

Modeling the Memory Window Distribution in FeFETs Considering Grain Variability

Kenichiro Sonoda, Shibun Tsuda, Tadashi Yamaguchi, Atsushi Amo, and Eiji Tsukuda
Renesas Electronics
 Ibaraki, Japan
 kenichiro.sonoda.xc@renesas.com

Abstract—The memory window distribution in FeFETs is evaluated by incorporating experimentally measured variations in grain number, grain size, and polarization direction in the ferroelectric film. Among the investigated factors, grain size reduction is found to be the most effective approach for improving the practically important lower bound of the memory window distribution.

Index Terms—FeFET, Grain, Variability

I. INTRODUCTION

Ferroelectric Field-Effect Transistors (FeFETs) have attracted significant attention as promising non-volatile memory devices due to their low-power operation and compatibility with CMOS processes. HfO₂-based ferroelectric films used in FeFETs are typically polycrystalline, consisting of both ferroelectric (FE) and paraelectric (PE) grains as illustrated in Fig. 1.

The spatial variations in these grains leads to statistical fluctuations in polarization and threshold voltage [1], which pose challenges for device integration. Although three-dimensional TCAD simulations can provide detailed insight into the impact of spatial grain variability on electrical characteristics [2], their high computational cost makes them unsuitable for routine use in wafer process development.

In this paper, we propose a simple model to predict the impact of spatial grain variability on the memory window (MW) and provide guidelines for MW improvement. The spatial variability is characterized by grain area, the proportion of FE grains in the total grain population, and the crystallographic orientation distribution of FE grains. These parameters are extracted from Automated Crystal Orientation Mapping in Transmission Electron Microscopy (ACOM-TEM) measurements [3].

II. MODELING

The MW is assumed to be a function of the effective remanent polarization of the entire FE film. This effective polarization is calculated as the sum of the remanent polarization of individual grains, weighted by their area and the cosine of their polarization direction.

The validity of this assumption is verified by comparing the TCAD simulation results obtained using two approaches: (1) modeling the FE layer as polycrystal and (2) approximating it as a single crystal with an effective remanent polarization. TCAD simulations are performed using Synopsys Sentaurus.

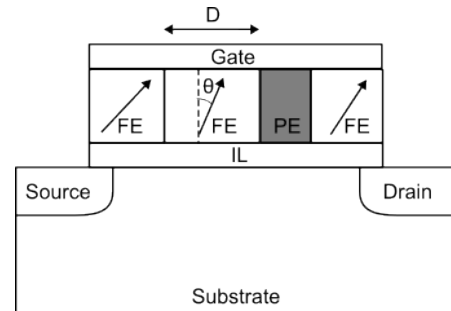


Fig. 1. Schematic view of FeFET with polycrystal FE layer. FE and PE represent ferroelectric and paraelectric grains, respectively. IL represents a SiO₂ interlayer.

Preisach-based ferroelectric hysteresis and FE-IL interface trap models are included in the simulation.

A Metal-Ferroelectric-Metal (MFM) capacitor is used to extract the linear permittivity ϵ_{FE} , saturation polarization P_s , remanent polarization P_r , and coercive field F_c of the FE layer, as shown in Fig. 2. The fabrication conditions of this sample are described in [4].

The polycrystal FE layer in the TCAD simulation is modeled by dividing the FE layer into N_{grain} grains, as shown in Fig. 3(a). Each grain is randomly assigned as ferroelectric with probability p . In contrast, the single crystal approximation uses an effective remanent polarization as $P_{\text{reff}} = P_r N_{\text{fe}} / N_{\text{grain}}$ where the number of FE grains N_{fe} follows a Poisson distribution with a mean of $p N_{\text{grain}}$ as shown in Fig. 3(b). The ratio of remanent polarization to saturation polarization is kept constant.

For each condition, 30 devices are generated and the simulation results are shown in Fig. 3(c). The good agreement between the two approaches confirms that representing the MW as a function of the effective remanent polarization is a valid approximation.

