OPEN ACCESS
2nd International Electronic Conference on Sensors and Applications
15–30 November 2015
www.mdpi.com/journal/sensors

Conference Proceedings Paper – Sensors and Applications

Performance Improvement of Aluminum doped MOHOS Total Dose Radiation Sensor Device by Fluorine Plasma Treatment

Wen-Ching Hsieh [1,*], Hao-Tien Daniel Lee [2], Fuh-Cheng Jong [3]

1. Department of Opto-Electronic System Engineering, Minghsin University of Science and Technology, Xinxing Rd, 1, Xinfeng 30401, Taiwan
2. ETOMS Electronics Corp, 12, Innovation 1st. Rd, Science-Based Industrial Park, Hsin-Chu 300, Taiwan; E-Mail: danieleewww@gmail.com
3. Electronic Engineering Department, Southern Taiwan University of Science and Technology, 1, Nan-Tai Street, Yungkang District, Tainan 710, Taiwan; E-Mail: fcjong@mail.stust.edu.tw

* Author to whom correspondence should be addressed; E-Mail: wchsieh@must.edu.tw; Tel.: +886-936-341-710.

Published: 11 November 2015

Abstract: Aluminum doped titanium nitride-silicon oxide-hafnium oxide-silicon oxide-silicon device with fluorine plasma treatment (hereafter F-Al-MOHOS) can be a candidate for total ionization dose (TID) radiation sensor application. In this report, the performance improvement in terms of TID radiation induced charge generation effect and charge-retention characterization for F-Al-MOHOS device is the main subject of this study. The F-Al-MOHOS reported in this study has demonstrated their potential application for non-volatile TID radiation sensing application in the future.

Keywords: high *k*; sensor; radiation; SONOS; SOHOS; MOS; TID

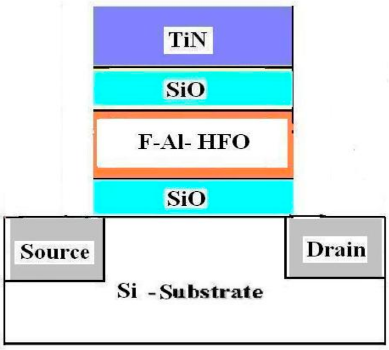
1. Introduction

Total ionizing dose (TID) radiation effect is the major application concern for the operation of electronic devices in advanced X-ray lithography semiconductor manufactory process and outer space application, as well as other harsh environments such as accelerators, where high and low energy particles exist. Total ionization dose (TID) radiation effects in traditional silicon-silicon dioxide-nitride-silicon dioxide-silicon (SONOS) non-volatile memory (NVM) devices have been studied previously. [1] Until now, little was known about the radiation response of SONOS–like devices with high k gate dielectric structure [2]. High-k gate dielectrics have been used for reducing transistor gate leakage current in the advanced nano-scale CMOS device technology. [2] Recently, conventional SONOS flash memory is replaced with SOHOS memory device. However, SOHOS device has worse data retention characteristic as well known. [2] The effects of radiation response of a few hafnium-based MOS devices have been reported. [2–3] But the data retention reliability of hafnium-based SONOS–like device as TID radiation sensor has not been well studied and it will be the main subject of this study. In order to improve the data retention performance of hafnium-based SONOS–like device for TID radiation sensor application, an aluminum doped titanium nitride–silicon oxide–hafnium oxide–silicon oxide–silicon device with fluorine plasma treatment (hereafter F-Al-MOHOS) is fabricated. The electrical performance of F-Al-MOHOS with various doping treatment after radiation exposure including radiation induced charge generation effect and charge-retention characterization are the main subjects of discussion in this report.

