Compact Modeling of Multi-Domain Ferroelectric FETs: Charge Trapping, Channel Percolation and Nucleation-Growth Domain Dynamics

Y. Xiang, M. Garcia Bardon, B. Kaczer, Md Nur K. Alam, L.-Å. Ragnarsson, K. Kaczmarek, B. Parvais, G. Groeseneken and J. Van Houdt

Abstract— The (doped-)hafnia-based ferroelectric FET (FeFET) is a promising candidate for low-power non-volatile memories and shows potential use as a steep-slope low-power logic device. This requires accurate modeling of the metal-ferroelectric-insulator-silicon (MFIS) gate stack electrostatics. Here we present a hardware-validated FeFET compact model that resolves three key aspects in the MFIS electrostatics pertaining to a multi-domain ferroelectric (FE) layer: 1) the non-radiative multi-phonon process-based charge trapping, 2) the source-to-drain channel percolation due to spatial non-uniformity of FE domain switching and 3) the nucleation-growth domain reversal dynamics using a phenomenological formalism. The polarization charge is calculated by discretized domain switching in transient under distributed coercive fields. Based on the comparison of the model versus experimental data on $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ n-FeFET hardware, we prove that the onset of FE V_{TH} lowering starts with the source-to-drain percolation path formation, when enough FE domains have been flipped up by the gate bias. We further demonstrate that the field-independent domain growth is the fundamental origin of the measured steep subthreshold slope during the downward I_D - V_G sweep. The model ultimately aims to lay down the groundwork for a unified FeFET compact model for both memory- and logic-oriented applications.

Index Terms— ferroelectric FETs (FeFETs), polarization switching, charge trapping, threshold voltage (V_{TH}) programming, steep subthreshold slope.

I. INTRODUCTION

EVER since its advent, the CMOS-compatible (doped-)hafnia ferroelectric materials [1] have ignited a lasting enthusiasm in FeFET-based low-power non-volatile memories (NVM) [2,3]. More recently, the experimentally observed steep subthreshold slope in FeFETs [4,5] has further inspired its potential use in low-power logic technologies but also sparked heated discussions on its exact physical origin [6-9]. In the scenario of NVM, the memory window (MW) lies in the shift of the V_{TH} state from high (“erased”) to low (“programmed”) by gate bias-programming [10], while for steep slope FeFETs (SSFeFETs) the so-called “voltage amplification” [6,7] is

Fig. 1. Schematic of the MFIS electrostatics in a FeFET. “IL” stands for the interfacial layer, and ψ_s for surface potential. The FE polarization charge P_{FE} in the FE layer alters the voltage drop across it V_{FE} , which accordingly modifies the “internal” gate node V_{int} above IL and hence the ψ_s at a given V_G . This is equivalent to a V_{TH} shift seen at the V_G node.

believed to concern the FE polarization (P_{FE})-modified surface potential ψ_s change (Fig. 1) that is in effect equivalent to a dynamic V_{TH} shift. Therefore, from either device physics understanding or technology assessment point of view, it is essential that the MFIS gate stack electrostatics in FeFETs (Fig. 1) be thoroughly investigated and correctly modeled.

In this context, various SPICE FeFET compact models (CMs) have been proposed for either NVMs [11,12] or SSFeFETs [8,9], where the V_G -dependent V_{TH} shift is passed through V_{FE} (Fig. 1). For all the progress made in existing CMs, there are yet three notable limitations in the V_{TH} shift modeling. First, the commonly observed charge trapping (CT) [5,9,13] in the polycrystalline (doped-)hafnia FE layer in gate stacks (Fig. 2(a)) is generally overlooked, which is however needed to decouple the trapping-induced positive $\Delta|V_{\text{TH}}|$ for experimental comparison. Second, the multi-domain (doped-)hafnia FE layer not only introduces a “scalar” coercive field (E_c) distribution, but also implies a spatial non-uniformity in domain switching [14,15]. Existing CMs, failing to address this aspect, would

Fig. 2. (a) Schematic of trapping-Fe contention. Charge trapping produces positive $\Delta|V_{\text{TH}}|$ (PBTI in n-FeFETs) that bears an opposite sign to FE V_{TH} programming. (b) Schematic of FE V_{TH} programming in a real-world multi-domain FeFET. The FE domain switching is nonuniformly scattered across the gate area due to the random spatial E_c distribution. Highly inverted source-to-drain percolation paths (solid arrow) beneath the positive domains are thus needed for the FE-induced V_{TH} reduction to become electrically “visible” (cf. the unsuccessful path in dashes).

This work is supported by imec’s Industrial Affiliation Program (IIAP). Y. Xiang, Md N. K. Alam, K. Kaczmarek, G. Groeseneken and J. Van Houdt are with imec, 3001 Leuven, Belgium and also with KU Leuven, 3001 Leuven, Belgium (correspondence email: yang.xiang@imec.be).

M. Garcia Bardon, B. Kaczer and L.-Å. Ragnarsson are with imec, 3001 Leuven, Belgium.

B. Parvais is with imec, 3001 Leuven, Belgium and also with Vrije Universiteit Brussel, 1050 Brussels, Belgium.

Fig. 3. Schematic of the transient FE-MOS solution in the FeFET CM, where the dual-way (“ ψ_s -to- V_{FE} ” and “ V_{FE} -to- V_{int} ”) self-consistent loop is calculated at every time instant [19].

miss the associated channel percolation path formation in order for V_{TH} shift to effect [16] (Fig. 2(b)). Further missing is a unified modeling approach to reconcile SSFeFETs and NVM-oriented FeFETs, whereas in measurements the steep slope behavior has been also observed on NVM-FeFETs [17]. This hints that the steep slope should be derivable from NVM-FeFET models based on e.g. domain switching dynamics [6,8,9].

This paper thus reports on a comprehensive FeFET CM aimed at addressing the aforementioned issues on the basis of our recent works [18,19]. The paper is organized as follows. In Section II, we introduce the framework of the FeFET CM, including the discretized ferroelectric polarization switching model [20] and the two-state nonradiative multi-phonon (NMP) charge trapping model [21]. In Section III, we elaborate on the percolation-aware FE V_{TH} -programming (V_{TH} -PGM) model and identify the central role of channel percolation in predicting the experimental observations on $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ (HZO) n-FeFETs. In Section IV, we further extend the V_{TH} -PGM model with a phenomenological nucleation-growth domain reversal mechanism [6] and confirm the field-independent domain growth as the origin of steep slope I_D - V_G in SSFeFETs. Finally, Section V summarizes the paper.

