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Performance Improvement of SAONOS Device as UV-total-dose Nonvolatile Sensor with Al_2O_3/SiO_2 Bilayer Blocking Oxide

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A silicon–alumina oxide–silicon oxide–silicon nitride–silicon oxide–silicon device with a bilayer Al_2O_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_2O_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,

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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 Al_2O_3/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 <100> substrate with a p-type resistivity of 15–25 ohm-cm. We used SiO_2 (obtained by thermal oxidation) for the tunneling oxide, Si_3N_4 [by chemical vapor deposition (CVD)] for the trapping layer, SiO_2 [by high-temperature CVD (HTO)] and Al_2O_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_2O_3 layer as the charge-blocking layer (hereafter SANOS device), and (3) a device with Al_2O_3/SiO_2 (Al_2O_3/HTO) as the bilayer stack charge-blocking layer (hereafter SAONOS device). The SiO_2–Si_3N_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.

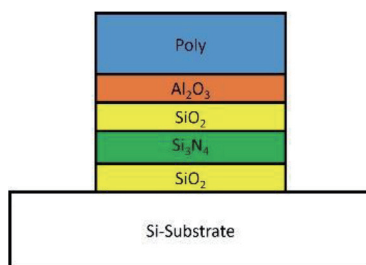

Fig. 1. (Color online) Cross-sectional view of an SAONOS device.

Table 1
Symbol list for various types of SAONOS devices with different charge-blocking layers.

Symbol	Charge-blocking layer
O	SiO_2 (single layer)
A	Al_2O_3 (single layer)
AO	Al_2O_3/SiO_2 (bilayer)

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 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 list for various UV-TD and PGV conditions for each SAONOS device.

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

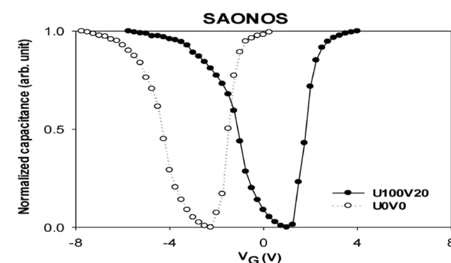

Fig. 2. C_G–V_G curve for an SAONOS device before UV irradiation and after UV-TD of 100 mW·s/cm^2.

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.

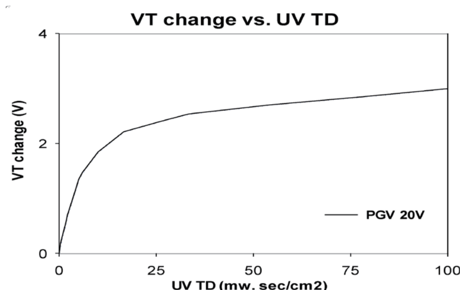

Fig. 3. Dependence of increase in V_T on UV-TD for SAONOS device under PGV of 20 V.

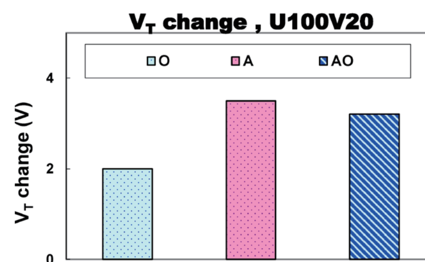

Fig. 4. (Color online) Comparison of the changes in V_T for the three SAONOS devices with different charge-blocking layers after UV-TD of 100 mW·s/cm^2 under PGV of 20 V.

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_2O_3 blocking layer demonstrated a slightly larger V_T shift than the SAONOS device with a bilayer stack Al_2O_3/SiO_2 charge-blocking layer after UV irradiation as shown in Fig. 4. Furthermore, the SAONOS device with a bilayer stack Al_2O_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_2O_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_2O_3 blocking layer in a metal–silicon oxide–silicon nitride–silicon oxide–silicon (MONOS) device.(9,10) Therefore, the SANOS/SAONOS device has a high-*k* Al_2O_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

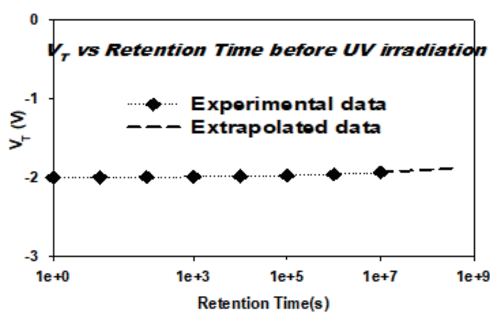

Fig. 5. V_T vs retention time for SAONOS device before UV irradiation.

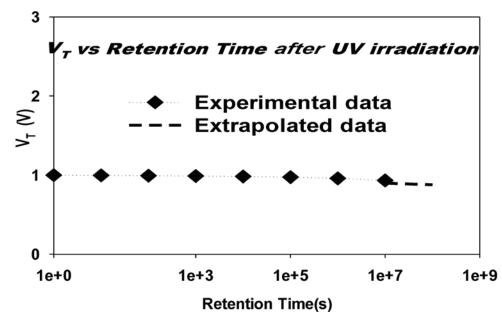

Fig. 6. V_T vs retention time for SAONOS device after UV-TD of 100 mW·s/cm^2 under PGV of 20V.

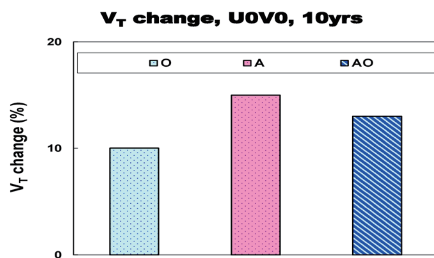

Fig. 7. (Color online) Comparison of change in V_T after 10 years of retention for three SAONOS devices with different charge-blocking layers before UV irradiation.

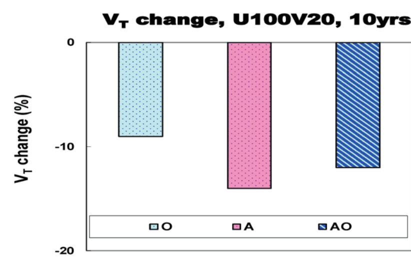

Fig. 8. (Color online) Comparison of change in V_T after 10 years of retention for three SAONOS devices with different blocking layers after UV-TD of 100 mW·s/cm^2 under PGV of 20 V.

to the relatively large barrier height of the thick SiO_2 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.[6,10,11] 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/cm^2 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 Al_2O_3 than that of high-temperature-annealed SiO_2.[5,9–13] 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 SiO_2 than that of Al_2O_3.[5,9–13] In comparison, the SAONOS device showed better reliability as a UV-TD sensor than the SANOS device. This result also agreed with previous studies.[5,9–13] Note that the SAONOS device demonstrated better UV-induced charge-retention reliability characteristics than the SANOS device. Because the SAONOS device has HTO SiO_2 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 Al_2O_3/SiO_2 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_2O_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_2O_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_2O_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_2O_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·s/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·s/cm^2 irradiation. However, V_T of the SAONOS device did not change significantly with only 100 mW·s/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.

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