The MW distribution is derived from the distribution of the effective remanent polarization, which is calculated using Monte Carlo simulations. The following sources of variability are considered:

- 1) The number of grains
- 2) Grain area
- 3) Polarization direction within the FE layer

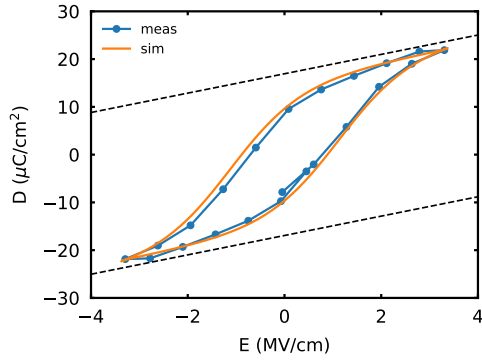


Fig. 2. D - E curve of an MFM capacitor. Simulated curves from Preisach model with parameters $\epsilon_{FE} = 22.9\epsilon_0$, $P_s = 16.93 \mu\text{C}/\text{cm}^2$, $P_r = 10.92 \mu\text{C}/\text{cm}^2$, and $F_c = 1.121 \text{ MV}/\text{cm}$.

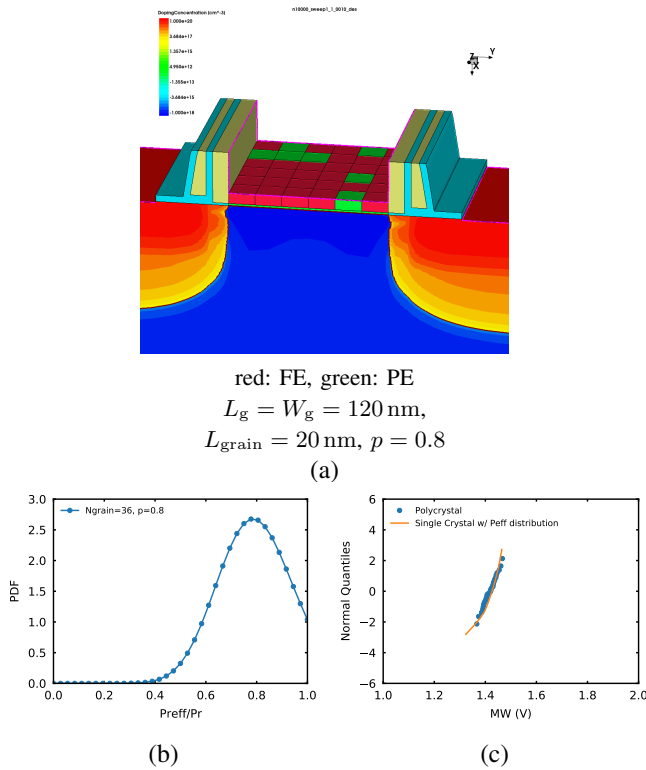


Fig. 3. Comparison of TCAD simulation results with polycrystal FE layer and single crystal FE layer. (a) Simulated FeFET with polycrystal FE layer. The FE grains are statistically distributed. (b) Probability distribution function of the effective remanent polarization for TCAD simulation with single crystal FE layer. (c) Q-Q plot of MW.

These variations are directly extracted from ACOM-TEM measurements.

The variation in the number of grains consists of two components:

- Variation in the total number of grains N_{grain}
- Variation in the number of ferroelectric grains N_{fe}

The variation in N_{grain} is described by a Poisson distribution with a mean determined from the area-weighted average

diameter $\overline{D_A}$. The variation in N_{fe} is expressed by a binomial distribution with the total number N_{grain} and the FE proportion p . Both the diameter $\overline{D_A}$ and the proportion p are extracted from ACOM-TEM data shown in Fig. 4 (a).

The variation in grain area is expressed using a Voronoi diagram with randomly placed seed points, as shown in Fig. 4 (b). The area distribution is well approximated by a gamma distribution with shape = 7/2 and scale = 2/7 [5] as shown in Fig. 5, which is useful to reduce computational time compared with generating the Voronoi diagram for each run.

The variation in polarization directions is modeled by fitting the probability distribution of polarization direction obtained from ACOM-TEM measurements to a beta distribution as shown in Fig. 6. The absolute value of the remanent polarization of an FE grain, P_{r0} , is determined by $P_r / (p \langle \cos \theta \rangle)$, where P_r is obtained from measurements of the MFM capacitor as shown in Fig. 2 and p and $\langle \cos \theta \rangle$ are extracted from ACOM-TEM data as shown in Figs. 4 and 6.

