

1370 IEEE ELECTRON DEVICE LETTERS, VOL. 40, NO. 9, SEPTEMBER 2019

Ionizing Radiation Effect on Memory

Characteristics for HfO2-Based

Ferroelectric Field-Effect Transistors

Kuen-Yi Chen, Yi-Shan Tsai, and Yung-Hsien Wu

, Senior Member, IEEE

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***Abstract— HfO2-based ferroelectric field-effect transis-tors (FeFET) on Si were employed as the platform to investigate the impact of60Co γ -rays radiation on memory characteristics. For pristine state, the memory window by*±*4 V sweeping for non-irradiated devices is 1.48 V which does not degrade with 300-krad and 10-Mrad radiation dose even though the remnant polarization (Pr) decreases due to radiation-induced oxygen vacancies (Vo) and lattice distortion in the ferroelectric material HfZrOx (HZO). With the radiation dose level, the devices still hold the current ratio between “1” and “0” state of 2.2* × *103by extrapo-lating to 10 years at 25*◦*C, which is comparable to that of non-irradiated devices. The most adverse effect of radiation is the deteriorated endurance caused by the increased number of Vo during cycling test (*+*5.5 V,* −*5 V/10 μs) as evidenced by memory window of 0.52 V at 106cycles for devices with 300-krad radiation dose. Furthermore, robust HZO and SiOx interacial layer against radiation is required to suppress the bond break so that the reliability can be improved.*** | devices for modern electronic systems, has been extensively investigated for radiation tolerance. For TID effect, thresh-old voltage variation, leakage current increase and retention degradation for high dose condition have been reported for cell devices of flash memory while peripheral circuitry is more vulnerable to TID effect since devices in the circuitry including high-voltage charge pump are with thick oxide thickness which is prone to trap charges. | | | | | |
| Ferroelectric | field | effect | transistor | (FeFET) | memory, |
| another promising non-volatile memory technology that can be the successor of flash memory, has aroused intense research interests for years since it enjoys fast switching and ultra-low power operation. In addition, the information in FeFET memory is determined by the direction of the polarization rather than the stored charges as flash memory and therefore the major concern of charge loss in flash memory does not occur. Besides, FeFET memory does not require charge pump circuitry due to the small operation voltage. These | | | | | |

***Index Terms— Ferroelectric, HfZrOx, FeFET, endurance, retention, reliability.***

I. INTRODUCTION   
**I** excite and detach the electrons from atoms or molecules ONIZING radiation is radiation with sufficient energy to

and may cause hard or soft error for semiconductor devices from the so-called total ionizing dose (TID) effect and single event effect (SEE). While TID indicates the accumulation effect of gradual and uniform radiation dose, SEE implies the effect from the instantaneous strike of a single particle in a local area that causes abrupt changes or transient behaviors in the circuits. As the process technology advances, the required energy to affect the device performance becomes lower and therefore ionizing radiation effect on semiconductor devices has been an essential topic for decades. Among various semiconductor devices, non-volatile memory devices play an important role in shaping human life, especially in AI and 5G era. Flash memory, the mainstream non-volatile memory

Manuscript received June 13, 2019; revised July 25, 2019; accepted July 25, 2019. Date of publication July 29, 2019; date of current version August 23, 2019. This work was supported by the Ministry of Science and Technology/Atomic Energy Council of Taiwan under the contract of MOST 108-2623-E-007-002-NU. The review of this letter was arranged by Editor A. Naeemi. (Corresponding author: Yung-Hsien Wu.)   
 The authors are with the Department of Engineering and System Science, National Tsing Hua University, Hsinchu 300, Taiwan (e-mail: yunhwu@mx.nthu.edu.tw).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2019.2931826

advantages make FeFET memory the most radiation-immune memory on the market. Nevertheless radiation effect has been explored for FeFET for years, most studies focus on conventional perovskite-type ferroelectric materials such as Bi3*.*15Nd0*.*85Ti3O12 (BNT) [1] and SrBi2Ta2O9 (SBT) [2] which cannot be integrated with VLSI technology and there-fore poses a limitation for further applications [3]. With the advent of VLSI-compatible HfO2-based ferroelectric material, it ushers in a new era of FeFET memory.

