Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 250-251

A-3-4

nMOSFET Reliability Improvement attributed to the Interfacial Dipole formed by La Incorporation in HfO_2

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1. INTRODUCTION

Metal/high-k nMOSFETs with a low threshold voltage (V_{th}) have been successfully demonstrated with La doped HfO_2 or $HfSiO_x$ by several groups [1,2,3,4,5]. Electropositive La diffused to the high-k/SiO_2 interface forms dipole, which shifts the band offset and therefore the effective work function (EWF) of electrode (Fig. 1). La incorporation did not cause mobility degradation. And even a reduced bulk trapping has been reported with La incorporation [1]. Thus, La doped HfO_2 gate dielectric seems to be a very strong candidate for future nMOS dielectric, but the effects of La-induced dipole on device performance and dielectric reliability have not been studied thoroughly. In this work, we investigate the reliability of nMOSFETs with La-doped HfO_2 dielectrics, whose device performance and V_{th} are suitable for future technology nodes applications.

2. EXPERIMENTAL

Transistors were fabricated using a gate-first integration flow. HfO_2 films were deposited by atomic layer deposition (ALD) The post high-k deposition treatments included plasma nitridation and a post-nitridation anneal. A molecular beam deposition (MBD) process was employed to deposit an ultra thin LaO_x cap on the high-k film before a metal gate electrode deposition. Mobility was extracted from 10μm x 1μm transistors using the NCSU CVC and mob2d models. For comparison, control HfO_2 devices were fabricated without the LaO_x cap. Both the La-doped HfO_2 gate stack and the control HfO_2 had the same final physical thicknesses (t_{phy} ~ 2.5 nm) and equivalent oxide thicknesses (EOT ~ 0.95 nm).

X-ray photoelectron spectroscopy (XPS) analysis shows that LaO/HfO phase segregation/separation occurred after the thermal process (Fig.2). Electron energy-loss spectroscopy (EELS) analysis confirmed that La piled up near the HfO_2/SiO_2 interface [2].

3. RESULTS AND DISCUSSION

To study the transient charging characteristics, pulsed drain current-gate voltage (I_d-V_g) and conventional DC I_d-V_g measurements were performed (Fig. 3). Due to a very thin high-k dielectric (<2 nm), transient charge trapping was negligible for both the La-doped and control device structures, leading to excellent mobility characteristics (Fig. 4) [6].

Fig. 5 presents gate leakage characteristics for gate and substrate injection. The La-doped HfO_2 shows a higher breakdown voltage (V_{bd}) for both accumulation and inversion regimes than control HfO_2. Both devices showed abrupt dielectric breakdown during the sweeps in inversion. Interestingly, the La-doped HfO_2 showed a multiple-step breakdown behavior under a gate injection stress. This difference might be due to the early breakdown at the interfacial oxide layer. Negligible area dependence of V_{bd} in both dielectrics suggests that the La incorporation did not cause additional extrinsic defects (Fig. 6). The temperature dependence of the gate leakage was insignificant for both dielectrics, which indicates that La incorporation did not increase the gate leakage (Fig. 7).

For gate injection stress (negative bias), the gate leakage characteristics plotted vs. oxide voltage (V_{ox}) were similar for both dielectrics (Fig. 8), with the initial breakdown occurring at the same V_{ox}. Unlike the abrupt breakdown in the control HfO_2, the gate leakage current in the La-doped sample progressively increased step-wise as the range of the voltage sweep increased. This result suggests that there is multiple breakdown step initiated from the interfacial oxide layer as mentioned above (Fig. 9) [7]. The inset in Fig. 9 presents the corresponding V_{th} and subthreshold slope. Negligible V_{th} changes indicate that these interface breakdowns do not mitigate the interface dipole effect.

During the inversion sweep, however, the leakage current (J_g) in the La-doped devices was significantly reduced as shown in Fig. 10. This result can be explained by the effective barrier height increase, which was induced by the dipole formation as illustrated in Fig.11. Using the FN tunneling approximation, the difference in barrier height between the control HfO_2 and La-doped HfO_2 was calculated to be about 0.3eV. This offset value well matched with the flatband voltage (V_{fb}) shift and it is a strong evidence for the dipole formation.

Therefore, the La-induced dipole field at the interface between SiO_2 and high-k retarded the carrier injection in the inversion sweep, which in turn decreased the gate leakage. Breakdown characteristics can be explained by this model also. The dipole near the interface regime appears to enhance the local field, which may lead to a local breakdown in accumulation. In inversion, however, the dipole compensates for the external field and increases the V_{bd}.

Fig. 12 shows the V_{th} shift after a 10000-sec PBTI stress as a function of the oxide voltage. La-doped devices showed the smallest V_{th} shift due to less density in the bulk traps. The results from the pulsed BTI test performed to minimize measurement-related relaxation of the trapped charges suggest that La-doping effectively reduces the density of the pre-existing traps or somehow retards the charge trapping, which is the primary reason for transient charge trapping and the initial V_{th} shift (Fig. 13).

