Improvement of TDDB reliability, characteristics of HfO$_2$ high-k/metal gate MOSFET device with oxygen post deposition annealing

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Abstract

In this work, influences of oxygen effect on an Hf-based high-k gate dielectric were investigated. A post deposition annealing (PDA) including oxygen ion after high-k dielectric deposition was used to improve reliability of the Hf-based high-k/metal gate device. The basic electrical characteristics of devices were compared with and without the PDA process. Experiment results show that the oxygen PDA did not degrade the drive current and effective oxide thickness of the Hf-based gate devices. In addition, reliability issues such as positive bias instability, negative bias instability and TDDB were also improved by the oxygen PDA significantly. During the TDDB test, the charge trapping was characterized by an in situ charge pumping system, which could make us to understand the variations of interface trap during the reliability stress easily.

1. Introduction

Hf-based dielectrics are considered as the leading high-k candidates with metal electrode for next generation of CMOS technology [1]. However, compared to the silicon oxide (SiO$_2$), the Hf-based dielectrics have a higher concentration of defects [2,3]. These defects play the role of charge trapping source, thus become one of the major issues [4–6] to cause significant reliability degradations including positive bias instability (PBTI), negative bias instability (NBTI) and TDDB (time dependent dielectric breakdown) [7,8]. Recently, it has been reported that these defects in hafnium-based oxides are oxygen-related defects, such as oxygen vacancies or oxygen interstitial defects [9,10]. Therefore, in this work we try use a post deposition annealing (PDA) under oxygen ambient to passive these trap defects. In addition, because of the mechanism of reliability degradation caused by the oxide-related defects has not been understood clearly yet, we also investigated the generation and passivation behaviors of the defect traps during the reliability degradation by combining the charge pumping system and TDDB test for the first time.

2. Experiments

A 32-nm technology was used as a vehicle to demonstrate device performances of Hf-base gate device. After standard cleaning, firstly deposited a SiO$_2$ interfacial layer at 900 °C and then the HfO$_2$ dielectric was formed by atomic layer deposition method sequentially. To study the dependence of electrical characteristics on PDA, two split HfO$_2$ transistors were fabricated with and without the oxygen PDA after HfO$_2$ layer. The oxygen PDA was performed at 500 °C for 60 s in O$_2$ ambient. Next, a TiN metal electrode was formed on top of the gate stack and followed by source/drain implant and 1000 °C activation anneal. Then, standard backend processes were employed sequentially to complete the device. Finally, basic electrical characteristics and reliability tests were executed with semiconductor parameter analyzer (HP4156B) and charge pumping measurements, respectively.

3. Results and discussions

Fig. 1 shows the $I_D/V_G$ curves of the Hf-oxide high-k gate devices. The drive current of nMOSFET is larger than that of pMOSFET for the higher mobility at n-channel. Compared to the oxygen PDA sample and control sample, no apparent differences are found in both the nMOSFET and pMOSFET. This implies that the drive current and the subthreshold swing were not degraded by the oxygen PDA. Similar results were also found in mobility measurements and the measured C/V curves as shown in the Figs. 2 and 3, respectively. As seen, the mobility did not degrade, while the C/V curves did not shift both in the nMOSFET/pMOSFET with the oxygen PDA. In addition, Fig. 3 also indicates the EOT of the oxygen PDA samples are equal to that of control sample for both nMOSFET and pMOSFET thus implies that the HfO$_2$ gate did not be re-grown.
under the condition of PDA at 500 °C for 60 s in O2 ambient. Furthermore, the gate leakage current (IG) was almost same for the samples with and without the oxygen PDA. In other words, the oxygen PDA ambient did not influence the dc characteristics of HfO2 gate more.

The impact of oxygen PDA on reliability was performed with PBI and NBI tests. In the PBI and NBI measurements, samples were stressed in gate terminal at 25 °C and V0 = V5 = V8 = 0 V. And the gate terminal voltages were Vg + 2.3 V and Vg – 1.8 V for PBI and NBI, respectively. Figs. 4 and 5 show the Ig degradation under PBI and NBI test, respectively. The oxygen PDA nMOSFET or pMOSFET has a lower Ig degradation than the control device for both long channel device (gate length = 10 μm) and short channel device (gate length = 32 nm). This means the oxygen PDA could improve the worsen reliability issue under stress. Moreover, we found the oxygen PDA also suppressed the VTH shift under NBI and PBI tests. Therefore, we conclude that the reliability degradations are strongly related to the traps in the HfO2 gate, but can be repaired by the oxygen PDA.

On the other hand, we investigated the effect of the oxygen PDA on trap generation during the reliability test with TDDB and field breakdown under a ramp voltage stress (RVS). A typical TDDB characteristic of an HfO2 gated NMOSFET stressed in Vg = 3.3 V, V5 = V8 = 0 V is illustrated in Fig. 6. Following the stress time increase, we could define the characteristic into three regions i.e., fresh region, soft breakdown SBD region and hard breakdown (HBD) region, respectively. SBD and HBD have been found to be
dependent on the quality of interfacial layer and high-k layer, respectively [11]. SBD starts with the formation of a localized conduction path in the interfacial SiO2 layer and has multi unstable conducting path. In SBD region, the gate stack does not whole breakdown, however, follows the voltage stress continuously, the traps localized areas increases and drives into high-k layer. In final, results in a gate punch through in the HBD region.

We combined a charge pumping system and TDDB test to inspect the generation of defect traps. In the past, the charge pumping system was widely used to investigate interface defects [12]. As shown in the insert of Fig. 6, the curve of Icp shifts to positive and rises up in the SBD region. This means the trap defects were continually generated from the fresh time to SBD time. However, as the stress time come to HBD region, the Icp could not be measured anymore for the huge defect traps and gate current. Thus, as indicated in Fig. 7, the oxygen PDA could extend the time for TDDB obviously in different kinds of dimensions means the oxygen PDA could passivate a lot of interface states. Similar phenomena were also found under ramp voltage stress condition as shown in Figs. 8 and 9 for the field breakdown and the Icp current of charge pumping test, respectively. Again, both the breakdown characteristic and Icp current of the oxygen PDA device are better than the control device. Furthermore, the lower Icp for the oxygen PDA device implies it has lower interface defects during the entire stress condition and thus can slow down the reliability degradation, including TDDB, NBI and PBI.

4. Conclusions

A post oxygen deposition annealing was proposed to enhance the Hf-oxide/metal-gate MOSFET device life time by passive oxide-related trap defects. The mechanism was evidenced by measuring the TDDB or field breakdown and Icp current in the same time. Thus, the device reliability issue can be improved by the oxygen deposition annealing. In addition, the oxygen deposition annealing does not lower drive current or increase oxide thickness (EOT).

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References
