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The Experimental Observation of Soft-Error Enhanced NBTI Degradation in Trigate FinFETs for the Near-cosmic Exploration of Drones

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Abstract- The near-cosmic exploration, such as airplane and drones, show significant impact in human civilization, in which ICs encounter cosmic ray that will induce soft-error-related reliability, especially when advanced trigate devices are used. This paper firstly reports soft-error enhanced NBTI degradation that can be observed by a novel *body-bias controlled random trap profiling technique*. The results show that device deterioration after X-ray irradiation and NBTI stress is much worse than those without X-ray treatment, and three damaged peaks on STI sidewalls have been detected, where the peak near S/D and STI corner is the reliability killer and reduces the life-time drastically. These results will provide and guarantee safer and reliable design of electronic systems used in the near-cosmic exploration.

1. Introduction

As cheap and reliable drones have been largely developed in recent years, people are excited about vital applications along with drones, and the near-cosmic exploration are becoming more popular, such as communication, agriculture, logistics, meteo-rology, and military applications (Fig. 1)[1]-[2]. However, the electronic devices face more challenges for near-cosmic exploration in comparison to consumer products which raise unavoidable soft-error issues, especially as trigate devices might be used in the future. Soft errors are induced by highly energetic neutrons, electrons, and protons emitting from cosmic ray which generates large quantity of hot electron-hole pairs as these radicals penetrate into devices. These pairs are re-collected by the built-in field of parasitic junctions of devices and damage the structure, resulting in dramatic increase of leakage and misallocation of stored information, (Fig. 2).

Although soft-error related reliabilities have been thoroughly studied in planar CMOS devices [3], very limited study on the trigate CMOS devices [4] can be available. In a near future, trigate device will be more popular as a key component in ICs, it raises our great interest on the analysis of soft-error in trigate devices. From these understandings, we may expect more durable and reliable drones in future near-cosmic exploration.

2. Device Preparation

Advanced 28nm poly-Si-gate bulk-trigate CMOS devices, with SiON insulator, were fabricated. Fig. 3 shows the structure. The device has typical fin width= 45nm, fin height= 10nm, and gate length= 36nm. Devices with different areas were used to examine their V_{th} variations.

3. Results and Discussion

A. Body-bias Controlled Random Trap Profiling Technique

Based on the theory of soft-error in planar devices, the radical-induced hole pairs cause the damage of S/D to channel junction. Therefore, in consideration of the triage structure, it is reasonable to be assumed that the hot holes pairs flow through the bulk between two adjacent STIs and lead to the damage on STI sidewalls. Therefore, soft-error mechanism can be evaluated from the observation of STI-sidewall traps. To realize this idea, the body-bias is applied to modulate the channel depletion region deeply into the channel depth direction so that STI-sidewall traps can be profiled, in combination with our previous random-trap fluctuation (RTF) technique on σV_{th}, [5-6], Fig. 4. To calculate the depth of channel depletion in from the fin top to the bulk, the positions of RTF can be determined, as shown in Table 1.

B. Soft-error Induced Degradation of Trigate Devices

Fig. 5 shows the generation scheme of highly-energetic radicals by X-ray radiation from the back-side of device to avoid the damage of gate oxide, which is in analogy to real cases because the radiation from the front end is shielded by the metal interconnection. Fig. 6 revealed that ΔV_{th} of the devices under X-ray is larger, compared to the control. To explain that ΔV_{th} is contributed from the STI sidewall but not gate oxide, random trap profiling technique [5] was applied, which shows comparable values under X-ray and the control. (Fig. 7). So, ΔV_{th} of device under X-ray is from STI sidewalls. By performing the steps in Table 1, the distribution of STI-sidewall traps can be obtained, (Figs. 8-10) where 2 damaged peaks on STI sidewalls were observed: the 1st is in the middle of STI sidewall and the 2nd is near the corner of S/D and STI, and the latter is much higher than the former. In Fig. 11, it is assumed that the secondary particles hit the STI sidewall and induce the 1st damaged peak on the sidewall, and then the generated hot electron-hole pairs are tore apart from the built-in field in the depletion region, where the hot holes drifted to the corner of S/D and STI, resulting in 2nd-peak generation. Since the amount of hot holes is much larger than the irradiating radicals, deterioration of the 2nd peak is dominant.