II. FEFET MODELING FRAMEWORK

A. FeFET CM Framework

The FeFET model adopts a composite FE-MOS system self-consistently coupled in transient [19] (Fig. 3). The MOS solution is given by a standard BSIM model [22] that covers the device electrostatics and transport beneath the interfacial layer (IL, normally SiO_x), with an internal voltage (V_{int}) [23] input to the gate node of BSIM. The FE layer simultaneously calculates V_{FE} via a time-discretized, dual-way feedback loop (Fig. 3) similar to that in [11,12]:

$$\begin{cases} V_{FE}(t) = \frac{C_{IL}(V_G(t) - V_{FB} - \psi_s(t))}{C_{IL} + C_{FE}} - \frac{Q_t(t)}{C_{IL} + C_{FE}} - \frac{env(P_{FE}(t))}{C_{IL} + C_{FE}} \\ V_{FE,0}(t) = C_{IL}(V_G(t) - V_{FB} - \psi_s(t)) / (C_{IL} + C_{FE}) \\ V_{FE,Q}(t) = -Q_t(t) / (C_{IL} + C_{FE}) \\ V_{FE,P}(t) = -env(P_{FE}(t)) / (C_{IL} + C_{FE}) \end{cases} \quad (1)$$

Here C_{IL} and C_{FE} refer to the capacitance of interfacial layer (IL) SiO_x and the paraelectric high-K component of the FE layer. Q_t and $env(P_{FE})$ relate to the trapped charge Q_t and FE polarization charge P_{FE} , respectively and will be explained later.

As written in Eqs. (1), V_{FE} consists of a baseline component $V_{FE,0}$ but also two extra components $V_{FE,Q}$ and $V_{FE,P}$ accounting for Q_t and P_{FE} , respectively (Fig. 3). This explicitly embeds voltage balance and charge conservation in the model at each

Fig. 4. Schematic of the discretized P_{FE} switching model. The bivariate Cauchy-distributed $f(E_c^-, E_c^+)$ is calibrated on metal-FE-metal capacitor measurements using a steady-state Preisach model [20] and used to sample the $N \times$ domains. Here the median $x_0(|E_c|) = 1.32$ MV/cm and the full width at half maximum $\gamma(|E_c|) = 0.57$ MV/cm. Note that for domain sampling, the region $f(E_c^- \geq 0, E_c^+ \leq 0)$ is truncated (dashed). The domain polarization P_i at time t is determined by comparing the sampled coercive fields (E_c^- , E_c^+) and the electric field calculated through $V_{FE}(t)$ in Eqs. (1).

time step t : the V_G -dependent Q_t - and P_{FE} -variation is triggered by the V_G -dependent $V_{FE,0}$, which already contains the feedback from ψ_s . Meanwhile, any V_G -dependent perturbation of Q_t or P_{FE} will in turn modify ψ_s through $V_{FE,Q}$ and $V_{FE,P}$, respectively, such that an eventual convergence is always achieved for the quadruplet (ψ_s , Q_t , P_{FE} , V_{FE}).

The self-consistently calculated V_{FE} will automatically alter V_{int} and thus translate to an apparent ΔV_{TH} seen by the node V_G . The ΔV_{TH} is derived at iso- V_{int} condition (equivalently also iso- ψ_s) using Eqs. (1) and it can be conveniently expressed as a function of Q_t and P_{FE} and tracked versus time t :¹

$$\begin{cases} \Delta V_{FE}(t)|_{\Delta\psi_s=0} = \frac{C_{IL}\Delta V_G(t) - \Delta Q_t(t) - \Delta env(P_{FE}(t))}{C_{IL} + C_{FE}} \\ \Delta V_{int}(t) = \Delta V_G - \Delta V_{FE} = \frac{C_{FE}\Delta V_G(t) + \Delta Q_t(t) + \Delta env(P_{FE}(t))}{C_{IL} + C_{FE}} \\ \Delta V_{TH}(t) \triangleq \Delta V_G|_{\Delta V_{int}=0} = -\frac{\Delta Q_t(t)}{C_{FE}} - \frac{\Delta env(P_{FE}(t))}{C_{FE}} \end{cases} \quad (2)$$

B. Discretized ferroelectric polarization switching

The global polarization P_{FE} in the gate stack is modeled by discretized domain polarization switching in a FE domain ensemble [11,12,24]. This approach does not prescribe a P_{FE} - V_{FE} relation and therefore allows to include the feedback of P_{FE} on V_{FE} per $V_{FE,P}$ in Eqs. (1), which is similar to [11,12]. The N domains are first instantiated with discrete coercive fields sampled under a calibrated bivariate coercive field distribution $f(E_c^-, E_c^+)$ [20]. The bistate ($\pm P_r$) domain polarization is then determined at each timestep t via a steady-state instant Preisach switching model (Fig. 4). Finally, the global P_{FE} will take the average over all domains at time t .

Note that the steady-state Preisach mechanism here uses instant domain dynamics as a first-order approximation. This will be augmented with the nucleation-growth domain dynamics [6] in Section IV, where the exact profile of f will be adjusted accordingly. However, the discretized, “ensemble” domain switching scheme will remain valid. Moreover, the $f(E_c^-, E_c^+)$ here only concerns the “scalar” E_c distribution without specifying the spatial configuration of the individual (E_c^-, E_c^+) pairs (Fig. 2(b)). The spatial configuration-related percolation effect will be handled by a dedicated “envelope function” in Section III.

C. Two-state NMP Charge Trapping Model

¹ $\Delta V_{TH}(t)$ is referenced to its iso-equivalent-oxide-thickness non-FeFET counterpart in its pristine state (i.e., no trapping has occurred).

