Article

Data-Driven Modeling of Low Frequency Noise Using Capture-Emission Energy Maps

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Abstract: A new approach for modeling low frequency noise is presented to enable the predictions of noise behavior from negative bias temperature instability (NBTI). The noise model is based on a capture-emission energy (CEE) map describing the probability density function of widely distributed defect capture-emission activation energies. To enlarge the capture-emission energy window and to perform the accurate estimation of the recoverable component of CEE, the Gaussian mixture model (GMM) is applied to the CEE map. This approach provides an efficient identification of noise sources and an in-depth noise analysis under both stationary and cyclo-stationary conditions.

Keywords: low frequency noise; negative bias temperature instability; capture-emission energy map; gaussian mixture model

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1. Introduction

In nanoscale CMOS devices, the stochastic behavior of a few defects can have a significant impact on the reliability of devices and their circuits [1–8]. The negative bias temperature instability (NBTI) is among the most critical reliability issues and can be described by capture-emission energy (CEE) maps [3–5,9–15]. Accurately modeling the NBTI relies on a combined methodology comprising thorough CEE maps and efficient models. However, CEE maps are limited by the stress-recovery measurement window [9,10,14–17]. An accurate estimation of the parameters of CEE distribution is crucial to enable full lifetime calculation of NBTI without measurement time extrapolation. The kinetics of defects responsible for NBTI has been explained by the random capture-emission process of charge carriers caused by oxide traps [9–15,18,19]. Moreover, it has been found that the recoverable component of NBTI and random telegraph signal (RTS) noise are due to same defects [19–25]. The discrete fluctuations of RTSs with widely distributed time or energy scales are the main source of low frequency ($1/f$) noise in nanoscale MOSFETs [20,21,26–29]. For the statistical analysis and rigorous modeling of noise behavior, it is crucial to incorporate the distribution of defects based on CEE maps, including large signal AC operations [27–30]. In particular, since the static random-access memory (SRAM) cell is a highly scaled device, the threshold voltage variation due to RTS is a major source of degradation in SRAM characteristics [30]. In the CEE map framework, the time-dependent variability of degradation such as NBTI and noise is reproduced under different bias and duty cycle conditions. In this study, CEE-based noise models are newly presented to allow a quantitative prediction for RTS and $1/f$ noise. The models utilize a Gaussian mixture model (GMM) for enlarging the capture-emission energy window and clustering the recoverable component from the fitted CEE map.

2. Theoretical Model

The capture-emission process of charge carriers is consistent with non-radiative multiphonon theory based on linear electron–phonon coupling [1]. In this theory, the capture-emission times are expressed as $\tau_{c,e}(E_c) = \tau_0 \exp(E_{c,e}/k_b T)$ where τ_0 is the temperature-independent pre-factor, k_b is the Boltzmann constant, T is the temperature, and E_c and E_e

are the capture and emission activation energy, respectively. The NBTI-induced threshold voltage shifts ΔV_{th} is related to the capture-emission processes of individual defects with a broad distribution of characteristic times. The step height observed in ΔV_{th} for small-area devices is due to individual defects, while for large-area devices similar defects are grouped together using a suitable distribution of defects [1,19]. This distribution is visualized in the CEE map, which can be directly obtained from experimental recovery curves of ΔV_{th} for various stress conditions by using $D(\tau_c, \tau_e) = -\partial^2 \Delta V_{th}(\tau_c, \tau_e) / \partial \tau_c \partial \tau_e$ [1]. The defect density map is represented in agreement with bivariate Gaussian distribution, describing the permanent and recoverable components. In the activation energy space, the density $D(E_c, E_e)$ is constructed by the joint probability density function [9,10,14,15]

$$D(E_c, E_e) = \frac{D_0}{2\pi\sigma_c\sigma_e\sqrt{1-\rho^2}} e^{\left[-\frac{1}{2(1-\rho^2)}\left(\frac{(E_c-\mu_c)^2}{\sigma_c^2} - \frac{2\rho(E_c-\mu_c)(E_e-\mu_e)}{\sigma_c\sigma_e} + \frac{(E_e-\mu_e)^2}{\sigma_e^2}\right)\right]} \quad (1)$$

