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► **To cite this version:**

Owen Gauthier, Sébastien Haendler, Quentin Rafhay, Christoforos Theodorou. Universality of trap-induced mobility fluctuations between $1/f$ noise and Random Telegraph Noise in nanoscale FD-SOI MOSFETs. Applied Physics Letters, 2023, 122 (23), 10.1063/5.0152734 . hal-04305435

HAL Id: hal-04305435

<https://hal.science/hal-04305435>

Submitted on 24 Nov 2023

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Universality of trap-induced mobility fluctuations between 1/f noise and Random Telegraph Noise in nanoscale FD-SOI MOSFETs

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(Dated: 19 May 2023)

Low frequency noise (LFN) and Random Telegraph Noise (RTN) are investigated statistically on nanoscale MOSFETs of a 28 nm fully depleted silicon-on-insulator technology. The analysis reveals that the mean noise level is well described by the carrier number fluctuations with correlated mobility fluctuations model. As for the RTN, it is shown that the mean amplitude of the signals is driven by correlated mobility fluctuations in strong inversion. The comparison between the extracted parameters of the LFN and RTN analysis demonstrates that the remote Coulomb scattering impact due to the trapped and detrapped charges remains the same on average for this technology, whether it is the average noise spectrum of all devices, or the average amplitude of the detected RTN signals.

Since the decade of 1970, the origin of flicker ($1/f$) noise in MOSFETs has been a subject of a continuous and fruitful debate: is it related to carrier number fluctuations (CNF) or mobility fluctuations (MF)? While authors like Hooge,¹ Kleinpenning² and Vandamme^{3,4} were establishing the approach that “ $1/f$ noise is no surface effect” but a semiconductor bulk effect related to scattering effects, others, like Fu,⁵ Reimbold⁶ and Ghibaudo,⁷ were on the contrary interpreting the measured fluctuations as a result of trapping/detrapping of carriers in oxide interface defects. The observation of discrete level switching in the measured current,^{8–10} now widely known as Random Telegraph Noise (RTN), contributed in the establishment of the CNF approach,^{11,12} because such sudden and specific amplitude transitions can only take place in trapping events. In parallel, many works demonstrated that MF are not necessarily bulk-related but can also be caused by CNF, due to remote Coulomb scattering noise related to the fluctuating trapped charge.^{13,14} Therefore a unified flicker noise model approach was adopted, called CNF/CMF: carrier number with correlated mobility fluctuations. The down-scaling of the devices area of CMOS technologies leads to higher levels of low frequency noise (LFN) and RTN, which can seriously affect the performances of analog and digital circuits,^{15,16} thus highlighting the importance of developing a realistic model. The CNF/CMF model has been successfully used to extract noise parameters and develop compact $1/f$ noise models until nowadays for all types of MOSFET architectures or channel materials,^{17–19} and also validated statistically. Nevertheless, the adoption of the CNF/CMF approach in the modeling of RTN amplitude has been scarce and limited to single device results,^{10,20–24} due to the bias-dependent appearance of CMF in the measured RTN. In this work, we evoke this subject by probing the CMF contribution in the average RTN amplitude for a statistical sample of 60 nanoscale devices, aiming to statistically validate the CNF/CMF model for RTN and compare the extracted parameter values to the ones obtained by the average $1/f$ noise.

Time and frequency domain drain current noise measurements were performed on 60 n-MOS devices from a 28 nm FD-SOI technology²⁵ with high- κ and metal gate, and equiv-

alent oxide thickness $EOT = 14 \text{ \AA}$. The devices have width $W = 80 \text{ nm}$ and length $L = 30 \text{ nm}$, and are studied for various gate voltages in the linear regime ($V_d = 50 \text{ mV}$). The noise measurements were done using a low-noise current-to-voltage amplifier and a HP35670A spectrum analyzer connected to the AC output of the amplifier. The LFN analysis is undertaken by measuring first the drain current noise power spectral density (S_{I_d}), and then normalizing by the transconductance ($g_m = \partial I_d / \partial V_g$) square to get the input-referred gate voltage noise ($S_{V_g} = S_{I_d} / g_m^2$), shown to be insensitive to electrical static variability,²⁶ assuming that LFN is dominated by charge trapping/detrapping mechanisms.