Although plentiful attempts have been made to improve the reliability performance of HfO2-based FeFET memory, the impact of TID on memory characteristics were rarely dis-cussed. Highly stable metal-ferroelectric-metal (MFM) capac-itors based on HfYOx under *γ* -ray radiation was first reported by Huang *et al.* [4] and demonstrated high immunity from radiation in terms of little changes of basic ferroelectric para-meters which is much improved as compared to conventional ferroelectric materials. Recently, Xiao *et al.* reported that HfZrOx (HZO) MFM capacitors on flexible mica substrate shows robust ferroelectricity against *γ* -ray radiation with 1 Mrad dosage [5]. Wang *et al.* [6] further investigated proton radiation effects on HfYOx MFM capacitors which it is highly resistive to proton radiation. However, almost none of previous studies refer to the actual HfO2-based FeFET memory which are formed on Si substrate rather than metal. The major structure difference between HfO2-based FeFET memory and MFM capacitor is the interface between ferroelectric material and the underlying substrate. For FeFET memory, the interfa-cial quality between ferroelectric material and Si is typically

0741-3106 © 2019 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications\_standards/publications/rights/index.html for more information.

CHEN et al.: IONIZING RADIATION EFFECT ON MEMORY CHARACTERISTICS FOR HfO2-BASED FeFETs 1371



|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |

Fig. 1. (a) Bi-directional ID-VG characteristic for FeFETs with various radiation doses. (b) Schematic for radiation-induced series channel resistance reduction where the extended S/D region is formed during annealing process.

worse than that of MFM capacitors due to the reaction during the subsequent thermal processes. It is the inferior interfacial quality that makes reliability issues, especially for endurance, a main concern for HfO2-based FeFET memory [7]. Therefore it is worth advancing the radiation study by transforming the platform from MFM capacitors to FeFET memory to bet-ter understand how radiation affects memory characteristics. In this work, FeFET memory based on ferroelectric HZO (FE-HZO) was adopted as the platform and the TID effect on remnant polarization (Pr*)*, interface quality, endurance and retention were reported.

II. EXPERIMENT

HZO-based FeFET memory devices formed on p-type Si substrate were employed as the platform to evaluation the TID effect on memory performance. After initial clean of the Si wafer, HfZrOx of 12 nm was deposited as the FE material by nano-laminate thermal ALD with HfO2:ZrO2 = 1:1 cycle ratio at 250◦C. Next, TiN was deposited to form the gate electrode. Then source/drain implantation by phosphorous was performed after required patterning. Finally the FeFET memory devices were complete by rapid thermal annealing at 600◦C for 30 sec to concurrently activate the source/drain dopants and crystalize the HZO into orthorhombic phase for ferroelectricity. Afterward, to assess the TID effect on memory performance, some devices were irradiated perpendicularly to the surface by60Co *γ* -ray with the dose of 300 krad and 10 Mrad at the radiation rate of 100 rad/sec. Typically, the acceptable level of TID for radiation-hardened semicon-ductor device is 1 Mrad. The reason of adopting 10 Mrad is to set a margin for safe operation. Memory window (MW) of the devices was defined by threshold voltage (VTH*)* shift for a bi-directional sweeping where VTH is extracted by using constant drain current of 5 × 10−7A.

