

IMPACTS OF FERROELECTRIC PARAMETERS ON THE ELECTRICAL CHARACTERISTICS OF FEFET FOR LOW-POWER LOGIC AND MEMORY APPLICATIONS

Kaifeng Wang, Qianqian Huang*, Chang Su, Liang Chen, Mengxuan Yang, Ru Huang*
Key Laboratory of Microelectronic Devices and Circuits (MOE), Institute of Microelectronics,
Peking University, Beijing 100871, CHINA

*Corresponding Author's Email: hqq@pku.edu.cn; ruhuang@pku.edu.cn

ABSTRACT

Considering ferroelectric domain switching dynamics, the influences of ferroelectric (FE) parameters on ferroelectric field-effect transistor (FeFET) characteristics are thoroughly investigated and simulated. It is shown that both remanent polarization and coercive field of FE have non-monotonic relationships with the subthreshold swing (SS) and hysteresis of FeFET. Competition between polarization switching and depolarization effect is found to be the origin of the above phenomenon. Based on the analysis, design guideline of FeFET for both logic and memory applications are reconsidered.

Keywords—FeFET; Preisach theory; Domain switching dynamics

INTRODUCTION

The CMOS-compatible HfO₂-based FeFETs have attracted much attention in the past decade. The negative capacitance (NC) property of the FE layer in the gate stack can contribute to sub-60 mV/dec subthreshold swing (SS) in the FeFET, which makes it a possible candidate as a steep-slope logic device, while it faces the hysteresis issue [1]. When designed with a large hysteresis window, the FeFET can be used to memorize information as low-power non-volatile memories [2]. For logic applications, although the physical mechanism of NC effect is still under debate, more and more researchers have reported that the NC phenomenon is derived from the domain switching dynamics of ferroelectrics [1, 3]. However, the design guideline of ferroelectric parameters for the device performance optimization is still lacking from the perspective of dynamic NC theory. Moreover, to optimize its characteristics as a memory though ferroelectric parameters design is also in big necessity.

In this work, influence of ferroelectric parameters on FeFET characteristics are thoroughly investigated based on dynamic Preisach model by using TCAD simulation tools. Moreover, the SS and hysteresis optimization of FeFET are reconsidered for both logic and memory applications.

DEVICES STRUCTURE AND SIMULATION SCHEME

The structures and their parameters used in the simulation are shown in Fig. 1. A bulk planar Si MOSFET with a gate length of 100 nm and an equivalent oxide

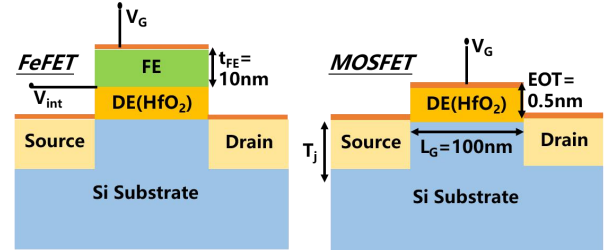


Figure 1: Simulation structures and parameters.

thickness of 0.5 nm is simulated. The only difference between the FeFET and the MOSFET in this work is the additional 10nm doped HfO₂ ferroelectric (FE) thin film in the gate stack. The ferroelectricity of the FE layer is described by the Preisach-based ferroelectric model implemented in Sentaurus TCAD [4] and this model has been proved its validity for doped HfO₂ based FeFETs [5]. The FE model parameters of doped HfO₂ ferroelectrics used in this work are the same as those in [6]. The FeFET is simulated by self-consistently solving the 2-D Poisson's equation, carrier continuity equations and Preisach-based ferroelectric model in TCAD [4]. Before the transient I_{DS}-V_{GS} simulation, we applied quasi-static sweep to initialize certain polarization states and bias conditions. After that, forward and reverse V_{GS} sweeping is applied in transient conditions as shown in Fig. 2(a). The simulated I_{DS}-V_{GS} curves are plotted in Fig. 2(b).

