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UV Total Dose Nonvolatile Sensor Using Silicon–Oxide–Nitride–Oxide–Silicon Capacitor with Oxy-nitride as Charge-trapping Layer

Fuh-Cheng Jong,[1] Wen-Ching Hsieh,[2*] Hao-Tien Daniel Lee,[3] and Shich-Chuan Wu[4]

[1]Electronic Engineering Department, Southern Taiwan University of Science and Technology,
1, Nan-Tai Street, Yungkang District, Tainan 710, Taiwan
[2]Department of Opto-Electronic System Engineering, Minghsin University of Science and Technology,
Xinxing Road 1, Xinfeng 30401, Taiwan
[3]Treasure Giant Technology Inc. 3F-1, 42, Lyushuei Road, Hsinchu City 30068, Taiwan
[4]National Nano Device Laboratories, No. 26, Prosperity Road 1, Hsinchu Science Park, Hsinchu 30078, Taiwan

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Silicon–oxide–nitride–oxide–silicon (SONOS) capacitor devices with an oxy-nitride as the charge-trapping layer (O-SONOS) could be candidates for UV total dose (TD) nonvolatile sensors. UV radiation induces a significant increase in the threshold voltage V_T of the O-SONOS UV TD nonvolatile radiation sensors. The experimental results indicate that the UV-induced increase in V_T for the O-SONOS capacitor device under positive gate bias stress (PGBS) is nearly 2 V after 100 mW·s/cm^2 TD UV radiation. The change in V_T for the O-SONOS capacitor after UV irradiation is also correlated with UV TD up to 100 mW·s/cm^2 irradiation. The charge-retention loss of the nonvolatile O-SONOS capacitor after a 10-year retention is below 10%. The UV TD information can be permanently stored and accumulated in nonvolatile O-SONOS capacitor devices. The O-SONOS capacitor device used in this study has demonstrated the feasibility of nonvolatile UV TD sensing.

1. Introduction

The measurement of UV irradiation total dose (TD) is very important in various UV radiation applications, such as biotechnology and medical technology. Semiconductor dosimeters offer 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–oxide–nitride–oxide–silicon (SONOS) capacitor 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 SONOS capacitor device and this UV-induced increase in V_T for the SONOS capacitor is correlated with UV TD. The reliability characteristic of V_T retention for the SONOS capacitor device is good, even after a 10-year retention. The UV TD information can be stored and accumulated in this nonvolatile SONOS capacitor device permanently.(1–6)

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[*] Corresponding author: e-mail: wchsieh@must.edu.tw
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For UV TD data writing, UV irradiation together with positive gate bias stress (PGBS) was impinged simultaneously on the SONOS capacitor device. Electrons from the valence band of the Si substrate can be excited by UV photons and the UV irradiation induces ionized electron–hole pairs in the silicon substrate of the SONOS capacitor device. The survival yield of the electron–hole pairs (escape from the recombination after UV radiation excitation in the substrate) depends on the electric field under PGBS.(7,8) Under PGBS, negative charges are injected from the substrate into the charge-trapping layer and trapped in the charge-trapping layer of the nonvolatile SONOS capacitor device. The build-up of negative charge changes the threshold voltage V_T, and the V_T shift depends on the absorbed TD of the UV irradiation. Electrons find it difficult to escape to the control gate owing to the relatively large barrier height of the thick SiO_2 blocking oxide. As a result, negative charges are accumulated permanently in the trapping layers of the SONOS capacitor device. This is the UV-radiation-induced charging process in the nonvolatile SONOS capacitor device.

However, the improvement of the UV-radiation-induced charging effect and the charge-retention reliability characterization of a SONOS device after UV irradiation have not been well studied; they are discussed in this study. A SONOS device with oxynitride as the charge-trapping layer (O-SONOS) was proposed in this study. The UV-radiation-induced charging effect and the charge-retention reliability of the O-SONOS devices were significantly improved. The electrical characteristics of the O-SONOS devices under various UV TD conditions, including radiation-induced charge effect, gate leakage current, and charge-retention reliability, are the main subjects of this study. Figure 1 shows the cross-sectional view of the SONOS devices. Figure 2 shows the charge generation and trapping states of the gate dielectric in the O-SONOS capacitor device after UV irradiation.