“checkerboard” of $\pm P_r$ FE domains in a MuD FeFET by substituting the high-resistance (HR) resistor for $-P_r$ and low-resistance (LR) resistor for $+P_r$, then we can study the percolation-induced ΔI_D (and $-\Delta V_{TH}$) in a MuD FeFET by looking at the percolation-induced conductance (G) increase in an RN per Fig. 6(b). Indeed, we can recast the fraction of LR resistors (ϕ_{LR}) into the normalized global P_{FE} in a FeFET and thus link the numerical value of the normalized P_c to the median percolation threshold ϕ_{LR} (ϕ_c). The normalization reads:

$$\begin{cases} P_{FE, norm} = \frac{\#(LR) - \#(HR)}{\#(LR) + \#(HR)} = \phi_{LR} - \phi_{HR} = 2\phi_{LR} - 1.0 \\ P_{c, norm} \triangleq P_c / P_r = 2\phi_c - 1.0 \end{cases} \quad (4)$$

Here we use Monte-Carlo SPICE simulations to profile the G - ϕ_{LR} relation of square RNs of different sizes (100/100 and 20/20, Fig. 6(a)). The size of RN should not be interpreted as the number of grains in the polycrystalline FE thin film, as different $\pm P_r$ sub-regions can co-exist within one grain [29]. By sweeping ϕ_{LR} , we find that an abrupt increase of conductance occurs at a median threshold ϕ_{LR} of ca. 0.59, namely $\phi_c \approx 0.59$. This agrees precisely with theoretical studies on the “site percolation” in infinite square lattices [26-28]. Moreover, the RN-extracted ϕ_c perfectly follows the “percolation universality” rule [27], meaning that it stays invariant with the RN size. This means that, for a given “shape” (W/L) of the FeFET, we can consistently apply the ϕ_c obtained on the RN of that W/L to derive the P_c in the FE layer, which in the case of square transistors yields $P_c \approx 0.18P_r$. For higher W/L ratios, the P_c can be similarly obtained from RN simulations (e.g., $P_c \approx 0.06P_r$ for $W/L = 2$) which can be found in our recent work [18].

Furthermore, we can construct the FE PGM-induced ΔV_{TH} ($\Delta V_{TH}^{(FE)}$) versus P_{FE} by studying the $\partial G / \partial P_{FE, norm}$ extracted from the RN (Fig. 7). This is done by approximating the $\Delta I_{D, lin}$ - P_{FE} in a FeFET at iso- V_G condition to the ΔG - $\Delta P_{FE, norm}$ in an RN ($P_{FE, norm}$ already converted from ϕ_{LR} per Eqs. (4)). Since for a given V_G , $\Delta I_{D, lin}$ is proportional to $-\Delta V_{TH}$, the $-\Delta V_{TH}^{(FE)}$ versus P_{FE} can be abstracted into a relation qualitatively similar to ΔG - $\Delta P_{FE, norm}$ and cast as an “envelope function” $env(P_{FE})$ (Fig. 7). The physical interpretation of $env(P_{FE})$ is that the FE V_{TH} PGM only becomes noticeable when the source-to-drain percolation of $+P_r$ domains sets in at $P_{FE} \geq P_c$, while for $P_{FE} < P_c$ the $+P_r$ domain population is too small to have the chance of percolation and hence does not contribute to FE V_{TH} PGM. Since for $P_{FE} < P_c$ the channel current is negligible, the $-V_{TH}^{(FE)}$ value at the “de-percolated” state cannot be deduced from the RN conductance. For this reason, we leave it as a fitting parameter “ A_o ” (Fig. 7) that can be subject to the operating history of the FeFET such as the degree of “erasing” (or “reset”). The piecewise $env(P_{FE})$ and the $\Delta V_{TH}^{(FE)}$ read:

$$\begin{cases} env(P_{FE}) = P_r \left\{ \frac{2(A_c - A_o) \operatorname{atan}[\lambda(P_{FE} - P_c)]}{\pi} + A_c \right\}, P_{FE} < P_c \\ env(P_{FE}) = P_r \left[\frac{1 - A_c}{P_r - P_c} (P_{FE} - P_c) + A_c \right], P_{FE} \geq P_c \\ V_{TH}^{(FE)}(t) = -\frac{\Delta env(P_{FE}(t))}{C_{FE}} \end{cases} \quad (5)$$

Note that the $env(P_{FE})$ also enters the V_{FE} expression in Eqs. (1), which not only shifts V_{TH} but also influences the calculation of P_{FE} and Q_t (Figs. 4 & 5, respectively). Hence the V_{FE} should be interpreted as an “electrical equivalent” global potential

TABLE I
CALIBRATED FE LAYER PARAMETERS FOR EXPERIMENTAL PREDICTION

Parameter ^a	Median value	Spread
Trap type	Acceptor-like	-
Trap density N_t	$2.6 \times 10^{20} \text{ cm}^{-3}$	-
Trap level E_t at flatband condition ^b	0.83 eV	0.22 eV
Relaxation energy S	1.9 eV	1.2 eV
Parabola curvature ratio R	0.32	-
FeFET FE layer thickness t_{FE}	8 nm	-
FE layer dielectric constant k_{FE}	37	-
Saturation polarization P_r	22.1 $\mu\text{C}/\text{cm}^2$	-
Coercive field $ E_c $	1.32 MV/cm	0.57 MV/cm
IL SiO_x thickness t_{IL}	0.8 nm	-

^a Trap band information per [5], FE parameters per [20].

^b Trap level referenced to Si mid-gap at the boundary of IL- SiO_x /Si. drop.

B. Percolation-based reproduction of experimental data

Below we discuss the modeling prediction of the measurement results on HZO planar n-FeFET hardware. The devices are fabricated with a replacement-metal-gate planar technology that can be found in [5]. Additional TiN/HZO/TiN metal-FE-metal capacitors (MFMCAPs) are used for FE-HZO thin film characterization [20]. Table I lists the calibrated trap band information in the FE layer in the FeFET gate stack [5] as well as the extracted HZO thin film properties on $100\mu\text{m} \times 100\mu\text{m}$ MFMCAPs [20]; the HZO thin film shows typical Preisach-extracted saturation polarization (P_r) and coercive field (E_c) values in literature [8].

1) BTI extended measure-stress-measure characterization

We use the extended measure-stress-measure (eMSM) technique [30] to study the V_{TH} shift versus voltage pulses of different overdrive amplitude and time (“ V_{ov} ” and “ t_{stress} ” in Fig. 8(a), respectively). The pulses are referenced to the initial V_{TH} of the device ($V_{TH,0}$) and the ΔV_{TH} is measured at $t_{measure}$ after a pulse. We assume that the multiple stresses pulses are mutually independent due to the long relaxation time in between (Fig. 8(a)). Clearly, our FeFET CM can reproduce the ΔV_{TH} - V_{ov} trend observed in experiments, which span four decades of different stress times. Here the percolation limit $P_c \approx 0.18P_r$ is used for the square transistor ($W/L = 10\mu\text{m}/10\mu\text{m}$), based on our RN-based study in Section III-A. The trap band and FE layer assume the calibrated parameters in Table I.