4. CONCLUSION

Formation of La-doped HfO_2 was found to provide higher breakdown voltage, lower gate leakage, and better immunity against PBTI and charge trapping compared to the control HfO_2. For the first time, the superior reliability characteristics of La-doped HfO_2 have been explained using the dipole induced by La incorporation. This result well corroborates with the dipole model proposed to explain the lower V_{th} of nMOS with metal/La doped high-k dielectric stack.

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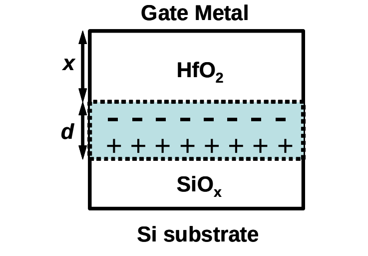

$$\Delta V_{FB} = -\frac{Q(x+d)}{\varepsilon_{ox}} + \frac{Q\cdot x}{\varepsilon_{ox}} = -\frac{Q\cdot d}{\varepsilon_{ox}}$$

Fig. 1. Schematic diagram of the effects of the dipole formation on the flatband voltage shift.

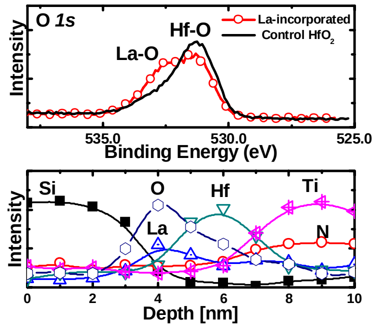

Fig. 2. XPS analysis shows that by incorporating La, LaO_x segregation has occurred. La piled up near the HfO_2/SiO_2 interface from the EELS analysis.

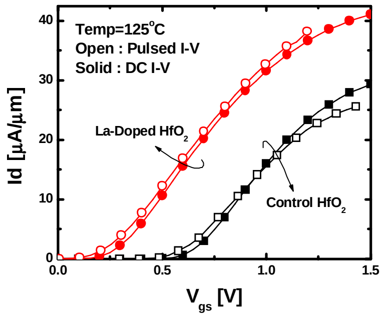

Fig. 3. Pulsed and conventional I_d-V_g characteristics show that the transient charge trapping was negligible for the both device structures.

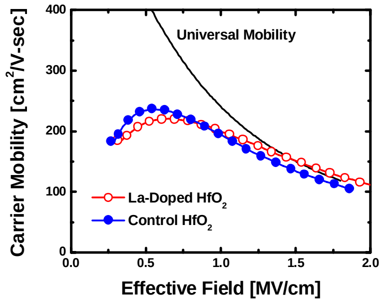

Fig. 4. Mobility characteristics also showed similar behavior.

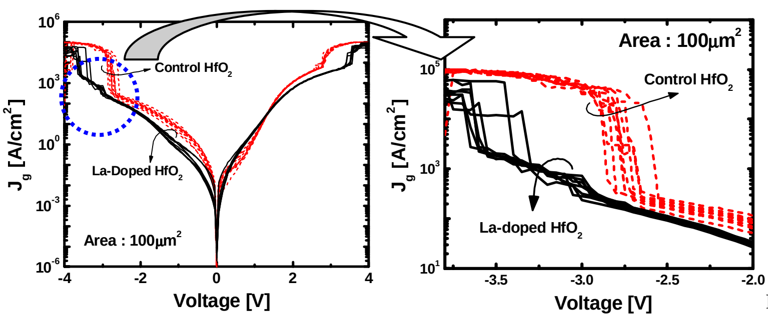

Fig. 5. The gate leakage characteristics of gate injection and substrate injection. The La-doped devices show a higher V_{bd} for both accumulation and inversion regimes. In addition, the La-doped device showed multiple-step breakdown in the gate side injection.

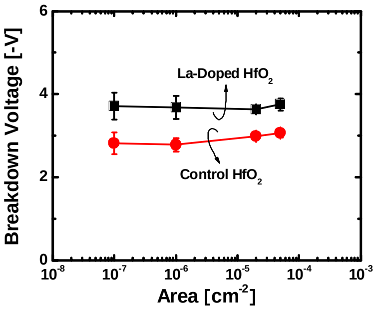

Fig. 6. The area dependence of V_{bd} is similar for both dielectrics. It suggests that the incorporated La did not increase the defects, which can reduce V_{bd} or J_{gate}

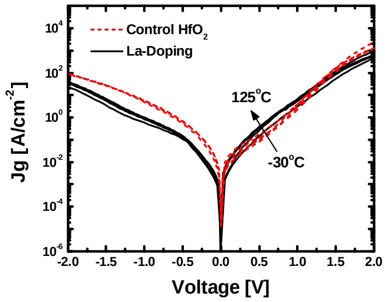

Fig. 7. The temperature dependence of the gate leakage was insignificant for both devices, which indicates that La did not assist the leakage increase.

