A Physical MFIS-FeFET Model with Awareness of Drain-Induced Spatially-Distributed Polarization and Ferroelectric Parametric Fluctuation

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***Abstract*—The spatially-distributed polarization effect in ferroelectric FET (FeFET) induced by nonzero drain bias is recently found to have a great influence on device and circuit performance, especially for content addressable memory operation, while this physics is ignored in conventional modeling method of FeFET. In this work, we developed a perturbative modeling framework for distributed FeFET, which can accurately capture the spatially-distributed polarization effect induced by the local coupling between polarization and channel charge, especially for large drain bias. Furthermore, considering the ferroelectric (FE) parameter fluctuation with the same statistical distribution but different spatial distribution, the FE parameter close to drain side of FeFET is found to be a crucial variation source for channel conduction, especially for coercive field, providing the guidance of robust FeFET device design strategies.**

***Keywords*—FeFET, spatially distributed polarization, physical model.**

I. INTRODUCTION

The HfO_2-based ferroelectric FET (FeFET) has drawn significant interests for emerging memory and computing applications [1-2] with high CMOS compatibility, good scalability and low power operation [3-4]. To evaluate FeFET performance, a lot of models for ferroelectric (FE) have been developed, by describing polarization switching characteristics of the multi-domain FE [5-7] (Fig. 1a). The FeFET device model is usually established by self-consistently calculation between FE and baseline MOSFET model. However, this prevailing modeling method is intrinsically a lumped treatment for FeFET with metal-ferroelectric-metal-insulator-semiconductor (MFMIS) structure, which is not accurate for practical FeFET without internal metal (MFIS-FeFET). For MFIS-FeFET, especially under nonzero high drain bias (V_D), polarization (P_{FE}) and FE voltage (V_{FE}) will be spatially distributed along the channel direction (Fig. 1b). Recently, we have demonstrated that drain-induced spatially-distributed P_{FE} in FeFET will significantly impact circuit performance, such as content addressable memory [8]. Furthermore, considering the FE parametric fluctuation with different spatial patterns in MFIS-FeFET, not only the non-uniformity of V_{FE} and P_{FE} distribution will be strengthened, but also the variability of channel conduction will be different compared with MFMIS-FeFET [9]. However, in conventional FeFET model, these physics are ignored due to the lumped treatment, where the channel conduction is modulated by averaged P_{FE}, showing uniform P_{FE} and immunity to parametric fluctuation with different spatial patterns. Fig. 1c shows a significant threshold voltage (V_{TH}) difference between MFMIS-FeFET and MFIS-FeFET, indicating evident deviation caused by lumped treatment. Therefore, to accurately describe the conduction behavior and evaluate device variability of MFIS-FeFET, establishing a physical model with awareness of spatially-distributed P_{FE} effect is in big necessity.

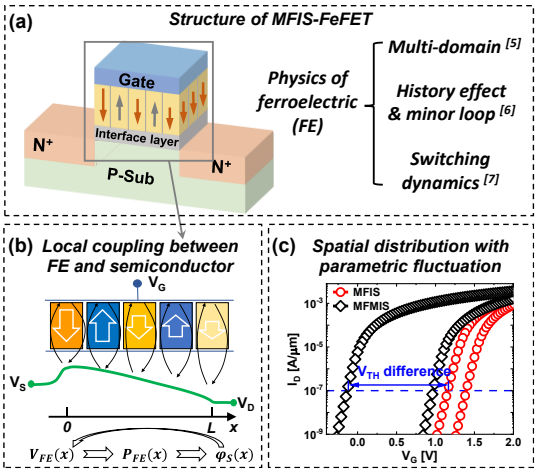

Fig. 1. (a) The schematic structure of MFIS-FeFET. (b) Spatially-distributed V_{FE} and P_{FE} originate from local coupling between FE and underlying semiconductor. (c) Significant V_{TH} difference between MFMIS- and MFIS- FeFET considering impact from FE parametric fluctuation and high V_D, indicating limitation of conventional lumped model.

