

Investigation of Bulk Traps Enhanced Gate Induced Leakage Current in Hf-based MOSFETs

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Recently, Hf-based high-k dielectrics have been investigated widely in order to replace conventional SiO₂ for reducing gate leakage current.

However, because of the high density of bulk traps, device with Hf-based dielectric also suffers mobility degradation and poor reliability. In addition, it has been reported that the bulk traps significantly enhance the gate induced drain leakage (GIDL) current in high-k devices. Nevertheless, the related mechanisms have not been revealed yet, especially, the role of charge trapping in high-k film should be understood in detail for suppressing the bulk traps enhanced gate induced leakage (BTE-GIDL).

In this work, we investigated the GIDL of HfZrO gated nMOSFETs with different Zr concentration in details. In addition, based on experimental data, the mechanism of BTE-GIDL current was also discussed.



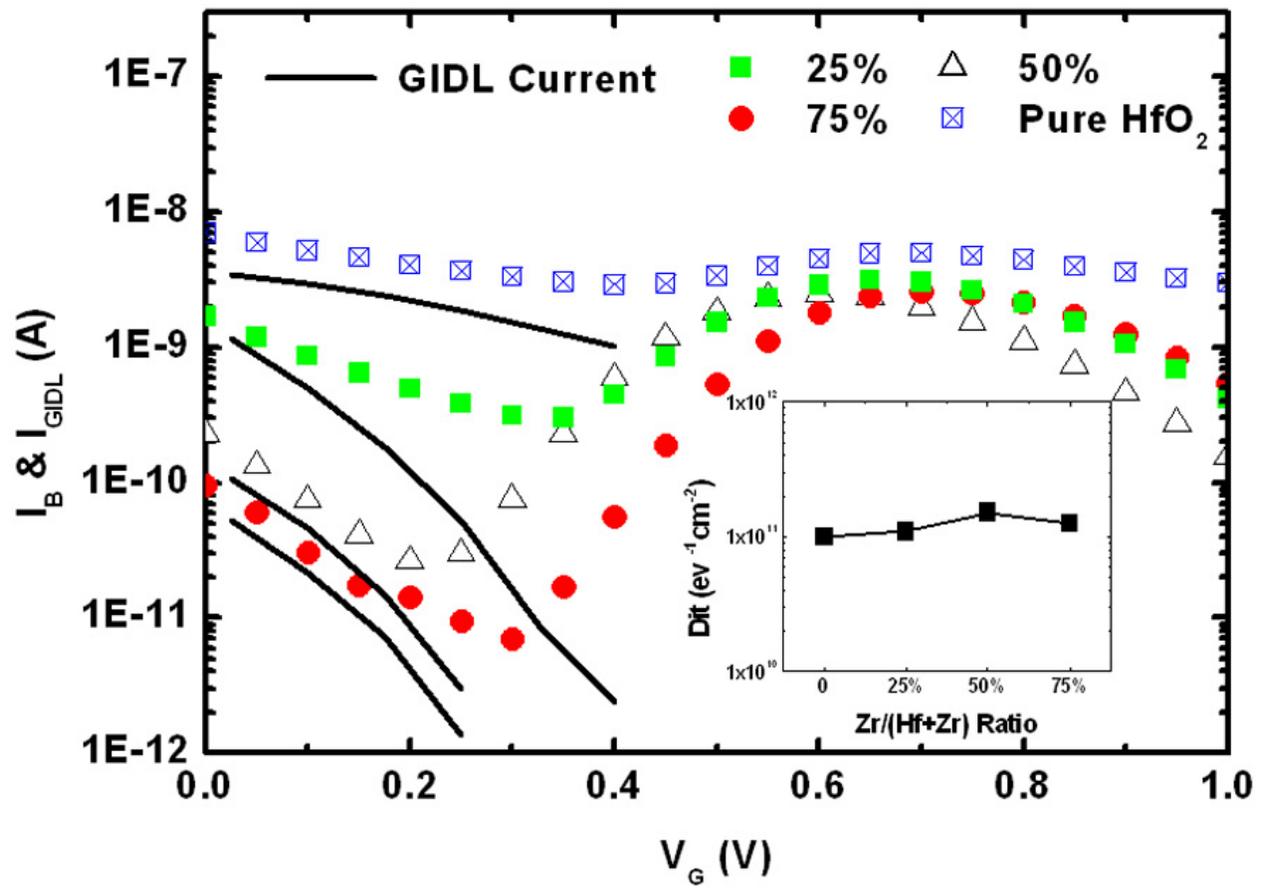


Fig. 1: Substrate current (symbols) and the extracted GIDL component (solid lines) $V_S V_G$ The inset shows $D_{it} V_S$ Zr ratio.

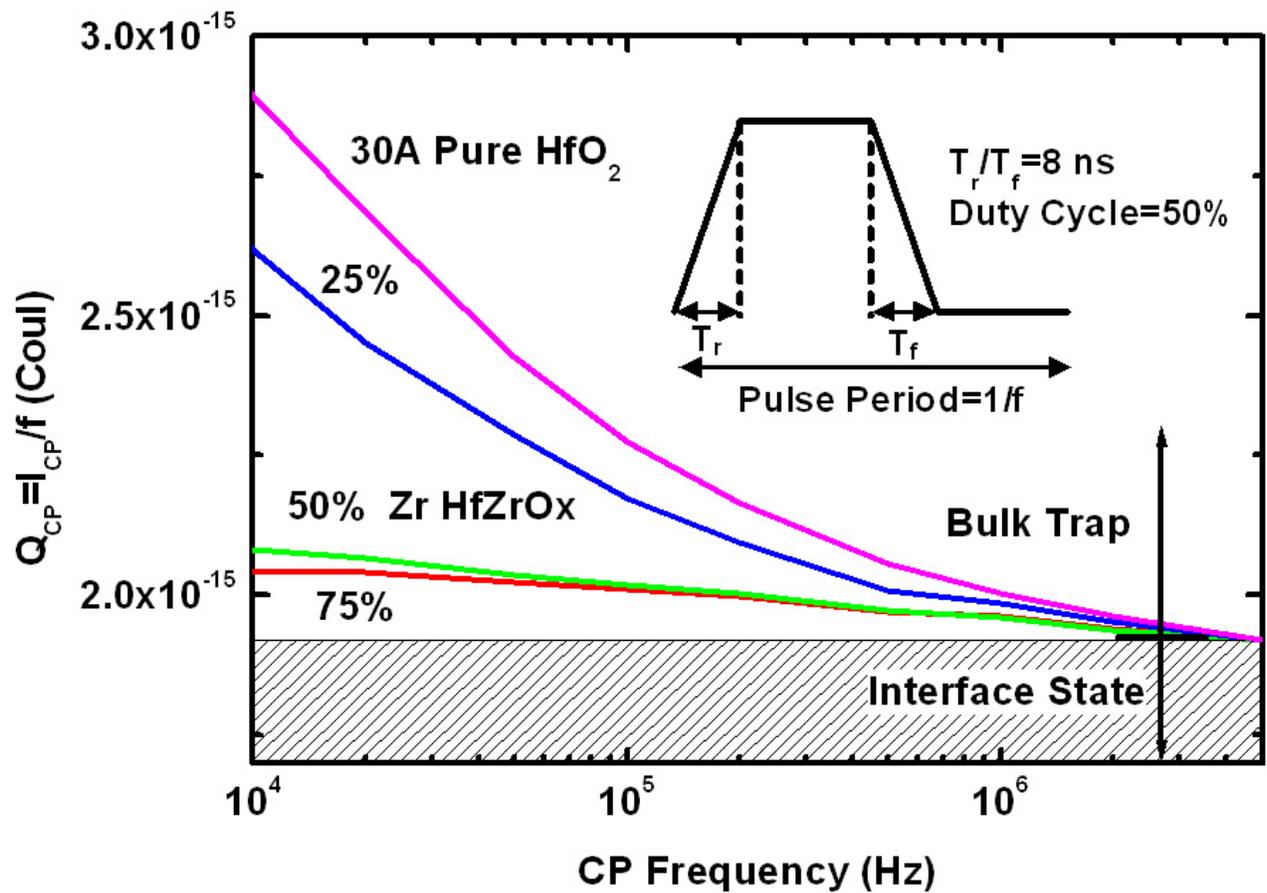


Fig. 2: The charge (Q_{CP}) contributed from bulk traps (solid lines) and interface states (slashed area) V_S charge pumping frequency.