RESULTS AND DISCUSSION

From transient NC (TNC) theory [1, 7], it is known that sub-60mV/dec SS is induced under the condition of

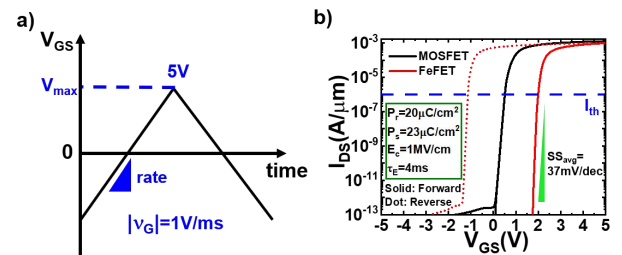


Figure 2: a) Gate voltage signal. b) The simulated I_{DS}-V_{GS} curves of MOSFET and FeFET. The parameters of the ferroelectric model are illustrated in the green box. The subthreshold region corresponds to the region where $I_{OFF} < I_{DS} < I_{th}$.

$|dP/dt| > |dQ/dt|$ in transient case [8-10], where P represents ferroelectric polarization charge area density and Q represents free charge area density. Due to the series relationship of FE-DE-Si layer and the Gauss' law, A_V and SS_{FeFET} of FeFET can be illustrated as follows.

$$SS_{FeFET} = \frac{\partial V_{GS}}{\partial V_{int}} \cdot \frac{\partial V_{int}}{\partial \lg I_{DS}} = \frac{SS_{MOSFET}}{A_V} \quad (1)$$

$$A_V = \frac{dV_{int}}{dV_{GS}} = 1 - \frac{d(E_{FE} \cdot t_{FE})}{dt} \cdot \frac{dt}{dV_{GS}} \quad (2)$$

$$E_{FE} = E_{app} - E_{dep} = \frac{Q}{\epsilon_0} - \frac{P}{\epsilon_0} \quad (3)$$

where E_{app} is the applied electric field and E_{dep} is the depolarization field across the FE layer. Define the sweeping rate of gate voltage as v_G , then the SS_{FeFET} is proved to be proportional to $(|dP/dt| - |dQ/dt|)^{-1}$ as Eq. (4) shows.

$$SS_{FeFET}^{-1} = SS_{MOSFET}^{-1} \left[1 + \frac{t_{FE}}{\epsilon_0 |v_G|} \cdot \left(\left| \frac{dP}{dt} \right| - \left| \frac{dQ}{dt} \right| \right) \right] \quad (4)$$

As for the hysteresis of FeFET, it is reported that the hysteresis of FeFET depends on the hysteresis of extracted Q_{FE} - V_{FE} loop in the FE layer of FeFET [7].

For ferroelectric materials, the domain switching is a positive feedback process [11]. However, when FE is in the NC state, mismatches between $|dP|$ and $|dQ|$ will result in the depolarization effect, which tends to reverse ferroelectric polarization. It will introduce a negative feedback mechanism into domain switching process [12]. Therefore, the actual switched polarization charge depends on the competition between the positive feedback mechanism of polarization switching and negative feedback mechanism of depolarization effect.

When E_c is relatively large, the polarization switching mechanism is dominant. Then larger remanent polarization P_r can result in larger polarization switching speed (Fig. 3(a)) and larger extracted Q_{FE} - V_{FE} loop in

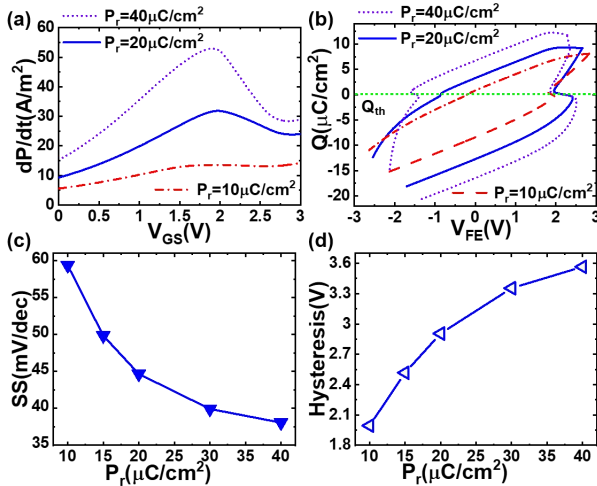


Figure 3: Simulation results with $E_c = 1.5 \text{ MV/cm}$. (a) dP/dt - V_{GS} curves, (b) Q_{FE} - V_{FE} curves, (c) SS - P_r curves, (d) Hysteresis- P_r curves