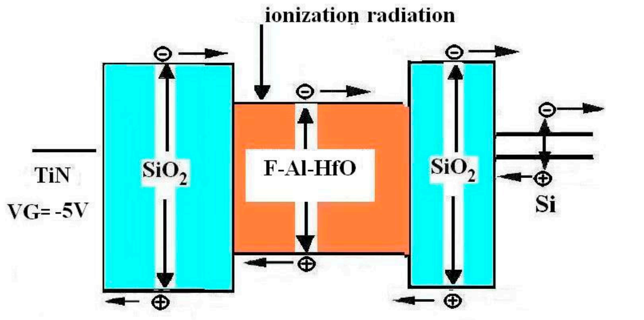
2. Experimental Section

F-Al-MOHOS devices with various doping treatment listed in Table 1, the N-channel MOHOS device were fabricated at the Taiwan National Nano Device Laboratories (NDL, Hsin-Chu, Taiwan). Starting wafers were 6" silicon (100) orientation with boron doped type substrates with a resistively of 15–25 Ω•cm. The tunneling silicon oxide SiO_2 was formed by using an advanced clustered vertical furnace on the wafers and its thickness was 3~5 nm, which was measured by spectroscopic ellipsometer. After the tunneling oxide formation, Si_3N_4 (10~20 nm) was deposited as the charge-trapping layers by using low-pressure chemical vapor deposition (LPCVD) for N (MONOS) device and HfO_2 films (10~20 nm) were deposited as the charge-trapping layers for the H (MOHOS) device, with precursors Hf (tert-butoxy) $_2$ (mmp) $_2$ in a metal organic chemical vapor deposition (MOCVD) system at 400 ~ 550°C. Al doped HfO_2 films were deposited as the charge-trapping layers for A1 and A2 sample, using Hf (tert-butoxy)$_2$(mmp)$_2$ and aluminum isopropoxide precursors in a metal organic chemical vapor deposition (MOCVD) system at 400 ~ 550 °C. A composition ratio between 20% and 30% of Al in Al doped MOHOS sample (hereafter Al-MOHOS) is achieved by controlling the deposition process parameters for A1 and A2 sample. To manipulate the F profile, CF_4 plasma with 30 sccm at 50W for 30 s condition was performed on (1) "F1" sample (CF_4 plasma before HfO_2 deposition) and on (2) "F2" sample (CF_4 plasma after HfO_2 deposition), and on (3) "AF" sample (CF_4 plasma before and after HfO_2 deposition) . However F1 sample and F2 sample, F treatment before HfO_2 deposition (hereafter pre F-MOHOS) and F treatment after HfO_2 deposition (hereafter post F-MOHOS), were prepared without Al doping. But AF sample, F treatment before and after HfO_2 deposition (hereafter pre-post F-MOHOS) was prepared with 20% Al doping. The blocking oxide (100–200 Å thickness) was deposited using LPCVD tetra ethyl oxysilane (TEOS) $Si(OC_2H_5)_4$. The control gate with 200~400 nm TiN metal gate was formed by the DC sputtering for all samples. The resulting structure is illustrated the Figure 1a. After gate patterning, source and drain were formed by implantation with arsenic atoms which were activated at 900°C for 30s. For comparison purpose, all the devices listed in Table 1 are with the same thickness of tunneling oxide, trapping oxide and block oxide.

In this paper, the V_T shifts due to Gamma irradiation on the F-Al-MOHOS devices prepared with various doping treatment were measured. The Gamma irradiation was performed on the F-Al-MOHOS devices with negative gate bias stress (NVS) ($V_G = -5$ V) by using a ^{60}Co irradiator source at room temperature. The V_T change of F-Al-MOHOS devices with various doping treatment were examined after the Gamma irradiation. The V_T was measured at room temperature from the experimental results of I_D-V_G curves by using a HP4156A parameter analyzer. Figure 1b shows the charge generation and trapping states of the gate dielectric for the F-Al-MOHOS device under NVS after ionization radiation exposure.