In this work, a physical MFIS-FeFET model covering drain-induced spatially-distributed effect of P_{FE} is proposed, where the local interaction between channel potential and ferroelectric polarization switching is considered, leading to good agreement with numerical simulation results. Besides,

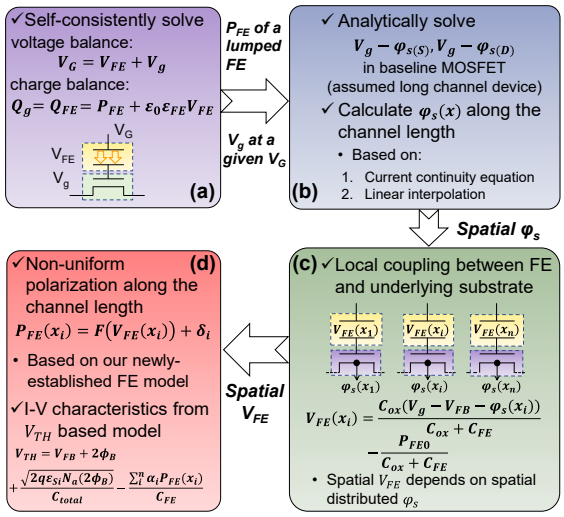

Fig. 2. The proposed perturbative modeling framework in this work. Started from (a) lumped treatment of FeFET, (b) spatially distributed surface potential $\varphi_s(x)$ is obtained under nonzero V_D, which is further utilized as a basis for (c) calculating distributed V_{FE} along the channel. (d) Correspondingly non-uniform P_{FE} due to the perturbative treatment leads to channel conduction with awareness of spatially distributed P_{FE} effect.

based on the proposed model, for FeFET with FE parameter fluctuation, the dependence of channel conduction on specific spatial pattern is discussed. Furthermore, device-to-device variation in FeFET with different variability sources are evaluated, indicating a crucial role of controlling grain size and elevating uniformity of E_C on optimizing device variability.

II. Modeling Framework

In our proposed model, to reflect non-uniform P_{FE} impacted by drain bias, the local coupling between FE layer and underlying semiconductor is highlighted. Inspired by the fact that surface potential φ_s is always spatial-position-related under nonzero V_D irrespective of device structure, the model is established in a perturbative way. As shown in Fig. 2a, started from lumped treatment of FeFET, uniform P_{FE} and internal metal gate potential V_g can be obtained by self-consistent calculation between FE layer and MOSFET. Then based on φ_s at source and drain side, spatial distribution of surface potential $\varphi_s(x)$ is calculated according to gradual channel approximation and channel current continuity (Fig. 2b). Different from conventional modeling method, where FE is directly in series with underlying MOSFET to obtain uniformly distributed V_{FE} and P_{FE}, spatially distributed φ_s is utilized as a pertubation to induce non-uniform V_{FE} along the channel, capturing the local coupling between FE and underlying substrate (Fig. 2c). Correspondingly, P_{FE} shows spatial non-uniformity, which is very different compared with lumped treatment result (Fig. 2d). Besides, a fitting parameter δ_i is introduced to extract more accurate P_{FE} distribution. It is intuitive that channel conduction modulated by P_{FE} can be reflected by an effective threshold voltage V_{TH}. Therefore, from the perspective of balancing between accuracy and simplicity, the I-V characteristics of MFIS-FeFET can be finally calculated by V_{TH}-based model [10] with modified parameter α_i.

In order to clearly illustrate the calculation process of $\varphi_s(x)$ and I-V dependence, adopted equations are listed in Fig. 3 in detail. As shown in Fig. 3a, Schroder method is utilized to accelerate calculation process of φ_s at source ($\varphi_{s(S)}$) and