III. RESULTS AND DISCUSSION

Fig. 1(a) shows the bi-directional ID-VGS transfer charac-teristics for devices with different radiation dose under ± 4 V gate voltage sweeping with drain biased at 0.08 V. All types of devices show counterclockwise hysteresis which implies that ferroelectric induced dipole switching rather than charge trapping dominates the hysteresis. From the transfer charac-teristics, 3 phenomena are observed after irradiation including (1) increased ID at off state, (2) higher ID at on state, and (3) almost unchanged subthreshold slope. For phenomenon (1), it may arise from irradiation-induced charge accumulation in the field oxide near the active region that makes leakage

Fig. 2. Dependence of cycling number on (a) switching current and (b) Pr for FeFETs with various radiation doses.

paths between the drain and source [2]. For phenomenon (2), it may be caused by radiation-induced trapped holes in the oxide that forms higher electron concentration at the extended S/D region, reducing series channel resistance as shown in Fig. 1(b) [8]. For phenomenon (3), it is consistent with the extracted interface trap density (Dit*)* for devices without irra-diation, with 300 krad and 10 Mrad irradiation, which are 2*.*2×Dit value is extracted from the C-V curves and the improved 1011, 1*.*2 × 1011and 0*.*9 × 1011eV−1cm−2respectively. The Dit after irradiation is due to the passivation of the Si surface dangling bonds and a decreased number of recombination centers at the HZO/Si interface [9]. In addition, the memory window (MW) for non-irradiated devices is 1.48 V which does not degrade with irradiation which is contrary to that reported for irradiated SBT [2]. In fact, the MW degradation is highly dependent on the extent of charge trapping effect. Typically thicker oxide is more vulnerable to charge trapping and thus SBT of 300 nm shows much worse charge trapping effect than this work where HZO of 12 nm is used.

Besides the MW test, reliability issues which are the impor-tant concerns for practical applications are discussed. For endurance test, a course of continuous +5.5/−5 V pulse with pulse width of 10 *μ*s was applied to the gate up to 106cycles. The cycling condition exceeds the minimum requirement for dipole switching and the relatively long pulse width is adopted to make the test more stringent. Fig. 2(a) shows the dependence of IG-VG characteristics on cycling numbers for device with different radiation doses. For non-irradiated device, the pristine curve reveals a current peak which corre-sponds to dipole switching and again confirms the ferroelec-tricity of the HZO film. As the cycling number increases, the peak position shifts with amplitude increase, suggesting that wake-up effect occurs which is expected to be mitigated by employing interfacial plasma treatment [10]. Similar trend is also observed for irradiated devices. However, it can be found that the switching current peak at the pristine state is reduced for irradiated devices and the current reduction becomes more pronounced as the radiation dose increases. By using Positive-Up-Negative-Down (PUND) method to eliminate the leakage component, the intrinsic Pr can be achieved and the results are shown in Fig. 2(b). An obvious Pr increase with cycling number is shown for devices with different radiation doses and it reaches a relatively stable state at 105cycles that is known as wake-up effect. Even though all the domain walls are depinned at the stable state, irradiated devices still exhibit smaller Pr than that of non-irradiated devices. It is generally perceived that electron-hole pairs are generated along with chemical bond break in the oxide film during ionizing radiation and some of the broken bonds would give rise to defects such

1372 IEEE ELECTRON DEVICE LETTERS, VOL. 40, NO. 9, SEPTEMBER 2019



|  |  |  |
| --- | --- | --- |
|  |  |  |

Fig. 3. X-ray diffraction pattern for HZO with various radiation doses.

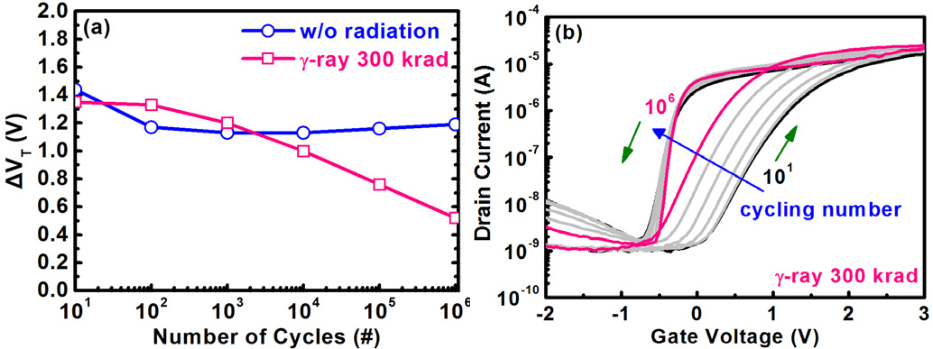


Fig. 4. (a) Dependence of *Δ*VT on cycling number for FeFETs with various radiation doses. (b) Evolution of ID-VG with cycling number for FeFETs with 300 krad radiation dose.