(a)

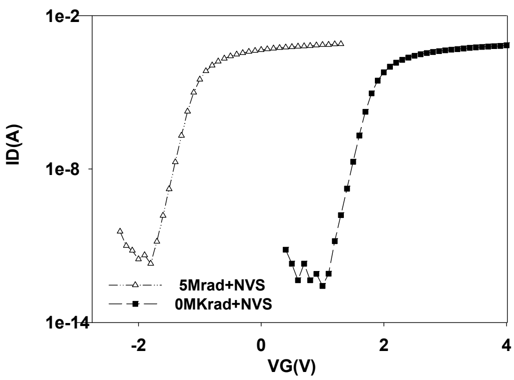


(b)

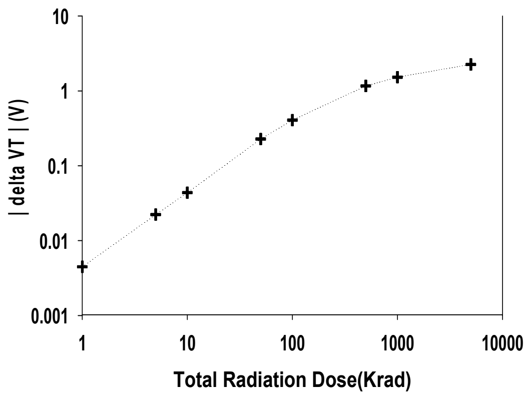
Figure 1. F-Al-MOHOS device (**a**) schematic cross-section (**b**) charge generation and trapping during irradiation.

Table 1. MOHOS devices prepared with various doping treatment in HfO_2 trapping layer.

	N	H	A1	A2	F1	F2	AF
Trapping layer	Si_3N_4	HfO_2	HfO_2	HfO_2	HfO_2	HfO_2	HfO_2
Al doping	no	no	20%	30%	no	no	20%
F treatment	no	no	no	no	Pre HfO_2 deposition	Post HfO_2 deposition	Pre and post HfO_2 deposition

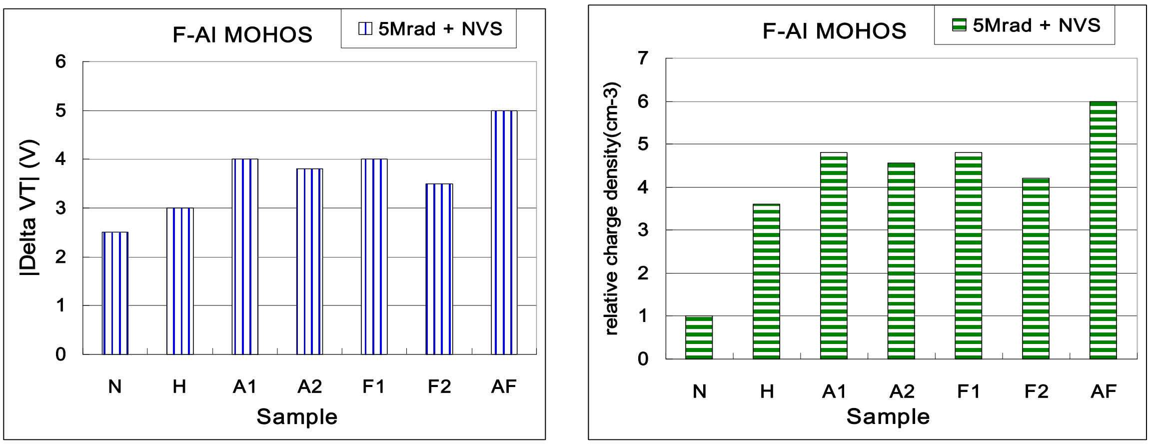


(a)



