Effect of Hydrogen Annealing on Hot-Carrier Instability of X-Ray Irradiated CMOS Devices

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In the very large scale integration (VLSI) technology, the need for high density and high performance integrated circuit (IC) chip demands advanced processing techniques that often result in the generation of high energy particles and photons. Frequently, the radiation damage are introduced by these energetic particles and photons during device processing. The radiation damage created by x-ray irradiation, which can often occur during metal sputtering process, has been shown to potentially enhance hot-carrier instability if the neutral traps which act as electron or hole traps in the silicon dioxide is not annealed out. In this paper, we investigate the effects of annealing using different hydrogen contents and temperatures on the device characteristics and hot carrier instability of 0.5 μm CMOS devices after 1500 mJ/cm² synchrotron x-ray irradiation. Three different annealing conditions were employed; 400 °C H₂, 450 °C H₂, and 400 °C H₂ + N₂. It is found that for all three different hydrogen anneals the normal characteristics of irradiated CMOS devices can be effectively recovered. The hot-carrier instability of both p- and n-channel MOSFETs are significantly enhanced after x-ray irradiation due to the creation of neutral traps and positively charged oxide traps. After high H₂ (100%) concentration anneals at 450 °C, the hot-carrier instability in irradiated n-channel devices is greatly reduced and comparable to the non-irradiated devices. Although the hot-carrier instability in p-channel devices is also significantly reduced after annealing, the threshold voltage shifts are still enhanced as compared to the devices without exposure to x-ray irradiation during maximum gate current stress. For those non-irradiated, but hydrogen-annealed p-channel devices, the hot-carrier instability was observed to be worse than the non-irradiated device without hydrogen annealing.

Key words: Radiation damage x-ray irradiation, hot carrier instability, radiation damage annealing, hydrogen annealing of insulator damage

INTRODUCTION

In the advanced CMOS technology, x-ray irradiation can often occur during device processing. The radiation effects due to x-ray have been of both practical and fundamental interests for many years. The radiation damage created by x-ray irradiation could result in degradation of MOSFET performance and long term MOSFET reliability if it is not completely annealed out. The radiation damage consists of interface traps, positively charged oxide traps, and neutral traps. The interface traps will degrade the device characteristics, whereas the positively charged oxide traps and neutral traps1,2 which can trap electrons or holes and increase the device degradation during hot-carrier injection. Although forming gas annealing can anneal out positively charged oxide traps and interface traps and recovers normal device characteristics, the residual radiation damages, mainly neutral traps, cannot be annealed out completely. Hot-carrier instability in irradiated and annealed n-3 and p-channel MOSFETs4 was shown to be enhanced due to the existence of neutral traps if the devices are stressed at the high gate current conditions, large gate bias in n-FETs and small gate bias in p-FETs. A high concentration hydrogen anneal has been used to effectively reduce the amount of residual radiation damages.6 In this paper, effects of annealing using high concentration hydrogen and different temperatures on hot-carrier instability of x-ray irradiated 0.5 μm CMOS devices are investigated.

EXPERIMENTS

CMOS devices of 0.5 μm design were used in this study. The detail fabrication processes can be found in Ref. 6. The oxide thickness is about 13.7 nm and n+-poly-gate are used for both n- and p-channel MOSFETs. Synchrotron x-ray irradiation with a dose of 1500 mJ/cm² (about 1.5 × 10⁷ rads) was performed after the completion of device fabrications. Three different annealing conditions for 30 min are employed after irradiations; (1) 400 °C H₂, (2) 400 °C H₂, and (3) 450 °C H₂. Device characteristics are measured before irradiation, after irradiation, and after annealing. Hot-carrier instability are compared between (1) devices before and after irradiations, (2) irradiated devices before and after annealing, (3) non-irradiated and irradiated devices after annealing. The procedures of radiation and annealing of test samples are summarized in Table I. Hot-carrier stress conditions employed are maximum substrate current stress for n-channel MOSFETs and maximum gate current stress for...
Table I. Summary of Irradiation and Annealing Conditions of Test Samples

<table>
<thead>
<tr>
<th>Measurement Conditions</th>
<th>Unirradiated:</th>
<th>Irradiated:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>before anneal</td>
<td>before irradiation</td>
</tr>
<tr>
<td></td>
<td>post 400°C H₂ + N₂ anneal</td>
<td>after irradiation—before anneal</td>
</tr>
<tr>
<td></td>
<td>post 400°C H₂ anneal</td>
<td>after irradiation and 400°C H₂ + H₂ anneal</td>
</tr>
<tr>
<td></td>
<td>post 450°C H₂ anneal</td>
<td>after irradiation and 400°C H₂ anneal</td>
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The device parameters monitored during hot-carrier stress are reverse saturation drain current for n-channel MOSFETs and threshold voltage for p-channel MOSFETs.

RESULTS AND DISCUSSION

Effect of X-ray Irradiation and Post-Irradiation Annealing on 0.5 μm CMOS Device Characteristics

The measured MOSFET parameters: threshold voltage, transconductance, apparent mobility, and subthreshold slope, of 0.5 μm n- and p-channel MOSFETs before and after x-ray irradiation and before and after annealing (pure H₂ or 50% H₂) are shown in Figs. 1, 2, 3, and 4, respectively. It is found that in the devices after irradiation and before annealing; (1) the threshold voltage shifts, (2) the transconductance decreases, (3) the apparent mobility decreases (4) the subthreshold slope increases. After annealing, the device characteristics were observed to be the same as before irradiation. These results suggested that the device characteristics are significantly degraded by the positively charged oxide traps and interface traps created by x-ray irradiation. The annealing after irradiation can completely anneal out positively charged oxide traps and interface traps and results in the recovery of device characteristics.

![Fig. 1](image1.png)  
**Fig. 1** — The threshold voltages of devices before and after x-ray irradiation and after annealing in 400°C H₂.

![Fig. 2](image2.png)  
**Fig. 2** — The normalized maximum transconductance of devices before and after x-ray irradiation and after annealing in 400°C H₂.

![Fig. 3](image3.png)  
**Fig. 3** — The apparent mobility of devices before and after x-ray irradiation and after annealing in 400°C H₂.

![Fig. 4](image4.png)  
**Fig. 4** — The subthreshold slope of devices before and after x-ray irradiation and after annealing in 400°C H₂.

Hot Carrier Effects

Hot carrier stress were employed to both n- and p-channel MOSFETs before irradiation, after irra-