Performance Improvement of SAONOS Device as UV-total-dose Nonvolatile Sensor with Al$_2$O$_3$/SiO$_2$ Bilayer Blocking Oxide

Wen-Ching Hsieh, Fuh-Cheng Jong, and Wei-Ting Tseng

1Department of Opto-Electronic System Engineering, Minghsin University of Science and Technology, Xinxing Rd, 1, Xinfeng 30401, Taiwan, ROC
2Electronic Engineering Department, Southern Taiwan University of Science and Technology, 1, Nan-Tai Street, Yungkang District, Tainan 71005, Taiwan, ROC

(Received June 17, 2019; accepted May 20, 2020)

Keywords: UV, sensor, radiation, SAONOS

A silicon–alumina oxide–silicon oxide–silicon nitride–silicon oxide–silicon device with a bilayer Al$_2$O$_3$/SiO$_2$ blocking oxide (SAONOS device) is a candidate ultraviolet (UV) nonvolatile total dose (TD) radiation sensor. In this work, UV radiation induces a significant increase in the threshold voltage $V_T$ for an SAONOS device under positive gate voltage (PGV). The change in $V_T$ for the SAONOS device after UV radiation has a correlation with UV-TD up to 100 mW·s/cm$^2$. The experimental results indicate that the radiation-induced increase in $V_T$ for the SAONOS device under PGV is nearly 3 V after 100 mW·s/cm$^2$ TD-UV radiation. The performance of the SAONOS device as a UV nonvolatile TD sensor was thus improved. Meanwhile, the experimental results show that the $V_T$ retention performance of the SAONOS device after UV irradiation is also improved after 10 years of retention. The SAONOS device in this study has demonstrated its feasibility for UV nonvolatile TD radiation sensing application in the future.

1. Introduction

The measurement of ultraviolet (UV) irradiation total dose (TD) is very important in various UV radiation applications. Semiconductor dosimeters have many advantages. The dose-sensing areas of semiconductor dosimeters are very small, and their dose sensitivity can be high in a small constrained space. A silicon–alumina oxide–silicon oxide–silicon nitride–silicon oxide–silicon device with a bilayer Al$_2$O$_3$/SiO$_2$ blocking oxide (hereafter SAONOS device) has been shown to be suitable for nonvolatile UV irradiation TD sensor applications.$^{(1-3)}$ UV irradiation induces a significant increase in the threshold voltage $V_T$ of the SAONOS device, and this UV-induced increase in $V_T$ is correlated with UV-TD. The reliability characteristic of $V_T$ retention for the SAONOS device is good, even after 10 years of retention. The UV-TD information can be permanently stored and accumulated in this nonvolatile SAONOS device.$^{(1-6)}$

For UV-TD data writing, UV irradiation was applied simultaneously with a positive gate voltage (PGV) to the SAONOS device. Under UV irradiation and a PGV, negative charges are injected from the substrate into the charge-trapping layer of the nonvolatile SAONOS device,
where they are trapped. The build-up of negative charges changes the threshold voltage $V_T$, and the $V_T$ shift depends on the absorbed TD of UV irradiation. As a result, negative charges are accumulated permanently in the trapping layers of the SAONOS device. This is the UV-radiation-induced charging process in the nonvolatile SAONOS device.\(^{(7,8)}\)

In this paper, we propose a device with a bilayer alumina oxide–silicon oxide $\text{Al}_2\text{O}_3/\text{SiO}_2$ structure as the charge-blocking layer. This device shows improved sensitivity and reliability as a UV-TD sensor compared with a device with a single uniform blocking layer. A SAONOS device with silicon oxide and alumina oxide as the bilayer stack charge-blocking layer was proposed in this study. The UV-radiation-induced charging effect and the charge-retention reliability of the SAONOS devices fabricated in this study were significantly improved. The electrical characteristics of the SAONOS devices under various UV-TD conditions, including the radiation-induced charge effect and charge-retention reliability, are the main subjects of this study. Figure 1 shows a cross-sectional view of one of the SAONOS devices.