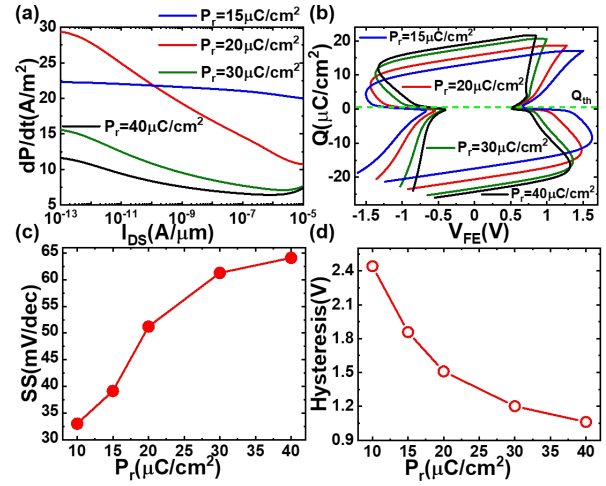


Figure 4: Simulation results with $E_c = 0.5 \text{ MV/cm}$. (a) dP/dt - I_{DS} curves, (b) Q_{FE} - V_{FE} curves, (c) SS - P_r curves, (d) Hysteresis- P_r curves

FeFET (Fig. 3(b)). According to the analysis above, the larger P_r will lead to the smaller SS (Fig. 3(c)) and the larger hysteresis (Fig. 3(d)) for FeFET. However, when E_c is relatively small, the depolarization effect becomes dominant. Then when P_r increases, the FeFET will meet the “dynamic polarization matching” condition [7] earlier due to the larger $|dP/dt|$ and it will turn to the NC state earlier. Besides, larger $|dP/dt|$ tends to induce larger depolarization field E_{dep} . Under the impact of E_{dep} , the $|dP/dt|$ corresponding to larger P_r can fall down to a smaller value at subthreshold region as Fig. 4(a) shows and the V_{FE} when FeFET reaches strong inversion becomes smaller as shown in Fig. 4(b). Therefore, when the depolarization effect becomes dominant, larger P_r will lead to the larger SS (Fig. 4(c)) and the smaller hysteresis (Fig. 4(d)) instead.

As for coercive field (E_c) of FE, the smaller E_c enables

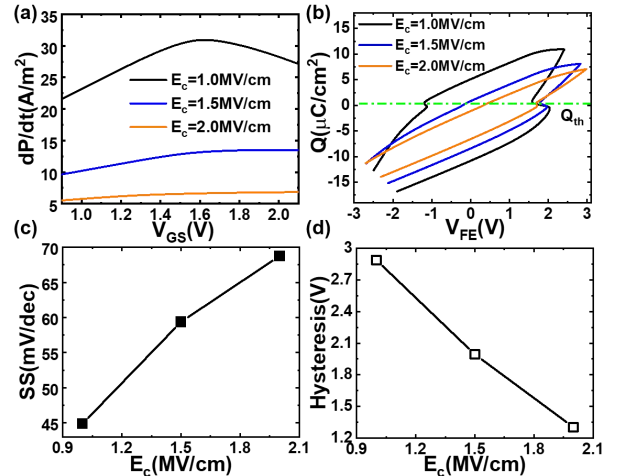


Figure 5: Simulation results with $P_r = 10 \mu\text{C/cm}^2$. (a) dP/dt - V_{GS} curves, (b) Q_{FE} - V_{FE} curves, (c) SS - E_c curves, (d) Hysteresis- E_c curves

more domains to switch when the $V_{\max}$ (as shown in Fig.2a) is constant, leading to the larger $|dP/dt|$ and extracted $Q_{FE}-V_{FE}$ loop as shown in Fig. 5 (a&b). Therefore, the smaller E_c results in the smaller SS and larger hysteresis when polarization switching is dominant at relatively small P_r (Fig. 5(c&d)). However, when FE is in the NC state, domains whose E_c is smaller than $|E_{app}-E_{dep}|$ will switch back. Then, smaller E_c makes $|dP/dt|$ falls down faster and the smaller V_{FE} when FeFET reaches strong inversion (Fig. 6(a&b)). When the depolarization effect becomes dominant at relatively large P_r , smaller E_c results in larger SS and smaller hysteresis as shown in Fig. 6 (c&d).