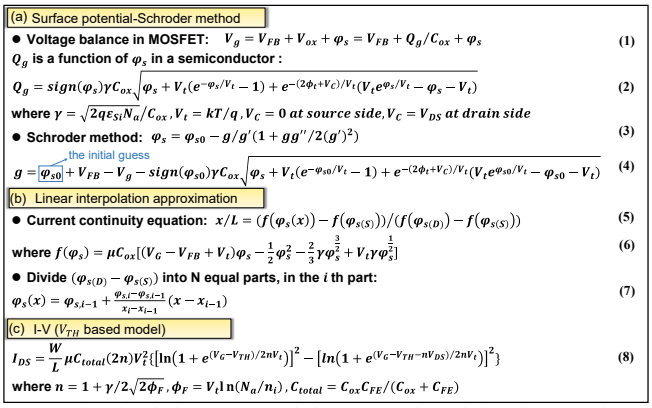

Fig. 3. The detailed equations of the proposed modeling framework. (a) Analytical approach of φ_s solution at source and drain side respectively. (b) Spatially distributed $\varphi_s(x)$ is obtained by linear interpolation. (c) The V_{TH}-based equation for describing I-V characteristics.

drain ($\varphi_{s(D)}$). Fig. 3b shows that $\varphi_s(x)$ for N equally divided channel positions is calculated by linear interpolation between φ_s obtained by N equally divided difference between $\varphi_{s(S)}$ and $\varphi_{s(D)}$. The I-V dependence of FeFET is calculated by an unified expression based on effective V_{TH} shown in Fig. 3c.

III. Results and Discussion

A. Spatially distributed polarization in FeFET

In order to validate the proposed model, we compare the electric characteristics obtained by TCAD simulation and our modeling approach. Under different drain bias, spatial distribution of V_{FE} and P_{FE} are shown in Fig. 4a and Fig. 4b respectively. It is noteworthy that with increasing V_D, the non-uniformity of V_{FE} aggravates and the gradient of P_{FE} increases. Besides, suppressed P_{FE} switching near drain side will impact channel conductivity, espeically under high V_D. However, for conventional modeling method, the effect of spatially distributed φ_s is averaged, leading to a uniform P_{FE} and weaker dependence of device conductivity on drain bias. It is implied that conventional model is available to evaluate MFIS-FeFET under low V_D but is limited for accurately describing device behavior under high V_D [11], which can also be validated by decreased hysteresis window with V_D

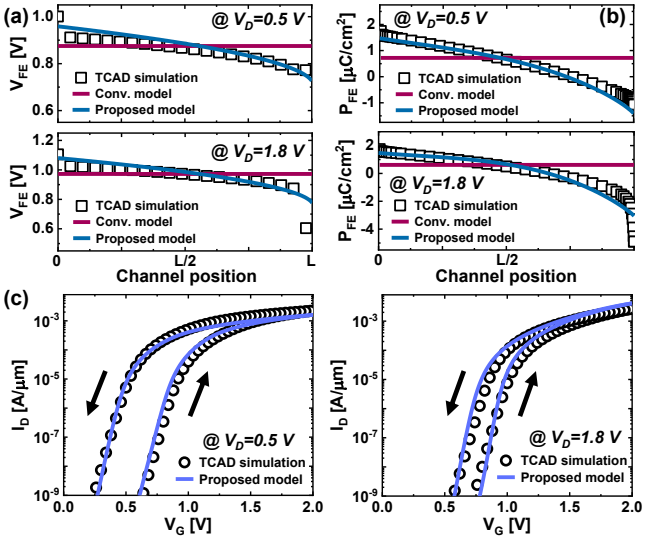

Fig.4 Comparison between results of the proposed model and TCAD simulation. Spatially-distributed (a) V_{FE} and (b) P_{FE} along the channel under different V_D values. (c) Good agreement of I_D-V_G curves between TCAD simulation and model results for various V_D values.