2. Experimental Details

The O-SONOS devices are prepared by adjusting the Si–O–N composition ratio during the nitride deposition of the SONOS capacitor for this study. SONOS capacitor structures were

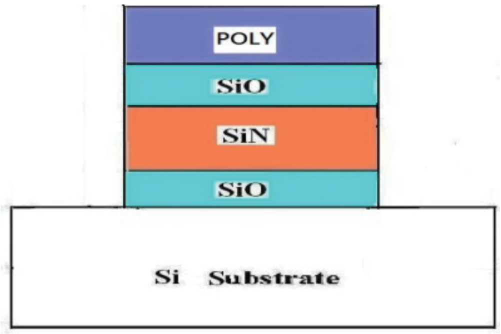


Fig. 1. (Color online) Cross-sectional view of a SONOS capacitor device.

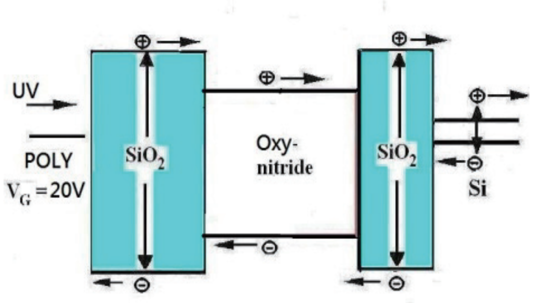


Fig. 2. (Color online) Charge generation and trapping in the O-SONOS capacitor after UV irradiation.

fabricated on a p-type resistivity 15–25 Ω-cm Si <100> substrate. We used thermal SiO_2 for the tunneling oxide, chemical vapor deposition (CVD) nitride Si_3N_4 for the trapping layer, CVD tetraethyl orthosilicate (TEOS) SiO_2 for the blocking oxide of the gate dielectric, and low-pressure CVD (LPCVD) poly silicon for the gate material. The tunneling silicon oxide (SiO_2) was formed on the wafers using an advanced clustered vertical furnace. After the tunneling oxide was formed, silicon nitride (Si_3N_4) was deposited as the charge-trapping layer by LPCVD on the SONOS capacitor device. Two types of SONOS capacitor devices were prepared by adjusting the gas flow-rate ratio of SiH_2Cl_2–NH_3 and SiH_2Cl_2–N_2O during charge-trapping nitride film deposition: (1) SONOS capacitor with standard nitride ($SiH_2Cl_2:NH_3 = 0.25:1$) as the charge-trapping layer (STD-SONOS), and (2) SONOS capacitor with oxy-nitride ($SiH_2Cl_2:NH_3 = 2:1$ and $SiH_2Cl_2:N_2O = 0.15:1$) as the charge-trapping layer (O-SONOS). The SiO_2–Si_3N_4–SiO_2 (ONO) gate stack consisted of a 1000–2000 Å silicon nitride and 50–150 Å bottom and top silicon oxides. The poly silicon (200–400 nm) was formed by LPCVD for the control gate. For comparison, the two types of SONOS capacitor devices had the same thicknesses of the tunneling oxide, trapping nitride, and blocking oxide layers. Figure 1 shows the cross-sectional view of the SONOS capacitor devices.

Before UV TD data writing, a negative gate bias stress (NGBS) of −40 V was impinged on the SONOS capacitor devices first to "erase" the native charge in the ONO trapping layer of these SONOS devices before UV irradiation. During UV TD data writing, UV irradiation (UV LED, wavelength 400 nm) together with PGBS was applied simultaneously on the SONOS capacitor devices. The various UV irradiation and PGBS conditions are listed in Table 1. After UV TD data writing, V_T was measured at room temperature using a HP4156A parameter analyzer. The experimental results of gate capacitance applied at various 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. Figure 2 shows the charge generation and trapping states of the gate dielectric in the O-SONOS capacitor device after UV irradiation.