It turns out that the percolation mechanism in our FeFET model is indispensable for the modeling prediction of the measured ΔV_{TH} - V_{ov} “turnaround” feature (Fig. 9(a)). Such

Fig. 8. (a) The applied V_G waveform during eMSM characterization. The V_{TH} shift of the device is measured at t_{meas} after stress of different length (t_{stress}) and amplitude (V_{ov}). The pulses are separated by long relaxation times ($> 2000 \text{ s}$). (b) The comparison between the experimental and simulated ΔV_{TH} - V_{ov} in eMSM across four decades of stress times.

Fig. 9. Visualization of the role of percolation in eMSM modeling. (a): The ΔV_{TH} - V_{ov} “turnaround” in experiments (Fig. 8) requires percolation, even with the calibrated $x_0(|E_c|)$ and $\gamma(|E_c|)$ in Fig. 5. The turnaround can be otherwise only obtained by artificially reducing $\gamma(|E_c|)$ by $\sim 9\times$. (b)(c): The decomposition of the simulated ΔV_{TH} - V_{ov} into (b) CT and (c) FE components. In (b), the $\Delta V_{TH}^{(CT)}$ - V_{ov} curves follow similar a power law with an exponent < 2 . In (c), a large exponent in $\Delta V_{TH}^{(FE)}$ - V_{ov} (> 3.4) is required to capture the overall ΔV_{TH} - V_{ov} “turnaround” in (a).

phenomenon can be understood as a positive BTI (PBTI)-dominated V_{TH} increase for lower V_{ov} (< 1.2 V) and a FE V_{TH} PGM-dominated V_{TH} descending thereafter. However, the turnaround behavior suggests that the ΔV_{TH} contributions of charge trapping and of FE V_{TH} PGM should follow remarkably different V_{ov} dependence (Fig. 9(b)(c)). Indeed, the success of the percolation model is that it introduces a very large exponent (~ 4.7) in the power-law dependence of $\Delta V_{TH}^{(FE)}$ on V_{ov} (Fig. 9(c)), such that it overturns the sluggish $\Delta V_{TH}^{(CT)}$ growth ($\sim V_{ov}^{2.0}$, Fig. 9(b)). This is not possible without invoking percolation, even if by using the calibrated FE parameters in Table I (Fig. 9(a)). As a reference, an artificially constructed $f(E_c^-, E_c^+)$ with $\sim 9\times$ smaller $|E_c|$ spread can qualitatively mimic the turnaround in a non-percolation manner (Fig. 9(a)), but this is way less plausible and hence not adopted.

It is worth noting that the fitted $\Delta V_{TH}^{(FE)}$ - V_{ov} (Fig. 9(c)) does not imply P_{FE} switching so nonlinearly versus V_{ov} in the case of percolation. In fact, the ΔP_{FE} during the t_{stress} appears rather quasi-linear ($\sim V_{ov}^{1.6}$, Fig. 10(a)); rather, it is the *arctan*-form of the $env(P_{FE})$ in Eqs. (5) that converts ΔP_{FE} nonlinearly into $\Delta V_{TH}^{(FE)}$ (Fig. 10(b)). In other words, the turnaround occurs because the P_{FE} is approaching P_c with increasing V_{ov} , along which the chance of percolation and the resultant $|\Delta V_{TH}^{(FE)}|$ increase significantly; this eventually eclipses the PBTI-like $\Delta V_{TH}^{(CT)}$ (Fig. 9(b)) and turns the net ΔV_{TH} into descending.

2) Quasi-DC $I_{D,lin}$ - V_G measurements prediction

We further use our FeFET CM to study the hysteretic and steep-slope behaviors in dual-trace $I_{D,lin}$ - V_G quasi-DC measurements; they are swept from -3 V to different maximum V_G ($V_{G,max}$) values (Fig. 11(a)). We argue that the SSFeFET “traits” can be interpreted under a unified physical ansatz, as is suggested by the steep slope observation on NVM-FeFETs [17]. Indeed, using the percolation model, we are able to reproduce both the hysteresis direction change with the $V_{G,max}$ and the local steep slope on the down-trace sweep (Fig. 11(b)).

Fig. 10. Simulated (a) P_{FE} - t evolution during t_{stress} and (b) the associated $\Delta V_{TH}^{(FE)}$ - P_{FE} after the t_{stress} , for V_{ov} between 0.8 and 1.8 V and $t_{stress} \sim 50$ s in Fig. 8. While ΔP_{FE} is only $\sim V_{ov}^{1.6}$, the *arctan* form of $\Delta V_{TH}^{(FE)}$ - P_{FE} in Eqs. (5) is highly nonlinear and leads to the $\Delta V_{TH}^{(FE)}$ $\sim V_{ov}^{4.7}$ in Fig. 9(c).

Fig. 11. Comparison of the (a) measured and (b) simulated $I_{D,lin}$ - V_G on $1\mu m/1\mu m$ FeFETs. V_{TH} is intercepted at $10nA \times W/L$. The local steep slope occurs during the down-sweep upon partial de-percolation of the positive domain “clusters” as P_{FE} drops from P_c .

For one thing, the change of hysteresis from positive ΔV_{TH} to negative is attributed to the turning point voltage (V_{TP}) that lies beyond $V_{G,max} = 2$ V (Fig. 12(a)). Hence sweeping to 2 V does not suffice to close in on P_c (Fig. 12(b)) and ends up with a positive ΔV_{TH} , similar to that in eMSM (Fig. 10). Moreover, we can relate the steep I_D - V_G slope on the down-sweep from $V_{G,max} = 3$ V to “de-percolation” by analyzing the V_{TH} snapback on ΔV_{TH} - V_G (Fig. 12(a)). As V_G is swept down from 3 V, P_{FE} will also depart from P_c (Fig. 12(b)), which will close the highly inverted conducting paths beneath the $+P_r$ domain clusters in a “branch-by-branch” fashion (Fig. 2(b)) and thus lead to successive V_{TH} snapbacks (Fig. 12(a)). It is the V_{TH} snapback in the subthreshold regime that eventually translates to the local steep slope on I_D - V_G .

Note that the interpretation of steep slope above implicitly assumes that the de-percolation process proceeds independently of the electric field, since the P_{FE} depolarization is modeled by instant Preisach switching (Section II-B) and will hence continue regardless of the V_{TH} snapback it is creating. In Section IV, we will demonstrate with more refined domain reversal dynamics that such field-independence is a necessary condition for the ΔV_{TH} snapback to manifest and consequently for the steep slope to be observed.

