Advanced Modeling of Charge Trapping: RTN, 1/f noise, SILC, and BTI

(Invited Paper)

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Abstract—In the course of years, several models have been put forward to explain noise phenomena, bias temperature instability (BTI), and gate leakage currents amongst other reliability issues. Mostly, these models have been developed independently and without considering that they may be caused by the same physical phenomenon. However, new experimental techniques have emerged, which are capable of studying these reliability issue on a microscopic level. One of them is the time-dependent defect spectroscopy (TDDS). Its intensive use has led to several interesting findings, including the fact that the recoverable component of BTI is due to reaction-limited processes. As a consequence, a quite detailed picture of the processes governing BTI has emerged. Interestingly, this picture has also been found to match the observations made for other reliability issues, such as random telegraph noise, 1/f noise, as well as gate leakage currents. Furthermore, the findings based on TDDS have lead to the development of capture/emission time (CET) maps, which can be used to understand the dynamic response of the defects given their widely distributed parameters.

INTRODUCTION

In order to improve on the device performance, large technological efforts have been made to scale down the transistor geometries to present-day dimensions. Despite the achieved progress, old unresolved reliability problems, such as BTI [1] and random telegraph noise (RTN) [2], have remained or become worse. In the case of RTN, the threshold voltage ($V_{th}$) may have fluctuations larger than typically used lifetime criteria of e.g. 30 mV. These fluctuations are the result of charge capture or emission events into and out of oxide defects [2]. Interestingly, each defect produces fluctuations with its own characteristic step height and time constants — a fact that has been exploited to identify the contributions of single defects in RTN signals. However, RTN experiments can only monitor the behavior of a defect around a certain gate bias and therefore suffer from a quite narrow experimental window. This is in contrast to the recently introduced TDDS method, which is used to analyze the recoverable component of BTI degradation on small-area devices. It covers the wide spectrum of non-equilibrium conditions, encountered for the stress conditions in BTI experiments. Due to this advantage, this method has proven extremely useful for studying the gate bias and temperature dependences of the charge capture ($\tau_c$) and emission ($\tau_e$) times. Since it allows to study single defects, it provides direct insight into the mechanism behind charge capture and emission.

TDDS AND ITS IMPLICATIONS

During a TDDS experiment, the gate bias is switched between the stress and recovery level, thereby initiating a certain kind of reactions, such as the charging and discharging of defects in the dielectric. These reactions are traced in the drain current based on their step heights and time constants. As they are stochastic processes, the bias switches must be repeated hundreds of times for accurate determination of their corresponding time constants, such as the mean capture ($\tau_c$) and emission ($\tau_e$) times in the case of charge trapping. An in-depth statistical analysis [3] revealed that charge capture and emission follow a Poisson process, characterized by its exponential probability density functions. Such a process is the result of a first-order reaction, such as elastic tunneling of charge carriers, pure thermal transitions (any kind of an atomic rearrangement without a charge transfer), and nonradiative multiphonon (NMP) transitions [4, 5]. All of them are possibly involved in charge trapping but the concept of the traditional reaction-diffusion model must be ruled out since it is incompatible with a Poisson process.

Beside these physical aspects, TDDS has also revealed several features which all investigated BTI defects have in common:

\begin{itemize}
  \item [(i)] Charge capture as well as emission are temperature dependent and have an activation energy in the range of $0.4 – 1.5 \text{ eV}$ [6].
  \item [(ii)] Two defect types exist, which significantly differ in their bias dependence. As demonstrated in Fig. 1, the emission times of the “fixed oxide traps” are insensitive to the gate bias while those of the “switching oxide traps” show a drop at lower voltages [7].
  \item [(iii)] Charge capture is strongly accelerated with increasing gate bias, but slowed down with higher frequencies in AC stress experiments [8, 9].
  \item [(iv)] Defects in their neutral charge state were found to disappear for random amounts of time, during which they do not capture or emit charge carriers. This volatility is thermally activated and has been tentatively linked to hydrogen in the dielectric [10].
  \item [(v)] The capture and emission times extracted from RTN and TDDS measurements match well (for instance shown for the defect B3 in Fig. 1). As this agreement is found for a large majority of the investigated defects, we conclude that BTI and RTN are dominated by the same defects (cf. Fig. 2) and must therefore be investigated together [11].
  \item [(vi)] TDDS studies on SiON nMOSFETs have revealed that electron capture and emission exhibit similar gate bias and temperature dependences as the fixed and switching hole traps in pMOSFETs. Interestingly, the same trapping behavior was also observed in device technologies based on high-$\kappa$ dielectrics [12]. This suggests that charge trapping in these cases rests upon the same general concepts with similar physical processes being involved [13].
\end{itemize}
The above observations result in a quite restrictive set of criteria for any reliability model that should cover the recoverable component of BTI as well as RTN. The simplest and most natural approach would be a two-state model, in which the forward and the backward transition between the two charge states are described by NMP processes. The underlying NMP theory [4, 14, 15] accounts for the contribution of lattice vibrations which ultimately allow the charge trapping processes as explained in the configuration coordinate diagram of Fig. 3. The NMP processes in a two-state model predict a pronounced temperature activation as well as a strong gate bias dependence for the capture and emission times. However, this model can neither give an explanation for the measured frequency dependence in the capture times nor reproduce the constant emission times over a large gate bias range of more than 1 V. The latter observation is reminiscent of pure thermal transitions, which are to first order independent of the gate bias. Such transitions would occur in bistable defects, which have two meta-/stable configurations separated by a thermal barrier. Interestingly, bistable defects, such as the $E^\prime$ center in the Harry-Diamond-Laboratory model [16], have already been proposed in the context of device reliability. Motivated by this idea, the defect model was extended to a bistable defect but with four states as in the state diagram of Fig. 4. In this model, charge capture and emission are now two-step processes between the stable states 1 and 2. Both can be reached via either of the metastable states $1'$ or $2'$, which opens two pathways for capture and emission. While one pathway

