On the distribution of the FET threshold voltage shifts due to individual charged gate oxide defects

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Abstract—The factors contributing to the FET threshold voltage shift \( \Delta V_{th} \) caused by charging of an individual trap, such as during Random Telegraph Noise (RTN), are discussed by analyzing device-calibrated simulation data. The \( \Delta V_{th} \) distribution is observed to be a convolution of i) the position of the trap along the channel, randomized by ii) the random dopant distribution (RDD) responsible for percolative transport in the FET channel. In our TCAD simulation data the RDD component is observed to be roughly log-normally distributed. “Meta-simulations” varying this log-normal component are able to qualitatively reproduce a range of observed \( \Delta V_{th} \) distribution shapes. In longer devices and/or in devices with high channel doping (or otherwise highly randomized channel potentials), the \( \Delta V_{th} \) distribution tends toward log-normal. In the other, more relevant cases, the exponential \( \Delta V_{th} \) distribution appears to be an acceptable approximation.

Keywords—Reliability, Trap impact, Variability, Distributions

I. INTRODUCTION

The device-to-device distribution of the total threshold voltage shifts \( \Delta V_{th} \) due to Random Telegraph Noise (RTN) and Bias Temperature Instability (BTI) in deeply scaled devices seems acceptably described by the so-called Defect-centric or Exponential-Poisson (EP) statistic [1-3]. This statistic assumes a Poisson-distributed number of charged traps in the gate oxide of each device, while the threshold voltage shift \( \Delta V_{th} \) caused by an individual trap in a device (and denoted here by a small \( \Delta V_{th} \)) is assumed to be exponentially distributed, with its Cumulative Distribution Function (CDF) described by

\[
1 - \exp\left(-\frac{\Delta V_{th}}{\eta}\right),
\]

where \( \eta \) is a physical quantity—the mean \( \Delta V_{th} \) per charged trap.

The factors contributing to \( \Delta V_{th} \) and its distribution are discussed here by analyzing device-calibrated TCAD simulation data. We observe that the contribution of individual charged defects to \( \Delta V_{th} \) is a convolution of i) the position of the trap along the channel, randomized by ii) the random dopant distribution (RDD) responsible for percolative transport in the FET channel. In our simulation data we observe the RDD component roughly log-normally distributed. We then perform “meta-simulations” in which we vary this log-normal component, and are able to qualitatively reproduce a range of observed \( \Delta V_{th} \) distribution shapes. In longer devices and/or in devices with high channel doping (or otherwise highly randomized channel potentials), the \( \Delta V_{th} \) distribution tends toward log-normal. In the other, more relevant cases, of shorter channels and less-randomized channel potentials, the exponential \( \Delta V_{th} \) distribution appears to be an acceptable approximation.

II. SIMULATION METHODOLOGY

We performed three-dimensional (3-D) numerical simulations of a 70nm bulk n-channel MOSFET featuring a 2.2 nm SiON gate oxide. Source and drain doping has a Gaussian vertical profile with a junction depth and peak doping calibrated to match Scanning Spreading Resistance Microscopy (SSRM) measurements [4]. Substrate and HALO doping profiles have been optimized to match the electrical characteristics, including statistical variability [4]. Simulations were carried out by means of the drift-diffusion module of the atomistic simulator GARAND [5], activating density-gradient quantum corrections to correctly reproduce the electrostatic effect of dopants and quantum confinement in the channel. The statistical \( \Delta V_{th} \) distribution was calculated by means of a Monte Carlo (MC) procedure [5], where a large number (1000) of transistors having a different atomistic configuration of substrate doping and a different position of a single charged trap over the channel area and at the Si/SiOx interface were simulated. From each simulation, \( \Delta V_{th} \) was...
obtained as the change of the gate voltage allowing the same current to be collected at the drain contact for the unoccupied (neutral) and the occupied (negatively charged) gate oxide trap. A read current of 160 \( \frac{W}{L} \text{nA} \) has been used for \( \Delta V_{\text{th}} \) evaluation.

III. RESULTS AND DISCUSSION

Fig. 1 classifies the distributions of \( \Delta V_{\text{th}} \) under progressively more complex assumptions. Specifically, it shows that already assuming a realistic continuous (CONT) doping (Fig. 1b) results in a distribution of \( \Delta V_{\text{th}} \)'s, as charged gate oxide traps closer to the FET junctions contribute less [6]. The introduction of RDD further randomizes the impact (Fig. 1c), resulting in an approximately exponential CDF (Fig. 1d). Note in Fig. 1d that the top portion of the RDD distribution follows the CONT distribution.