In order to obtain the MW from the effective remanent polarization P_{reff} , the following empirical expression is proposed:

$$\text{MW} = \frac{\text{MW}_{\text{max}} - \text{MW}_{\text{min}}}{1 + \exp(-(P_{\text{reff}} - aP_c)/bP_c)} + \text{MW}_{\text{min}} \quad (1)$$

with $\text{MW}_{\text{max}} = 2F_c T_{\text{fe}} = 1.79 \text{ V}$, $\text{MW}_{\text{min}} = -0.2 \text{ V}$, $P_c = \epsilon_{\text{FE}} F_c$, $a = 5.3$, $b = 2.0$, and T_{fe} is the FE layer thickness. This formula yields smaller MW values than those for an ideal FeFET without an interlayer (IL) [6], as shown in Fig. 7. The discrepancy is attributed to FE-IL interface traps. The FE polarization and the interface trap charges act in opposite directions, resulting in a reduced MW [7].

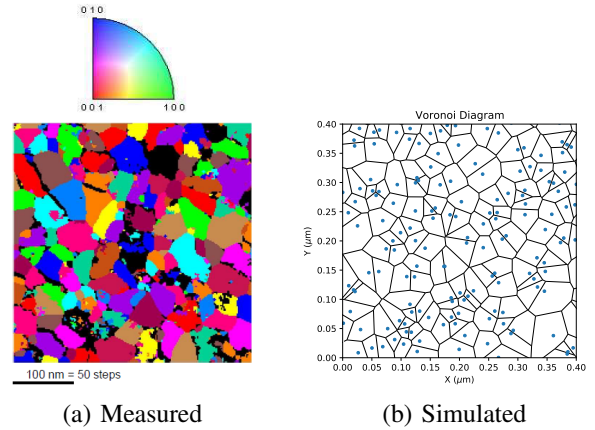


Fig. 4. Grain map of FE layer. (a) Measured data obtained from ACOM-TEM. The color represents the FE crystal orientation. The black regions represent PE grains. $\overline{D_A} = 39 \text{ nm}$, $p = 0.871$. (b) Simulated data obtained from a Voronoi diagram with randomly placed seed points.

III. RESULTS AND DISCUSSION

The distributions of the effective remanent polarization and MW simulated using the proposed model are shown in Fig. 8. The average value of the normalized effective polarization is $p \langle \cos \theta \rangle = 0.566$. The width of the distribution is governed

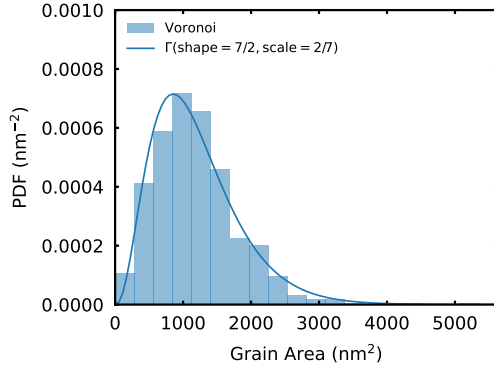


Fig. 5. Probability distribution function of grain areas.

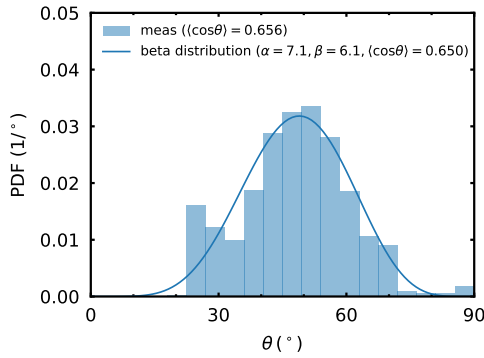


Fig. 6. Probability distribution function of FE polarization direction. Measured data are obtained from ACOM-TEM. The angle θ is the angle between the direction perpendicular to the interface and the polarization direction.

by the variations in the number of grains, their areas, and polarization directions within the FE layer. The measured MW distribution in an FeFET memory array is well described by the proposed model.

To improve MW variability, three scenarios are examined: increasing the FE grain proportion p , reducing the grain

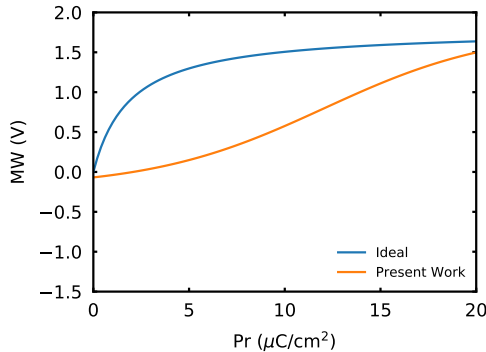


Fig. 7. MW as a function of remanent polarization. The ideal curve is from [6].

