High Pressure H$_2$/D$_2$ Annealed SONOS Nonvolatile Memory Devices

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1. Introduction

The poly-Si-oxide-nitride-oxide-silicon (SONOS) nonvolatile memory (NVM) device based on localized charge storage in charge trapping layer has received much attention due to lower program/erase (P/E) voltage, better scalability and endurance characteristics.[1] However, we need to achieve a fast P/E speed as well as long data retention time. In the retention loss model, there are several mechanisms, such as the direct back tunneling and thermal excitation of trapped charges.[2]

Therefore, the decay rate of trapped charges could be reduced by increasing the tunnel oxide thickness and the energy level of the trap.[3] Also, the generation of reduced Dit and decrease the generation of Dit under the P/E cycles which causes charge loss through tunneling oxide should be minimized to obtain the lower decay rate of trapped charges.[4][5] Especially, the decay rate of trapped charges in erase mode very much depends on Dit due to the relatively deeper hole trap than electron trap in the nitride band gap. Therefore, in order to improve the endurance and retention characteristics of SONOS NVM devices, we have proposed and investigated the new post-metallization annealing at high pressure (HP) in H$_2$ or D$_2$ ambient since HP annealing can effectively passivate Dit and decrease the generation of Dit under the P/E cycles.[6]

2. Device Fabrication

A 2-nm-thick SiO$_2$ was thermally grown as a tunnel oxide, followed by deposition of 6-nm-thick Si$_3$N$_4$ on tunnel SiO$_2$. Next, 6.5-nm-thick SiO$_2$ blocking layer was deposited by LPCVD. After fabrication of n$^+$ poly-Si gated SONOS capacitors, post-metallization annealing in HP pure H$_2$ or D$_2$ ambient was performed at 400°C for 30min. For comparison, control device was annealed in a conventional atmospheric pressure hydrogen (H$_2$/N$_2$:4%/96%) forming gas (FG).

3. Results & Discussion

In order to investigate the effect of HP post-metallization annealing on P/E speed, memory window (MW) after biasing P/E voltages at 1ms was extracted as shown in Fig. 1. It is known that high pressure post-metallization annealing has no significant effect on P/E speed.

Figure 2 shows the retention characteristics of SONOS devices annealed in HP-D$_2$ ambient at 10 atm. Compared with control samples annealed in FG ambient at 1atm (Fig. 3), HP-D$_2$ annealed SONOS devices show the lower charge decay rates both before and after 10$^7$ P/E cycles (±12V, 1ms). In addition, the better endurance characteristics were obtained as shown in Fig. 4. It could be explained by the reduced generation of Dit under P/E cycles.

To confirm the variation of Dit, quasi-static capacitance versus voltage (QSCV) curves of fabricated SONOS devices annealed in each ambient were obtained under the P/E cycles. Compared with control devices (Fig. 5), FG annealed devices at 10 atm showed a smaller Dit both before and after P/E cycles. Also, HP-D$_2$ annealed devices at 10 atm showed a lower generation of Dit under the P/E cycles than HP-H$_2$ annealed devices at 10atm (Fig. 8) due to the kinetic isotope effect of deuterium. Therefore, it is known that HP annealing is very efficient to passivate Dit and Si-D bonds reduce the generation of Dit under the P/E cycles which in turn, make the better endurance and retention characteristics of SONOS devices.

Consistently, the decay rate of trapped charges as a function of post-metallization annealing conditions was investigated as shown in Fig. 9. It was confirmed that lower charge loss rate was obtained with the decreased Dit and charge loss rate of excess hole state depended on the Dit more significantly than charge loss rate of excess electron state.

Figure 10 shows the SIMS depth profiles of hydrogen and deuterium ions in SONOS devices annealed in HP-H$_2$ or D$_2$ as well as conventional FG ambient. With increasing annealing pressure, the higher concentration of hydrogen was observed. SONOS devices annealed in HP-D$_2$ ambient clearly showed a deuteron SIMS peak. In contrast, deuteron peak was not observed in the other devices annealed in hydrogen ambient.

4. Summary

The effect of post-metallization annealing at HP in H$_2$ or D$_2$ ambient on reliability characteristics of SONOS devices has been investigated. Compared with control devices annealed in FG ambient at 1atm, SONOS devices annealed in HP pure H$_2$ or D$_2$ ambient show improved endurance and retention characteristics without the significant degradation of P/E speed. It can be explained by significantly improved Dit and a large kinetic isotope effect of deuterium that reduces the generation of Dit under the P/E electrical stress.

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References

Fig 1. (a) Program and (b) erase characteristics of fabricated SONOS devices annealed in each ambient.

Fig 2. Retention Characteristics of SONOS devices annealed in HP-D₂ (10atm).

Fig 3. Retention Characteristics of SONOS devices annealed in FG (1atm).

Fig 4. Endurance characteristics of SONOS devices.

Fig 5. QSCV curves of SONOS devices annealed in FG (1atm) as a function of P/E cycles.

Fig 6. QSCV curves of SONOS devices annealed in FG (10atm) as a function of P/E cycles.

Fig 7. QSCV curves of SONOS devices annealed in HP-D₂ (10atm) as a function of P/E cycles.

Fig 8. QSCV curves of SONOS devices annealed in HP-H₂ (10atm) as a function of P/E cycles.

Fig 9. Charge decay rate of fabricated SONOS devices annealed in each ambient.

Fig 10. SIMS depth profiles of ONO stack annealed in H₂ or D₂ ambients.
(a) Hydrogen profiles, (b) Deuterium profiles.