Defect-Oriented Degradations in Recent VLSIs: Random Telegraph Noise, Bias Temperature Instability and Total Ionizing Dose

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Keywords: RTN, BTI, TID, Trap-Detrap, Reaction-Diffusion

Abstract

This paper introduces Random Telegraph Noise (RTN) and Bias Temperature Instability (BTI) and Total Ionizing Dose (TID). They are correlated and caused from the same type of defects in gate and field oxides.

Introduction

Reliability issues such as Bias Temperature Instability (BTI) has been dominant factors to restrict lifetimes of semiconductor devices. BTI gradually degrades performance of MOS transistors. It was first reported in 1967[1]. Behavior of a single charge in the channel is becoming a significant problem on heavily scaled LSIs. Characteristics of the MOSFETs are fluctuated by the charge behavior. It is called the RTN (Random Telegraph Noise). The origin of BTI is the defects trapping and detrapping carriers in gate oxide. BTI is basically the same degradation as the RTN. But it has the effect for the longer-term than RTN[2].

This paper briefly explains RTN and BTI in terms of traps, which are also the origins of radiation-induced degradation called TID (Total Ionizing Dose).

Interface and Oxide Traps

There are two types of defects related to gate dielectrics in MOS devices. These defects can trap holes or electrons. Thus they can be called as “traps”. One is called the interface trap (D_{it}) which is an dangling bond of Si-H between silicon and gate dielectrics. It is also called the P_b center[3]. The other is the oxide trap (D_{ot}) existing inside of SiO_2 insulators. It is also called as the E’ center[4].

These traps cause RTN (Random Telegraph Noise) and BTI (Bias Temperature Instability) mainly discussed in many papers of semiconductor devices and circuits outside of the radiation field. They also cause TID (Total Ionizing Dose) by continuous long-term particle irradiation in the outer space.

Random Telegraph Noise

RTN (Random Telegraph Noise) is the phenomenon that can fluctuate transistor current temporarily as shown in Fig. 1[5] due to the oxide traps[6]. If an oxide trap captures a carrier, its drain current reduces. If the trapped carriers are emitted, the current is recovered. Time constants τ_c and τ_e are defined as the time when the drain current stays at high-current state (H-state) and low-current state (L-state) respectively (Fig. 2). RTN has a large impact on CMOS image sensors. Because of the rapid scaling, RTN become significant in digital circuits in addition to variations. The Pelgrom’s law suggest that the fluctuation by process variations is proportional to the square root of the device size, while the fluctuation due to RTN is proportional to the device size. For example, threshold voltage fluctuations by process variations and RTN (ΔV_{thPV}, $\Delta V_{\mathrm{thRTN}}$) are expressed as follows.

$$\Delta V_{\mathrm{thPV}} \propto 1/\sqrt{LW} \tag{1}$$

$$\Delta V_{\mathrm{thRTN}} \propto 1/LW \tag{2}$$

Recent studies show that ΔV_{th} caused by RTN grows more rapidly than the threshold variation caused by random dopant fluctuation. It is reported that RTN-induced ΔV_{th} may exceed RDF-induced threshold variation at the 3σ level in 22 nm technology[5].

Bias Temperature Instability

BTI is the phenomenon in which the threshold voltage (V_{TH}) of MOS transistors is gradually degraded when the stress bias is applied on the transistor gate. When the stress bias is released or decreased, degraded V_{TH} recovers.

There are hot discussions related to the origins of BTI[7]. Alam proposes the Reaction-Diffusion (RD) model in which hydrogen in the interface trap causes BTI [8]. Kazcer et. al. proposes the atomistic trap-based model in which oxide traps in gate dielectrics capture or emit carriers in the transistor channel. It is also called the trap-detrap (TD) model. Figure 3 shows the interface and oxide traps.

In the RD-model, hydrogen is removed from the Si-SiO_2 interface by a chemical reaction as shown in Eq. 3.

$$\mathrm{Si} - \mathrm{H} + \mathrm{h}^{+} \leftrightarrow \mathrm{Si}^{*} + \mathrm{H} \tag{3}$$

The Si dangling bond denoted as Si^{*} acts as an interface trap.

In the TD model, BTI is caused by the oxide trap which is discussed in the previous RTN section. Each trap has different τ_{c} and τ_{e} that can be changed by bias conditions and temperature. If $\tau_{\mathrm{c}} << \tau_{\mathrm{e}}$, captured carriers are regarded to be captured permanently (BTI). On the other hand, If $\tau_{\mathrm{c}} \simeq \tau_{\mathrm{e}}$, carriers repeats capture and emission over and over (RTN).

