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Analytical model for anomalous Positive Bias Temperature Instability in La-based HfO_2 nFETs based on independent characterization of charging components

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ABSTRACT

Incorporation of rare earth capping layers in the gate stack is an effective technique to tune the threshold V_{TH} voltage of advance CMOS technologies. Furthermore, a reduction of the positive V_{TH} drift (instability) has been reported for rare-earth doped nFETs under positive gate bias stress at high temperature. However, a non-optimized process can lead to an anomalous V_{TH} behavior. We demonstrate that two independent components are responsible for this anomalous behavior which can be decoupled, individually studied, and then projected for meaningful lifetime extrapolations.

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1. Introduction

As the scaling of Metal–Oxide–Semiconductor Field Effect Transistors (MOSFETs) continues, the oxide electric field increases during operation, resulting in significant shifts of the device parameters such as threshold voltage V_{TH}. This critical reliability phenomenon called Positive Bias Temperature Instability (PBTI) for the case of nFETs is due to charging of defects in the gate dielectrics [1–3]. A significant reduction of V_{TH} instability has been reported in planar nFETs with rare earth elements incorporated into the gate stack [4–9]. However, an anomalous V_{TH} behavior is often observed in such stacks, which impedes successful lifetime extrapolation. Here we demonstrate that this anomalous behavior is due to two independent mechanisms, which can be decoupled, individually investigated, and then projected for meaningful lifetime extrapolations.

2. Experimental

ISSG/2 nm-HfO_2 nFETs w/o and with La-doping were perturbed by positive gate stress at different gate stress voltage V_{STRESS} and temperature T (see Fig. 1). Large $10 \times 0.5\ \mu m^2$ nFETs were used for BTI lifetime assessments and $90 \times 70\ nm^2$ (nominal) nFETs to study the impact of single traps in the V_{TH} of the devices. The stress time t_{STRESS} ranged from 1 up to 10^4 s. The I_S after stress was registered for times t_{RELAX} as long as 10^4 s and afterwards transformed to ΔV_{TH} [10].

The La capping layer was introduced between the HfO_2 and the PVD TiN layers for effective-work-function tuning [4]. The devices followed the conventional flow for DRAM peripheral transistors.

3. Results and discussion

For the La-free HfO_2 nFETs, Fig. 2a shows the expected positive and always increasing ΔV_{TH} as a function of t_{STRESS} due to electron trapping. After removing V_{STRESS}, a monotonic recovery of the V_{TH} is observed and usually explained by electron discharge [11–12]. For the La-doped devices (Fig. 3), however, an anomalous and negative ΔV_{TH} for the shortest t_{RELAX} and t_{STRESS} is registered. Note that the maximum magnitude of ΔV_{TH} is *not* obtained at the shortest t_{RELAX}. Below we investigate the origin of this effect.

According to Fig. 4, the BTI behavior in La-doped nFETs strongly depends on V_{STRESS}. For a lower V_{STRESS}, an always-negative ΔV_{TH} is obtained independently of the t_{RELAX} and t_{STRESS}. This negative ΔV_{TH} is almost canceled out at higher V_{STRESS} (Fig. 4a). Moreover, ΔV_{TH} as a function of t_{STRESS} at fixed t_{RELAX} (Fig. 4b) deviates from the expected power-law dependence used for lifetime extrapolation.

In order to gain more insight into the anomalous PBTI process, the experiment was repeated at different T's. Fig. 5 shows that the negative and anomalous BTI behavior vanishes at lower T. An identical ΔV_{TH} trend with T was observed for all applied V_{STRESS} (not shown). This indicates that *two separate components/mechanisms are responsible for the behavior observed in these stacks*. The usual electron trapping component that causes a positive shift is weakly thermally activated [11,12]. *However, a second mechanism with a high activation energy produces a negative ΔV_{TH} and disappears at low T.*