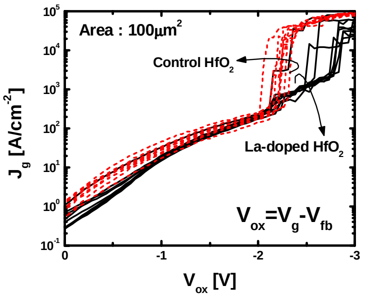

Fig. 8. In J_g as a function of V_{ox}, the gate leakage characteristics were similar. For both devices, the initial breakdown occurred at the same V_{ox}.

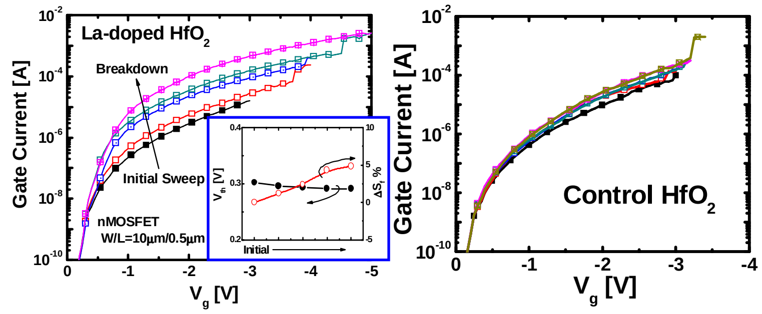

Fig. 9. Unlike the abrupt breakdown for the control HfO_2, the La-doped sample shows a progressive increase in gate leakage current as the sweep range increases. The corresponding V_{th} shows that these interface breakdowns do not mitigate the interface dipole effect.

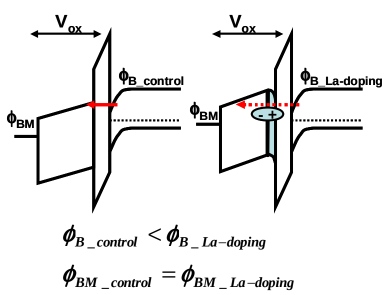

Fig. 11. The La-induced dipole formation between the interface and high-k retarded the injected charges, which in turn decreased the gate leakage.

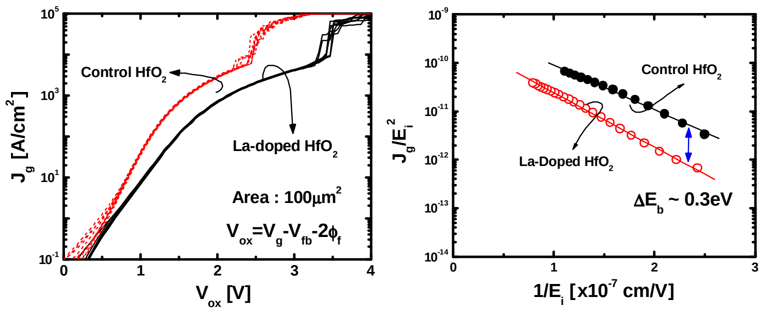

Fig. 10. In the substrate injection, the gate current for both devices followed FN. However, the J_g for La-doped devices was significantly reduced. The calculated barrier height difference for FN tunneling between the control HfO_2 and La-doped HfO_2 was about 0.3eV, which was induced from the dipole formation resulting in the reduced gate leakage at the substrate injection.

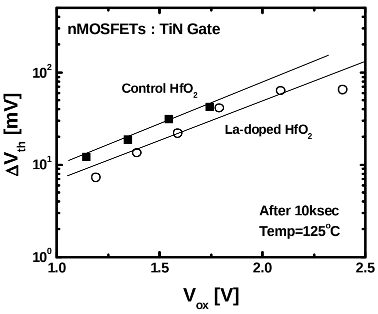

Fig. 12. V_{th} shift after PBTI stress as a function of the oxide voltage. The La-doped device showed the smallest V_{th} shift, which is due to fewer transient traps and less interface degradation.

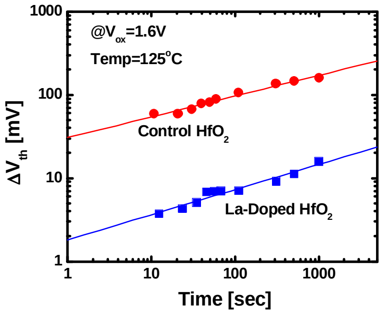

Fig. 13. The results from the pulsed BTI test for minimal trapped charge relaxation suggest that La doping effectively reduces the pre-existing traps, which are the primary reason fir transient charge trapping and initial V_{th} shift.