### 2. Experimental Details

Three types of SAONOS devices were prepared by adjusting the charge-blocking layer composition of the SAONOS devices in this study. SAONOS device structures were fabricated on a Si $\langle 100 \rangle$ substrate with a p-type resistivity of 15–25 ohm-cm. We used SiO$_2$ (obtained by thermal oxidation) for the tunneling oxide, Si$_3$N$_4$ [by chemical vapor deposition (CVD)] for the trapping layer, SiO$_2$ [by high-temperature CVD (HTO)] and Al$_2$O$_3$ [by metal-organic chemical vapor deposition (MOCVD)] for the blocking oxide, and Si [polysilicon, by low-pressure chemical vapor deposition (LPCVD)] for the gate material for the SAONOS device. The three types of SAONOS devices prepared by adjusting the composition of the charge-blocking layer during deposition are listed in Table 1: (1) a device with a single SiO$_2$ (HTO) layer as the charge-blocking layer (hereafter SONOS device), (2) a device with a single high-$k$ Al$_2$O$_3$ layer as the charge-blocking layer (hereafter SANOS device), and (3) a device with Al$_2$O$_3$/SiO$_2$ (Al$_2$O$_3$/HTO) as the bilayer stack charge-blocking layer (hereafter SAONOS device). The SiO$_2$–Si$_3$N$_4$–SiO$_2$ (hereafter ONO) gate stack consisted of a 1000–2000 Å silicon nitride layer and 50–150 Å bottom and top oxide layers. The polysilicon layer (200–400 nm) used for the control gate was formed by LPCVD. For comparison, the three types of SAONOS devices had the same thicknesses of the tunneling oxide, trapping nitride, and blocking oxide layers.

| Symbol | Charge-blocking layer                  |
|-------|--------------------------------------|
| O     | SiO$_2$ (single layer)               |
| A     | Al$_2$O$_3$ (single layer)           |
| AO    | Al$_2$O$_3$/SiO$_2$ (bilayer)        |

Fig. 1. (Color online) Cross-sectional view of an SAONOS device.
Before UV-TD data writing, a negative gate voltage (hereafter NGV) of \(-40\) V was first applied to the SAONOS device to “erase” the native charge in the alumina oxide–silicon nitride–silicon oxide AONO trapping layer of these SAONOS devices before UV irradiation. During UV-TD data writing, UV irradiation (UV LED, wavelength 400 nm) was supplied simultaneously with a PGV to the SAONOS device. The various UV irradiation and PGV conditions are listed in Table 2. After UV-TD data writing, \(V_T\) was measured at room temperature using an HP4156A parameter analyzer. The experimental results of the gate capacitance at various applied gate voltages (\(C_G-V_G\)) were obtained with a computer-controlled HP4284 parameter analyzer, and the \(C_G-V_G\) curves were measured by sweeping \(V_G\) at room temperature.

3. Results and Discussion

3.1 Radiation-induced \(V_T\) shift in SAONOS device after UV irradiation

Figure 2 shows the \(C_G-V_G\) curves for an SAONOS device before and after UV irradiation. The SAONOS device is initially in the erased state. An NGV (\(V_G=-40\) V) was first applied to the SAONOS device to “erase” the native charge in the ONO trapping layer. For UV-TD data writing, UV irradiation and a PGV (\(V_G=20\) V) were applied simultaneously to the SAONOS device. As shown in Fig. 2, \(V_T\) is about \(-2\) V for the SAONOS device before UV irradiation and about 1 V for the device after a UV-TD of 100 mW·s/cm\(^2\) under a PGV (\(V_G=20\) V). As illustrated in Fig. 2, the \(C_G-V_G\) curve of the SAONOS device shifted to the right after UV-TD of 100 mW·s/cm\(^2\) under a 20 V PGV. This indicates that a UV-TD of 100 mW·s/cm\(^2\) induces an increase in \(V_T\) of 3 V for the SAONOS device under a PGV of 20 V. This positive \(V_T\) shift is in agreement with previous studies\(^{(1-3)}\) and is due to an increase in the net total negative trapped charges accumulated in the AONO gate dielectric layer after UV-TD irradiation. This radiation-induced positive \(V_T\) shift in the UV-irradiated SAONOS device under a PGV of 20 V results from electrons excited by UV photons being injected over the Si-SiO\(_2\) potential barrier into the trapping layer and finally being trapped in the nitride trapping layer of AONO.\(^{(1-3)}\)

The UV radiation writing induces a significant increase in \(V_T\) for the SAONOS device. It is considered that this change in \(V_T\) is mostly due to the significant increase in the number of trapped electrons in the gate dielectric AONO after UV-TD data writing. It is considered that

### Table 2

| Symbol  | UV TD (mW·s/cm\(^2\)) | PGV (V) |
|---------|-----------------------|---------|
| U0V0    | 0                     | 0       |
| U100V0  | 100                   | 0       |
| U0V20   | 0                     | 20      |
| U100V20 | 100                   | 20      |