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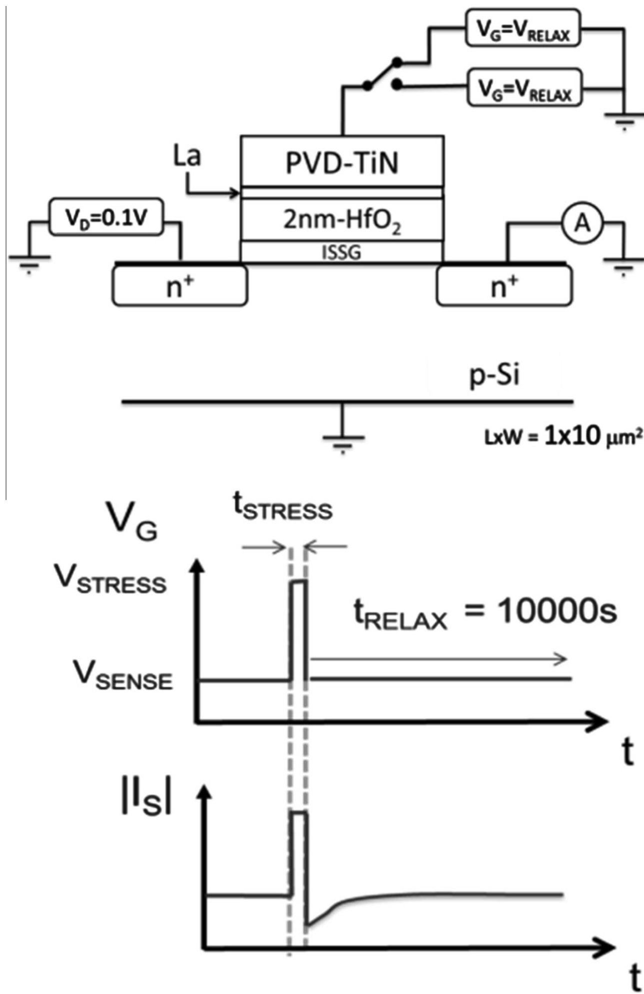

Fig. 1. Measurement procedure for studying ΔV_{TH} nMOSFETs under gate stress. Source current I_S is registered as a function of time and transformed into ΔV_{TH} through the $I_S - V_G$ of the fresh device [10].

Based on these experimental findings, the ΔV_{TH} traces are modeled by two components that follow the expected universal model [10] but with opposite signs according to Eq. (1).

$$\Delta V_{TH}(t_{stress}, t_{relax}) = \frac{\Delta V_{TH}^{+}}{1 + B^{+}(t_{relax}/t_{stress})^{\beta^{+}}} + \frac{\Delta V_{TH}^{-}}{1 + B^{-}(t_{relax}/t_{stress})^{\beta^{-}}} + \Delta V_{TH,P} \quad (1)$$

where the first and second terms refer to the positive and negative recoverable components. The last component is related to the permanent component. The long individual long relaxation traces obtained at different t_{STRESS} are fitted all together and *the negative and the positive components of the BTI degradation are separated, independently evaluated and extrapolated to operating conditions*.

Fig. 6 illustrates the result for one of the traces. The sum of both negative and positive components excellently describes the experimental data for the whole relaxation period of more than 7(!) decades. Note that the composite ΔV_{TH} trace is lower than 30 mV at this particular T and V_{STRESS} condition, *leading to a false conclusion of low-defect dielectrics*. However, both ΔV_{TH} components have large magnitudes and will not compensate at other stress conditions. The independently extracted negative and positive BTI components at fixed t_{RELAX} are plotted in Fig. 7. Conversely to the ΔV_{TH} curves in Fig. 4b, *the separated BTI components follow the expected power-law trends with t_{STRESS} and V_{STRESS}* [2,3].