C. Soft-error Enhanced NBTI of Trigate Devices

Next, triage devices after X-ray radiation were immediately stressed under NBTI condition for pMOSFET, and the results of trap distribution are given in Fig. 12. The 3rd peak has been found on the sidewall of STI tail. In Fig. 13, during NBTI stress, the gate electrons, tunneling from the gate oxide, drift into the channel depletion region and are accelerated by the built-in field. Finally, the accelerated electrons gain sufficient energy so as to surmount the STI oxide barrier, causing the damage of the sidewall of STI tail. Meanwhile, these 3 peaks grow rapidly during NBTI stress for the devices after X-ray treatment. Especially, in Fig. 14, the 2nd peak is very close to the S/D and channel junction which dominates the deterioration of devices, and the NBTI-life-time prediction confirms this hypothesis.

In summary, with increasing interests in the near-cosmic exploration by using drones, the reliability of electronic devices posed great concerns of the soft-error related issues. To have a first hand analysis, an experimental methodology has been developed successfully to evaluate soft-error incurred on the STI sidewall of trigate devices by using a special random trap analysis technique. The results show that there are 3 damaged peaks on STI sidewall after NBTI stress and X-ray radiation. The 1st peak was generated by the X-ray bombardment in the middle of the STI-sidewall; the 2nd one is caused by hot-hole injection after the bombardment; the 3rd one is induced by the accelerated hot electrons from the gate terminal. Among them, the 2nd peak dominates the deterioration of devices since it is very close to the junction of S/D and channel. These valuable experimental observations may help us on the reliable design of trigate devices against the soft-error in the near-cosmic exploration.

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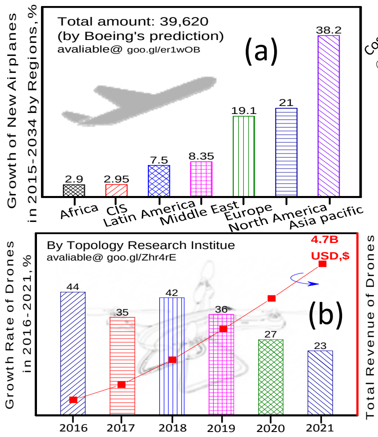

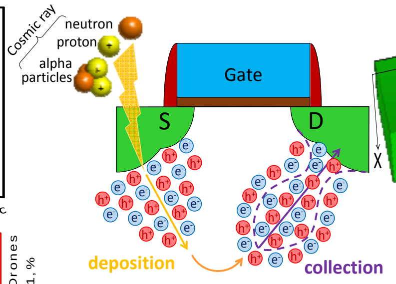

Fig. 2 Soft errors are induced by highly energetic secondary ions, particles, and radicals, which are penetrated into the devices and generate a large number of hot electron-hole pairs, resulting in the destruction of devices.

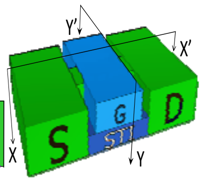

Fig. 3 The trigate MOSFET prepared in this work.

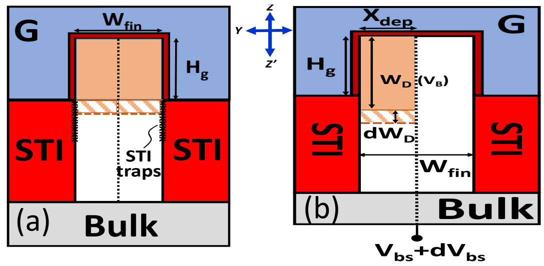

Fig. 4 (a) The hot-e-/h+ collected from the bulk to S/D will damage the sidewalls of STI, and thus create traps, i.e., by observing STI traps, the soft-error can be evaluated. **(b)** By modulating the depletion region from the fin-channel to bulk through the bulk biases, the STI traps can be evaluated from the Vth variation.