We have additionally studied the dimensional scaling aspect of the FeFET percolation model in our recent work [18]. This matters because changing W/L will alter the shape of the lattice in percolation theory, making the P_c value no longer conserve [27]. For example, P_c will drop from $0.18P_r$ to $0.06P_r$ as W/L changes from 1 to 2 and will further reduce at shorter L [18]. In addition, for FeFETs with exceedingly large W/L , we can conveniently combine the percolation model with sub-FET parallelizing (Fig. 13(b)), where the transistor is sliced in width direction into multiple sub-FETs. This reduces the W_{sub}/L of each sub-FET such that the associated “sub- P_c ” can be easily looked up (e.g., “sub- P_c ” $\approx 0.06P_r$ for $W_{sub}/L = 2$) without

Fig. 12. (a): Simulated on-the-fly ΔV_{TH} during the $I_{D,lin}$ - V_G sweeps in Fig. 11. ΔV_{TH} is referenced to the starting point of the sweeps (-3 V). The “turning point voltage” V_{TP} ($= 2.1$ V) defines the $V_{G,max}$ for ΔV_{TH} - V_G to turn around. The V_{TH} snapback upon de-percolation occurs during the down-sweep from 3 V, which causes the steep slope on $I_{D,lin}$ - V_G (Fig. 11(b)). (b): The associated $\Delta V_{TH}^{(FE)}$ versus P_{FE} simulated using $env(P_{FE})$.

Fig. 13. (a) Comparison of the measured and simulated $I_{D,lin}$ - V_G sweeps for different transistor W/L values up to $V_{G,max} = 2$ V. The $1\mu m/70nm$ FeFET reaches $\Delta V_{TH} < 0$ as contrary to the positive ΔV_{TH} in the $1\mu m/1\mu m$ FeFET, and it shows local steep slope on the down-sweep. (b) Scheme of sub-FET parallelizing for simulating the $1\mu m/70nm$ FeFET. Each sub-FET assumes $W_{sub}/L = 140nm/70nm$ and has a "sub- P_c " of $0.06P_r$, which is smaller than the P_c for $W/L = 1\mu m/1\mu m$ ($\approx 0.18P_r$) and makes the percolation path formation more easily.

having to resort to the cumbersome P_c extractions from Monte-Carlo RN simulations [18]. Using this method, we can predict the experimentally observed negative ΔV_{TH} in $1\mu m/70nm$ FeFETs when the $V_{G,max}$ is only 2 V (Fig. 13(a)). Compared to the $1\mu m/1\mu m$ device (Fig. 11), the $1\mu m/70nm$ FeFET has a lower "sub- P_c " ($\approx 0.06P_r$) in each constituting $140nm/70nm$ sub-FET, which means easier percolation and hence a lower threshold P_{FE} needed to "program" the V_{TH} . The percolation in $1\mu m/70nm$ FeFETs also makes de-percolation possible and thus contributes to the steep slope during down-sweep (Fig. 13(a)).

IV. NUCLEATION-GROWTH DOMAIN REVERSAL DYNAMICS AND STEEP SLOPE

So far, we have approximated the switching of individual FE domains by the instant Preisach model (Fig. 4), which does not include detailed domain reversal dynamics and hence is not able to cover the full picture of steep slope device physics. Meanwhile, although the commonly used nucleation-limited switching (NLS) model [11,12,24,31] does describe the domain reversal dynamics, it nevertheless misses the capability of reproducing the steep slope characteristics in SSFeFETs. This leads us to upgrading the instant Preisach switching model (Section II-B) to an NLS-derived, nucleation-growth (NG) domain reversal dynamics model, that phenomenologically explains the steep slope I - V through the proposed field-independent domain growth [6]. Note that the charge trapping model and the channel percolation model remain unchanged.

We use the NLS scheme in [24] as the starting point for our NG model. The NLS model conceptualizes a slow, rate-limiting, field-dependent nucleation step and a subsequent fast, "unstoppable" domain growth step [31] (Fig. 14(a)). The nucleation barrier is characterized by a statistical distribution of

Fig. 14. (a) Comparison of the schematics (for domain i) of the two-step NLS model [31] and the continuous nucleation-growth (NG) model. The Weibull process coordinate $\theta_i(t)$ follows [24]. (b) Schematic of $\tau_{sw,i}^*$ (i.e., for $\Delta P_i > 0$) calculation in the NG model for domain i . The $\tau_{sw,i}^*$ in growth step is phenomenologically locked to the minimum $\tau_{sw,i}^*$ that has been set in the previous nucleation step ($\tau_{nuc,min,i}^*$). This guarantees that even if $V_{FE}(t)$ decreases due to the negative feedback from ΔP_{FE} , $\tau_{sw,i}^*$ will not increase but still respect $\tau_{nuc,min,i}^*$. The $\tau_{sw,i}^-$ during $\Delta P_i < 0$ can be similarly determined for $V_G < 0$, $V_{FE} < 0$.

TABLE II
EXTRACTED HZO THIN FILM NUCLEATION DYNAMICS PARAMETERS [20]

Parameter	Median value	Spread
Activation field $ E_a ^a$	1.28 MV/cm	0.64 MV/cm
Merz's law field dependence α	3.602	-
High-field switching time limit τ_0	< 80 ns (< 5 ns) ^b	-
Weibull shape parameter β	1.014	-

^a $|E_a|$ follows a Gaussian distribution [20].

^b $\tau_0 \sim 80$ ns (upper bound) was quantitatively fitted to our previous experiments [20], while our latest measurements have demonstrated a low-field (~ 4 MV/cm) switching time < 5 ns, meaning $\tau_0 < 5$ ns. This is confirmed by our in-house atomistic simulations ([32], $\tau_0 \sim 10^{-12}$ s).

the activation field E_a [24] resembling the $f(E_c^-, E_c^+)$ in Fig. 4. However, we do not use the original NLS approximation suggested by [31], that a domain can flip up/down all together (Fig. 14(a)). This would misleadingly equate the "incipient" critical nuclei ($\sim 10^0$ nm³ [33]) to fully reversed domains ($> 10^1$ nm³ [29,33,34]). Rather, we believe that even for the non-rate-limiting "fast growth" step in NLS [31], we need to model it as a finite-rate process instead of an instant one. For this reason, we seek to "augment" the NLS model into our NG model.