Figure 1 shows the measured substrate current and the extracted GIDL current as a function of gate voltage in nMOSFET with 30 Å HfZrOx. In contrast to the traditional bell-shaped impact ionization current, an additional component of substrate current is observed at low V_G regime (below 0.4V), and suspected to the BTE-GIDL current. As seen, the BTE-GIDL current firstly decreases with Zr ratio in HfO₂, and then becomes saturated as Zr ratio exceeds 50%. The interface trap densities (D_{it}) measured by rising/falling time varied charge pumping ((T_r/T_f) -CP) on HfZrOx devices with different Zr/ (Hf+Zr) ratios are inserted in Fig. 1. D_{it} values are almost constant for different Zr/ (Zr+Hf) ratios, thus implies the incorporation of Zr does not degrade the interface quality and the observed Zr ratio dependence of GIDL is not related to D_{it} . On the other hand, bulk trapping from charge pumping exhibits a dependence on Zr ratio, as shown in Fig. 2, where the recombined charge (Q_{CP}) caused by both bulk traps and interface states were measured by f-CP method. The Q_{CP} from the bulk trapping are believed to represent the bulk trap density in high-k film. The data of Fig. 2 reveals a decrease of bulk traps with increasing Zr contents. It is worth to note that the reduction of bulk trap density from CP also becomes saturated as the Zr ratio exceeds 50%. The exactly same trend between Q_{CP} and BTE-GIDL with Zr ratio supports the bulk trapping mechanism of BTE-GIDL. The above data also suggests the incorporation of Zr can effectively reduce bulk traps and thus the BTE-GIDL current. In addition, the incorporation of Zr into HfO₂ decreases the grain boundary, and thus inducing a larger grain boundary area in the highly Zr-doped film. The higher O₂ diffusivity along grain boundaries results in a less oxygen vacancy to form

bulk traps in the high-k dielectrics.

Furthermore, Fig. 3 shows the GIDL currents of nMOSFETs with different HfO₂ thickness. To eliminate the influence of different equivalent oxide thickness (EOT), GIDL was plotted as a function of drain to gate electrical field (E_{DG}). The GIDL current consists of high and low E_{DG} two distinct regions. At high E_{DG} region, the GIDL current is come from the band-to-band tunneling (BBT), and is independent of gate stack thickness under the same E_{DG}. While at low E_{DG} region, the GIDL shows a strong dependence of high-k thickness, it is suspected to the trap-assisted tunneling (TAT). Because, the bulk trap density decreases with decreasing high-k thickness, the reduced GIDL in TAT region in thinner HfO₂ is attributed to its lower bulk trap density.

Based on the above discussions, we propose the mechanism of BTE-GIDL as the electron trapping induced band bending, as illustrated in the insert of Fig. 3, where, the band diagrams before and after electron trapping are denoted as the solid line and dashed line, respectively. At low V_{DG} (TAT region), the barrier height of metal gate/high-k (~1.9 eV) for electron is lower than that of ~5.7 eV at high-k/SiO₂ (IL) interface for hole, thus the electron trapping into high-k film injected from metal gate becomes dominant, and results in more band-bending at gate-drain region, to decrease the tunneling distance and increase the GIDL current, respectively (illustrated by the dash lines in the inset of Fig 3). Another possible mechanism is the trap assisted tunneling. The BTE-GIDL is attributed to the trap assisted tunneling from traps located at the remote IL/high-k interface.