Fig. 1 Near cosmic exploration business projections: Not only (a) traditional transportation of airplanes, but also (b) the applications of drones, are increasing in the coming years. The threat of cosmic ray becomes important.

$$\begin{cases} \sigma V_{th,shift} = \sqrt{\sigma V_{th,stress}^2 - \sigma V_{th,fresh}^2} = \dfrac{q}{C_{ox}}\sigma D_{trap} & \textbf{(1)} \\ \sigma D_{trap} = \dfrac{C_{ox}}{q}\sigma V_{th,shift} & \textbf{(2)} \end{cases}$$

$$\begin{cases} W_D = \dfrac{-X_{dep} + \sqrt{X_{dep}^2 + 4\varepsilon_{si}X_{dep}/(C_{ox}Y)}}{2} & \textbf{(3)} \\ Y = \dfrac{dV_{th}}{dV_{bs}} & \textbf{(4)} \end{cases}$$

Table 1 Eqs.(1)-(2) The soft-error induced STI traps induce the random-trap-fluctuation (**RTF**). The amount of STI trap density can be determined. **Eqs.(3)-(4)** The total depletion width from the top of fin-height to the fin bulk between two adjacent STI regions, W_D, can be calculated from the body effect.

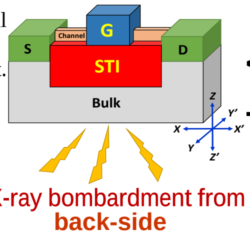

Fig. 5 To study the impact of soft-error on trigate devices, the scheme of X-ray bombardment from the back-side was applied.

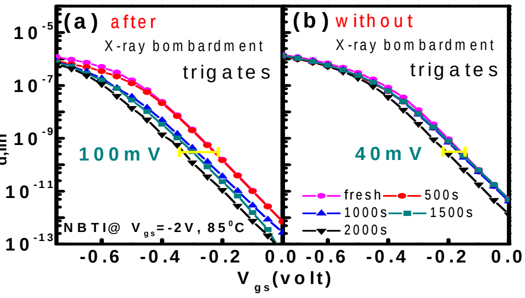

Fig. 6 The comparisons of I_dV_{gs} characteristics after NBTI stress, with and without X-ray radiations. It was found that the V_{th} shift after X-ray radiations is more serious than that without X-ray radiations.

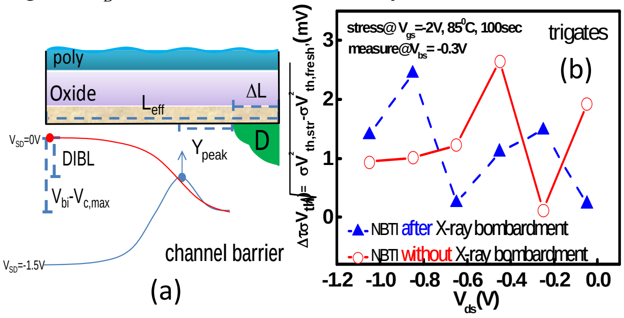

Fig. 7 (a) The method to determine the location of traps. (b) Traps generated on gate dielectric before/after X-ray radiation are comparable**.**

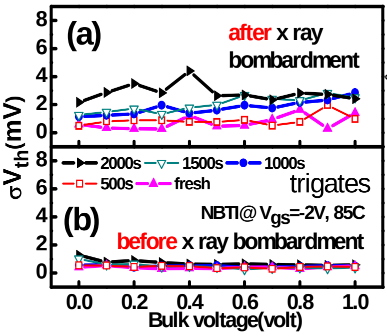

Fig. 8 The V_{th} variation is sensitive as a measure of V_{th} variation into the deep depletion region after X-ray radiation, by changing the bulk bias.

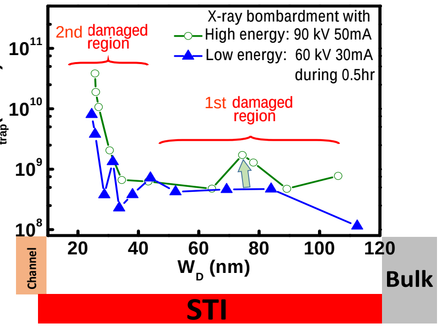

Fig. 9 From the fin top to the bulk between STI, the distributions of STI traps shows 2 peaks after X-ray radiation, i.e., one peak in the bulk between STI and the other one near the corner of STI and the channel.

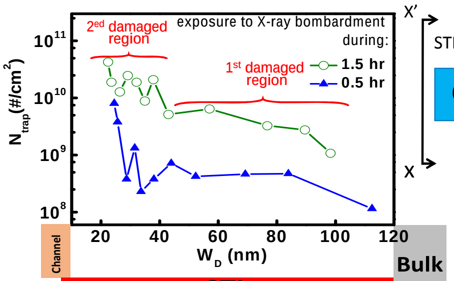

Fig. 10 After long-term bombardment under X-ray radiation, 1.5 and 0.5hrs, both 2 peaks grow rapidly, and the 2nd peak is much higher than the 1st one, which indicates that the major damage happens at the corner of STI and channel under the soft error stress.