Examples of noise power spectral densities (PSD) for different gate voltages are shown in Fig. 1. Since S_{V_g} follows a log-normal distribution,²⁷ the mean spectra calculated in Fig. 1 correspond to the geometric mean processed through the logarithm of S_{V_g} . The mean spectra exhibit a $1/f$ slope, where some Lorentzian-shaped spectra associated with RTN are observed with a characteristic plateau and a $1/f^2$ slope, with an example shown in Fig. 1(b). The $1/f$ slope allows the application of the CNF/CMF model for the input-referred gate voltage noise S_{V_g} given by,^{13,14}

$$S_{V_g} = S_{V_{fb}} \left(1 + \Omega \frac{I_d}{g_m} \right)^2. \quad (1)$$

Here, $\Omega = \alpha_{sc} \mu_{eff} C_{ox}$ where α_{sc} is the Coulomb scattering coefficient, μ_{eff} is the charge carrier mobility and C_{ox} the oxide capacitance per unit area. $S_{V_{fb}}$ is the flat-band voltage spectral density given by,¹⁴

$$S_{V_{fb}} = \frac{q^2 k_B T N_t \lambda}{W L C_{ox}^2 f}, \quad (2)$$

where q is the elementary charge, k_B the Boltzmann constant, T the device’s channel temperature, λ the tunnel attenuation distance ($\approx 1 \text{ \AA}$ in SiO_2), f the frequency and N_t the volumetric trap density in $\text{cm}^{-3} \cdot \text{eV}^{-1}$. The product $\alpha_{sc} \cdot \mu_{eff}$ was shown to be constant from weak to strong inversion,¹⁷ so that

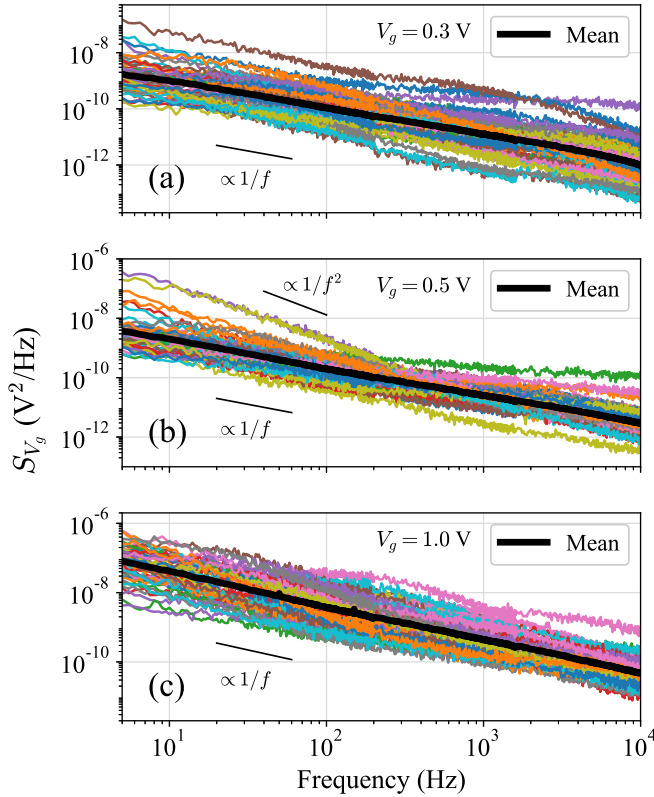


FIG. 1. (a-c) Input-referred gate voltage noise PSD (S_{V_g}) for all measured dies at gate voltage $V_g = 0.3$ V, $V_g = 0.5$ V and $V_g = 1.0$ V. The black lines correspond to the geometric mean spectra.