$2 \leftrightarrow 1'$ is associated with the switching trap behavior, the other ($2 \leftrightarrow 2'$) can explain the fixed oxide traps (see Fig. 5). Interestingly, the four-state NMP model was also found to reproduce the frequency dependence in item (iii), as demonstrated in [8]. As such, this model gives a detailed description of the recoverable BTI degradation.

In contrast to the recoverable component of BTI, much less is known about the permanent component. In the two-stage model [18], it is assumed to be coupled to the charge trapping process while in [1, 6] it is modeled as a separate and independent process. In order to account for the permanent BTI degradation, the four-state NMP model can also be extended within the framework of the two-stage model [18]. There, a positive defect is allowed to undergo a defect transformation to a new state with a fixed positive charge. However, the four-state NMP model cannot account for the volatility of the defects, mentioned in item (iv). Consequently, the model has to include an additional inactive state labeled $0$, in which the
defect cannot capture a charge carrier. As the defects probably vanish in their neutral charge state [19], the state 0 must be connected to either of the states 1 or \(1'\). The exact chemical reaction behind the transition \(0 \leftrightarrow 1/1'\) has not been clarified yet. However, it is likely to involve hydrogen since the amount of volatility in the recoverable BTI defects was found to vary with the background hydrogen content in the dielectric. This suggests that possible defect candidates are likely to contain hydrogen atoms, as is for instance the hydrogen bridge [20, 21].

**Capture/Emission Time Maps**

The four-state NMP model includes metastable states, which are only passed temporarily during a capture or emission event. For DC stress conditions, it can be reduced to an effective two-state model, essentially showing the behavior of first-order reactions \([8, 22]\). As a consequence, the BTI degradation and recovery curves of large-area devices can be interpreted as a collection of “independent” first-order processes with certain combinations of capture and emission times for each defect. As such, one can build capture/emission time (CET) maps, in which each defect contributes with a certain threshold voltage shift. These CET maps (see Fig. 6) can be calculated from a complete set of BTI recovery curves, which include all combinations of stress and relaxation times within a typical measurement window.

Experimental CET maps \([8, 23, 24]\) were found to show wide distributions of capture and emission times ranging from microseconds up to at least 10 ks and have their strongest contributions somewhere close to the diagonal \(\tau_c = \tau_e\). Analytically, they have been successfully described by a combination of two bivariate Gaussian distributions, corresponding to the recoverable and the permanent component of BTI, respectively. It is noted here that the capture and emission times are directly related to the defect parameters of the four-state NMP model. As such, the observed distributions of capture and emission times reflect a wide spread in the defect parameters. The latter can be argued to be due to large variations of bond lengths and angles in the atomic structures of the defects, consistent with theoretical investigations \([25–27]\). Interestingly, it could also be demonstrated that the reaction-diffusion model \([28]\) as well as elastic tunneling of charge carriers yield CET maps which are distinct from the experimental ones. Therefore both models must be ruled out as a possible explanation for BTI (cf. Fig. 6).

**The Four-State NMP Model as an Explanation for Stress-Induced Leakage Currents**

Recent investigations \([29–32]\) have revealed that the fluctuations in the drain and the gate current can be correlated (see Fig. 7). It may be argued that this correlation is associated with the captured charge which locally repels the inversion layer thereby decreasing the direct tunneling current. However, simulations based on the non-equilibrium Green’s function method have demonstrated that this effect can be ruled out due to a too small magnitude of the gate current fluctuations \([33]\). Another explanation \([34, 35]\) is based on a four-state NMP model and relies on trap-assisted tunneling (TAT) \([36–38]\) through the defect producing the drain current noise. As illustrated in Fig. 8, the TAT current is described by two consecutive NMP transitions \(1' \leftrightarrow 2 \leftrightarrow 1\). It is emphasized that this current only flows upon hole capture when the defect is positive (state 2) but is stopped upon hole emission when
with a long list of criteria obtained from TDDS measurements and CET maps. It could also be demonstrated that those BTI defects are also responsible for RTN. Moreover, the four-state NMP model also gives an explanation for fluctuations in the gate current, thereby further corroborating the validity of this model. As such, this model provides a comprehensive description of oxide defects in reliability issues and unravels related reliability topics, such as SILC. As the model is determined by its defect parameters, understanding the nature of their distributions is of high importance.

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