The NG model is centered around a continuous function $\chi_i(\theta_i)$ (Fig. 14(a)) for each domain i , that smoothly combines the "conceptual" nucleation and growth steps in NLS [31]:

$$\begin{cases} \chi_i(\theta_i) \triangleq \Delta P_i / (2P_r) = \pm [\tanh(\eta[\theta_i - H]) + 1] / 2 \\ \theta_i = 1 - \exp\{-h_i^\beta(t)\} \\ h_i(t) = \int_{t_0}^t 1/\tau_{sw,i}(\tilde{t}) d\tilde{t} \end{cases} \quad (6)$$

Here, η and H are empirical parameters that can be adjusted to account for e.g., FE grain size refinement [36]. The "nucleation history parameter" $h_i(t)$, its exponent β and the Weibull temporal process $\theta_i(t)$ are formulated after [24]. The t_0 refers to the instant when V_{FE} turns positive (for polarizing from $-P_r$ to $+P_r$) or negative (for depolarizing from $+P_r$ to $-P_r$). $\tau_{sw,i}(t)$ is the domain-specific characteristic switching time and is related to the sampled activation field $E_{a,i}$ (see Eqs. (7)).

To guarantee that nucleation should be the only rate-limiting step during domain reversal (Fig. 14(a)), we employ a phenomenological approach to determine $\tau_{sw,i}(t)$, based on both $E_{FE}(t)$ (or $V_{FE}(t)$) and its direction (see Fig. 14(b)):

1. During nucleation, only "incipient" nuclei are formed, meaning ΔP_i is negligible and does not impose a noticeable negative feedback to V_{FE} through the " $V_{FE,p}$ " term in Eqs. (1). Hence V_{FE} will keep increasing with V_G according to " $V_{FE,0}$ " (Eqs. (1)), and $\tau_{sw,i}$ can safely fall back to the field-dependent expression $\tau_{Merz,i}$ in NLS per Merz's law [35].
2. During growth, significant polarization ΔP_i will be reversed, which would negatively feedback to V_{FE} through the " $V_{FE,p}$ " term in Eqs. (1), that can even lead V_{FE} to decreasing. This would in turn increase $\tau_{Merz,i}$ to be greater than the minimum $\tau_{sw,i}$ the domain has experienced during nucleation, thus contradicting the fundamental concept of "non-rate-limiting, fast growth step" [31]. To ensure that domain growth not overtake nucleation as the rate-limiting step, we phenomenologically lock $\tau_{sw,i}$ to its minimum value from the preceding nucleation step ($\tau_{nuc,min,i}$). This essentially leads to a field-independent domain growth step, which proceeds with a $\tau_{sw,i}(t)$ that is always smaller than (or equal to) $\tau_{nuc,min,i}$ and disregards the larger $\tau_{Merz,i}(t)$ when $V_{FE}(t)$ indeed snaps back.

Fig. 15. Modeling prediction of (a) the eMSM (cf. Fig. 8) and the (b) I_D - V_G sweeps (cf. Fig. 11), where the instant Preisach model is replaced by the NG dynamics model. In (a), the ΔV_{TH} - V_{OV} turnaround in eMSM is successfully reproduced. For the I_D - V_G prediction in (b), even with percolation, the down-sweep steep slope can only be reproduced with the field-independent domain growth in the NG model, but not with the misused, fully field-dependent Merz model even during growth.

Summarized mathematically, the NG model reads as follows:

$$\begin{cases} \tau_{Merz,i}(t) = \tau_0 \exp\left(\left|\frac{E_{a,i}}{V_{FE}(t)/t_{FE}}\right|^\alpha\right) \\ \tau_{sw,i}(t) = \min(\tau_{Merz,i}(t), \tau_{nuc-min,i}(t_0, t)) \end{cases} \quad (7)$$

Here the $\tau_{nuc-min,i}(t_0, t)$ refers to the minimum $\tau_{sw,i}$ experienced from t_0 to t . The NLS parameters τ_0 , α , β and E_a distribution in Eqs. (7) are extracted from temporal-voltage measurements on MFMCAPs [20]; Table II). Because of the setup and device-related parasitic RC time constants (τ_{RC}) in the measurement ($\sim 10^{-9}$ s – 10^{-6} s) [20], the extracted NLS parameters (τ_0 , E_a , etc.) can exhibit considerable discrepancies among literature [11,24,33], depending upon the exact experimental setups. Nevertheless, the possible imperfection in the NLS parameters in Table II is not expected to compromise their use in interpreting our eMSM ($>10^{-2}$ s, Fig. 8(a)) or quasi-DC $I_{D,lin}$ - V_G experiments ($\sim 10^1$ s, Fig. 11(a)). We argue this because these experiments were conducted at significantly “slower” time scales than τ_{RC} , where the NLS model fitting is essentially undisturbed by τ_{RC} and can be safely applied to eMSM and $I_{D,lin}$ - V_G . In real-life digital circuits, the typical low-field ($\sim 10^0$ MV/cm), room-temperature (300 K) switching time in (doped-)hafnia is believed to range $\sim 10^0$ ns [32], as is experimentally confirmed in [37] (~ 0.9 ns at ~ 6 MV/cm).

Replacing the instant Preisach model with the NG model, we can simultaneously reproduce (Fig. 15) the measured eMSM ΔV_{TH} - V_{OV} in Fig. 8 and the dual-trace I_D - V_G sweeps for different $V_{G,max}$ in Fig. 11. Clearly, the simulated ΔV_{TH} - V_{OV} turnaround (Fig. 15(a)) confirms the effect of spatial percolation of flipped-up regions in the FE layer on the channel conducting path formation (Fig. 2(b)). Following a parallel reasoning, the hysteresis direction change versus $V_{G,max}$ (Fig. 15(b)) can be also qualitatively reproduced.

Most importantly, the I_D - V_G steep slope reproduction in Fig. 15(b) suggests that de-percolation alone does not suffice to engender the steep slope, if the field-independent domain growth is not included. This can happen if we wrongly apply the field-dependent Merz’s law throughout the domain reversal including the growth step. In this case, even with the help of $env(P_{FE})$, the model cannot reproduce the steep slope (Fig. 15(b)). Indeed, as shown in Fig. 12, it is the V_{TH} snapback in the subthreshold regime that leads to the local steep slope during $I_{D,lin}$ - V_G down-sweep. This would not be allowed (Fig. 16(a)) if we mistakenly apply the field-dependent Merz’s law to both nucleation and growth, because the negative-feedback field dependence of $\tau_{Merz,i}$ will then adjust the depolarization