the parameter Ω is sufficient to describe the mobility fluctuation impact on charge carriers. The fitting parameters $S_{V_{fb}}$ and Ω can be extracted using the quantity $\sqrt{S_{V_g}}$ to take advantage of its linear dependence with I_d/g_m , with the intercept corresponding to $\sqrt{S_{V_{fb}}}$ and the slope to $\sqrt{S_{V_{fb}}} \cdot \Omega$.^{17,28,29} The CNF/CMF model fit on the measured quantity $\sqrt{S_{V_g}}$ extracted at $f = 10$ Hz is presented Fig. 2(a) as a function of I_d/g_m and Fig. 2(b) as a function of the gate voltage for better readability of the scattered data, showing very good agreement. As with S_{V_g} , the mean value extracted from $\sqrt{S_{V_g}}$ corresponds to the geometric mean of the logarithm of the quantity. The parameters of the CNF/CMF model extracted from the linear regression are $S_{V_{fb}} = 1.3 \cdot 10^{-3}$ mV²/Hz and $\Omega = 4.2$ V⁻¹.

Examples of RTN signals for different devices at selected gate voltages are shown in Fig. 3 with their associated histograms. Different signatures are observed, depending on the number of active traps inducing RTN, where a 2-level signal corresponds to 1 active trap as in Fig. 3(a) and Fig. 3(c), and a 4-level signal associated to 2 active traps at the same time as in Fig. 3(b). The statistical analysis of RTN is undertaken employing the detection of discrete levels using the histogram smoothed by a kernel density estimation,³⁰ where the amplitudes ΔI_d of the isolated active traps are extracted.

While the RTN amplitude analysis using the CNF/CMF model was already performed for isolated traps,^{10,20–24} a sta-

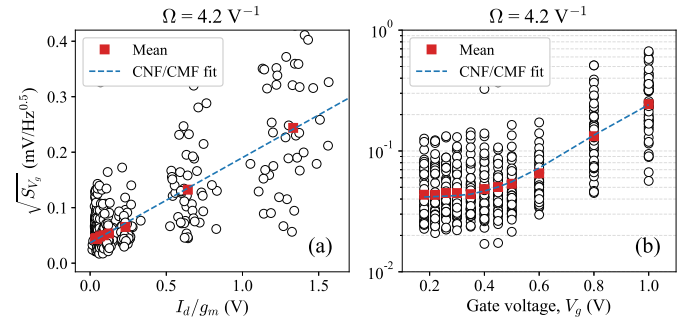


FIG. 2. (a) Square root of the input-referred gate voltage noise extracted at 10 Hz ($\sqrt{S_{V_g}}$) as a function of I_d/g_m for all measured dies. (b) $\sqrt{S_{V_g}}$ as a function of the gate voltage. Red squares are the geometric mean values, and blue dashed lines are the CNF/CMF model fits.