where $D_0 = (V_s/V_0)^\gamma$ is a voltage-dependent amplitude with the stress voltage V_s and the constants V_0 and γ . $\mu_{c,e}$ and $\sigma_{c,e}$ are the mean values and standard deviations of $E_{c,e}$, respectively. A correlation coefficient is defined as $\rho = \text{covariance}(E_c, E_e) / \sigma_c\sigma_e$. For defects being charged up to the stress time t_s and not yet being discharged at the recovery time t_r , the threshold voltage shift is calculated by integrating over the activation energy map as follows [9,10,14,15]

$$\Delta V_{th}(t_s, t_r) = \int_0^\infty \int_0^\infty D_r(E_c, E_e) P_{occ}(E_c, E_e, t_s, t_r) dE_c dE_e + \int_0^\infty \int_0^\infty D_p(E_c, E_e) P_{occ}(E_c, E_e, t_s, t_r) dE_c dE_e \quad (2)$$

where $D_r(E_c, E_e)$ and $D_p(E_c, E_e)$ are the recoverable and permanent component, respectively, and $P_{occ}(E_c, E_e, t_s, t_r)$ is the occupancy probability map for the applied stress and recovery waveform. The occupancy probability P_{occ} after t_s and t_r is described by [1]

$$P_{occ}(E_c, E_e, t_s, t_r) = \left(1 - e^{-\frac{t_s}{\tau_c(E_c)}}\right) e^{-\frac{t_r}{\tau_e(E_e)}} \quad (3)$$

For AC stress and recovery patterns with the signal duty cycle α , and the signal frequency f , the probability to be occupied after the high gate-source voltage V_{gs}^h will be written as [30]

$$P_{occ}(E_c, E_e, t_s, t_r) = \frac{1 - e^{-\frac{\alpha}{f\tau_c}}}{1 - e^{-\frac{1}{f}\left(\frac{\alpha}{\tau_c} + \frac{1-\alpha}{\tau_e}\right)}} \left(1 - e^{-t_s\left(\frac{\alpha}{\tau_c} + \frac{1-\alpha}{\tau_e}\right)}\right) \quad (4)$$

Trap-related processes are the most likely cause of the fluctuation in the number of charge carriers. The contribution of multiple-trap levels leads to a noise power spectrum expressed by the superposition of a single Lorentzian noise as follows [27]

$$S_N(\omega) = \sum_{i=1}^{N_t} S_{N,i}(\omega) = 4 \sum_{i=1}^{N_t} \Delta N_i^2 \frac{\tau_{eff,i}}{1 + \omega^2 \tau_{eff,i}^2} \quad (5)$$

where $\Delta N_i^2 = A_i^2 \tau_{c,i} \tau_{e,i} / (\tau_{c,i} + \tau_{e,i})^2$ is the variance of the fluctuation ΔN in the number of carriers N , A_i is the amplitude, N_t is the number of traps following a Poisson distribution, and ω is the angular frequency. With the assistance of capture-emission activation energies, a change in charge state can occur even if the energy levels of the traps are higher or lower than the Fermi level compared to a few $k_b T$, resulting in $1/f$ noise [31–35]. Assuming that A_i is random variables identically distributed and the effective times constants are

statistically independent, the noise power spectrum of the occupancy $P_{occ}(E_c, E_e, t_s, t_r)$ of the traps in the energy element ΔE_c and ΔE_e is given by [34,35]

$$S_N(\omega) = 4N_t^* A^2 \frac{\tau_c \tau_e}{(\tau_c + \tau_e)^2} \frac{\tau_{eff,i}}{1 + \omega^2 \tau_{eff,i}^2} P_{occ}(E_c, E_e, t_s, t_r) \Delta E_c \Delta E_e \quad (6)$$

where N_t^* is the trap density per unit area. Given that the trap distribution is described by the normalized density $D_r^*(E_c, E_e)$ of the recoverable component, the average noise power spectrum for a device with a width W and length L is converted to an integral expression

$$\overline{S_N(\omega)} = 4N_t^* W L A^2 \int_0^\infty \int_0^\infty \frac{\tau_c \tau_e}{(\tau_c + \tau_e)^2} \frac{\tau_{eff}}{1 + \omega^2 \tau_{eff}^2} D_r^*(E_c, E_e) P_{occ}(E_c, E_e, t_s, t_r) dE_c dE_e \quad (7)$$