3. Results and Discussion

3.1 Radiation-induced V_T shift in O-SONOS after UV irradiation

Figure 3 shows the C_G–V_G curve for a O-SONOS device before and after UV irradiation. The initial state of the O-SONOS capacitor device is in the erased state. NGBS ($V_G = -40$ V) was impinged on the O-SONOS capacitor device first to "erase" the native charge in the ONO trapping layer. For UV TD data writing, UV irradiation together with PGBS ($V_G = 20$

Table 1
Symbol list for various UV TD and PGBS conditions on O-SONOS device.

Symbol	UV TD (mW·s/cm^2)	PGBS V_G (V)
V0E0	0	0
V0E100	100	0
V20E0	0	20
V20E100	100	20

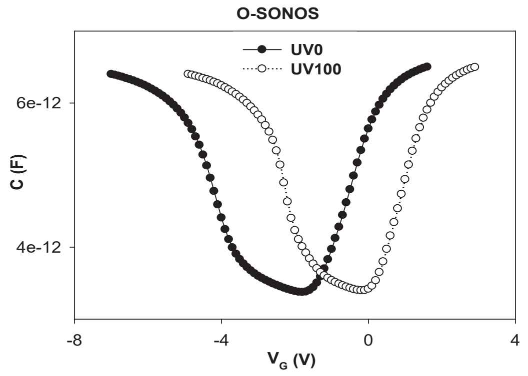


Fig. 3. C_G–V_G curve for an O-SONOS device before UV irradiation and after UV TD 100 mW·s/cm^2 irradiation.

V) was impinged simultaneously on the O-SONOS capacitor devices. As shown in Fig. 3, V_T is about 0 V for the O-SONOS capacitor device before UV irradiation, and it is about 2 V for the O-SONOS device after 100 mW·s/cm^2 TD UV irradiation under PGBS (V_G = 20 V). As illustrated in Fig. 3, the C_G–V_G curve of O-SONOS shifted to the right after UV TD irradiation up to 100 mW·s/cm^2 under 20 V PGBS. This indicates that 100 mW·s/cm^2 TD UV irradiation induces an increase in V_T (about 2 V) for the O-SONOS capacitor under 20 V PGBS. This positive V_T shift result is in agreement with previous studies.(1–3)

The positive V_T shift is due to an increase in the net total negative trapped charges accumulated in the ONO gate dielectric layer after UV TD irradiation under 20 V PGBS. These radiation-induced positive V_T shifts in the UV-irradiated O-SONOS device under 20 V PGBS result from electrons excited by UV photons, and then injected under 20 V PGBS over the Si–SiO_2 potential barrier into the trapping layer, and finally trapped in the nitride trapping layer of ONO.(1–3)

UV TD irradiation and PGBS were applied on the O-SONOS capacitor device simultaneously for writing data by UV radiation. When the O-SONOS capacitor structures are subjected to UV TD irradiation, electrons from the silicon substrate can be excited by UV photons. These free carriers are swept by an electric field under PGBS over the Si-SiO_2 potential barrier and injected into the ONO gate dielectric layer, and some of these carriers are captured by the charge trap centers in ONO trapping layer. The UV radiation writing induces a significant increase in V_T for O-SONOS capacitor devices. It is considered that this V_T change is mostly due to the significant increase in the amount of electron trapped charges in the gate dielectric ONO after UV TD data writing. It is considered that the amount of trapped electrons in the gate insulator due to UV TD data writing is greater than the amount of trapped holes in the gate dielectric ONO after UV TD data writing. The change in V_T in this case can be correlated to the amount of trapped charges and the exposure TD of UV radiation as well. These trapped charges are accumulated in the gate dielectric layer, so the UV TD record cannot be destroyed or disturbed by the UV TD data write and read. For the UV TD data erase, the data in the SONOS capacitor devices can be erased to the original null state by the charge injection mechanism.