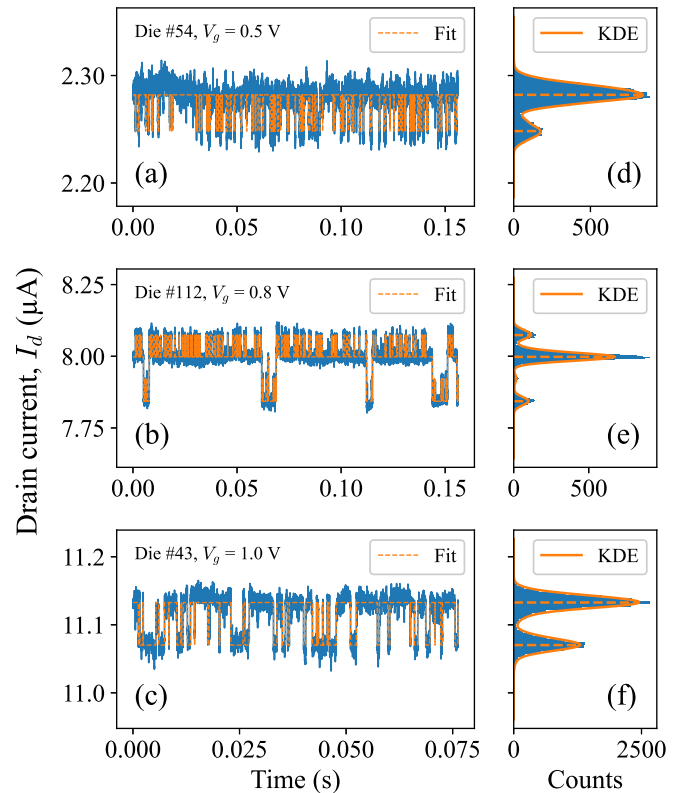


FIG. 3. (a-c) Examples of time-domain drain current noise measurements showing RTN for different devices and gate voltages. (d-f) Associated histograms with kernel density estimation smoothing and the detected levels.

tistical study seems to have not yet been achieved. With the developed methodology for RTN parameter extraction, between 15 and 25 isolated traps were detected per V_g , allowing the analysis on a new statistical level. As done for the LFN analysis, RTN amplitudes and their mean values are presented Fig. 4 as a function of I_d/g_m and gate voltage. The amplitudes are expressed in terms of threshold voltage shifts $\Delta V_t = \Delta I_d/g_m$. The results show an explicit linear relation be-

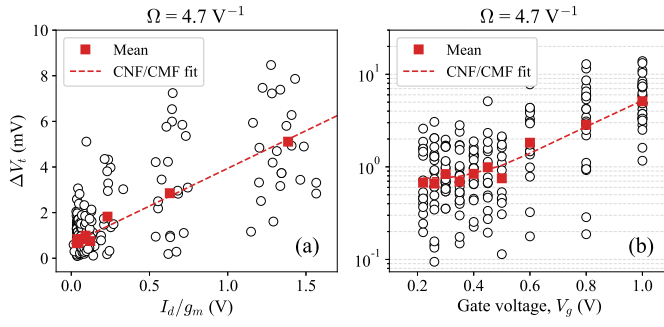


FIG. 4. (a) RTN amplitude (ΔV_t) as a function of I_d/g_m for all detected signals. (b) ΔV_t as a function of the gate voltage. Red squares are the geometric mean values, and red dashed lines are the CNF/CMF model fits.

tween ΔV_t and I_d/g_m especially in strong inversion, showing clear evidence of the presence of mobility fluctuations correlated to the fluctuating trapped charge.

Following the same analysis as done in Ref. 14 for the total surface charge Q_{ss} , in the case of a RTN (single trap) we can derive from $1/\mu_{eff} = 1/\mu_{eff,0} + \alpha_{sc}Q_{ss}$ that $-\Delta\mu_{eff}/\mu_{eff}^2 = \alpha_{sc}q$, because $\Delta Q_{ss} = q$. Of course, here α_{sc} is different for every trap, depending on its position (in oxide depth or horizontal) with regards to the carrier channel. Then, since the total current shift from the trapped charge is $\Delta I_d = -(\partial I_d/\partial V_g)\Delta V_{fb} + (\partial I_d/\partial \mu_{eff})\Delta\mu_{eff}$, a similar CNF/CMF model can be expressed for the case of a single trap inducing RTN,^{20,31}

$$\Delta V_t = -\Delta V_{fb} \left(1 + \Omega \frac{I_d}{g_m} \right), \quad (3)$$

where ΔV_{fb} is the flat-band voltage shift. Despite the fact the CNF/CMF model of Eq. (3) refers to the electrostatic impact of a single RTN trap, it fits well the data in Fig. 4, where the extracted parameters from the linear regression are $\Delta V_{fb} = -0.70$ mV and $\Omega = 4.7$ V⁻¹. The value of Ω is very close to the extracted value from the noise PSD data, revealing that the mean CMF strength can be extracted from either LFN or RTN statistical measurements and can be used to model both types of noise.

