Depolarization Field Induced Instability of Polarization States in HfO_2 Based Ferroelectric FET

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***Abstract*— Doped HfO_2 based ferroelectric FET (FeFET) exhibits a greatly improved retention performance compared with its perovskite counterpart due to its large coercive field, which prevents domain flip during retention. In this work, however, through extensive temperature dependent experimental characterization and modeling, we are demonstrating that: 1) with FeFET geometry scaling, the polarization states are no longer stable, but exhibit multi-step degradation and cause reduced sense margin in distinguishable adjacent levels or even eventual memory window collapse; 2) the instability is caused by the temperature activated accumulation of switching probability under depolarization field stress, which could cause domain switching within the retention time at operating temperatures.**

I. Introduction

Ferroelectric FET (FeFET) based on ferroelectric HfO_2 (Fig.1(a)) recently emerges as a promising candidate for embedded nonvolatile memory (NVM), empowering multiple compute-in-memory applications, such as synaptic weight cell for deep learning accelerator (Fig.1(b)) and content addressable memory, etc. [1]. All of the promising applications will not be feasible without stable polarization states that can retain over time. For the case of synaptic weight cell or the multi-level cell (MLC) applications, the stability requirements will extend beyond the stable binary states in the single bit memory to also stable intermediate levels. Stability is usually considered to be one of the greatest advantages of HfO_2 based FeFET, thanks to its orders of magnitude higher coercive field (E_C ~ 1 MV/cm), compared with its perovskite counterpart (E_C ~ 50 kV/cm) [2]. This has allowed its thickness scaling into the ~nm regime and retention lifetime extended to 10-year, a critical challenge for FeFET based on perovskite ferroelectric materials. However, in this work, we show that HfO_2 based FeFET is not free from the stability concerns, especially with device scaling.

In FeFET, due to the loading effect of the semiconductor substrate, there is a depolarization field in the ferroelectric layer during retention that is opposing the polarization (Fig.1(c)). Additionally, it has been confirmed that the nucleation limited polarization switching process is exponentially dependent on the applied electric field [3]. The polarization switching probability is accumulating under the applied stress and could eventually induce a polarization switching (Fig.1(d)). Therefore, even though the depolarization field is usually much weaker than that induced by write pulses, domain switching could still happen at the retention time scale. Such an effect is usually not noticeable in a large size FeFET that contains a significant number of domains as few domains switching rarely makes an impact (Fig.1(e)) [4]. However, in a scaled FeFET with a limited number of domains, even single domain switching could clearly reveal itself and cause state collapse (Fig.1(f)).

To delve into the details of polarization switching, retention under different temperatures is performed to probe the temperature dependent nucleation process (Fig.2). The domain nucleation is temperature activated, with the activation energy determined by the energy gain from the domain switching and the energy cost from the polarization discontinuity on the surface [3]. Temperature mainly affects the nucleation delay through the time constant τ in the switching probability such that it takes a longer or stronger pulse to switch the same domain at lower temperatures (Fig.1(d)). Thus, it is possible that unstable polarization states at a high temperature will be stabilized again by decreasing the operating temperature (Fig.1(f)). In this work, we are using the temperature as the control variable to study the depolarization field induced instability in FeFET with different geometrical sizes.

II. Temperature Dependence of Polarization Switching in Ferroelectric Devices

A previously developed ferroelectric model for both the metal-ferroelectric-metal (MFM) capacitor and FeFET [5] are utilized in this work, augmented with the temperature dependence description (Fig.3(a)). It considers the ferroelectric layer as a film composed of multiple independent domains, whose switching probability is calculated at each time step. A Monte Carlo approach is applied to simulate the domain flipping, given the switching probability. Such a model can well capture scalability, variation, stochasticity, and accumulation in FeFET, where the last behavior describes the accumulation of switching probability under an applied electric field, which is directly related with the polarization state stability studied in this work. With this model, the switching dynamics in an MFM capacitor at 300K (Fig.3(b)) and 200K (Fig.3(c)) are well captured. The model can also reproduce the measured polarization (P_{FE}) map under different pulse amplitudes and widths at different temperatures (Fig.4). These results clearly show the delayed polarization switching and lower P_{FE} that can be switched at 200K compared with 300K.