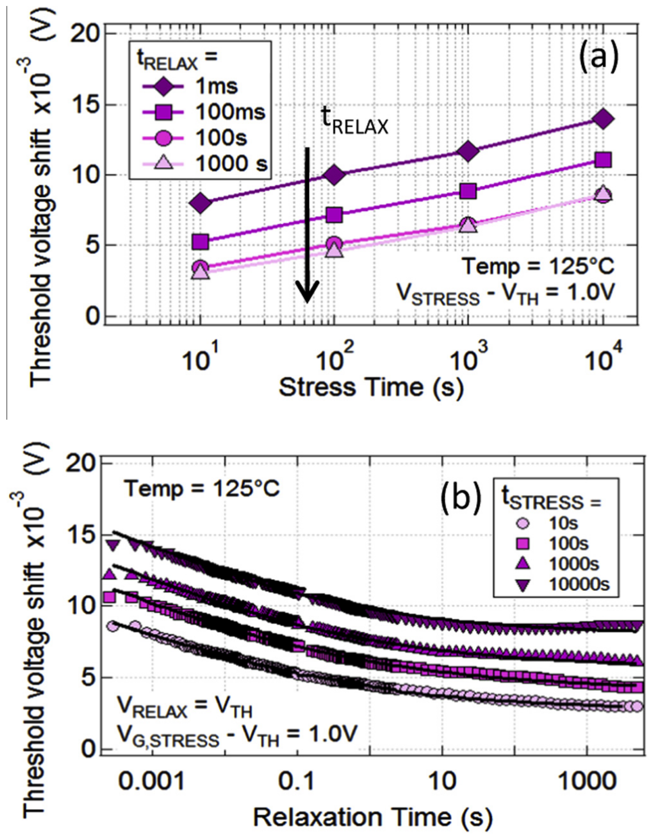

Fig. 2. (a) A progressive positive ΔV_{TH} is observed after positive gate stress at high temperature for La-free nFETs due to electron charging [11]. (b) ΔV_{TH} immediately recovers after the stress bias removal.

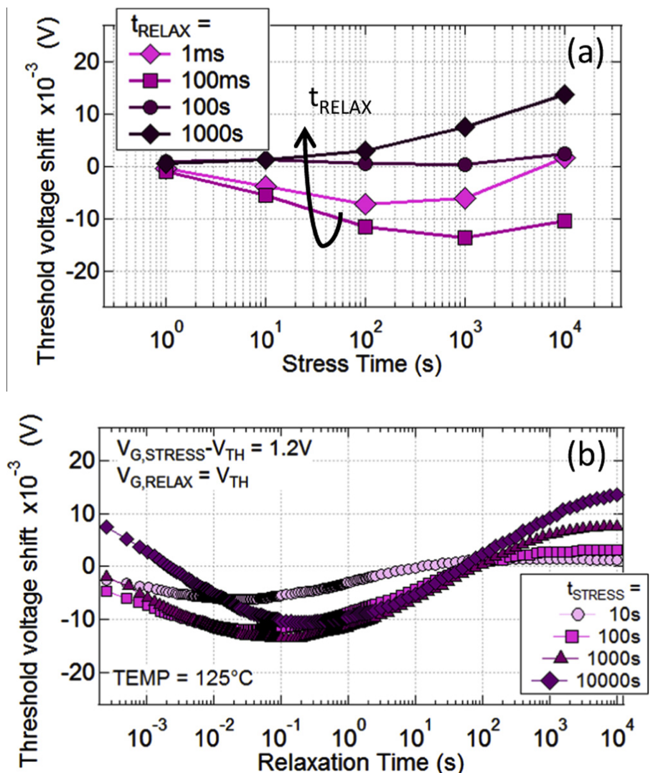

Fig. 3. (a) For the La-doped HfO_2 nFETs, an anomalous ΔV_{TH} is obtained for the shortest t_{RELAX}. This behavior tends to disappear when ΔV_{TH} is registered at longer t_{RELAX}. Note in (b) the change of ΔV_{TH} sign at about t_{RELAX} = 100 s.

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