3.2 V_T increase vs UV TD in O-SONOS capacitor after UV irradiation

The V_T increase is plotted against the UV irradiation TD for O-SONOS capacitors under 20 and 10 V PGBS as shown in Fig. 4. The V_T increase as a function of UV TD for the O-SONOS capacitor device under 20 V PGBS is shown in Fig. 4. The increase in O-SONOS V_T can be correlated to the increase in UV TD and the increase in the amount of negative trapped charges in the gate dielectric as well. However, V_T increased more slowly when the UV TD is larger than 30 mW·s/cm^2. The experimental results of this study are in agreement with those of previous studies.(1–3)

The dependence of the V_T shift on UV TD for O-SONOS was clearer under 20 V PGBS than under 10 V PGBS, as shown in Fig. 4. Under a higher PGBS, electrons are swept by a higher electric field and more electrons were captured by more charge trap centers of the ONO trapping layer.

Figure 5 shows the V_T change vs PGBS for an O-SONOS capacitor device after various UV TD irradiations. The V_T of O-SONOS capacitors was changed visibly under a high PGBS (V_G = 20 V) even with low UV TD (5 mW·s/cm^2) irradiation, but the threshold voltage of O-SONOS capacitors was not changed significantly under low PGBS (V_G = 10 V) even with high UV TD (100 mW·s/cm^2) irradiation, and also changed negligibly with a high PGBS (V_G = 20 V) under zero UV TD irradiation (0 mW·s/cm^2). It is considered that the increase in threshold voltage is due to an increase in the amount of electron trapped charges in the gate dielectric ONO layer after UV TD irradiation together with PGBS.

The comparisons of V_T increase in the two types of SONOS devices under various UV irradiation conditions are shown in Figs. 6(a) and 6(b). The symbol list for various UV and PGBS conditions on the SONOS device is shown in Table 1. As illustrated in Fig. 6(a), the change in the V_T of SONOS was ignorable under only UV TD irradiation conditions (without PGBS), and also ignorable under only PGBS conditions (without UV TD irradiation). It is considered that both UV TD irradiation and PGBS should be applied to the O-SONOS capacitor

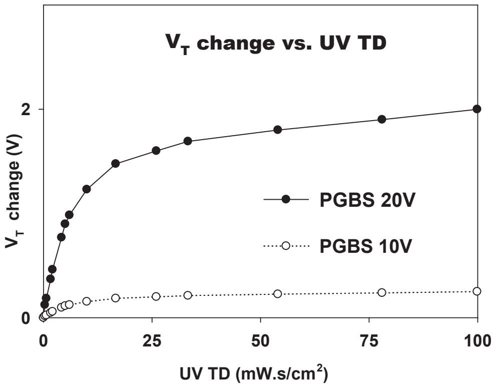


Fig. 4. Dependence of V_T increase on UV irradiation TD for a O-SONOS under 20 and 10 V PGBS.

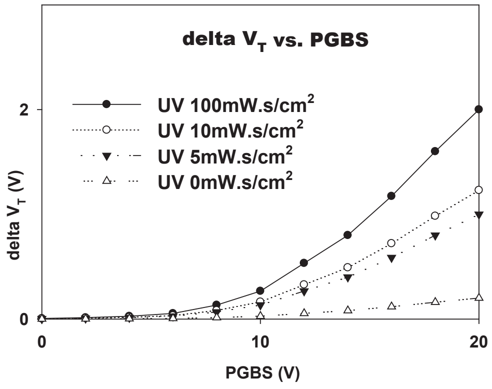


Fig. 5. Delta V_T vs PGBS for an O-SONOS device after UV 100 mW·s/cm^2 TD irradiation, UV 10 mW·s/cm^2 TD irradiation, UV 5 mW·s/cm^2 TD irradiation, and UV 0 mW·s/cm^2 TD irradiation.