The temperature dependence of I_D-V_G hysteresis loops is first measured in a FeFET at different temperatures, ranging from 20K to 300K (Fig.5(a)). During DC sweep, the hysteresis window enlarges first and then saturates with further temperature decrease, as observed in [6]. Such a behavior is also reproduced with the FeFET model (Fig.5(b)). Additionally, the model also captures the decrease of subthreshold swing (SS) with temperature lowering, which is also partially responsible for the V_{TH} increase in the forward sweep with temperature reduction (Fig.5(c)) due to thermal excitation of free carriers in the subthreshold region. The P_{FE}-V_G hysteresis loops (Fig.5(d)) clearly show that the switched P_{FE} reduces with temperature lowering while the required V_G to reach the same state increases, consistent with longer nucleation delay at lower temperatures. This is mainly responsible for the hysteresis window expansion with temperature lowering.

The switching dynamics of the memory window in a FeFET as a function of pulse widths and pulse amplitudes are measured at 300K and then calibrated with the FeFET model (Fig.6(a)). With the reasonably calibrated model, the switching dynamics at 80K is predicted (Fig.6(b)), showing reduced memory window compared with 300K. The I_D-V_G curves after write with different pulse widths at 3.4V (Fig.6(c)) demonstrate the reduced memory window yet steeper subthreshold slope at 80K compared with 300K. To study the temperature dependence of polarization switching in FeFET, the I_D map after memory write with different pulse widths and amplitudes are measured and simulated using the calibrated model (Fig.6(d)-(k)). For a large FeFET (W/L=1μm/240nm), the I_D is reduced when lowering the temperature from 300K (Fig.6(d)) to 80K (Fig.6(h)). The I_D along a vertical cutline at V_G=3V (Fig.6(l)) clearly demonstrate a delay of the polarization switching at lower temperatures. To simulate the large device, the FeFET model with 2000 domains are used, considering a domain size of approximately 10nm [3]. The model can qualitatively reproduce the temperature dependence of the switching dynamics (Fig. 6(e) and (i)), showing delayed switching at lower temperatures. Along the vertical cutline, the model exhibits a smooth transition of the I_D as a function of pulse width, which unfortunately is not shown in the measured data due to limited resolution taken, but otherwise has been reported before [7]. Similar measurements (Fig.6(f), (j), and (n)) and simulations (Fig.6(g), (k), and (o)) are performed on a scaled FeFET (W/L=160nm/34nm). In this case, FeFET model with only 20 domains are utilized for simulation. Similar conclusions are reached as the large FeFET case, except for more abrupt switching in the switching dynamics (Fig.6(n-o)), a signature for single domain switching [8]. This is because in a scaled FeFET with a limited number of domains, few domain or single domain switching induces a significant charge change, which can be clearly observed.

III. Temperature Dependence of the Stability of Polarization States in FeFET

With the temperature dependence of polarization switching extensively characterized and modeled, the retention in a large and scaled FeFET at different temperatures are investigated. Fig.7(a-c) shows the I_D-V_G hysteresis for a large FeFET (W/L=1μm/240nm) at 300K, a scaled FeFET (W/L=80nm/34nm) at 300K and 4K, respectively. Fig.7(d-f) shows their corresponding retention performance. The results show that for a large FeFET at high temperature (Fig.7(d)), all the polarization states are stable, suggesting decent retention performance. When the device geometry is scaled, however, I_D in one of the intermediate state decreases in discrete steps and eventually fully collapses into another state (Fig. 7(e)), suggesting retention failure of the scaled device. This abrupt change in the polarization indicates single domain switching induced by the depolarization field, posing significant challenges into device scaling for high density memory or synaptic weight cell. Further, by decreasing the retention temperature to 4K, all the polarization states become stable, confirming the increase of nucleation delay at low temperatures.

Retention performance is also simulated using the calibrated FeFET models. Fig.8(a-c) shows the retention performance for a large FeFET (2000 domains) at 300K, a scaled FeFET (20 domains) at 300K and 4K, respectively. It qualitatively reproduces the measured retention performance. In a large FeFET, all the states are stable when subject to the depolarization field stress (Fig.8(d)). Actually, for state S_4, degradation in the P_{FE} can be observed, but it is not significant due to the abundant domains existed in a large device. For a scaled FeFET, however, abrupt switching in the I_D during retention at 300K is observed (Fig.8(b)), similar to the measured retention characteristics (Fig.7(e)). Exact matching with measured data is challenging as it requires the full knowledge of all domain information, such as the time constant, the size, etc. Therefore, we are only targeting at qualitative understanding of the observed phenomena in this work. The abrupt change in I_D corresponds to the single domain switching (Fig.8(e)) [8]. The switching can be suppressed by lowering the retention temperature to 4K (Fig.8(c)), where all the states become stable again. Fig.8(f) shows that during retention, the switching probability of a domain is accumulating with time [5]. For 300K, due to smaller time constant, the switching probability is much higher than 4K, thus inducing a polarization switching in the retention time scale. For 4K, however, the accumulation is also happening, but the magnitude is significantly smaller, greatly extending the retention lifetime.