where $\tau_{eff} = (1/\tau_c + 1/\tau_e)^{-1}$ is the effective time. Note that the term $P_{occ}(E_c, E_e)$ is similar to the occupancy of traps $f_T(1 - f_T)$ described by a Fermi function f_T , reflecting the fact that traps with higher occupancy probability contribute to noise power. The equivalent gate voltage noise power spectrum of MOSFETs in the linear region is given by $S_{V_g}(\omega) = q^2 \overline{S_N(\omega)} / (W^2 L^2 C_{ox}^2)$ where C_{ox} is the gate oxide capacitance per unit area. Under cyclo-stationary square wave excitation, the noise behavior is governed by the time during the on-state, $\tau_{c,on}$ and $\tau_{e,on}$, and the times during the off-state, $\tau_{c,off}$ and $\tau_{e,off}$. The effective and characteristic times are written as [28]

$$\tau_{eff}^* = \left(\frac{\alpha}{\tau_{on}} + \frac{1 - \alpha}{\tau_{off}} \right)^{-1}, \quad \tau_{c/e}^* = \left(\frac{\alpha}{\tau_{c/e,on}} + \frac{1 - \alpha}{\tau_{c/e,off}} \right)^{-1} \quad (8)$$

with $\tau_{on} = (1/\tau_{c,on} + 1/\tau_{e,on})^{-1}$, $\tau_{off} = (1/\tau_{c,off} + 1/\tau_{e,off})^{-1}$.

For an accurate estimation of CEE distribution, a GMM of the distributions appears to be a natural choice for two components of Gaussian distributions. Given a two-dimensional random variable $E_a = (E_c, E_e)$, with mean μ_i and covariance Σ_i , the GM density function of two Gaussian components is given by [36–39]

$$p(E_a) = \sum_{i=1}^2 \pi_i \mathcal{N}(E_a | \mu_i, \Sigma_i) \quad (9)$$

where π_i is the weight of the i -th mixture component, subject to $0 \leq \pi_i \leq 1$ and $\pi_1 + \pi_2 = 1$. The i -th independent normal distribution is

$$\mathcal{N}(E_a | \mu_i, \Sigma_i) = \frac{1}{\sqrt{2\pi} |\Sigma_i|} e^{-\frac{1}{2} (E_a - \mu_i)^T \Sigma_i^{-1} (E_a - \mu_i)} \quad (10)$$

The expectation maximization (EM) algorithm is used to compute the parameters of each Gaussian component [36–38]. It is an iterative algorithm that estimates a maximum likelihood solution of the parameters, based on an expectation (E) step and a maximization (M) step. The GMM is used for clustering Gaussian components, by realizing that two bivariate Gaussian distributions of fitted CEE map can represent clusters. The soft clustering method is applied to estimate cluster membership posterior probabilities [39]. The method assigns a cluster membership score to each data point and ranks the points by their cluster membership score, allowing some data points to belong to multiple clusters.

3. Results and Discussion

The devices used for measurements were fabricated using a manufacturable remote plasma nitride oxide (RPNO) process. The gate oxide of devices used for measurements was grown with both furnace and rapid-thermal based processes. Following N_2 -plasma nitridation and post-nitridation anneal of the gate oxide, an undoped poly-Si gate layer was deposited. For p+ gates, B was implanted, and rapid-thermal annealing was then

performed in N_2 for different durations. The threshold voltage shifts are obtained on pMOSFETs ($W = 10 \mu\text{m}$, $L = 0.14 \mu\text{m}$, $t_{ox} = 2.2 \text{ nm}$), performing the ultrafast measure-stress-measurements [9,10]. With a measuring delay time of $1 \mu\text{s}$, the temperature-accelerated measurement scheme was used to extend to the experimental stress-recovery window of $10^7 \mu\text{s}$. Noise measurements are conducted using an HP 3582A spectrum analyzer (1 Hz–25 kHz) and a Brookdeal 5004 low noise voltage amplifier connected at the output terminal. A bias resistance at the output terminal is chosen to be 10 times larger than the small signal channel resistance. The noise power spectrum is adjusted to subtract the noise due to the measurement system, which consists of the noise due to the amplifier and the bias resistance, and the thermal noise of device under test. Figure 1a shows experimental recovery data of ΔV_{th} following stress time with numerical data for $V_{gs} = -2.0 \text{ V}$ and $T = 125^\circ\text{C}$. Numerical data of ΔV_{th} are obtained by integrating the CEE distribution in (2), which is calculated by taking the derivatives of measured data, as shown in Figure 1b. Figure 2a shows a scatter plot of GMM data using the soft clustering method. The cluster membership posterior probabilities in the interval (0.45,0.55) are members of both components with six shared data points. The estimated parameters of permanent component are $\mu_{c1} = 1.593 \text{ eV}$, $\mu_{e1} = 1.604 \text{ eV}$, $\sigma_{c1} = 0.203 \text{ eV}$, $\sigma_{e1} = 0.098 \text{ eV}$, $\rho_1 = 0.035$, and those of recoverable component are $\mu_{c2} = 0.908 \text{ eV}$, $\mu_{e2} = 0.997 \text{ eV}$, $\sigma_{c2} = 0.376 \text{ eV}$, $\sigma_{e2} = 0.317 \text{ eV}$, $\rho_2 = 0.8537$. Using the estimated parameters of GMM model, the CEE distributions are produced in the extended energy space exceeding experimental window, as observed in Figure 2b. The inset of Figure 2b shows a plot of the relative error values which are less than 0.5%.