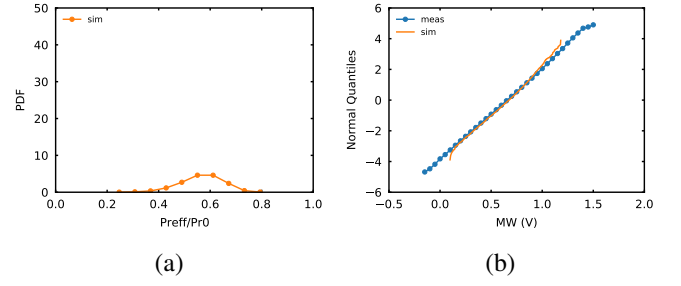


Fig. 8. Measured and simulated statistical distribution of the MW. (a) Simulated PDF of the normalized effective remanent polarization, (b) Q-Q plot of MW. $L_g = 120$ nm, $W_g = 140$ nm.

size, and aligning the polarization direction of FE grains perpendicular to the interface. Increasing the proportion p improves the median and the variation in MW as shown in Fig. 9. Reducing the grain diameter $\overline{D_A}$ does not affect the median MW, but improves its variation as shown in Fig. 10. The effect of polarization alignment is investigated using three types of distributions as shown in Fig. 11. Aligning the polarization direction distribution toward the direction normal to the interface improves the median of MW, but worsens its variability as shown in Fig. 12.

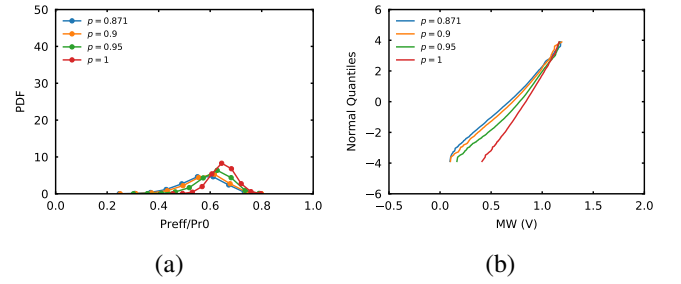


Fig. 9. Statistical distribution of the effective remanent polarization and the MW for different values of the FE proportion p . (a) Simulated PDF of the normalized effective remanent polarization, (b) Q-Q plot of MW. $L_g = 120$ nm, $W_g = 140$ nm.

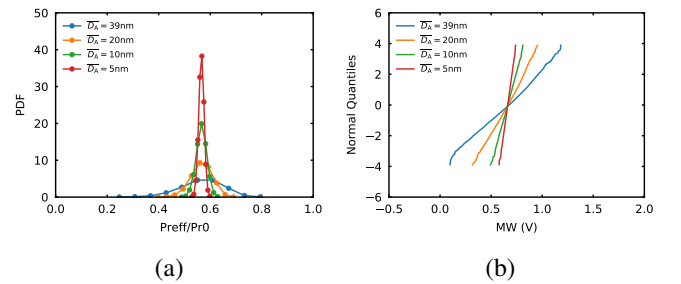


Fig. 10. Statistical distribution of the effective remanent polarization and the MW for different values of the grain diameter $\overline{D_A}$. (a) Simulated PDF of the normalized effective remanent polarization, (b) Q-Q plot of MW. $L_g = 120$ nm, $W_g = 140$ nm.

Among the factors investigated in this study, reducing the grain size is the most effective approach to improve the practically important lower bound of the distribution. In the above

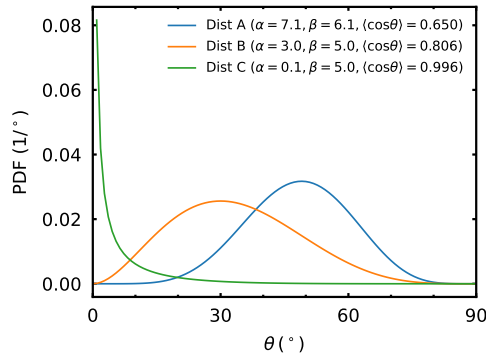


Fig. 11. Benchmark functions for investigating polarization direction distribution dependence. α and β are the parameters of the beta distribution. The angle θ is the angle between the direction perpendicular to the interface and the polarization direction. Dist A is identical to the curve in Fig. 6.

