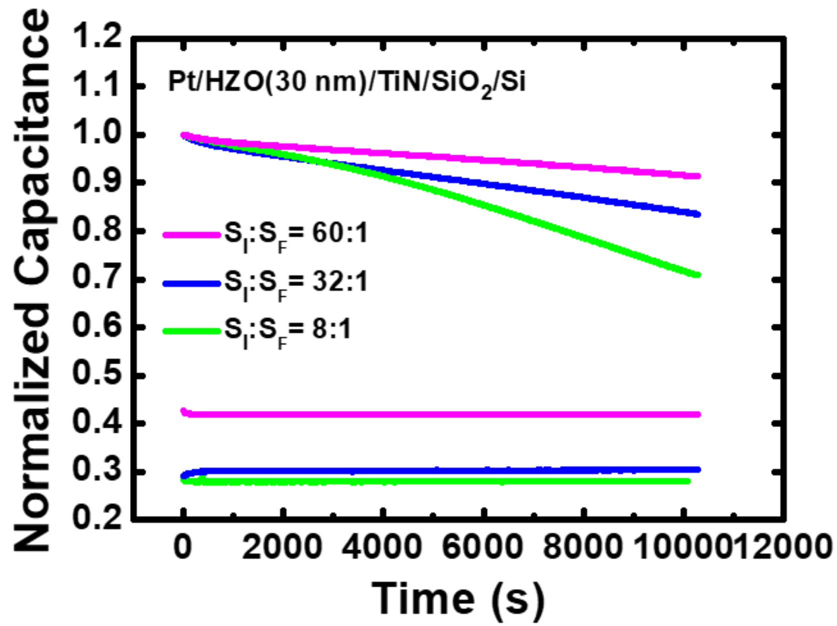

Figure S1. (a) Comparisons in C-t characteristics of the MFMIS capacitors using 30-nm-thick HZO thin films with variations in S_I/S_F. The pulse amplitudes for program on/off operations were set as -6 and +6 V, respectively, when the pulse width was fixed at 10 μs.