In the RD-model, the V_{TH} degradation is proportional to t^{n}. The value of n is 1/4 for diffusion of hydrogen (atomic H) and 1/6 for that of molecular H_2[9]. In the TD-model, the V_{TH} degradation is proportional to $\log(t)$.

Fig. 4 is the measurement results indicating the relationship between BTI and RTN[10]. The left graph (a) shows smooth degradation curves of larger devices, while the right graph (b) shows discrete curves of smaller devices. In the smaller devices, the number of defects is a few. Each discrete change corresponding to the carrier capture in a single defect. The smooth degradation of larger devices is the summation of carrier captures in many defects.

Total Ionizing Dose

By Total Ionizing Dose (TID), oxide and interface traps are generated. Those defects exist in gate oxide and also field oxide (so called Shallow Trench Isolation (STI)). Note that BTI is

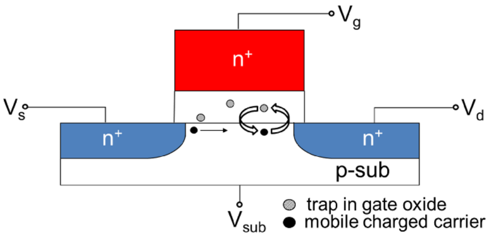

Figure 1: Random telegraph noise.

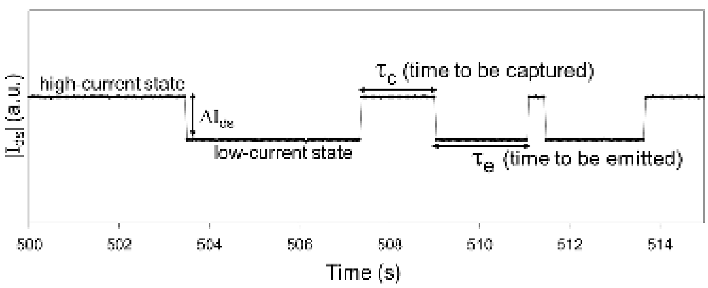

Figure 2: Drain current fluctuation by RTN.

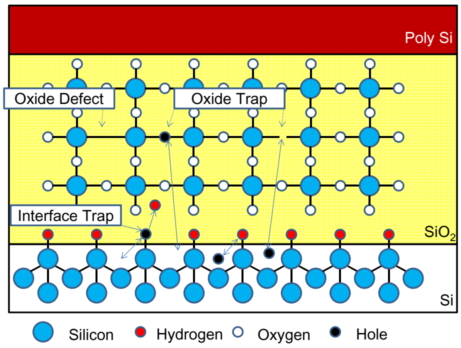

Figure 3: Interface and oxide traps.

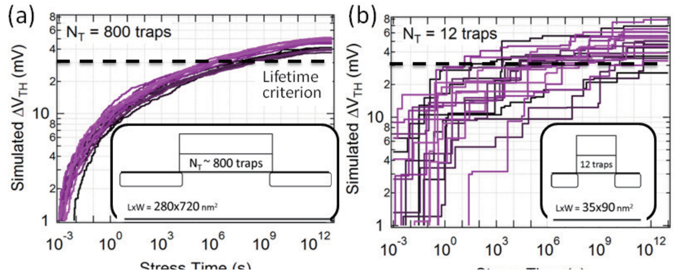

Figure 4: Two BTI stress curves: Larger devices have smooth degradation curves (a), while smaller devices have discrete curves (b).

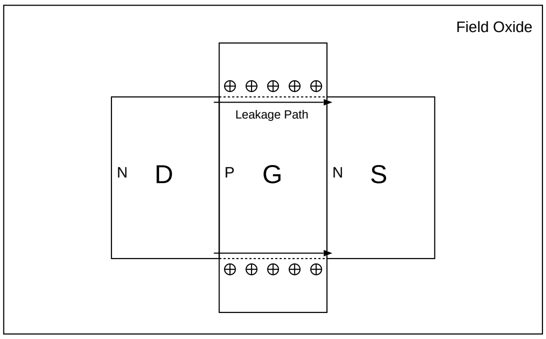

Figure 5: Total Ionizing Dose: Leakage current by trapped carriers.

only from defects in gate oxide. Radiation particle generates electron and hole pairs in oxide. Electrons are diffused or drifted away quickly from oxide, while holes remains in those oxide and trapped by defects[11]. By the trapped holes in field oxide, short-circuit current flows regardless of the gate voltage as shown in Fig. 5. These trapped carriers also exist in gate oxide, which degrades transistor performance.

Summary

This paper briefly introduces defect-oriented degradations in recent VLSIs such as RTN, BTI and TID. These degradations are caused by oxide and interface defects which can capture (trap) carriers. There are lots of papers telling us the physics of these traps. But no widely-accepted theory can be found. There are still hot discussions especially in the origins of BTI.

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