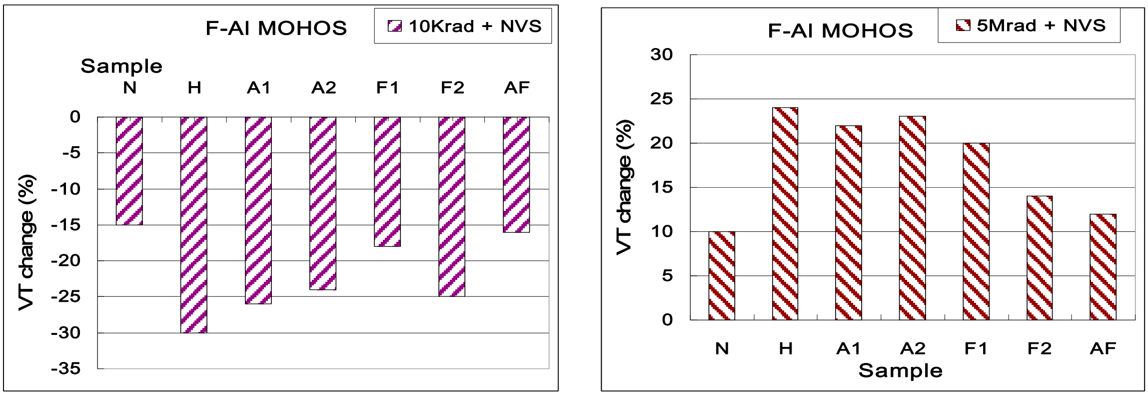
(b)

Figure 2. (**a**) I_D-V_G curve for MOHOS device after 5 Mrad TID gamma irradiation; (**b**) |dela V_T| increase as a function of Gamma radiation TID for MOHOS device.



(a) (b)

Figure 3. Comparison for F-Al-MOHOS devices with various doping treatment after 5 Mrad TID irradiation (**a**) for |Delta V_T| (**b**) for relative charge density.



(a) (b)

Figure 4. Comparison for V_T change with 10yrs retention time under $V_G = -5$ V for varies F-Al-MOHOS devices after (**a**) 10 krad TID irradiation (**b**) 5 Mrad TID irradiation.

3. Results and Discussion

Figure 2a shows I_D-V_G curve for a typical MOHOS device with NVS ($V_G = -5$ V) and processed with Gamma radiation up to 5 Mrad TID. After 5Mrad irradiation, a significant negative V_T shift of the MOHOS device is observed in the figure which is a result of increase of positive charges in the trapping layer caused by ionization radiation. The radiation-induced negative V_T shift in the irradiated MOHOS device is induced by a combination of loss stored charge in the HfO_2 trapping layer and a build-up of positive charge from asymmetric trapping of electrons and holes in the trapping layer. [1,3] The |delta V_T| of MOHOS device increases as a function of Gamma TID is indicated in Figure 2b. It also shows a quasi-linear correlation of |delta V_T| versus Gamma TID below 100 krad in log scale, but |delta V_T| increases more sharply after Gamma irradiation levels up to 100 krad TID. [1,3]

The |delta V_T| and charge density comparison after 5Mrad TID Gamma irradiation for various F-Al-MOHOS devices shown in Table 1 are illustrated in Figure 3a and Figure 3b, respectively. The trapped charge density can be calculated from delta V_T using Terman method. [2] The radiation induced V_T shift of MOHOS without doping is more significant than that of SONOS, which results from more radiation induced trapped charges into the HfO_2 trapping layer than Si_3N_4 charging layer. The improvement on the radiation induced V_T shift effect can be achieved by tuning a suitable Al ratio in HfO_2 and the results indicate that more significant TID radiation induced charging effect is achieved with 20% Al content in the HfO_2 trapping layer in this study, as shown in Fig3a. Therefore, the improvements on the radiation induced V_T shift performance in this paper may be attributed to the higher radiation induced positive trap density results from doping suitable Al content into the HfO_2 charge-trapping layer. In addition, radiation induced charge generation efficiency for MOHOS with F treatment sample (hereafter F-MOHOS) is also enhanced due to radiation induced high density positive trapped charges in F-MOHOS device due to fluorine incorporation into HfO_2 trapping layer. The experimental results show that radiation induced charge density of AF sample (F-Al-MOHOS device with 20% Al doping and F treatment both pre- and post-HfO_2 deposition) is 6 times larger than that of MONOS device.