as oxygen vacancies (Vo) which then serve as trap sites for carriers. It is the radiation-induced Vo that lead to substantial Pr reduction for devices with radiation [11]. Another possible reason for the degraded Pr after radiation may be the structure change. As the x-ray diffraction pattern shown in Fig. 3, the peak at 30.5◦is used to discern ferroelectric orthorhombic (o) phase in HfO2 system. As the radiation doses increases to 10 Mrad, the peak of o-phase shifts 0.19◦toward higher 2*θ* value, suggesting that high energy radiation could induce lattice distortion and degrade the ferroelectricity. Note that the MW of FeFET memory is determined by coercive field (EC*)* and the thickness of the ferroelectric film rather than Pr [12], and therefore irradiated devices with degraded Pr still display comparable MW.

Fig. 4(a) shows the dependence ofVTH (VTH difference between both states) on cycling number for devices with various radiation doses. Non-irradiated devices reveal quite stable MW up to 106cycles. On the other hand, devices with 300 krad radiation show significant MW closure with cycling and the MW degrades to 0.52 V at the cycling number of 106. The evolution of ID-VGS with cycling number for devices with 300 krad radiation are shown in Fig. 4(b). The asymmetric VTH shift (different behavior for forward and reverse sweeping) with cycling number can be illustrated by the band diagram for both gate pulse polarities. For the band diagram for +5.5 V pulse shown in Fig. 5(a), electrons are injected from p-type substrate. However, the number of electrons (minority carriers) available for injection is not high enough in p-type substrate and thus the electron trapping effect in HZO is insignificant (VTH unchanged), even though radiation induces a certain amount of defects in the HZO. On the other hand, for the band diagram for -5 V pulse shown in Fig. 5(b), holes (majority carriers) are injected from p-type substrate and then get trapped in HZO. The amount of trapped holes increases for irradiated devices since more defects (traps) are generated during irradiation. At the same time, back tunneling of electrons in HZO also occurs. Both electrons and holes movement make the negative shift (VTH decrease). Note that the interfacial layer (IL) between HZO and Si substrate

Fig. 5. Energy band diagram for (a) positive and (b) negative gate bias.

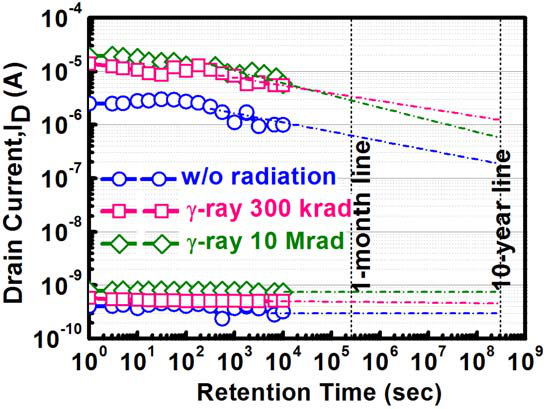


Fig. 6. Room-temperature retention performance in terms of ID mea-sured at VD = 0.08 V and VG = 0 V for FeFETs with various radiation doses.

is caused by the reaction during thermal treatment which is physically confirmed as SiOx film of 1.1 nm. To mitigate the cycling-induced VTH degradation for irradiated devices, enhancing the bonding strength of interfacial layer and HZO is a prerequisite which may be achieved by incorporating N atoms [10] or high-pressure hydrogen annealing process [13]. Fig. 6 shows the retention performance for devices with different radiation doses. The retention was measured at 25◦C by reading drain current at VG = 0 V for both high and low VTH states. The results indicate that both high (low VTH*)* and low current (high VTH*)* states keep stable with retention time up to 104sec for all types of devices. The 10-year extrapolated current ratio of 2*.*2 × 103and 1*.*2 × 103are obtained for devices with 300 krad and 10 Mrad respectively. Typically retention degrades by depolarization field (Edep*)* for fast decay component and gate leakage for long-term component. Since the EC for HZO is so high that the adverse effect of Edep is not significant [14]. Leakage caused by electrons injection from both gate electrode and substrate due to the attraction by dipole polarization plays a more critical role in determining retention characteristics. Because irradiated devices possess a lower Pr, a smaller amount of electrons are injected and thus charge trapping is less pronounced, leading to relatively stable retention performance.