IV. Conclusions

In this work, we have investigated the temperature dependent retention performance of FeFET with geometry scaling. We are showing that depolarization field induced polarization switching could become a serious issue for FeFET scaling due to the potential loss of the device sensing margin or complete failure. Such polarization instability is caused by the thermally activated accumulation of switching probability under depolarization field, which eventually induces a domain flip. Therefore, for future FeFET technology scaling, special attention has to be paid in mitigating the depolarization field induced retention loss and extend the device retention lifetime.

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Polarization Switching During FeFET Retention

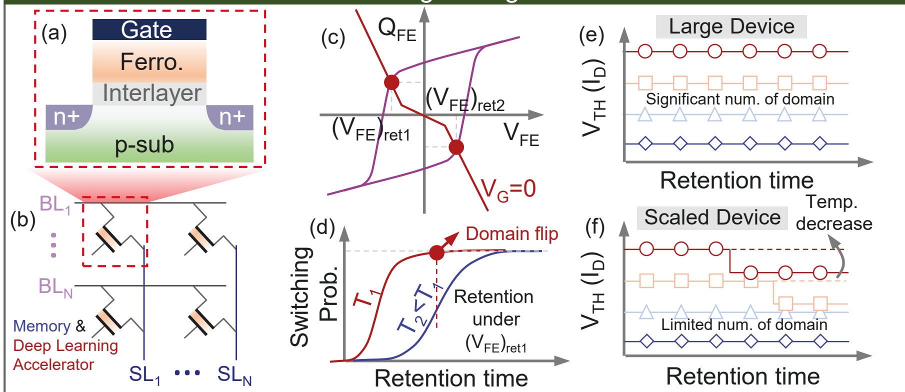

Fig.1. (a) FeFET is promising for (b) embedded nonvolatile memory and deep learning accelerator applications. However, maintaining state stability under (c) depolarization field is challenging due to the (d) accumulation of domain nucleation prob. Such single domain flipping is pronounced in (f) scaled devices with a limited num. of domains compared with (e) large devices.

Temp. Dependence of Ferroelectric Switching

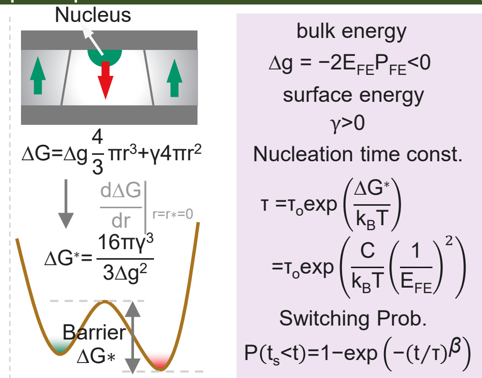

Fig.2. Temperature provides a probe of nucleation process in switching dynamics (Fig.1(f)), which is temperature activated. Lower temp. delays the nucleation process, hence improves the retention.

Temperature Dependence of Polarization Switching in MFM Capacitor

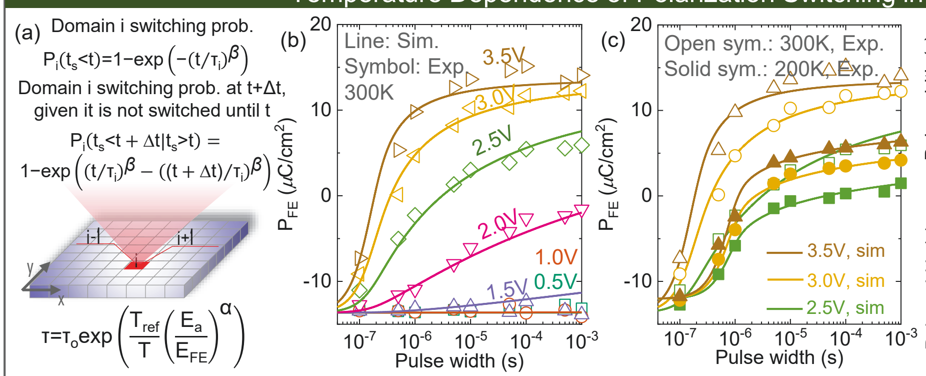

Fig.3. (a) The ferroelectric model used is a distributed Monte Carlo model, where at each time step the switching prob. is calculated and domain switching is simulated. (b) The switching dynamics in a 10nm $Hf_{0.5}Zr_{0.5}O_2$ MFM capacitor at 300K is well reproduced by the model. (c) The temperature dependent switching is captured by the model as well.