2. Transfer characteristics of MFMIS-FETs with variations in S_I/S_F and HZO thickness

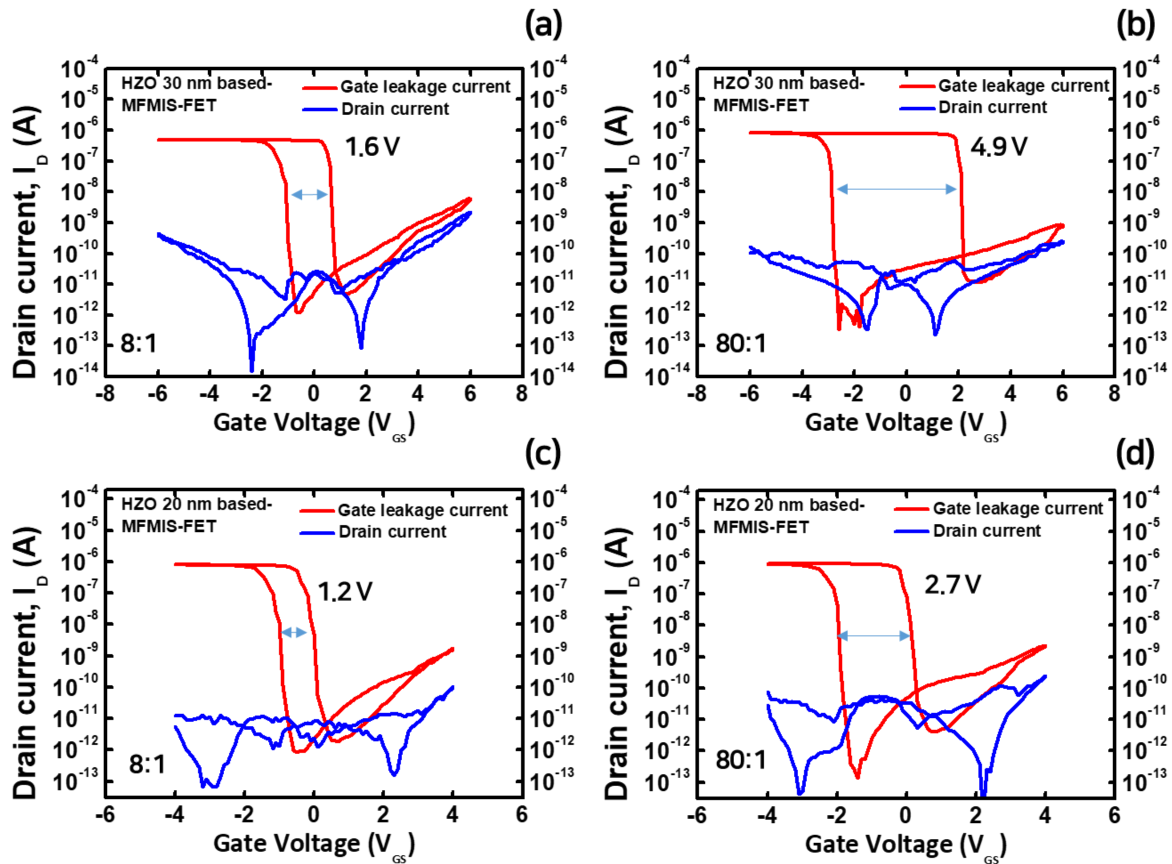

Figure S2. Transfer curves of the MFMIS-FETs using 30-nm-thick HZO thin films with S_I/S_F ratios of (a) 8 and (b) 80, and using 20-nm-thick HZO thin films with S_I/S_F ratios of (c) 8 and (d) 80. The drain current values were measured at a V_{DS} of -0.5 V. The V_{GS} sweep ranges were varied to ±6 and ±4 V for the devices using 30- and 20-nm-thick HZO gate insulators, respectively. The memory window increased with increasing the HZO film thickness and S_I/S_F of MFMIS gate stacks.

3. Program and retention characteristics of MFMIS-FETs with variations in HZO thickness

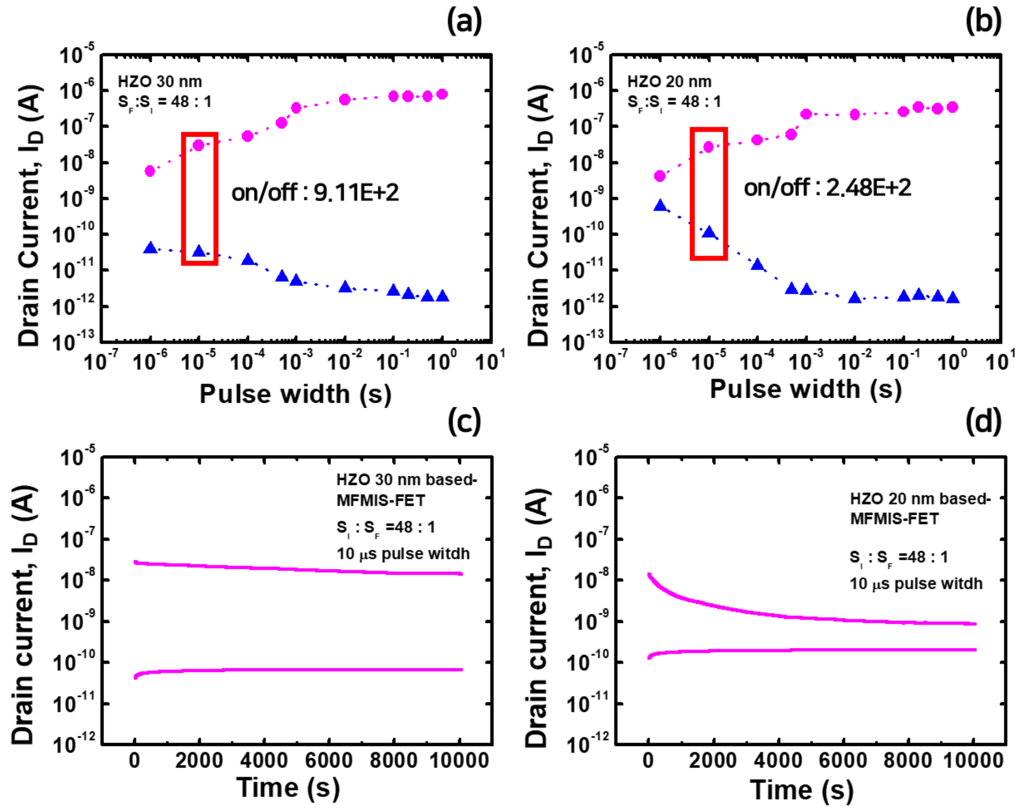

Figure S3. Variations in on/off programmed drain currents for the MFMIS-FETs with S_I/S_F of 48 as a function of program pulse duration in a range from 1 µs to 1s, when the HZO thickness was varied to (a) 20 nm and (b) 30 nm. Variations in on/off programmed drain currents for MFMIS-FETs (S_I/S_F=48) using (c) 20- and (d) 30-nm-thick HZO thin films. The device using 30-nm-thick HZO shows better program and retention characteristics than those of the device using 20-nm-thick HZO due to more effective voltage distribution and more efficient use of ferroelectric polarizations. When the HZO film thickness increased to 30 nm, the polarizations correspoinding to operating points are determined to be close to the saturated polarizations. Minor loops are not robust to the depolarized fields during the retention period.