To better visualize the agreement in trends and model fits between the two sets of data, the measured normalized mean drain current noise PSD and mean RTN amplitude are represented in Fig. 5 as a function of the drain current, with the CNF only, the CNF with access resistance noise,³² and the CNF/CMF model fits. The model fits shows the necessity of taking into account CMF, because a sole CNF model fit with or without access resistance noise contribution is not correctly representing noise variations in strong inversion in both noise PSD and RTN data sets.

The good agreement with the CNF/CMF model is a first demonstration that the RTN amplitude is statistically driven by MF in strong inversion for FD-SOI nanoscale MOSFETs. Moreover, the extracted Ω values are similar whether the data are taken from the PSD with S_{I_d} , or from the extracted RTN amplitudes ΔV_t . Hence, the mobility sensitivity of the trapped

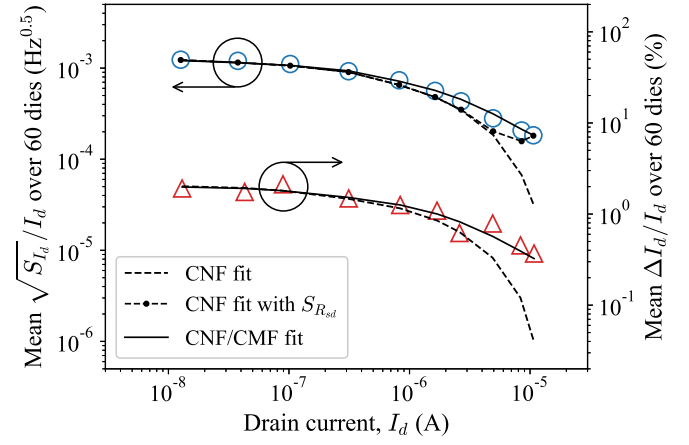


FIG. 5. Normalized mean drain current noise ($\sqrt{S_{I_d}}/I_d$) and normalized mean RTN amplitude ($\Delta I_d/I_d$) over 60 measured devices, as a function of drain current. CNF only, CNF with access resistance noise ($S_{R_{ad}}$) and CNF/CMF model fits are represented in black dashed lines, dash dotted lines and straight lines respectively, showing the need of considering a MF impact to better model the noise variations in strong inversion.

and detrapped charge carriers is on average the same whether the power spectral density of $1/f$ noise or the RTN pulse amplitude is concerned.