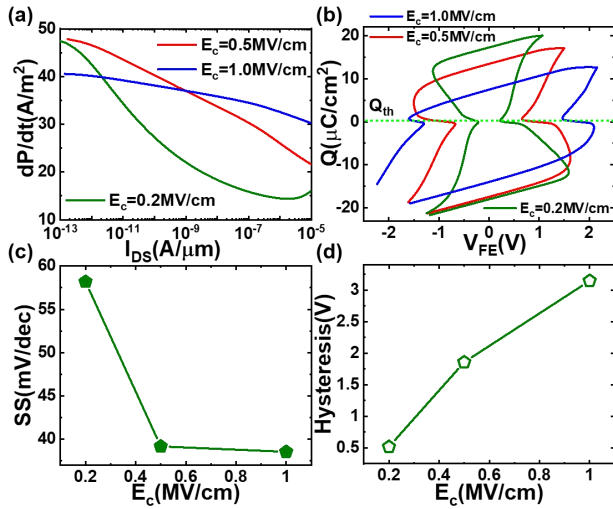


Figure 6: Simulation results with $P_r=15 \mu C/cm^2$. (a) $dP/dt-I_{DS}$ curves, (b) $Q_{FE}-V_{FE}$ curves, (c) SS- E_c curves, (d) Hysteresis- E_c curves

Based on the above discussion, it is shown that both P_r and E_c have non-monotonic relationships with the SS and hysteresis of FeFET, and thus the optimization of FeFET needs to be reconsidered for different applications. For low-power logic applications, although the FeFET can obtain steep SS behavior, neither P_r nor E_c can optimize the SS and hysteresis of FeFET simultaneously. The fundamental conflict between SS and hysteresis optimization makes the logic applications of FeFET still challenging. As for the memory applications, large E_c should be chosen to obtain large memory window (MW) since the maximum MW is $2E_c \cdot t_{FE}$ [13]. In this situation, the polarization switching mechanism is dominant. Large MW and small writing energy can be obtained with large P_r according to the analysis above. Therefore, ferroelectric material with large E_c and large P_r is recommended for FeFET as a memory device.

CONCLUSION

In this work, the impacts of ferroelectric parameters

on FeFET characteristics are thoroughly investigated and simulated based on Preisach model. It is shown that both P_r and E_c have non-monotonic relationships with the SS and hysteresis of FeFET due to the competitive mechanisms between polarization switching and depolarization effect. Design guideline of FeFET for different applications are also reconsidered.

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REFERENCES

- [1] B. Obradovic, T. Rakshit, R. Hatcher, J. Kittl, et al.; proceedings of the 2018 IEEE Symposium on VLSI Technology, 2018, 51-2
- [2] K. Maekawa, T. Yamaguchi, T. Ohara, A. Amo, et al.; proceedings of the 2019 IEEE International Electron Devices Meeting (IEDM), 2019, 15.4. 1-4. 4
- [3] H. Wang, Q. Huang, M. Yang, X. Zhang, et al. Science China Information Sciences, 62(8).2019.89401
- [4] T. Sentaurus. Version O-2018.06 [M]. Synopsys, Mountain View, CA, USA. 2018.
- [5] S. Mueller, E. Yurchuk, S. Slesazek, T. Mikolajick, et al.; proceedings of the 2013 Joint IEEE International Symposium on Applications of Ferroelectric and Workshop on Piezoresponse Force Microscopy (ISAF/PFM), 2013, 248-51
- [6] M. H. Park, Y. H. Lee, H. J. Kim, Y. J. Kim, et al. Advanced Materials, 27(11).2015.1811-31
- [7] H. Wang, M. Yang, Q. Huang, K. Zhu, et al.; proceedings of the 2018 IEEE International Electron Devices Meeting (IEDM), 2018, 31.1. 1-1. 4
- [8] C. Jin, T. Saraya, T. Hiramoto, M. Kobayashi. proceedings of the 2019 Symposium on VLSI Technology, 2019, T220-T1
- [9] C. Jin, T. Saraya, T. Hiramoto, M. Kobayashi. IEEE Journal of the Electron Devices Society, 7(2019).368-74
- [10] C. Jin, T. Saraya, T. Hiramoto, M. Kobayashi. IEEE Journal of the Electron Devices Society, 8(2020).429-34
- [11] J. C. Wong, S. Salahuddin. Proceedings of the IEEE, 107(1).2018.49-62
- [12] Phillips. Physics Bulletin, 17(10).2013.367-
- [13] U. Schroeder, C. S. Hwang, H. Funakubo. Ferroelectricity in doped hafnium oxide: materials, properties and devices [M]. Woodhead Publishing, 2019.