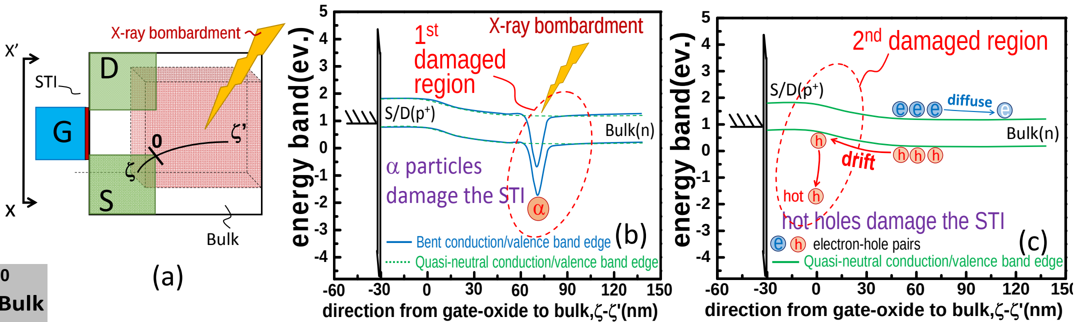

Fig. 11 To understand why there are 2 peaks generated: (a) after X-ray radiation, (b)-(c) the band-diagram from the corner of source/channel to the bulk in STI. It is assumed that the X-ray radiation has been bombarded in the bulk region between STIs, resulting in 1st damaged region, and then the hot e-/h+ pairs were tore apart. The hot holes are further drifted by the built-in field between S/D and channel and induce the damage at the corner of STI and S/D.

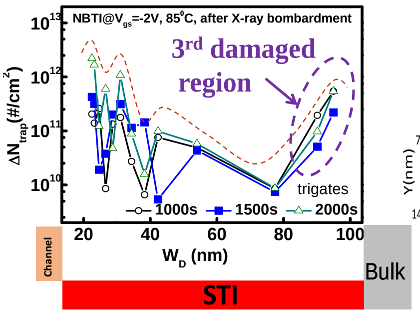

Fig. 12 The STI traps profiles after X-ray radiation and NBTI stress show that a 3rd peak was observed at the end of the STI. Moreover, it is noticed that the 2nd peak became broader and increasing.

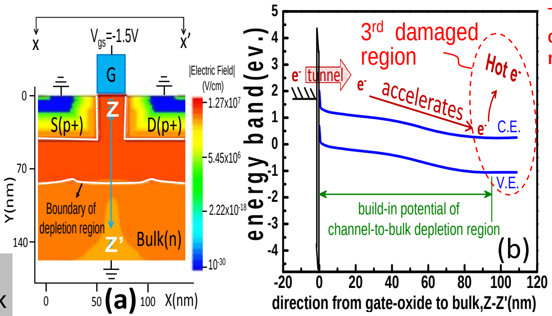

Fig. 13 (a) The simulated electric field distribution during NBTI stress, (b) the band-diagram from **Z to Z'**, in which it was shown that the electrons, tunneling from the gate oxide, have been accelerated by the built-in field in the channel depletion and became hotter so as to damage at the end of STI, resulting in the 3rd damage region.

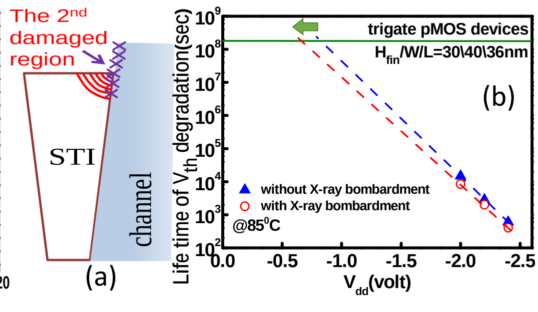

Fig. 14 (a) The 2nd peak on the STI at the S/D and STI corner after X-ray radiation and NBTI stress shows the largest impact, (b) The life-time prediction in consideration of soft-error-enhanced NBTI stress, which shows that the degradation after X-ray radiation is much worse than that without X-ray treatment.