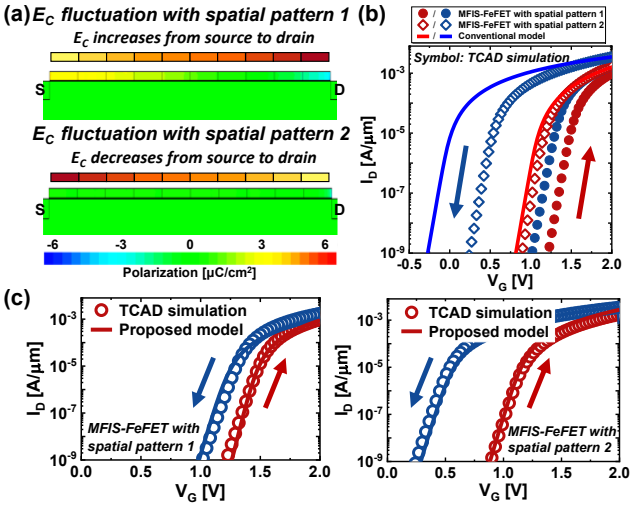

Fig. 5. (a) Spatially distributed P_{FE} in FeFET with two different spatial patterns of E_C fluctuation, where E_C increases and decreases from source to drain respectively. (b) Different from conventional model for lumped FeFET, transfer characteristics of distributed FeFET is strongly dependent on spatial pattern of E_C fluctuation. (c) Good agreement of I_D-V_G curves between TCAD simulation and proposed model.

of 1.8V (Fig. 4c). In contrast, our proposed model shows good agreement with simulated electrical characteristics (Fig. 4c), indicating the awareness of V_D-induced spatially-distributed P_{FE} effect in the preturbative model. More importantly, based on the above analysis, it is clear that impact of drain bias will be more evident considering FE parametric fluctuation for spatially distributed grains, which will be discussed in the following part.

B. Impact of spatial pattern in polycrystalline FE on FeFET

For HfO_2-based FE, it is intrinsically polycrystalline including different structural phases, such as orthorhombic, monoclinic and tetragonal phases [12-13]. In addition, ferroelectricity shows variation among FE grains, exhibiting parametric fluctuation. Furthermore, considering the local coupling between FE and channel, FE parametric fluctuation will result in non-uniform channel conduction. Therefore, for a given scalar distribution of FE parameter, device characteristics of MFIS-FeFET will show dependence on spatial pattern.

In our proposed model, consideration of local interaction between FE and channel enables discussion of impacts from spatial pattern. To clearly illustrate local coupling effect in MFIS-FeFET, Fig. 5a shows P_{FE} distribution for FE grains with different E_C values distributed along the channel. It is observed that position-dependent φ_s will induce position-dependent P_{FE} for FE grain with the same E_C, which will be more significant under high drain bias. Furthermore, spatially distributed P_{FE} will modulate underlying channel conductivity accordingly, resulting in spatial pattern dependence of transfer characteristics as shown in Fig. 5b. However, conventional model fails to reflect this intrinsic property caused by multi-grain FE in distributed device. The accurate results plotted in Fig. 5c demonstrates the effectiveness of our proposed model.

To further inverstigate the relationship between spatial pattern of FE parametric fluctuation and device characteristics, scalar distribution of E_C is assigned with two different values. The conduction band are shown in Fig. 6b. Different from lumped treatment, the shape of conduction band is directly dependent on specific spatial pattern. It is

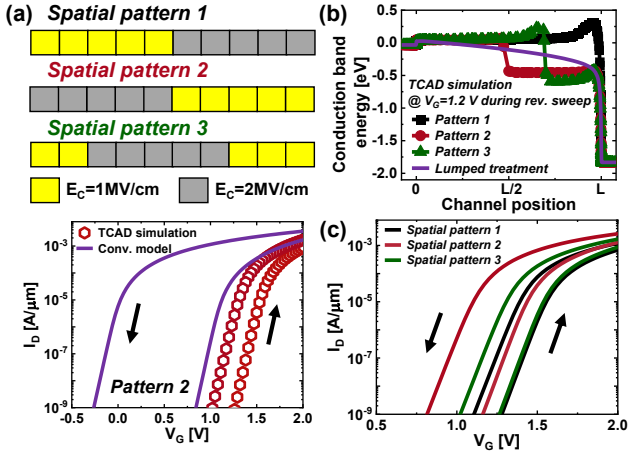

Fig. 6. (a) Three typical spatial patterns of E_C and significant V_{TH} deviation caused by conventional model for FeFET with pattern 2. (b) Conduction band of FeFET with various spatial patterns under V_G=1.2V during reverse sweep. The distributed FeFETs show non-uniform channel conduction dependent on E_C pattern. (c) Correspondingly different I_D-V_G curves due to different spatial patterns along the channel in MFIS-FeFET.

