Total ionizing dose effects on data retention characteristics of 55nm SONOS flash

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Abstract. This paper researched on the effect of different bias conditions on the data retention characteristics of 55nm SONOS flash at a high total dose of 200 Krad(Si). The results show that the degradation of SONOS flash data retention characteristics is the most serious under static bias condition. And the data error rate is positively correlated with read frequency. But overall, the total ionizing dose (TID) has little effect on the data retention characteristics of SONOS flash.

1. Introduction
Flash is a kind of non-volatile memory used for data storage. It has the advantages of high storage density, no loss of data when power off, multiple programming and low production cost. It is not only widely used in the field of consumer electronics, responsible for storing important programs and data information in the field of military and aerospace. Particles in space radiation environment will cause ionizing radiation effects on flash, including total ionizing dose (TID) effect and single event effect (SEE), which will cause data loss and even function failure of flash, and seriously affect the reliability of spacecraft. Therefore, it is of great significance to research on the radiation effects of flash for the development of aerospace microelectronics.

Flash has floating-gate type and charge-trapping type. In the floating-gate flash, the charge is stored in the conductive polysilicon floating-gate layer; in the charge-trapping flash, the charge is stored in the insulating silicon nitride layer and trapped by deep level traps. Due to the different ways of charge storage, the charge-trapping flash has stronger radiation resistance than the floating-gate type, which is more suitable for space radiation environment [1]. There have been many researches on the TID effects of charge-trapping flash [2-3], but there are still some limitations, such as the bias conditions are not comprehensive enough. In this paper, the effect of TID on the data retention and function of 55nm SONOS flash under different bias conditions is studied by the experiment.

2. Experimental methods

2.1. Devices
The experimental device is a kind of radiation-hardened SONOS flash test chip being developed by Beijing Microelectronics Technology Institute. The memory capacity is 64Mbit and the process size is 55nm. The basic SONOS structure is shown in Figure 1. The data "0" or "1" is stored by trapping electrons or holes in the silicon nitride. SONOS memory cells have programmed and erased two states. The programmed SONOS memory cells store electrons in the silicon nitride, representing data "0"; while the erased SONOS memory cells store holes in the silicon nitride, representing data "1".
The basic functions of flash include reading, programming and erasing. The programming and erasing operations of this flash change the threshold voltage of the SONOS memory cell by injecting electrons or holes into the silicon nitride through F-N tunneling effect. When reading, a read voltage is applied on the control gate (CG), which is between the threshold voltage of programming state and erasing state. According to the drain current, it can distinguish whether the SONOS memory cell is programmed or erased.

![Image of SONOS memory cell structure]

**Figure 1.** The structure of the SONOS memory cell.

### 2.2. Experimental methods

The TID experiment was conducted with $^{60}$Co $\gamma$-ray source, and the radiation dose rate was 50 rad(Si)/s. A total of 3 experimental groups are set up, each experimental group contains 3 identical devices. Before the experiment, ensure that all test devices function properly.

In order to study the effect of TID on two different states of SONOS memory cells, 5Ah data was written before irradiation experiment, so that the number of memory cells in programmed state and erased state accounted for half of the total memory capacity respectively.

In order to study the influence of different bias conditions on the data retention characteristics of SONOS flash, there are three kinds of conditions in the irradiation experiment: no bias state, static biased state, and dynamic read-only state. Group 1# is under no bias state, means that the device does not apply any bias voltage. Group 2# is under static bias state, means that provide 3.3V power supply voltage to the device, and the other ports are grounded to make it in standby mode. Group 3# is under dynamic read-only state, means that the device circulates read operation. The specific experimental conditions are shown in Table 1.

| Condition            | Group | Number | Data   | TID (Krad(Si)) |
|----------------------|-------|--------|--------|----------------|
| No bias              | 1#    | P1     | P2     | P3             |
| Static bias          | 2#    | P4     | P5     | P6             |
| Dynamic read-only    | 3#    | P7     | P8     | P9             |

The initial total dose was 100 Krad(Si), then 50 Krad(Si) was added each time, and the final total dose was 200 Krad(Si). After each irradiation, devices were tested in the field immediately, and each
test time was within 1 hour. After the test, the irradiation experiment was continued. This method can ensure that the annealing time at room temperature after irradiation is very short, and will not have a significant impact on the test results.

In order to study the TID effect on the data retention characteristics of the devices, after 100 Krad(Si), 150 Krad(Si) and 200 Krad(Si) irradiation, only the read test was carried out to record the number of data errors.