Figure 1. Threshold voltage shifts ΔV_{th} and capture-emission energy (CEE) map. (a) Numerical data with measured data of ΔV_{th} . (b) Comparison of numerical data with measured data of CEE map.

To investigate how the trap distribution influences RTS noise, the integrand of $\overline{S_N(\omega)}$ for the recoverable component in (7) is numerically calculated and visualized as a function of E_e and E_c under stationary DC condition at a particular frequency. It is shown in Figure 3a that a peak is distinct at $E_c = 1.10 \text{ eV}$ and $E_e = 0.65 \text{ eV}$ for $f = 1 \text{ Hz}$, and moves to relatively low activation energies $E_c = 0.75 \text{ eV}$ and $E_e = 0.45 \text{ eV}$ as the frequency increases to $f = 1 \text{ kHz}$. As illustrated in the inset of Figure 3a, these results arise from different RTSs, indicating that faster components of shallow trap states for $f = 1 \text{ kHz}$ are situated close to lower activation energies [40]. To examine the behavior of cyclo-stationary RTS, the times are modeled as $\tau_{c,off} = m \cdot \tau_{c,on}$ and $\tau_{e,off} = \tau_{e,on} / m$, where the factor m is assumed to be greater than one [28,40]. In the off state, τ_c and τ_e are multiplied and divided by m , as they increase and decrease with a decrease in the gate voltage, respectively [28,40]. For $m = 50$, a peak moves to higher emission energy E_e , as shown in Figure 3b.

Figure 2. CEE map with fitted Gaussian mixture (GMM) using soft clustering. (a) Scatter plot of GMM data. (b) Comparison of GMM data with numerical data of CEE map.

Figure 3. Integrands of $\overline{S_N(\omega)}$ for the recoverable component. (a) $f = 1\text{ Hz}$ and $f = 1\text{ kHz}$ under stationary condition for $V_{gs} = -2\text{ V}$. (b) $f = 1\text{ Hz}$ and $m = 50$ under cyclo-stationary condition for $V_{gs} = -2\text{ V}$.

$1/f$ noise power is calculated by using (7) with the recoverable component obtained from GMM with soft clustering. It is observed in Figure 4a that the recoverable component of CEE map gives a $1/f$ spectrum form with a slope of -1 . For asymmetric RTSs ($\tau_{c,on}/\tau_{e,on}$), cyclo-stationary condition may lead to an increase in noise power [28]. Figure 4b shows a linear relationship between $S_{V_g}(\omega)$ and ΔV_{th} after a stress time $t_s = 1000\text{ s}$. The same strong correlation is also observed for the device with SiON/poly-Si gate [20].

Figure 4. $1/f$ noise spectrum and threshold voltage shifts for $t_s = 1000$ s. (a) $S_{V_g}(\omega)$ for $V_{gs} = -2$ V, $N_t^* = 2.0 \times 10^{12}$ cm $^{-2}$ (b) $S_{V_g}(\omega)$ versus ΔV_{th} for $N_t^* = 2.0 \times 10^{12}$ cm $^{-2}$.

4. Conclusions

In conclusion, with a recoverable component of NBTI stress-recovery, a new noise model is formulated based on a fitted CEE map with soft clustering of GMM. The proposed model offers the following unique features: (1) The model is based on the occupancy of defects in the capture-emission energy map. Therefore, it allows modeling of the noise under both stationary as well as cyclo-stationary excitation conditions. (2) The GMM with soft clustering enlarges the CEE window and performs independent estimations of two distinct components of CEE map, enabling the accurate calculation of noise characteristics. (3) New theoretical expressions can capture the noise behavior in terms of activation energies and provide the identification of noise sources and the reliable prediction of $1/f$ noise from NBTI.

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