Fig. 2. \(C_G-V_G\) curve for an SAONOS device before UV irradiation and after UV-TD of 100 mW·s/cm\(^2\).
the number of trapped electrons in the gate insulator due to UV-TD data writing is greater than the number of trapped holes in the gate dielectric AONO after UV-TD data writing. This change in $V_T$ is correlated with the number of trapped charges and also with the TD of UV radiation. These trapped charges are accumulated in the gate dielectric layer, so the UV-TD record cannot be destroyed or disturbed by UV-TD data writing or reading. The UV-TD data in the SAONOS device can be erased to the original null state by the opposite charge injection mechanism.

3.2 $V_T$ increase vs UV TD in SAONOS device after UV irradiation

The increase in $V_T$ is plotted against UV-TD for the SAONOS device under a PGV of 20 V in Fig. 3. The increase is correlated with the increase in UV-TD and also with the increase in the number of negative trapped charges in the gate dielectric. However, $V_T$ increased more slowly when UV-TD was larger than 30 mW/s/cm$^2$. The experimental results of this study are in agreement with those of previous studies.(1–3)

The $V_T$ shift induced by the UV-TD for the SAONOS device was greater under a PGV of 20 V than under a PGV of 10 V. Under a higher PGV, electrons were swept by a higher electric field and more electrons were captured by the larger number of charge-trapping centers of the ONO trapping layer. $V_T$ of the SAONOS device changed significantly under a high PGV ($V_G = 20$ V) even with irradiation with a low UV-TD (5 mW/s/cm$^2$), but $V_T$ of the SAONOS device did not change significantly under a low PGV ($V_G = 10$ V) even with irradiation with a high UV-TD (100 mW/s/cm$^2$). The change in $V_T$ of the SAONOS device was ignorable under only UV irradiation (without a PGV), and also the change in $V_T$ was ignorable under only a PGV (without UV irradiation). It is considered that both UV-TD irradiation and a PGV must be applied to the SAONOS device simultaneously to write UV-TD radiation data, and that the significant increase in $V_T$ is due to a significant increase in the number of trapped electrons in the gate dielectric AONO layer after simultaneous UV-TD irradiation and PGV. The experimental results of this study are in agreement with those of previous studies. (1–3)

A comparison of changes in $V_T$ for the three SAONOS devices with different charge-blocking layers after a UV-TD of 100 mW/s/cm$^2$ under a PGV of 20 V is shown in Fig. 4.
To enable a comparison, the three SAONOS devices had the same thicknesses of the tunneling oxide, trapping nitride, and blocking oxide layers. The $V_T$ shift for the SANOS/SAONOS device was greater than that for the SONOS device after UV irradiation, as shown in Fig. 4, which resulted from the fact that the number of UV-TD radiation-induced charges trapped in the SANOS/SAONOS device is greater than that in the SONOS device under a PGV. Note that the SANOS device with a single Al$_2$O$_3$ blocking layer demonstrated a slightly larger $V_T$ shift than the SAONOS device with a bilayer stack Al$_2$O$_3$/SiO$_2$ charge-blocking layer after UV irradiation as shown in Fig. 4. Furthermore, the SAONOS device with a bilayer stack Al$_2$O$_3$/SiO$_2$ charge-blocking layer demonstrated a larger $V_T$ shift than the SONOS device with a single SiO$_2$ blocking layer after UV irradiation as shown in Fig. 4. As mentioned before, the Al$_2$O$_3$ blocking layer is a high-$k$ dielectric material and therefore shows a larger increase in $V_T$ after UV irradiation under a high PGV than the single SiO$_2$ blocking layer. This result also agreed with previous studies for an Al$_2$O$_3$ blocking layer in a metal–silicon oxide–silicon nitride–silicon oxide–silicon (MONOS) device. Therefore, the SANOS/SAONOS device has a high-$k$ Al$_2$O$_3$ blocking layer with a larger volume and a greater build-up of radiation-induced negative charges due to UV irradiation, and therefore showed a larger $V_T$ increase after UV irradiation under a high PGV than the SONOS device. It is interesting to note that the UV-TD radiation-induced increase in $V_T$ of the SANOS device was nearly twice that of the SONOS device after a 100 mW/s/cm$^2$ UV-TD under a 20 V PGV.