device simultaneously for writing UV TD radiation data, and the significant increase in V_T is due to a significant increase in the amount of electron trapped charges in the gate dielectric ONO layer after UV TD irradiation and PGBS simultaneously. As shown in Fig. 6(b), the UV TD radiation-induced V_T increase of the O-SONOS device was 1.4 times larger than that of the STD-SONOS device after 100 mW·s/cm^2 UV TD under 20 V PGBS. The UV TD radiation-induced V_T shift of the O-SONOS capacitor is more significant than that of the STD-SONOS capacitor as shown in Fig. 6(b), which results from the fact that the amount of UV TD radiation-induced charges trapped in the O-SONOS capacitor is greater than that in the STD-SONOS capacitor under PGBS. For comparison, the two types of SONOS capacitor devices had the same thicknesses of the tunneling oxide, trapping nitride, and blocking oxide layers.

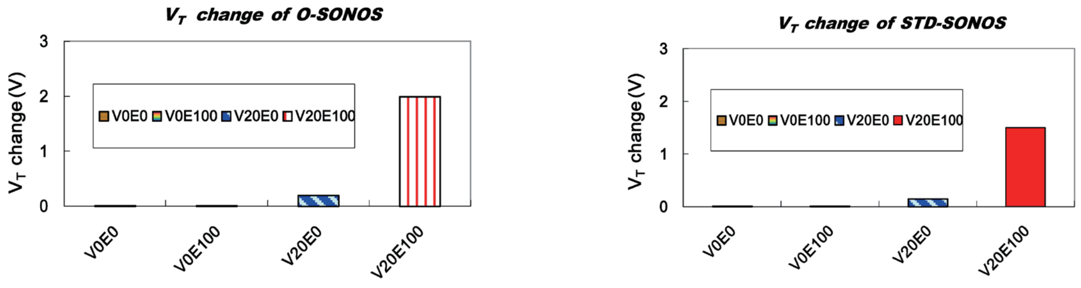
3.3 Measurement of gate leakage current

The gate leakage current vs gate voltage (I_G–V_G) curves for an O-SONOS capacitor device before and after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS are shown in Fig. 7. As illustrated in Fig. 7, the gate oxide leakage current of the O-SONOS capacitor device did not increase significantly after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS.

The gate currents of the two types of SONOS capacitor devices at V_G 20 V after various UV irradiations are indicated in Figs. 8(a) and 8(b). As illustrated in the figures, the gate current of the O-SONOS capacitor device at V_G 20 V did not increase significantly after various UV irradiations. The gate current of the STD-SONOS device at V_G 20 V increased more significantly than that of the O-SONOS capacitor after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS.

3.4 V_T stability vs retention time

The V_T vs retention time for an O-SONOS capacitor device before and after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS is illustrated in Figs. 9(a) and 9(b), respectively. As illustrated in Fig. 9(a), the increase in V_T with time for the pre-UV-irradiated O-SONOS



(a)

(b)

Fig. 6. (Color online) (a) V_T change of O-SONOS devices after various UV irradiations and (b) V_T change of STD-SONOS devices after various UV irradiations.