Fig. 16. Simulated (a) ΔV_{TH} - V_G and (b) $\Delta V_{TH}^{(FE)}$ - P_{FE} during the $I_{D,lin}$ - V_G sweeps as in Fig. 12, with the instant Preisach model replaced by the NG dynamics model. The de-percolation during down-sweep can only cause the V_{TH} snapback if the field-independent domain growth is present in the NG model. This is not possible if we wrongly apply the field-dependent Merz’s law to the entire domain switching process, even if we allow it to follow the same $env(P_{FE})$ -based $\Delta V_{TH}^{(FE)}$ - P_{FE} in (b). switching rate at which P_{FE} departs from P_c during de-percolation (Fig. 16(b)), such that any potential V_{TH} snapback will be automatically smeared out. In fact, the V_{TH} snapbacks appear in Fig. 12 exactly due to the crude field-independent “dynamics” in the instant Preisach model ($\tau_{sw,i} \equiv 0$). Therefore, in order for the steep slope to appear during de-percolation, it is essential that the minimum characteristic switching time set by the rate-limiting domain nucleation step (i.e., $\tau_{nuc-min,i}$) be faithfully upheld during the subsequent domain growth. In other words, it is the field-independent domain growth that governs the de-percolation profile along the V_G -axis, which will eventually determine the V_{TH} snapback effect that is needed for the steep slope behavior.

V. CONCLUSIONS

This work presents a physics-based FeFET compact model that builds on a transient, self-consistent solution of the FE-MOS electrostatics with a discretized ferroelectric polarization switching scheme. The model addresses three involved physical aspects that are crucial to the electrical interpretation of FeFETs: 1) the nonradiative multi-phonon charge trapping, 2) the channel percolation effect from the spatial configuration of FE domains and 3) the phenomenological nucleation-growth domain reversal dynamics. Based on a comprehensive hardware validation, we conclude that

1. The onset of source-to-drain FE domain percolation determines the channel conducting path formation that is needed to electrically sense the V_{TH} change, thus defining the gate bias required to initiate the programming of the FeFET V_{TH} . Consequently, there is a channel geometry factor acting on top of the polarization charge in modulating the drain current.
2. Field-independent domain growth is the fundamental origin of the steep subthreshold slope. It operates in the course of channel “de-percolation” through unchecked FE domain depolarization, which ultimately causes V_{TH} to snapback in subthreshold region and steepens the I_D - V_G .
3. The NLS-derived, nucleation-growth interpretation of the steep slope I - V , although being phenomenological, provides an alternative modeling approach of SSFeFETs, thus opening up the possibility of establishing a unified understanding of NVM-FeFETs and logic-oriented SSFeFETs. Further investigation of domain reversal dynamics is needed for refining the field-independent domain growth formalism.

ACKNOWLEDGMENT

The authors gratefully acknowledge M. Thesberg (TU Wien), Ph. Roussel, A. S. Verhulst, B. Truijen, B. O'Sullivan, U. Celano and S. Clima for the fruitful discussions.