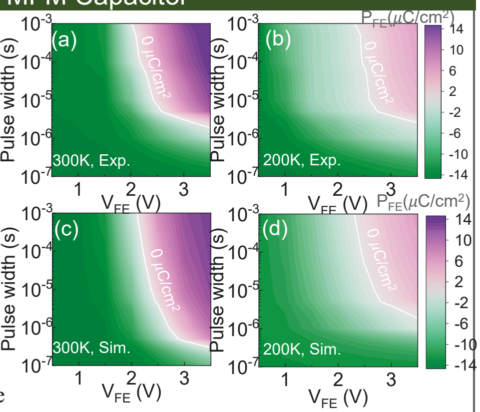

Fig.4. (a)/(b) Measured and (c)/(d) simulated polarization map as a function of pulse width and amplitude at 300K/200K, respectively.

Temperature Dependence of the I_D-V_G Hysteresis Window In FeFET

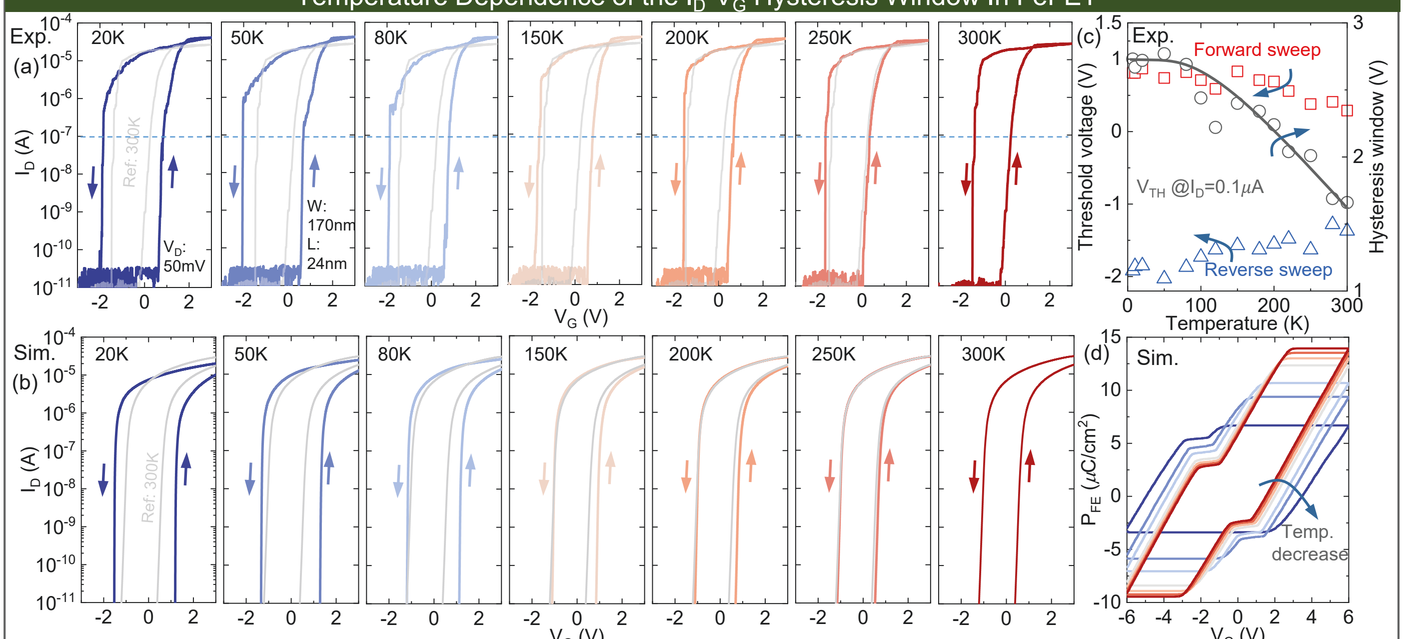

Fig.5. (a) Measured and (b) simulated I_D-V_G hysteresis curves for FeFET at different temperatures ranging from 20K to 300K. With the temperature decrease, the subthreshold swing decreases and (c) the hysteresis window expands as higher V_G is required to switch the same polarization at lower temperatures. As a result, the hysteresis window increases. (d) The P_{FE}-V_G hysteresis loops expands and the switched P_{FE} is reduced at lower temperatures. This causes the plateau of the hysteresis window at extremely low temperatures due to the small P_{FE}.