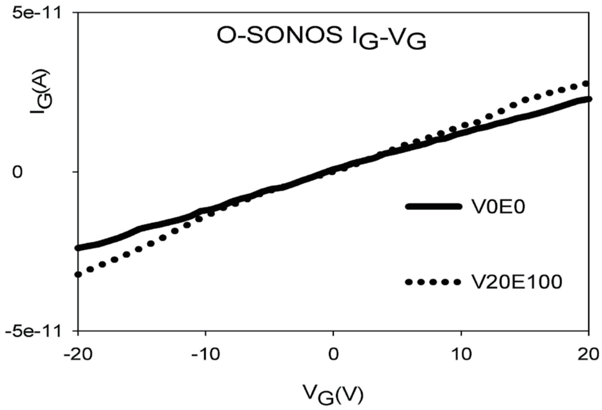
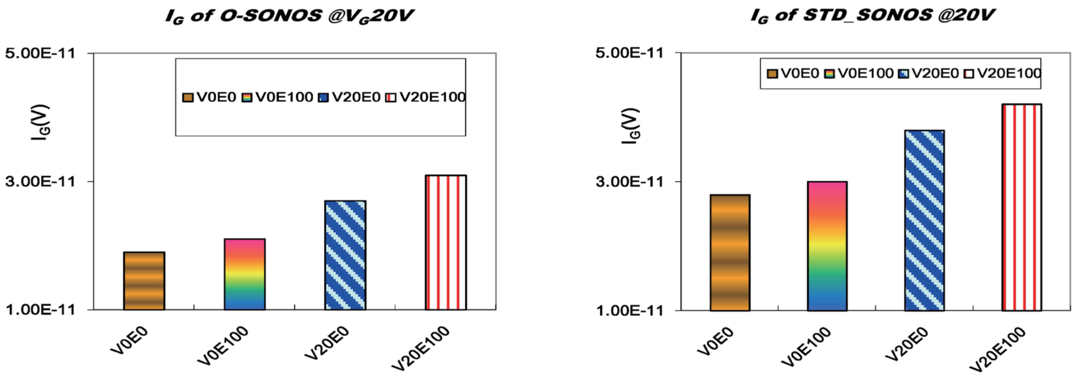
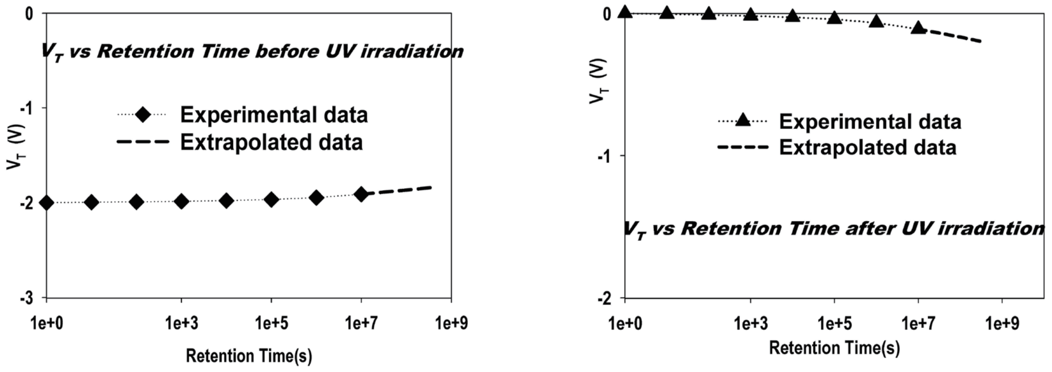


Fig. 7. Gate leakage current vs gate voltage (I_G–V_G) curves for an O-SONOS device before UV irradiation and after UV TD 100 mW·s/cm^2 irradiation under 20 V PGBS.



(a) (b)

Fig. 8. (Color online) Gate currents of (a) O-SONOS devices at V_G = 20 V after various UV irradiations and (b) STD-SONOS devices at V_G = 20 V after various UV irradiations.

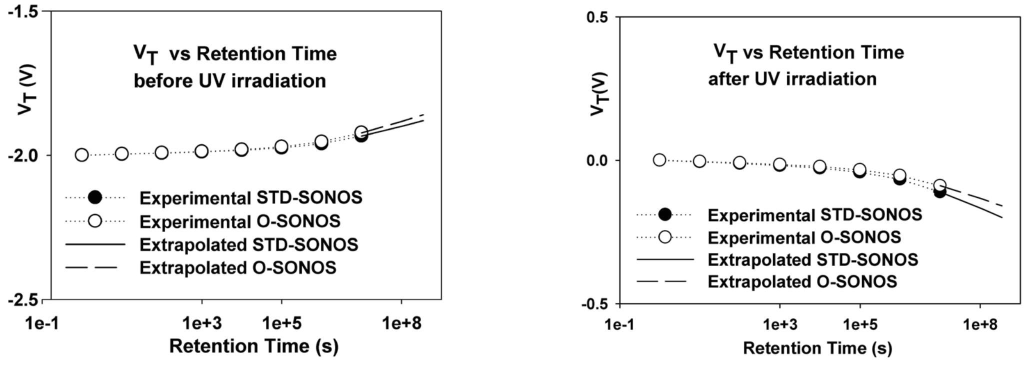


(a) (b)