- ¹F. N. Hooge, "1/f noise is no surface effect," *Physics Letters A* **29**, 139–140 (1969).
- ²F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, "Experimental studies on 1/f noise," *Rep. Prog. Phys.* **44**, 479 (1981).
- ³L. Vandamme, "Bulk and surface 1/f noise," *IEEE Transactions on Electron Devices* **36**, 987–992 (1989).
- ⁴L. Vandamme, X. Li, and D. Rigaud, "1/f noise in MOS devices, mobility or number fluctuations?" *IEEE Transactions on Electron Devices* **41**, 1936–1945 (1994).
- ⁵H.-S. Fu and C.-T. Sah, "Theory and experiments on surface 1/f noise," *IEEE Transactions on Electron Devices* **19**, 273–285 (1972).
- ⁶G. Reimbold, "Modified 1/f trapping noise theory and experiments in MOS transistors biased from weak to strong inversion—Influence of interface states," *IEEE Transactions on Electron Devices* **31**, 1190–1198 (1984).
- ⁷G. Ghibaudo, "Calculation of Surface Charge Noise at the Si-SiO₂ Interface," *physica status solidi (a)* **104**, 917–930 (1987).
- ⁸K. S. Ralls, W. J. Skocpol, L. D. Jackel, R. E. Howard, L. A. Fetter, R. W. Epworth, and D. M. Tennant, "Discrete Resistance Switching in Submicrometer Silicon Inversion Layers: Individual Interface Traps and Low-Frequency ($1/f$) Noise," *Phys. Rev. Lett.* **52**, 228–231 (1984).
- ⁹M. J. Kirton, M. J. Uren, S. Collins, M. Schulz, A. Karmann, and K. Scheffer, "Individual defects at the Si:SiO₂ interface," *Semicond. Sci. Technol.* **4**, 1116 (1989).
- ¹⁰K. K. Hung, P. K. Ko, C.-M. Hu, and Y. C. Cheng, "Random Telegraph Noise of Deep-Submicrometer MOSFETs," *IEEE Electron Device Letters* **11**, 90–92 (1990).
- ¹¹O. Roux dit Buisson, G. Ghibaudo, and J. Brini, "Model for drain current RTS amplitude in small-area MOS transistors," *Solid-State Electronics* **35**, 1273–1276 (1992).
- ¹²E. Simoen, B. Dierickx, C. Claeys, and G. Declerck, "Explaining the amplitude of RTS noise in submicrometer MOSFETs," *IEEE Transactions on Electron Devices* **39**, 422–429 (1992).
- ¹³K. Hung, P. Ko, C. Hu, and Y. Cheng, "A unified model for the flicker noise in metal-oxide-semiconductor field-effect transistors," *IEEE Transactions on Electron Devices* **37**, 654–665 (1990).
- ¹⁴G. Ghibaudo, O. Roux, C. Nguyen-Duc, F. Balestra, and J. Brini, "Im-