In order to study the TID effect on the function degradation of the devices, after 200 Krad(Si) irradiation and the completion of the read test, the devices were tested for erase, and finally tested for program.

3. Experimental results

When the total dose was 100/150/200 Krad(Si), the devices of 3 groups were tested under four different read frequencies: 6MHz, 25 MHz, 30 MHz and 40 MHz. The results are as follows:

(1) There is only data error from "0" to "1", and the error distribution is discrete.

(2) Data error rate is positively correlated with read frequency.

(3) The data error rate of the devices under static bias condition is significantly higher than that under no bias condition and dynamic read-only condition, which is the most stringent bias condition for TID experiment.

Figure 2. The average data error rate of devices with a total dose of 100/150/200 Krad(Si) under three different bias conditions.
The average data error rate of each group is shown in Figure 2(a) - 2(c). Overall, the error rate of the experimental devices is very low. When the read frequency is 40MHz after the 200Krad(Si) total dose irradiation, the maximum average error number of the devices under static bias conditions is 83, and the maximum error rate is only 2.5E-6.

When the total dose was 200 Krad(Si), all functions of experimental devices did not fail. However, when the devices were programmed with 5Ah data, the average program time increased from 50.28s to 54.12s, which means that the program function was slightly degraded.

4. Discussion

4.1. Only data error from "0" to "1"

After total dose irradiation, the experimental devices had data errors from "0" to "1". When the flash reads the stored data, it needs to apply the read voltage on the selected SONOS gate in the row direction, and charge the selected bit line through the sensitive amplifier in the column direction. The current of read IRD and reference Iref is compared by sensitive amplifier, as shown in Figure 3. If IRD is higher than Iref, the read data is "1"; if IRD is lower than Iref, the read data is "0".

![Figure 3. Current mode sensitive amplifier.](image)

There are two reasons for data errors caused by total dose irradiation.

The first reason is that the amount of charge stored in the silicon nitride trap of the SONOS memory cell changes, resulting in the V_TH drift of SONOS. Analyze the mechanism of SONOS V_TH drift under total dose irradiation:

(a) The ionization of Oxide and Silicon Nitride by γ-ray irradiation generates electron-hole pairs.
(b) The electrons or holes stored in the Silicon Nitride trap are excited to the conduction band or valence band.
(c) A large number of electrons are stored in Silicon Nitride of programmed state SONOS, which generates an electric field from the tunnel oxide and the blocking oxide to the Silicon Nitride and sweeps the electrons out of the Silicon Nitride; the electric field generated by the hole storage in Silicon Nitride of erased state SONOS is opposite to the programmed state and attracts the electrons to the Silicon Nitride.
(d) The holes become oxide-trapped charge and interface-trapped charge.
(e) Part of the electrons and holes recombine.
(f) Part of the electrons and holes are trapped in Silicon Nitride.

It is mainly (c) (d) (f) that causes the $V_{TH}$ drift of SONOS. The holes trapped faster than the electrons in the ONO stack [2]. The electrons in Silicon Nitride of programmed state SONOS are swept out, and the holes increase because of trapped faster, so the $V_{TH}$ drifts to the decreasing direction. The electrons in Silicon Nitride of erased state SONOS are attracted, and the holes increase, so the $V_{TH}$ drift is not obviously.

The second reason is that the leakage current of SONOS increases, which leads to the error of reading data. In deep submicron process, STI is usually used to isolate transistors in deep submicron process as shown in Figure 4. SONOS can be equivalent to a main transistor and two parasitic transistors in parallel. The gate oxide thickness of parasitic transistors is larger, so the $V_{TH}$ before irradiation is larger and the leakage current is lower. However, after the irradiation, the positive trap charges are generated in the oxide due to the accumulation of holes, and the larger gate oxide thickness of parasitic transistors leads to significant negative drift of $V_{TH}$, forming leakage paths.

![Figure 4](image)

**Figure 4.** Radiation accumulates charges in the STI, forming parasitic transistors in parallel with SONOS and generating leakage paths.

The above two reasons work together in the total dose irradiation, causing the $I_{RD}$ of the programmed SONOS to increase. When it is larger than $I_{ref}$, the stored data "0" will be read as "1". The $I_{RD}$ of the erased is originally larger than $I_{ref}$, even if it is increased, the correctness of the data will not be affected. Therefore, after total dose irradiation, there are only the data errors from "0" to "1" in the experimental devices.