Temperature Dependence of Polarization Switching Dynamics in FeFET

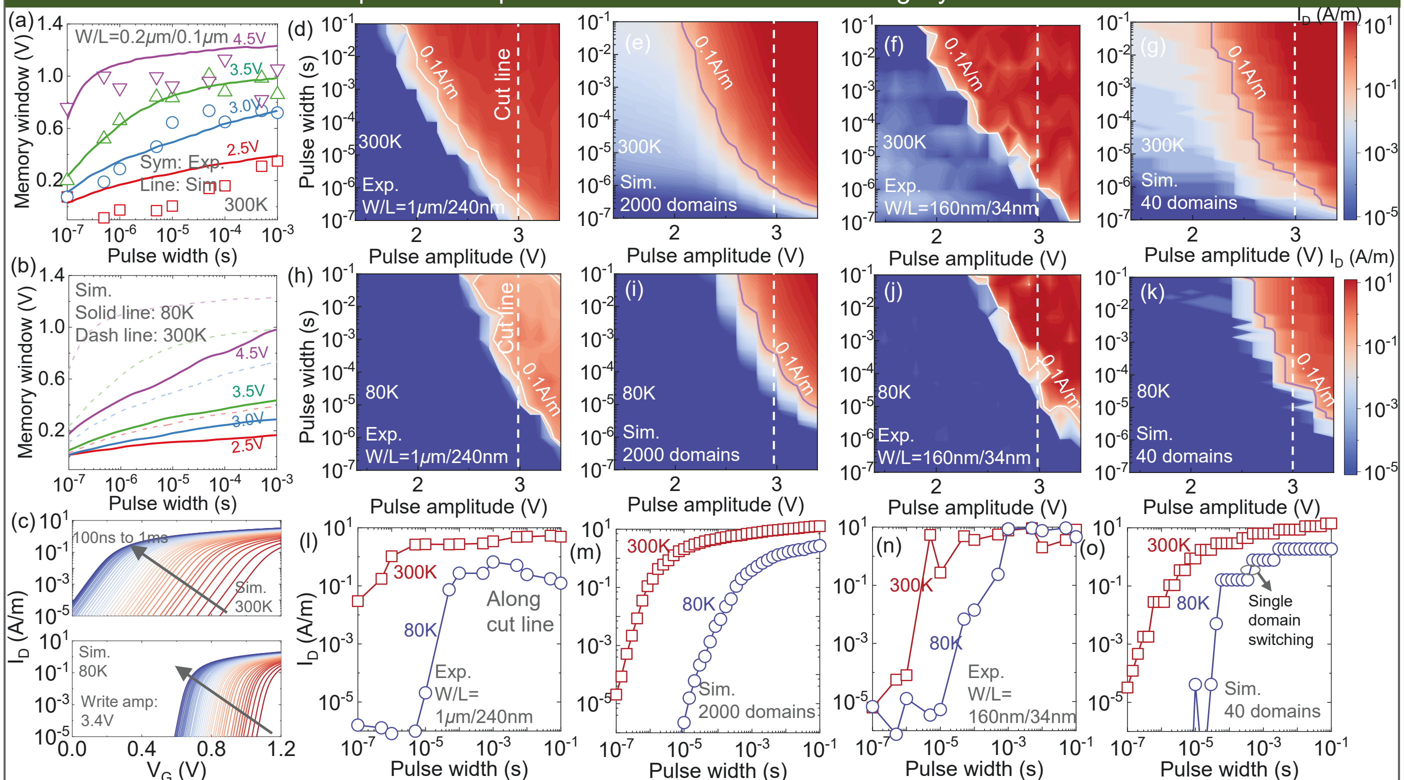

Fig.6. (a) The FeFET model can nicely capture the switching dynamics in FeFET. (b) The memory window is reduced at 80K compared with 300K. (c) The I_D-V_G curves at 300K and 80K reflects the temperature dependent switching. Measured/simulated I_D map for (d)/(e) a large and (f)/(g) a scaled FeFET at 300K. Similar results are shown in (h-k) for 80K. The model can qualitatively capture the temperature dependent switching dynamics. I_D as a function of pulse width for (l)/(m) measured/simulated large device and (n)/(o) measured/simulated scaled device.