The two contributions to the RDD \( \Delta V_{\text{th}} \) distribution are deconvoluted in Fig. 2. It is apparent that \( \Delta V_{\text{th}} \) is controlled by i) the position of the trap along the channel, randomized by ii) the random dopant distribution (RDD). This latter contribution appears from Fig. 2b to be approx. log-normal, with the parameter \( \sigma_{\text{perc}} = \sim 0.35 \) (\( \mu = 0 \)), hence

\[
F = \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{\ln r}{\sqrt{2\sigma_{\text{perc}}}} \right),
\]

where

\[
r = \frac{\Delta V_{\text{th,RDD}}}{\Delta V_{\text{th,CONT}}}. \tag{3}
\]

We note that the log-normal distribution is invoked in some percolation studies [7], as well as describing the distribution of the number of steps in the game of “Chutes and Ladders” (MC simulation: \( \mu = 3.49, \sigma = 0.59 \)) [8].

![Fig. 3](image)

Fig. 3: (a) The result of a 1000-sample meta-simulation assuming a convolution of CONT \( \Delta V_{\text{th}} \) impact (Fig. 1b) and different amounts of RDD impact, represented by varying \( \sigma_{\text{perc}} \) (note: \( \sigma_{\text{perc}} = 0 \) means no additional RDD impact). The dashed line illustrates exponential fitting of the CCDF tail with \( \eta = 10.2 \text{ mV} \). (b) The same data as in (a), truncated at \( \sim 0.1 \text{ mV} \) to emulate measurement resolution. (c) The same data as in (a), truncated at 0.15 mV, in a quantile/log-normal plot.

We now perform a limited, 1000-sample meta-simulation in which the RDD contribution is varied through the parameter \( \sigma_{\text{perc}} \) (Fig. 3a). A range of \( \sigma_{\text{perc}} \)'s can describe a range of \( \Delta V_{\text{th}} \) distributions, from the original CONT distribution (i.e., no additional RDD: \( \sigma_{\text{perc}} = 0 \)), cf. Fig. 1b) to a distribution with a strong low-percentile tail (\( \sigma_{\text{perc}} = 1 \)). We note that the tails of all thus-generated distributions, which control the shape of the total device-to-device \( \Delta V_{\text{th}} \) EP distribution [1,2], still appear exponential-like (i.e., approx. straight lines in the Complementary CDF \( \Delta V_{\text{th}} \) plot, cf. Fig. 3a). The parameter \( \eta \) (cf. Eq. 1) extracted by fitting these tails in Fig. 3a appears to scale with \( \sigma_{\text{perc}}^2 \), namely \( \eta \propto 0.01 \sigma_{\text{perc}}^2 \text{ (V)} \).

The behavior in Fig. 3a is observed in real-world RTN and Time-Dependent Defect Spectroscopy (TDDS) measurements [9]. The application of back bias changes the contribution of dopants and results in a variation of the low-percentile tail emulated by varying \( \sigma_{\text{perc}} \) (Fig. 4) [10].
We note that the single-trap $\Delta V_{th}$ (i.e., the RTN) distribution has been claimed to be log-normally distributed [12, 13]. (N.b.: this is unrelated to attempts to describe the total $\Delta V_{th}$ distribution as log-normal.) This is not entirely surprising—e.g., our meta-simulated distributions in Fig. 3a, replotted in a log-normal plot (Fig. 3c), resemble closely the distributions reported in Ref. 12.

The log-normal nature of the percolative conduction can become more pronounced in longer devices (i.e., when the impact of the FET junctions can be neglected) and/or in devices with high channel doping (or otherwise highly randomized channel potentials). Fig. 5 shows an extended meta-simulation with 10$^5$ samples per distribution. The RDD contribution is again varied through the parameter $\sigma_{\text{perc}}$ (cf. Fig. 3a). For $\sigma_{\text{perc}} > 0.35$, the $\Delta V_{th}$ distributions visibly deviate from exponential and tend toward log-normal behavior at progressively higher percentiles. Note, however, that a deviation from an exponential behavior of the $\Delta V_{th}$ distribution at a certain percentile will influence only much higher percentiles of the total $\Delta V_{th}$ distribution [14]. Fig. 5 shows that for short devices (i.e., with appreciable impact of the CONT distribution) with low channel doping (i.e., low $\sigma_{\text{perc}}$), the exponential distribution, controlled by the single, physically-based parameter $\eta$, appears to be an acceptable approximation of the $\Delta V_{th}$ distribution.

**ACKNOWLEDGMENT**

The authors are grateful to Dr. Amr Haggag (Apple Computers) for stimulating discussions and suggestions. The work has been in part supported by the European Commission under FP7 project 261868 (MORDRED) and project 619234 (MoRV).

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