In this section, V_T retention time stability of MOHOS devices is discussed and these properties are important for their potential application usage for TID radiation sensor. It is noted that the decay of the V_T with time for MOHOS device after irradiation is a result of charge tunneling out from the HfO_2 trapping layer. Figure 4a and Figure 4b shows the V_T stability versus time under NVS ($V_G = -5$ V) for F-Al-MOHOS devices with various implantation processes after 10Krad and 5Mrad TID Gamma irradiation, respectively. The device with HfO_2 as the charge-storage layer shows the worst charge-retention characteristics compared to Si_3N_4. It seems that the device with HfO_2 trapping layer is degraded in term of data storage capacity by providing tunneling leakage path induced by HfO_2-SiO_2 (O–H) interface trap states. [2] But the charge retention performance of Al-MOHOS can be increased by increasing the Al doping ratio up to 30%. Doping high percentage of Al into pure HfO_2 film can enhance the crystallization temperature of Al-HfO_2 compound (Aluminum doped hafnium oxide) and improve the charge retention characteristic of the device due to improvement of leakage current after high temperature S/D annealing processes. [4] Meanwhile, the charge-retention characteristic of F plasma treatment MOHOS device has also been significantly improved. It shows that the charge-retention performance of the F-MOHOS device with NVS ($V_G = -5$ V) after low TID (10 kard) irradiation, the condition of pre-F treatment is better than post-F treatment. But the charge-retention performance after high TID (5 Mard) irradiation for the F-MOHOS device with NVS ($V_G = -5$ V), the condition of post-F treatment is better than pre-F treatment. This result obviously indicates that the pre-F-treatment is suggested to be used to improve V_T-retention for low TID irradiated MOHOS device (with positive V_T and in program state), the reason is that pre-F-treatment is viable for the passivation on the bottom tunneling path of charge storage layer (trapping oxide and tunneling oxide interface) in this case. Also, the post-F-treatment is recommended for the improvement of V_T-retention for high TID irradiated MOHOS device (with negative V_T and in erase state), because post-F-treatment is effective to passivate the top tunneling path of charge storage layer (trapping oxide and block oxide interface) in this device. [5]

4. Conclusions

The experimental results show that radiation induced charge density of F-Al-MOHOS device with 20% Al doping and pre-post F treatment is 6 times larger than that of MONOS device. In brief, the significant improvements in terms of radiation induced charging effect and charge-retention characterization of F-Al-MOHOS device may be achieved by doping suitable Al content and pre-post F treatment for the HfO2 charge-trapping layer. The F-Al-MOHOS reported in this study has demonstrated their potential application for non-volatile TID radiation sensing application in the future.

Acknowledgments

The authors would also like to thank National Nano Device Laboratories (NDL), National Tsing Hua University (NTHU), and Nation Chiao Tung University (NCTU) to provide the instruments for wafer fabrication and testing. This paper was funded in part by the National Science Council (NSC) sponsor.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Draper, B.; Dockerty, R.; Shaneyfelt, M.; Habermehl, S.; Murray, J. Total dose radiation response of NROM-style SOI non-volatile memory elements. *IEEE Trans. Nucl. Sci.* **2008**, *55*, 3202–3205.
2. Cheng, Yonghong; Ding, Man; Wu, Xinglong; Xin Liu; Wu Kai Irradiation Effect of HfO2 MOS Structure under Gamma-ray. In Proceedings of the IEEE International Conference on Solid Dielectrics, Bologna, Italy, June 30 – July 4, **2013**
3. Hsieh, W. C.; Lee, H. D.; Jong, F. C. An Ionizing Radiation Sensor Using a Pre-Programmed MAHAOS Device. *Sensors* **2014,** *14,* 14553-14566.
4. Tsai, P.-H.; Chang-Liao, K.S.; Liu, C.-Y.; Wang, T.-K.; Tzeng, P.J.; Lin, C.H. Novel SONOS-Type Nonvolatile Memory Device with Optimal Al Doping in HfAlO Charge-Trapping Layer. *IEEE Electron Device Lett.* **2008**, *29*, 265–268.
5. Wu, W.C.; Lai, C-S; Wang T-M; Wang J-C; Hsu C. W.; Lo W-C; Chao, T.S. Carrier Transportation Mechanism of the TaN/HfO2/IL/Si Structure With Silicon Surface Fluorine Implantation. *IEEE Trans. Electron Devices.* **2008**, *55*, 1639–1646.