Stability of Polarization State Subject to Depolarization Field

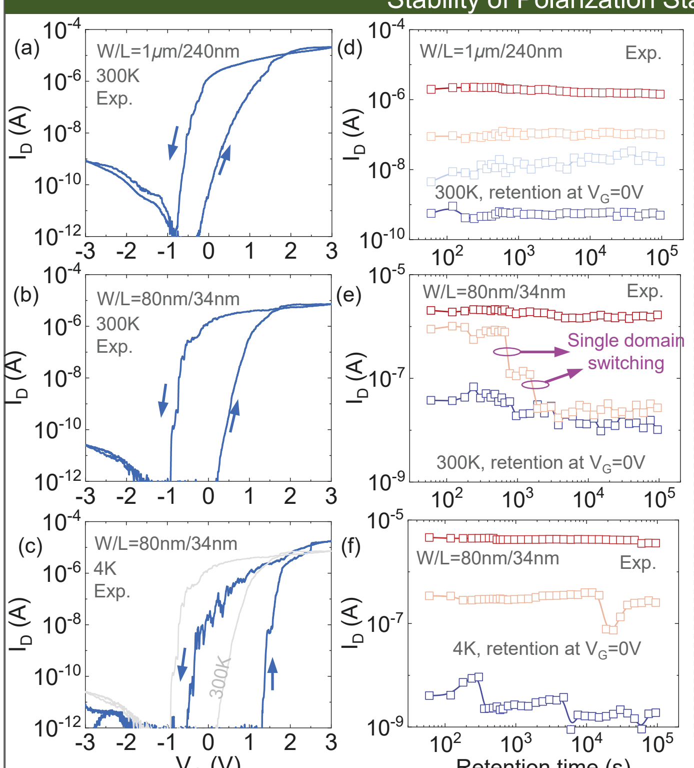

Fig.7. I_D-V_G curves for (a) large device at 300K, (b)/(c) scaled device at 300K/80K. (d) All the states are stable in a large device (e) but abrupt switching during retention due to single domain switching is observed. (f) By decreasing the temp., switching is inhibited, thus stability is retained.

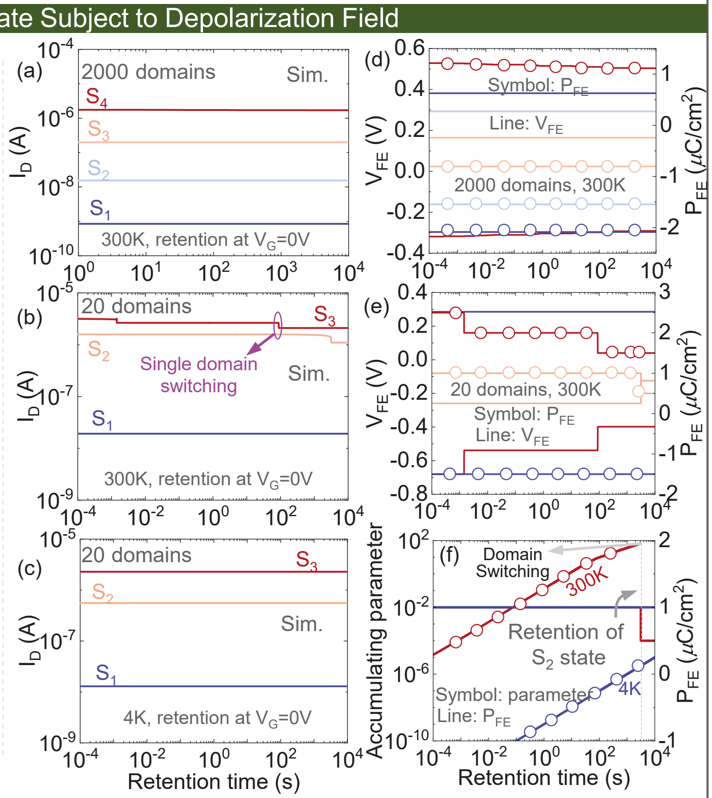

Fig.8. (a-c) Simulated stability of FeFET states capture the same trend in Fig.7. The V_{FE} and P_{FE} during retention at 300K for (d) a large and (e) scaled device shows pronounced switching effect in scaled device. (f) At low temp. the switching prob. accumulation is inhibited.