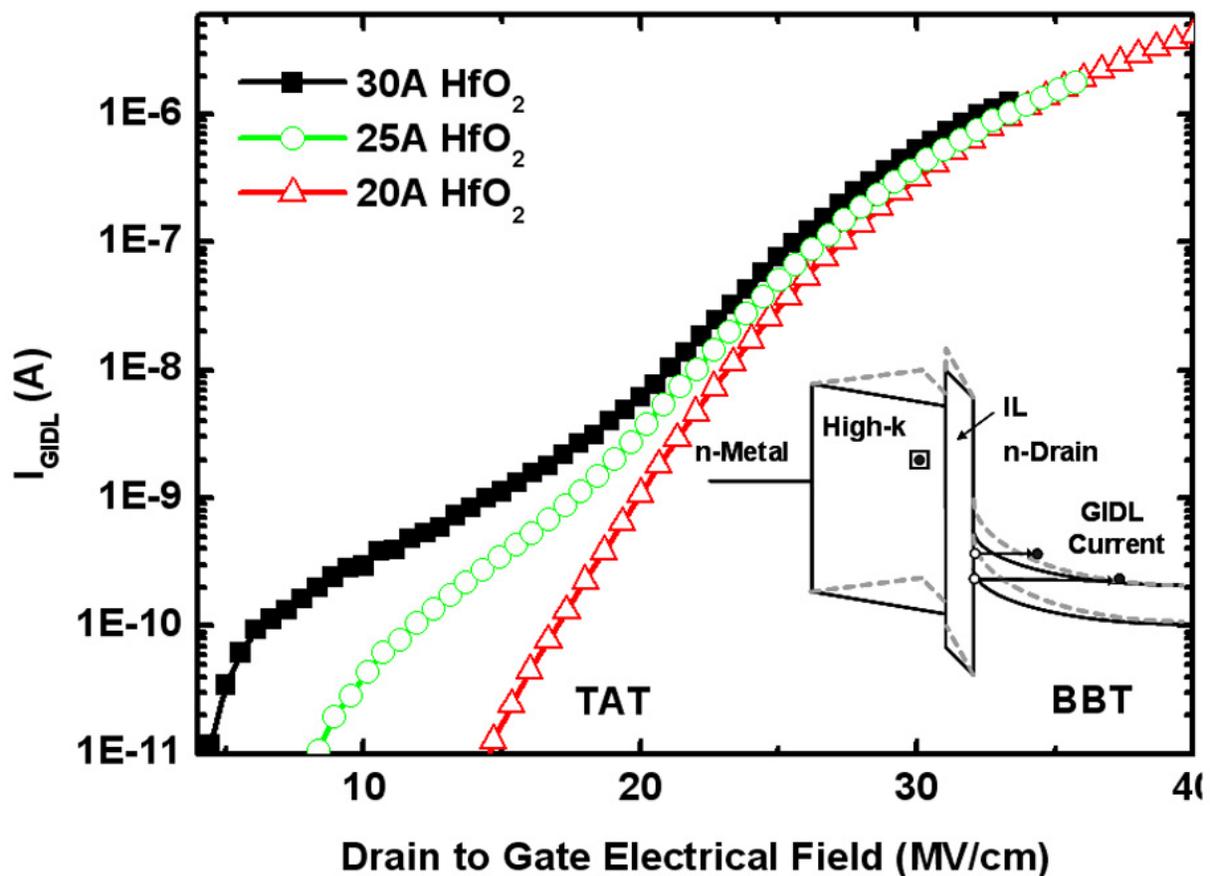


Fig. 3: GIDL current measured at $V_G=0V$ V_S electrical field. The inset shows the band diagrams before (solid line) and after (dashed line) capturing electrons by bulk traps.