### 3.3 $V_T$ stability vs retention time

$V_T$ vs retention time for an SAONOS device before and after irradiation with a 100 mW/s/cm$^2$ UV-TD under a 20 V PGV is illustrated in Figs. 5 and 6, respectively. As illustrated in Fig. 5, the increase in $V_T$ with time for the SAONOS device is a result of negative charges naturally tunneling from the tunneling oxide into the nitride trapping layer of the SAONOS device before UV irradiation. As shown in Fig. 6, the decrease in $V_T$ with time for the UV-irradiated SAONOS device is a result of UV-radiation-induced negative charges naturally tunneling out from the nitride trapping layer into the tunneling oxide. For the SONOS-type nonvolatile device, it was difficult for the electrons in the trapping layer to escape to the control gate owing

![Fig. 5. $V_T$ vs retention time for SAONOS device before UV irradiation.](image1)

![Fig. 6. $V_T$ vs retention time for SAONOS device after UV-TD of 100 mW/s/cm$^2$ under PGV of 20V.](image2)
to the relatively large barrier height of the thick SiO₂ blocking oxide. As a result, negative charges accumulated permanently in the layers. The predicted change in $V_T$ after 10 years of retention was extrapolated from the experimental $V_T$–$T$ curve after 1 year of retention, as shown in Figs. 5 and 6. The charge-retention loss of the nonvolatile SAONOS device after 10 years of retention was predicted to be below 10%.

Figures 7 and 8 respectively show comparisons of the change in $V_T$ after 10 years of retention for the three types of SAONOS devices with different charge-blocking layers before and after irradiation with 100 mW·s/cm² UV-TD under a 20 V PGV. The loss of stored negative charges from the SANOS device after UV irradiation was greater than that of the SONOS device, as shown in Figs. 7 and 8. As explained previously, the larger negative-charge loss with the retention time was observed for the SANOS device owing to the smaller energy band gap of Al₂O₃ than that of high-temperature-annealed SiO₂. In contrast, a smaller negative-charge loss with the retention time was observed for the SONOS device owing to the larger energy band gap of HTO SiO₂ than that of Al₂O₃. In comparison, the SAONOS device showed better reliability as a UV-TD sensor than the SANOS device. This result also agreed with previous studies. Note that the SAONOS device demonstrated better UV-induced charge-retention reliability characteristics than the SANOS device. Because the SAONOS device has HTO SiO₂ as a part of the charge-blocking layer, it exhibited a better charge-retention reliability characteristic than the SANOS device before and after UV illumination. The charge-retention loss of the nonvolatile SAONOS device after 10 years of retention was below 10%. The nonvolatile SAONOS device had very good reliability in terms of $V_T$ retention, even after 10 years. The UV-TD information can also be permanently stored and accumulated in the nonvolatile SAONOS device.

4. Conclusions

The sensitivity and reliability of an UV-TD sensor are both increased if the charge-blocking layer composition is varied in the right way. Regarding the trade-off between UV-TD sensor sensitivity and reliability, the SAONOS device with a bilayer stack Al₂O₃/SiO₂ as the charge-blocking layer simultaneously showed a higher UV-TD sensitivity response performance.
and better reliability as UV-TD sensor. We demonstrated that using Al$_2$O$_3$ with a high dielectric constant $k$ as a charge-blocking layer markedly improves the UV-TD sensitivity. The UV-TD sensitivity decreases with decreasing HTO SiO$_2$ charge-blocking layer composition ratio. However, HTO SiO$_2$ with a charge-blocking layer having a higher energy band gap is associated with good retention of negative charges trapped inside the charge-trapping layer. The retention of negative charges inside the trapping layer increases with the HTO SiO$_2$ charge-blocking layer composition ratio. Also, the retention of negative charges inside the trapping layer decreases with decreasing high-$k$ Al$_2$O$_3$ blocking layer composition ratio. The SONOS device shows better UV-TD sensing reliability than the SANOS device but poorer UV-TD sensitivity performance as a UV-TD sensor. Because of the trade-off between the UV-TD sensitivity and the UV-TD sensing reliability, an optimal charge-blocking composition is required to optimize the UV-TD sensitivity performance and the UV-TD sensing reliability. Both UV-TD sensitivity and UV-TD sensing reliability are important for UV-TD sensors, so we used a bilayer stack Al$_2$O$_3$/SiO$_2$ as the charge-blocking layer instead a single blocking layer for this study. Because the UV-TD response performance and reliability have the same importance, the thicknesses of the Al$_2$O$_3$ and SiO$_2$ layers in the bilayer stack trapping layer were equal in this study. As shown from the experimental data, the increase in $V_T$ of the SAONOS device was nearly 3 V, which was nearly twice that of the SONOS device after 100 mW/cm$^2$ UV-TD irradiation under a PGV of 20 V. The UV-irradiation-induced change in $V_T$ for the SAONOS device also had a correlation with UV-TD up to 100 mW/cm$^2$ irradiation. However, $V_T$ of the SAONOS device did not change significantly with only 100 mW/cm$^2$ UV-TD irradiation (without PGV) or with only a PGV (without UV-TD irradiation). The charge-retention loss of the nonvolatile SAONOS device after 10 years of retention was below 10%. The results obtained in this study have demonstrated that UV-TD information can be permanently stored and accumulated in the nonvolatile SAONOS device.