noted that the channel position related to the highest energy barrier is approximately the closest position of FE grain with high E_C to drain side. In addition, height of the energy barrier is higher when the position is closer to drain side. This is originated from smaller switched P_{FE} caused by reduced V_{FE} near drain side. Moreover, the related hysteresis window will be smaller as shown in Fig. 6c. Therefore, for MFIS-FeFET considering FE parametric fluctuation along the channel, FE grain near drain side can be regarded as a crucial variation source for device conduction.

C. Variability of MFIS-FeFET due to parametric fluctuation

According to the above analysis, spatially-distributed FE grains will result in variability of MFIS-FeFET. Based on the proposed perturbative model, we evaluate variability and compare impacts from fluctuation of different FE parameters. A Gaussian distribution is utilized to specify value of FE parameter to reflect variation among FE grains. For different FeFET devices, specific parameter values in a given set of FE parameter are randomly assigned along the channel. Fig. 7a shows the device variability caused by E_C fluctuation. For evaluation of device variability, a Gaussian

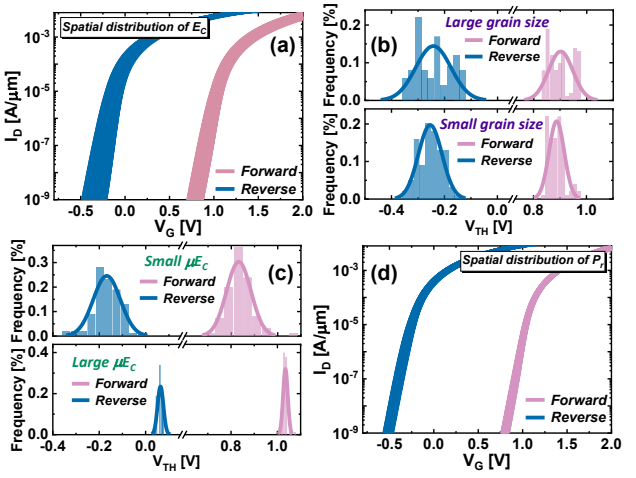

Fig. 7. For statistically Gaussian distribution of E_C, (a) randomly spatial patterns among FeFET devices leads to I_D-V_G dispersions. device-to-device variation will be suppressed by (b) decreasing grain size and (c) elevating average E_C value (μE_C).(d) For statistically Gaussian distribution of P_r, randomly spatial patterns among FeFET devices leads to smaller I_D-V_G dispersions compared with that caused by E_C fluctuation.

function fitting is adopted to obtain mean (μV_{TH}) and standard deviation value (σV_{TH}) of V_{TH}. As shown in Fig. 7b, with grain size down-scaling, σV_{TH} decreases due to weakened impact of a single grain. Moreover, for the scalar distribution of E_C with the same standard deviation (σE_C), larger mean E_C (μE_C) will lead to lower σV_{TH} under the same sweep voltage range, showing suppressed variability among FeFET devices (Fig. 7c).

Besides, it is known that ferroelectricity variation can also be reflected by fluctuation of switchable polarization. As a comparison, variability of device V_{TH} caused by spatially-distributed remnant polarization (P_r) is shown and smaller than that caused by E_C distribution with the same grain size, which indicates stronger dependence of V_{TH} on E_C [14-16]. Therefore, robust characteristics of FeFET can be realized by decreasing grain size and elevating uniformity of E_C values among FE grains.

IV. Conclusion

In this work, we have developed a perturbative modeling framework for MFIS-FeFET with awareness of spatially distributed effect of P_{FE}. By considering local coupling between polarization switching and surface potential, the model shows good agreement with numerical simulation. Besides, it is capable to reflect the device-to-device variation due to fluctuation of spatially distributed FE parameters, showing the importance of suppressed E_C fluctuation.

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