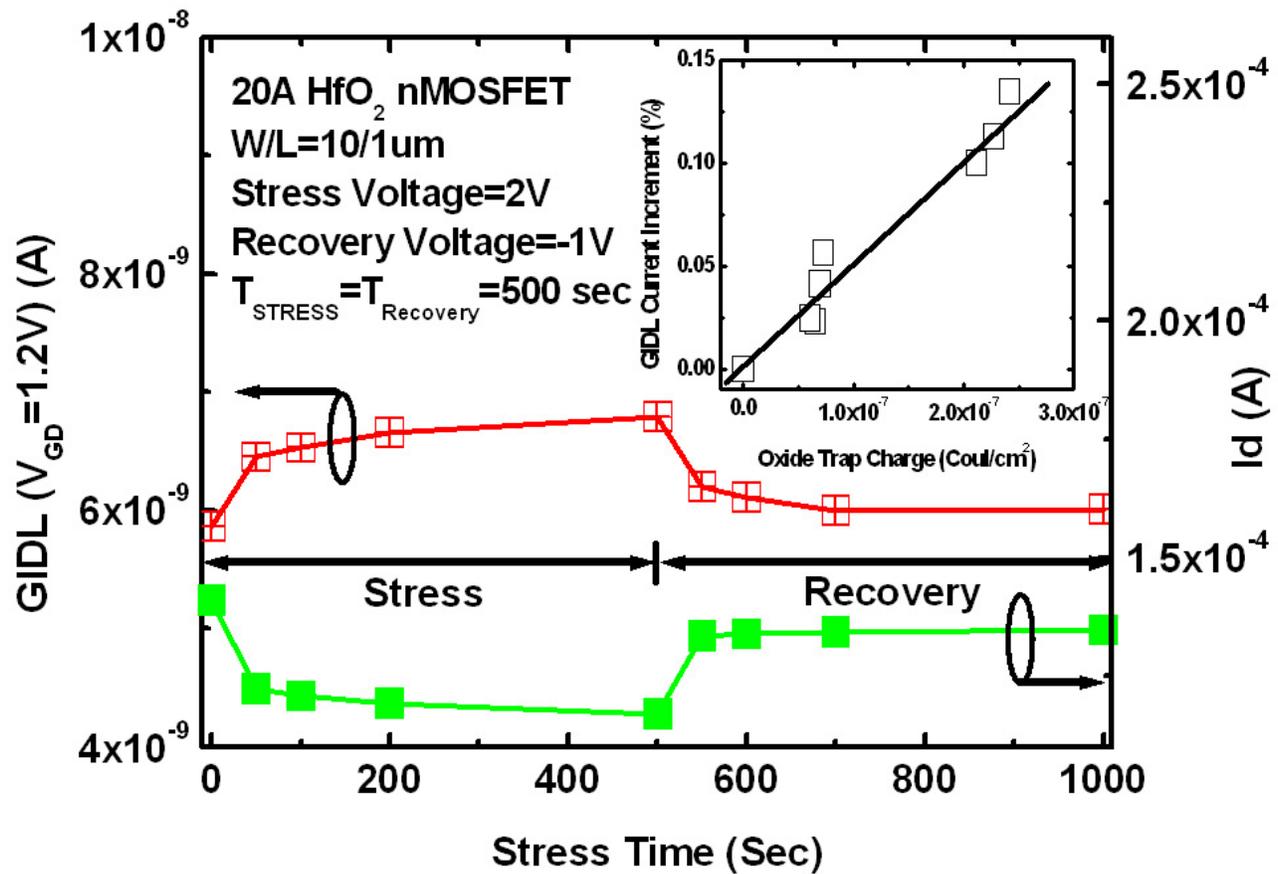


Fig. 4: The GIDL current (square) measured at $V_{DG}=1.2V$ and drain current at $V_G=1.2V$ (circle) during positive and negative stress V_S stress time.

Figure 4 shows the GIDL current and the linear drain current as a function of stress time. After positive voltage stress, increase of BTE-GIDL, and decrease of linear drain current are observed. Because no apparent G_m degradation is observed after stress, the degradation of drain current is attributed to the positive ΔV_{th} , which is induced by the electron trapping in high-k dielectrics. The trapped electrons were calculated from the stress induced V_{th} shift. As shown in the inset of Fig. 4, the trapped electrons in dielectric increase with stress time, thus result in a higher GIDL current.

In summary, the effects of Zr/ (Hf+Zr) ratios and high-k thicknesses on GIDL were studied in details. Experimental results showed a strong correlation between bulk trap density and BTE-GIDL. The BTE-GIDL was reduced by adding Zr into HfO₂ or thinning the high-k film due to the less bulk traps in the dielectric. In addition, the electrical stress also increases BTE-GIDL by increasing the trapped charge.