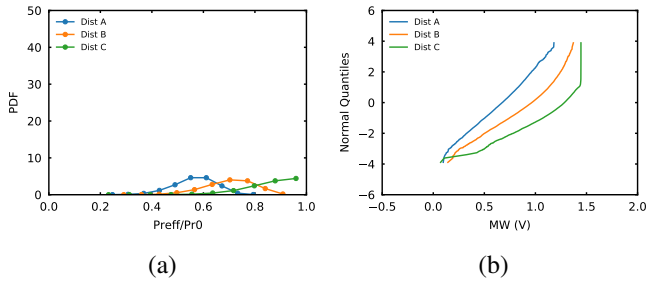


Fig. 12. Statistical distribution of the effective remanent polarization and the MW for different polarization direction distribution. (a) Simulated PDF of the normalized effective remanent polarization, (b) Q-Q plot of MW. $L_g = 120$ nm, $W_g = 140$ nm.

analysis, the diameter $\overline{D_A}$ and the proportion p were treated as independent variables. In actual HfO_2 -based ferroelectric films, however, a reduction in $\overline{D_A}$ suppresses the formation of the paraelectric monoclinic phase, thereby increasing p [8]. Consequently, reducing the grain size is expected to improve not only variability but also the median of the MW.

IV. CONCLUSION

A compact and computationally efficient model for predicting the MW distribution in FeFETs has been proposed, incorporating the measured variations in grain number, grain size, and polarization direction in the FE film. Among the factors investigated in this study, grain size reduction is the most effective approach for improving the practically important lower bound of the distribution. This approach allows efficient estimation of the MW distribution from the grain map with significantly reduced time compared to three-dimensional TCAD simulations.

REFERENCES

[1] C. Garg, N. Chauhan, S. Deng, A. I. Khan, S. Dasgupta, A. Bulusu, and K. Ni, "Impact of Random Spatial Fluctuation in Non-Uniform Crystalline Phases on the Device Variation of Ferroelectric FET," *IEEE Electron Device Letters*, vol. 42, no. 8, pp. 1160–1163, 2021.

[2] D. Lizzit, T. Bernardi, and D. Esseni, "Multi-level Operation of FeFETs Memristors: the Crucial Role of Three Dimensional Effects," in *ESSDERC 2022 - IEEE 52nd European Solid-State Device Research Conference (ESSDERC)*, pp. 344–347, 2022.

[3] T. Kämpfe, N. Vogel, M. Weisheit, D. Utes, P. Polakowski, I. Richter, B. Volkmann, J. Müller, S. Beyer, M. Trentzsch, S. Dünkel, T. Büttner, and K. Seidel, "Phase and Orientation Mapping of Ferroelectric HfO_2 Grains in 22-nm FDSOI FeFETs," in *Proceedings of the IEEE International Symposium on Applications of Ferroelectrics (ISAF)*, 2018.

[4] K. Maekawa, T. Yamaguchi, T. Ohara, A. Amo, E. Tsukuda, K. Sonoda, H. Yanagita, M. Inoue, M. Matsuura, and T. Yamashita, "Impact of Homogeneously Dispersed Al Nanoclusters by Si-monolayer Insertion into $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ Film on FeFET Memory Array with Tight Threshold Voltage Distribution," in *2019 IEEE International Electron Devices Meeting (IEDM)*, pp. 15.4.1–15.4.4, 2019.

[5] J.-S. Ferenc and Z. Néda, "On the size distribution of Poisson Voronoi cells," *Physica A: Statistical Mechanics and its Applications*, vol. 385, no. 2, pp. 518–526, 2007.

[6] K. Toprasertpong, M. Takenaka, and S. Takagi, "Memory window in ferroelectric field-effect transistors: Analytical approach," *IEEE Transactions on Electron Devices*, vol. 69, no. 12, pp. 7113–7119, 2022.

[7] E. Yurchuk, J. Müller, S. Müller, J. Paul, M. Pešić, R. van Bentum, U. Schroeder, and T. Mikolajick, "Charge-trapping phenomena in HfO_2 -based FeFET-type nonvolatile memories," *IEEE Transactions on Electron Devices*, vol. 63, no. 9, pp. 3501–3507, 2016.

[8] J. Park, C. Chung, B. Ku, S. Yun, K. Park, and C. Choi, "Grain size engineering via a $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ seed layer for FeFET memory and synaptic devices," *Nanoscale*, vol. 17, pp. 10324–10333, 2025.