4.2. **Data error rate is positively correlated with read frequency**

After total dose irradiation, the number of data errors changes with different read frequencies, and the error rate increases with the increase of reading frequency. It has been analyzed that SONOS will degrade due to total dose irradiation, resulting in the increase of read current $I_{RD}$. Therefore, when comparing $I_{RD}$ and $I_{ref}$ through the sensitive amplifier, the difference between them will be reduced, making the speed of current comparison slower, and finally leading to the slower speed of reading data. Therefore, as the reading frequency increases, the number of reading errors will gradually increase.

4.3. **Static bias is the most stringent bias condition**

Under total dose irradiation, the data error rate under static bias condition is significantly higher than that under no bias and dynamic read-only conditions. Irradiation generates electron-hole pairs. With the drift, diffusion and recombination of the electron-hole pairs, the holes become oxide-trapped charge and interface-trapped charge, resulting in the threshold voltage drift and leakage current.
increase. The electrons and holes generation rate \( G \) and recombination rate \( R \) introduced by irradiation are expressed by the following formula [4]:

\[
GR = G - R = Dg_0Y(E)
\]

\( GR \) is the net generation rate, \( D \) is the radiation dose rate, \( g_0 \) is the initial electron-hole pairs generation rate, and \( Y(E) \) is positively correlated with the electric field.

Under the three kinds of bias conditions, the different voltage of each port will lead to different distribution of internal potential and electric field. Under the dynamic read-only condition, the electric field distribution in the memory cells is variable, which has different effects on the electrons and holes introduced by irradiation. For the selected memory cell, the positive reading voltage is applied to the gate. This state is conducive to the collection of electrons and the reverse migration of holes, and intensifies the effect of radiation on the introduction of charges. If the memory cell is not selected, the negative voltage will be applied to the gate, and the reverse movement and recombination of the carriers will weaken the previous effect. For the static bias condition, because the applied voltage is fixed, the internal electric field distribution is constant, which always intensifies the separation of electrons and holes in the same direction, weakens the recombination effect, introduces more irradiation charges, and causes the maximum degeneration. For the no bias condition, the electron-hole pairs generated by irradiation will have a large degree of recombination and less degeneration due to the absence of external electric field. Therefore, static bias is the most stringent bias condition for total dose experiment.

4.4. No functions fail just program slight degradation

After the total dose of 200 Krad(Si) irradiation, all functions of experimental devices did not fail. However, the program degenerates slightly and the program time increases. During Flash programming, it is necessary to generate high voltage through a charge pump, and transmit it to the gate of the selected SONOS memory cells through the high voltage path.

Figure 5 shows a typical Dickson charge pump, and its actual output high voltage can be calculated by the following formula [5]:

\[
V_{\text{OUT}} = V_{\text{MAX}} - R_{\text{OUT}} \times I_{\text{LOAD}}
\]

\( V_{\text{OUT}} \) is the actual output high voltage of the charge pump, \( V_{\text{MAX}} \) is the output voltage of the charge pump when the load is 0, \( R_{\text{OUT}} \) is the charge pump output resistance, and \( I_{\text{LOAD}} \) is the charge pump load current. As the load current increases, the actual output high voltage will decrease.

Under the total dose irradiation, the \( V_{\text{TH}} \) drift and leakage current increase are more serious because the gate oxide thickness of charge pump high-voltage MOS transistor is thicker than that of ordinary MOS transistor. At the same time, the leakage current of transistors and memory arrays on the high-voltage path will also increase, which will increase the load current of charge pump under irradiation and reduce the actual output high voltage, which will slow down the programming speed and increase the programming time.

![Figure 5. Dickson charge pump.](image)
The experimental device has a radiation-hardened design for the charge pump and the high voltage path, which improves the load capacity of the charge pump and reduces the leakage current of the high voltage path, so that the device has a strong radiation resistance. All functions of experimental devices did not fail under the total dose of 200Krad (Si), and just the program degenerates slightly.

5. Conclusions
In this paper, the TID effect of radiation-hardened SONOS flash in 55nm process developed by Beijing Microelectronics Technology Institute is researched on through the TID experiment. The results show that various experimental bias conditions have different effects on the data retention characteristics of SONOS flash, among which the data retention characteristics of devices under static bias condition deteriorate most seriously. It is found that the data error rate is positively correlated with read frequency. Overall, the TID has little effect on the data retention characteristics of SONOS flash.

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