Fig. 9. V_T vs retention time for an O-SONOS device: (a) before UV irradiation and (b) after UV TD 100 mW·s/cm^2 irradiation under 20 V PGBS.

capacitor device is a result of negative charges naturally tunneling from the tunneling oxide into the oxy-nitride trapping layer of the O-SONOS device before UV irradiation. As shown in Fig. 9(b), the decrease in the V_T with time for the post-UV-irradiated O-SONOS capacitor device is a result of UV-radiation-induced negative charges naturally tunneling out from the oxy-nitride trapping layer into the tunneling oxide. For the SONOS-type nonvolatile device, the electrons in the trapping layer find it difficult to escape to the control gate owing to the relatively larger barrier height of the thick SiO_2 blocking oxide. As a result, negative charges accumulate permanently in the layers. The predicted change in V_T after a 10-year retention was extrapolated from the experimental V_T–T curve after a 1-year retention, as shown in Figs. 9(a) and 9(b).(6,9,10)

Figures 10(a) and 10(b) show the comparison of the charge-retention reliability characteristics of the two types of SONOS capacitor devices before UV irradiation and after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS. However, the O-SONOS demonstrated better UV-induced charge-retention reliability characteristics than the STD-SONOS. This result also agreed with the previous study of an O-SONOS device with an oxy-nitride charge-trapping layer.(5,9,10) The V_T loss from the preirradiated device as a function of annealing temperature was investigated to confirm the effect of the rich incorporation of O on the gate oxide leakage current and the charge-retention reliability characteristics of SONOS in previous studies.(5,9,10) A much deeper charge trap energy level (E_{TA}) was observed for an O-SONOS with an oxy-nitride trapping layer than for the STD-SONOS in previous studies.(5,9,10) Therefore, the O-SONOS device with deeper charge traps in the oxy-nitride trapping layer showed better UV-induced charge-retention reliability characteristics than the STD-SONOS devices. The charge-retention loss of the nonvolatile O-SONOS capacitor after a 10-year retention is below 10%. The nonvolatile O-SONOS capacitor devices have very good reliability characteristics of V_T retention, even for 10 years. The UV TD information can be permanently stored and accumulated in the nonvolatile O-SONOS capacitor devices.



(a) (b)

Fig. 10. Comparison of V_T vs retention time for O-SONOS and STD-SONOS devices: (a) before UV irradiation and (b) after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS.

4. Conclusions

As shown in the experiment data, the V_T increase of the O-SONOS capacitor was nearly 2 V, and was 1.4 times larger than that of the STD-SONOS capacitor after 100 mW·s/cm^2 TD UV irradiation under 20 V PGBS. The UV-irradiation-induced change in V_T for the O-SONOS capacitor also has a strong correlation to UV TD up to 100 mW·s/cm^2 irradiation. However, the V_T of the O-SONOS capacitor was not changed clearly with 100 mW·s/cm^2 TD UV irradiation only (without PGBS) or with 20 V PGBS only (without UV TD irradiation). Moreover, the O-SONOS devices with deeper charge traps in the oxy-nitride trapping layer showed better UV-induced charge-retention reliability characteristics than the STD-SONOS devices. The 100 mW·s/cm^2 UV-induced charge-retention loss of the nonvolatile O-SONOS capacitor after a 10-year retention is below 10%. The results obtained in this study have demonstrated that the UV TD information can be permanently stored and accumulated in nonvolatile O-SONOS capacitor devices.

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