**Acknowledgments**

The authors thank the National Nano Device Laboratories (NDL), National Tsing Hua University (NTHU), and National Chiao Tung University (NCTU) for providing the instruments needed for wafer fabrication and testing. This study was funded in part by the National Science Council (NSC).

**References**

1. W. C. Hsieh, H. T. Lee, F. C. Jong, and S. C. Wu: Proc. 2013 Int. Conf. Advanced Infocomm Technology (IEEE, 2013) 163.
2. F. C. Jong, W. C. Hsieh, H. T. Lee, and S. C. Wu: Sens. Mater. 8 (2018) 1831.
3. A. Abraham, N. Nicola, N. Diana, and M. Curiel: Key Eng. Mater. 605 (2014) 380.
4. W. C. Hsieh, H. T. Lee, F. C. Jong, and S. C. Wu: Sens. Mater. 5 (2016) 577.
5. W. C. Hsieh, H. T. Lee, F. C. Jong, and S. C. Wu: Sens. Mater. 9 (2016) 1023.
6. W. C. Hsieh, H. T. Lee, F. C. Jong, and S. C. Wu: Sens. Mater. 7 (2017) 969.
7. T. R. Oldham and F. B. McLean: IEEE Trans. Nucl. Sci. 50 (2003) 483.
8. Y. Cheng, M. Ding, X. Wu, X. Liu, and K. Wu: Proc. 2013 Int. Conf. Solid Dielectrics (IEEE, 2013) 764.
9. J. P. Colonna, E. Nowak, and G. Molas: Proc. 27th Int. Conf. Microelectronics (MIEL) (2010) 1.
About the Authors

**Wen-Ching Hsieh** received her B.S. degree in physics from National Cheng Kung University (NCKU), Tainan, Taiwan, in 1986 and her Ph.D. degree from the Institute of Nuclear Science of National Tsing Hua University (NTHU), Hsinchu, Taiwan, in 1994. From 1994 to 1995, she was with Winbond Electronics Corporation, Hsinchu, Taiwan, as a research engineer in the Memory R&D Division, where she worked on the development of flash EEPROM memory devices. In 1996, she joined the Memory R&D Division of Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan, as a technical manager, where she worked on the simulation and characterization of flash memory devices. Since 2000, she has been with the Department of Opto-Electronic System Engineering in Minghsin University of Science and Technology (MUST), Hsinchu, Taiwan, where she is currently an associate professor. She is the supervisor of the Semiconductor Photosensor Nanodevice Laboratory at MUST. Her research interests are radiation/photosensor devices using advanced NVM device processes including high-k gate dielectrics and metal gates. She has published over 50 technical papers.

**Fuh-Cheng Jong** received his B.S. degree in electrical engineering from Chinese Culture University (CCU), Taipei, Taiwan, in 1987 and his Ph.D. degree from the Institute of Electronics Engineering of National Chiao Tung University (NCTU), Hsinchu, Taiwan, in 1997. From 1994 to 1996, he was with Winbond Electronics Corporation, Hsinchu, Taiwan, as a research engineer in the Memory Product Division, where he worked on the development of flash EEPROM memory devices. In 2000, he joined the Memory R&D Division of Macronix, Hsinchu, Taiwan, as a technical manager, where he worked on the characterization of flash memory devices. Since 2002, he has been with the Department of Electronic Engineering in Southern Taiwan University, Tainan, Taiwan, where he is currently an assistant professor.

**Wei-Ting Tseng** received his B.S. degree in opto-electronic system engineering from Minghsin University of Science and Technology (MUST), Hsinchu, Taiwan, in 2018. His research interests are photosensor devices using advanced NVM device processes including high-k gate dielectrics.