IV. CONCLUSION

The impact of *γ* -ray radiation on the performance of HZO-based FeFET memory on Si was studied. Pr decreases with radiation does due to the radiation-induced Vo and lattice distortion. However, for devices with 300 krad dose, the MW at pristine state still maintains as the non-irradiated devices and 10-year extrapolated current ratio of 2*.*2 × 103between high/low VTH states are achieved. The most adverse effect of radiation is the endurance performance where the MW degrades to 0.52 V at the cycling number of 106due to hole trapping from radiation-induced defects. Further improvement of the bonding strength of interfacial layer and HZO against radiation is required.

CHEN et al.: IONIZING RADIATION EFFECT ON MEMORY CHARACTERISTICS FOR HfO2-BASED FeFETs 1373



REFERENCES

[1] Q. Shi, Y. Ma, Y. Li, and Y. Zhou, “Drastic reduction of leakage current in ferroelectric Bi3*.*15Nd0*.*85Ti3O12 films by ionizing radia-tion,” *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater.*

*At.*, vol. 269, no. 4, pp. 452–454, 2011. doi: [10.1016/j.nimb.2010. 12.066](http://dx.doi.org/10.1016/j.nimb.2010.12.066).

[2] S. A. Yan, Y. Xiong, M. H. Tang, Z. Li, Y. G. Xiao, W. L. Zhang, W. Zhao, H. X. Guo, H. Ding, J. W. Chen, and Y. C. Zhou, “Impact of total ionizing dose irradiation on electrical property of ferroelectric-gate field-effect transistor,” *J. Appl. Phys.*, vol. 115, no. 20, May 2014, Art. no. 204504. doi: [10.1063/1.4878416](http://dx.doi.org/10.1063/1.4878416).

[3] J. Müller, T. S. Böscke, U. Schröder, S. Mueller, D. Bräuhaus, U. Böttger, L. Fre, and T. Mikolajick, “Ferroelectricity in simple binary ZrO2 [and HfO2](http://dx.doi.org/10.1021/nl302049k),” *Nano Lett.*, vol. 12, no. 8, pp. 4318–4323, Jul. 2012. doi: [10.1021/nl302049k](http://dx.doi.org/10.1021/nl302049k).

[4] F. Huang, Y. Wang, X. Liang, J. Qin, Y. Zhang, X. Yuan, Z. Wang, B. Peng, L. Deng, Q. Liu, L. Bi, and M. Liu, “HfO2-based highly stable radiation-immune ferroelectric memory,” *IEEE Electron Device Lett.*, vol. 38, no. 3, pp. 330–333, Mar. 2017. doi: [10.1109/LED.2017. 2653848](http://dx.doi.org/10.1109/LED.2017.2653848).

[5] W. Xiao, C. Liu, Y. Peng, S. Zheng, Q. Feng, C. Zhang, J.

Zhang, Y. Hao, M. Liao, and Y. Zhou, “Thermally stable and radi-ation hard ferroelectric Hf0*.*5Zr0*.*5O2 thin films on muscovite mica for flexible nonvolatile memory applications,” *ACS Appl. Electron.*

*Mater.*, vol. 1, no. 6, pp. 919–927, May 2019. doi: [10.1021/acsaelm. 9b00107](http://dx.doi.org/10.1021/acsaelm.9b00107).