4. Memory Retention characteristics with variations in HZO film thickness and program pulse duration

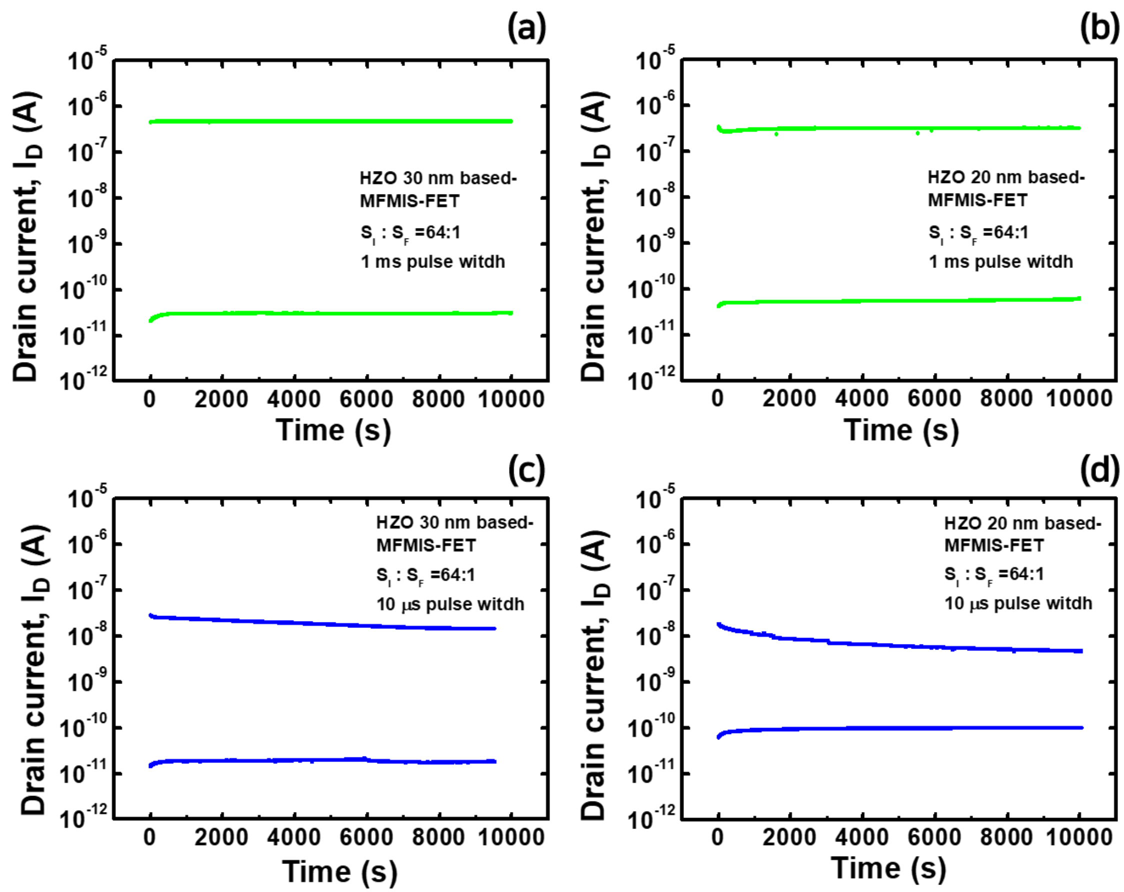

Figure S4. Comparisons in retention characteristics of the MFMIS-FETs using (a) 20- and (b) 30-nm-thick HZO gate insulators, when the program pulse width was fiexd at 1 ms. Comparisons in retention characteristics of the MFMIS-FETs using (c) 20- and (d) 30-nm-thick HZO gate insulators, when the program pulse width was fiexd at 10 µs. The S_I/S_F of the MFMIS gate stack was 60. When the program pulse width was set as 1 ms, more robust retention behavior could be secured with a larger memory on/off ratio, because the ferroelectric polarizations were fully switched during the program operations due to the pulse duration longer than the typical switching times for polarization reversal in the HZO thin films.