REFERENCES

- [1] J. Müller *et al.*, "Ferroelectric Zr_{0.5}Hf_{0.5}O₂ thin films for nonvolatile memory applications", *Appl. Phys. Lett.*, 99, 2011, art. 112901, doi:10.1063/1.3636417.
- [2] M. Trentzsch *et al.*, "A 28nm HKMG super low power embedded NVM technology based on ferroelectric FETs", *2016 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2016, pp. 11.5.1-11.5.4, doi:10.1109/IEDM.2016.7838397.
- [3] K. Florent *et al.*, "Vertical Ferroelectric HfO₂ FET based on 3-D NAND Architecture: Towards Dense Low-Power Memory", *2018 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2018, pp. 2.5.1-2.5.4, doi:10.1109/IEDM.2018.8614710.
- [4] Z. Krivokapic *et al.*, "14 nm Ferroelectric FinFET Technology with Steep Subthreshold Slope for Ultra Low Power Applications", *2017 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2017, pp. 15.1.1-15.1.4, doi:10.1109/IEDM.2017.8268393.
- [5] M. N. K. Alam *et al.*, "On the Characterization and Separation of Trapping and Ferroelectric Behavior in HfZrO FET," in *IEEE J. Elec. Dev. Soc.*, vol. 7, pp. 855-862, 2019, doi:10.1109/JEDS.2019.2902953.
- [6] J. Van Houdt and P. Roussel, "Physical Model for the Steep Subthreshold Slope in Ferroelectric FETs", *IEEE Elec. Dev. Lett.*, vol. 39, no. 6, pp. 877-880, 2018, doi:10.1109/LED.2018.2829604.
- [7] M. N. K. Alam, P. Roussel, M. Heyns and J. Van Houdt, "Positive non-linear capacitance: the origin of the steep subthreshold-slope in ferroelectric FETs", *Scientific Reports*, 9, 2019, art. 14957, doi:10.1038/s41598-019-51237-2.
- [8] C. Jin, T. Saraya, T. Hiramoto and M. Kobayashi, "Physical Mechanisms of Reverse DIBL and NDR in FeFETs With Steep Subthreshold Swing", *IEEE J. Elec. Dev. Soc.*, vol. 8, pp. 429-434, 2020, doi:10.1109/JEDS.2020.2986345.
- [9] B. Obradovic, T. Rakshit, R. Hatcher, J. A. Kittl and M. S. Rodder, "Ferroelectric Switching Delay as Cause of Negative Capacitance and the Implications to NCFETs", *2018 Symposium on VLSI Technology*, Honolulu, HI, 2018, pp. 51-52, doi:10.1109/VLSIT.2018.8510628.
- [10] T. Mikolajick, U. Schroeder and S. Slesazek, "The Past, the Present, and the Future of Ferroelectric Memories", *IEEE Trans. Elec. Dev.*, vol. 67, no. 4, pp. 1434-1443, doi:10.1109/TED.2020.2976148.
- [11] K. Ni, W. Chakraborty, J. Smith, B. Grisafe and S. Datta, "Fundamental Understanding and Control of Device-to-Device Variation in Deeply Scaled Ferroelectric FETs," *2019 Symposium on VLSI Technology*, Kyoto, Japan, 2019, pp. T40-T41, doi:10.23919/VLSIT.2019.8776497.
- [12] S. Deng *et al.*, "A Comprehensive Model for Ferroelectric FET Capturing the Key Behaviors: Scalability, Variation, Stochasticity, and Accumulation", *Proc. Symposium on VLSI Technology*, 2020, pp. TF1.4.1- TF1.4.2.
- [13] Y. Higashi *et al.*, "Impact of Charge trapping on Imprint and its Recovery in HfO₂ based FeFET," *2019 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2019, pp. 15.6.1-15.6.4, doi:10.1109/IEDM19573.2019.8993472.
- [14] I. Stolichnov *et al.*, "Genuinely Ferroelectric Sub-1-Volt-Switchable Nanodomains in Hf_{1-x}Zr_xO₂ Ultrathin Capacitors", *ACS Appl. Mater. Interfaces*, 10, pp. 30514-30521, 2018, doi:10.1021/acsami.8b07988.
- [15] U. Celano *et al.*, "Ferroelectricity in Si-Doped Hafnia: Probing Challenges in Absence of Screening Charges", *Nanomaterials*, 10(8), 1576, 2020, doi:10.3390/nano10081576.
- [16] B. Kaczer *et al.*, "The Relevance of Deeply-Scaled FET Threshold Voltage Shifts for Operation Lifetimes", *2012 IEEE International Reliability Physics Symposium (IRPS)*, Anaheim, CA, 2012, pp. 5A.2.1-5A.2.6, doi:10.1109/IRPS.2012.6241839.
- [17] H. Mulaosmanovic *et al.*, "Impact of Read Operation on the Performance of HfO₂-Based Ferroelectric FETs", *IEEE Elec. Dev. Lett.*, vol. 41, no. 9, pp. 1420-1423, 2020, doi:10.1109/LED.2020.3007220.
- [18] Y. Xiang *et al.*, "Implication of Channel Percolation in Ferroelectric FETs for Threshold Voltage Shift Modeling", *2020 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2020, pp. 18.2.1-18.2.4.
- [19] Y. Xiang *et al.*, "Physical Insights on Steep Slope FEFETs including Nucleation-Propagation and Charge Trapping", *2019 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2019, pp. 21.6.1-21.6.4, doi:10.1109/IEDM19573.2019.8993492.
- [20] M. N. K. Alam *et al.*, "HfZrO Ferroelectric Characterization and Parameterization of Response to Arbitrary Excitation Waveform", *Proc. IEEE SOI-3D-Subthreshold Microelectronics Technology Unified Conference (S3S)*, San Jose, CA, USA, 2019, art. 3.01.
- [21] G. Rzepa *et al.*, "Comphy — A compact-physics framework for unified modeling of BTI", *Microelectronics Reliability*, vol. 85, pp. 49-65, 2018, doi:10.1016/j.microrel.2018.04.002.
- [22] H. Agarwal *et al.*, "BSIM-BULK106.2.0 MOSFET Compact Model: Technical Manual", *Univ. California, Berkeley*, 2017, bsim.berkeley.edu/models/bsimbulk/.
- [23] M. A. Wahab and M. A. Alam, "A Verilog-A Compact Model for Negative Capacitance FET" (version 1.1.3), *nanoHUB*, doi:10.4231/D3QZ22K3Z.
- [24] C. Alessandri, P. Pandey and A. C. Seabaugh, "Experimentally Validated, Predictive Monte Carlo Modeling of Ferroelectric Dynamics and Variability," *2018 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, 2018, pp. 16.2.1-16.2.4, doi:10.1109/IEDM.2018.8614607.
- [25] M. Pešić *et al.*, "Physical Mechanisms behind the Field-Cycling Behavior of HfO₂-Based Ferroelectric Capacitors", *Adv. Func. Mater.*, 26, pp. 4601-4612, 2016, doi:10.1002/adfm.201600590.
- [26] S. Kirkpatrick, "Percolation and Conduction", *Rev. Mod. Phys.*, vol. 45, no. 4, pp. 574-588, 1973, doi:10.1103/RevModPhys.45.574.
- [27] D. Stauffer, "Scaling theory of percolation clusters", *Phys. Rep.*, vol. 54, 1, pp. 1-74, 1979, doi:10.1016/0370-1573(79)90060-7.
- [28] B. J. Last and D. J. Thouless, "Percolation Theory and Electrical Conductivity", *Phys. Rev. Lett.*, vol. 27, no. 25, pp. 1719-1721, 1971, doi:10.1103/PhysRevLett.27.1719.
- [29] H. Mulaosmanovic, T. Mikolajick and S. Slesazek, "Accumulative Polarization Reversal in Nanoscale Ferroelectric Transistors", *ACS Appl. Mater. Interfaces*, 10, pp. 23997-24002, 2018, doi:10.1021/acsami.8b08967.
- [30] B. Kaczer *et al.*, "Ubiquitous relaxation in BTI stressing—New evaluation and insights," *2008 IEEE International Reliability Physics Symposium (IRPS)*, Phoenix, AZ, 2008, pp. 20-27, doi:10.1109/RELPHY.2008.4558858.
- [31] A. K. Tagantsev, I. Stolichnov, N. Setter, J. S. Cross, and M. Tsukada, "Non-Kolmogorov-Avrami switching kinetics in ferroelectric thin films", *Phys. Rev. B*, 66, 2002, art. 214109, doi:10.1103/PhysRevB.66.214109.
- [32] S. Clima *et al.*, "Ferroelectric Switching in FEFET: Physics of the Atomic Mechanism and Switching Dynamics in HfZrO_x, HfO₂ with Oxygen Vacancies and Si dopants", *2020 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2020, pp. 4.2.1-4.2.4.
- [33] K. Lee *et al.*, "Stable Subloop Behavior in Ferroelectric Si-doped HfO₂", *ACS Appl. Mater. Interfaces*, 11, pp. 38929-38936, 2019, doi:10.1021/acsami.9b12878.
- [34] A. K. Saha, K. Ni, S. Dutta, S. Datta and S. Gupta, "Phase field modeling of domain dynamics and polarization accumulation in ferroelectric HZO", *Appl. Phys. Lett.*, 114, 2019, art. 202903, doi:10.1063/1.5092707.
- [35] W. J. Merz, "Domain Formation and Domain Wall Motions in Ferroelectric BaTiO₃ Single Crystals", *Phys. Rev.*, vol. 95, no. 3, pp. 690-698, 1954, doi:10.1103/PhysRev.95.690.
- [36] H. K. Yoo *et al.*, "Engineering of Ferroelectric Switching Speed in Si Doped HfO₂ for High-Speed 1T-FERAM Application", *2017 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2017, pp. 19.6.1-19.6.4, doi:10.1109/IEDM.2017.8268424.
- [37] X. Lyu, M. Si, P. R. Shrestha, K. P. Cheung and P. D. Ye, "First Direct Measurement of Sub-Nanosecond Polarization Switching in Ferroelectric Hafnium Zirconium Oxide", *2019 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2019, pp. 15.2.1-15.2.4, doi:10.1109/IEDM19573.2019.8993509.