[6] Y. Wang, F. Huang, Y. Hu, R. Cao, T. Shi, Q. Liu, L. Bi, and M. Liu,“Proton radiation effects on Y-doped HfO2-based ferroelectric memory,”*IEEE Electron Device Lett.*, vol. 39, no. 6, pp. 823–826, Jun. 2018. doi: [10.1109/LED.2018.2831784](http://dx.doi.org/10.1109/LED.2018.2831784).

[7] T. Ali, P. Polakowski, S. Riedel, T. Büttner, T. Kämpfe, M. Rudolph, B. Pätzold, K. Seidel, D. Löhr, R. Hoffmann, M. Czernohorsky, K. Kühnel, P. Steinke, J. Calvo, K. Zimmermann, and J. Müller,“High endurance ferroelectric hafnium oxide-based FeFET memory without retention penalty,” *IEEE Trans. Electron Devices*, vol. 65, no. 9, pp. 3769–3774, Sep. 2018. doi: [10.1109/TED.2018.2856818](http://dx.doi.org/10.1109/TED.2018.2856818).

[8] R. L. Pease, S. D. Clark, P. L. C[ole, J. F. Krieg, and J. C. Pic](http://dx.doi.org/10.1109/TED.2018.2856818)kel, “Total dose response of transconductance in MOSFETs at low temperature,”*IEEE Trans. Nucl. Sci.*, vol. 41, no. 3, pp. 549–554, Jun. 1994.

[9] S. Maurya, “Effect of zero bias Gamma ray irradiation on HfO2 thin films,” *J. Mater. Sci., Mater. Electron.*, vol. 27, no. 12, pp. 12796–12802, Dec. 2016. doi: [10.1007/s10854-016-5412-6](http://dx.doi.org/10.1007/s10854-016-5412-6).

[10] K.-Y. Chen, P.-H[. Chen, and Y.-H. Wu, “E](http://dx.doi.org/10.1007/s10854-016-5412-6)xcellent reliability of ferro-electric HfZrO*x* free from wake-up and fatigue effects by NH3 plasma treatment,” in *Proc. Symp. VLSI Circuits*, Jun. 2017, pp. T84–T85. doi: [10.23919/VLSIC.2017.8008572](http://dx.doi.org/10.23919/VLSIC.2017.8008572).

[11] K. K[lyukin and V. Alexandrov, “E](http://dx.doi.org/10.23919/VLSIC.2017.8008572)ffect of intrinsic point defects on ferroelectric polarization behavior of SrTiO3,” *Phys. Rev. B, Condens.*

*Matter*, vol. 95, no. 3, Jan. 2017, Art. no. 035301. doi: [10.1103/ physrevb.95.035301](http://dx.doi.org/10.1103/physrevb.95.035301).

[12] [H.-T. Lue, C.-J. W](http://dx.doi.org/10.1103/physrevb.95.035301)u, and T.-Y. Tseng, “Device modeling of ferroelec-tric memory field-effect transistor (FeMFET),” *IEEE Trans. Electron Devices*, vol. 49, no. 10, pp. 1790–1798, Oct. 2002. doi: [10.1109/TED. 2002.803626](http://dx.doi.org/10.1109/TED.2002.803626).

[13] [S. Oh, J. S](http://dx.doi.org/10.1109/TED.2002.803626)ong, I. K. Yoo, and H. Hwang, “Improved Endurance of HfO2-based metal-ferroelectric-insulator-silicon structure by high-pressure hydrogen annealing,” *IEEE Electron Device Lett.*, vol. 40, no. 7, pp. 1092–1095, Jul. 2019. doi: [10.1109/LED.2019.2914700](http://dx.doi.org/10.1109/LED.2019.2914700).

[14] N. Gong and T.-P. Ma, “Why i[s FE–HfO](http://dx.doi.org/10.1109/LED.2019.2914700)2 [more suitable t](http://dx.doi.org/10.1109/LED.2019.2914700)han PZT or SBT for scaled nonvolatile 1-T memory cell a retention perspective,”*IEEE Electron Device Lett.*, vol. 37, no. 9, pp. 1123–1126, Sep. 2016. doi: [10.1109/LED.2016.2593627](http://dx.doi.org/10.1109/LED.2016.2593627).