- proved Analysis of Low Frequency Noise in Field-Effect MOS Transistors,” *physica status solidi (a)* **124**, 571–581 (1991).
- ¹⁵C. Leyris, F. Martinez, M. Valenza, A. Hoffmann, J. Vildeuil, and F. Roy, “Impact of Random Telegraph Signal in CMOS Image Sensors for Low-Light Levels,” in *2006 Proceedings of the 32nd European Solid-State Circuits Conference* (2006) pp. 376–379.
- ¹⁶K. Takeuchi, T. Nagumo, S. Yokogawa, K. Imai, and Y. Hayashi, “Single-charge-based modeling of transistor characteristics fluctuations based on statistical measurement of RTN amplitude,” in *2009 Symposium on VLSI Technology* (2009) pp. 54–55.
- ¹⁷E. G. Ioannidis, C. A. Dimitriadis, S. Haendler, R. A. Bianchi, J. Jomaah, and G. Ghibaudo, “Improved analysis and modeling of low-frequency noise in nanoscale MOSFETs,” *Solid-State Electronics* **76**, 54–59 (2012).
- ¹⁸C. G. Theodorou, N. Fasarakis, T. Hoffman, T. Chiarella, G. Ghibaudo, and C. A. Dimitriadis, “Flicker noise in n-channel nanoscale tri-gate fin-shaped field-effect transistors,” *Appl. Phys. Lett.* **101**, 243512 (2012).
- ¹⁹R. K. Kammeugne, C. Theodorou, C. Leroux, X. Mescot, L. Vauche, R. Gwoziecki, S. Becu, M. Charles, E. Bano, and G. Ghibaudo, “Thorough Investigation of Low Frequency Noise Mechanisms in AlGaIn/GaN and Al₂O₃/GaIn HEMTs,” in *2021 IEEE International Electron Devices Meeting (IEDM)* (2021) pp. 39.4.1–39.4.4.
- ²⁰T. A. Karatsori, C. G. Theodorou, X. Mescot, S. Haendler, N. Planes, G. Ghibaudo, and C. A. Dimitriadis, “Study of Hot-Carrier-Induced Traps in Nanoscale UTBB FD-SOI MOSFETs by Low-Frequency Noise Measurements,” *IEEE Transactions on Electron Devices* **63**, 3222–3228 (2016).
- ²¹T. A. Oproglidis, T. A. Karatsori, C. G. Theodorou, D. Tassis, S. Barraud, G. Ghibaudo, and C. A. Dimitriadis, “Origin of Low-Frequency Noise in Triple-Gate Junctionless n-MOSFETs,” *IEEE Transactions on Electron Devices* **65**, 5481–5486 (2018).
- ²²T. A. Oproglidis, T. A. Karatsori, C. G. Theodorou, A. Tsormpatzoglou, S. Barraud, G. Ghibaudo, and C. A. Dimitriadis, “Impact of Hot Carrier Aging on the 1/f and Random Telegraph Noise of Short-Channel Triple-Gate Junctionless MOSFETs,” *IEEE Transactions on Device and Materials Reliability* **21**, 348–353 (2021).
- ²³C. L. N. Pavan, R. Divakaruni, A. Chakravorty, and D. R. Nair, “Characterization and Analysis of Random Telegraph Noise in Scaled SiGe Channel HKMG pMOSFETs,” *IEEE Transactions on Electron Devices* **69**, 456–461 (2022).
- ²⁴B. C. Lee, Y. Seo, C. Kim, Y. Kim, M.-K. Joo, and G.-T. Kim, “Understanding random telegraph noise in two-dimensional BP/ReS₂ heterointerface,” *Appl. Phys. Lett.* **120**, 253507 (2022).
- ²⁵N. Planes, O. Weber, V. Barral, S. Haendler, D. Noblet, D. Croain, M. Bocat, P.-O. Sassoulas, X. Federspiel, A. Cros, A. Bajolet, E. Richard, B. Dumont, P. Perreau, D. Petit, D. Golanski, C. Fenouillet-Béranger, N. Guillot, M. Rafik, V. Huard, S. Puget, X. Montagner, M.-A. Jaud, O. Rozeau, O. Saxod, F. Wacquant, F. Monsieur, D. Barge, L. Pinzelli, M. Mellier, F. Boeuf, F. Arnaud, and M. Haond, “28nm FDSOI technology platform for high-speed low-voltage digital applications,” in *2012 Symposium on VLSI Technology (VLSIT)* (2012) pp. 133–134.
- ²⁶C. G. Theodorou, E. G. Ioannidis, S. Haendler, E. Josse, C. A. Dimitriadis, and G. Ghibaudo, “Low frequency noise variability in ultra scaled FD-SOI n-MOSFETs: Dependence on gate bias, frequency and temperature,” *Solid-State Electronics* **117**, 88–93 (2016).
- ²⁷E. Ioannidis, C. Theodorou, S. Haendler, C. Dimitriadis, and G. Ghibaudo, “Impact of low-frequency noise variability on statistical parameter extraction in ultra-scaled CMOS devices,” *Electronics Letters* **50**, 1393–1395 (2014).
- ²⁸A. Tataridou, G. Ghibaudo, and C. Theodorou, “Influence of series resistance on the experimental extraction of FinFET noise parameters,” in *2020 IEEE 33rd International Conference on Microelectronic Test Structures (ICMTS)* (2020) pp. 1–4.
- ²⁹A. Tataridou, G. Ghibaudo, and C. Theodorou, “A Method for Series-Resistance-Immune Extraction of Low-Frequency Noise Parameters in Nanoscale MOSFETs,” *IEEE Transactions on Electron Devices* **67**, 4568–4572 (2020).
- ³⁰O. Gauthier, S. Haendler, P. Scheer, A. Vernhet, Q. Rafhay, and C. Theodorou, “Enhanced statistical detection of random telegraph noise in frequency and time domain,” *Solid-State Electronics* **194**, 108320 (2022).
- ³¹G. Ghibaudo, O. Roux, and J. Brini, “Modeling of conductance fluctuations in small area metal–oxide–semiconductor transistors,” *physica status solidi (a)* **127**, 281–294 (1991).
- ³²G. Ghibaudo and T. Bouchacha, “Electrical noise and RTS fluctuations in advanced CMOS devices,” *Microelectronics Reliability* **42**, 573–582 (2002).