Direct White Noise Characterization of Short-Channel MOSFETs

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Introduction of Device Lab Inc.

Spin-off company from University of Tsukuba

- Founded in April 2017
- Based in Tsukuba, Japan (1 hour from Tokyo)
- Focus on electric characterization of devices
  - Entrope® High-Frequency Noise Probe
  - Measurement solutions for electron devices
Outline

- Noise in MOSFETs
  - Low frequency (1/f, RTN)
  - High-frequency (thermal, shot)
- Measurement systems
  - Conventional systems (low-frequency)
  - High-frequency noise probe
- Results
  - Bias-dependent noise spectra
  - White noise evaluation
  - Equation of Fano factor for modeling
- Our recent challenge for quantum computing
- Summary
Schematic diagram of MOSFET noise

- Conventional measurement (LNA, fast IV) “dc”
- Flicker Low freq.
- Thermal noise, Shot noise
- Noise figure measurement “ac”
- Capacitive coupling
- Jitter Phase noise

- Practical frequency limit in LFN systems: 100 kHz-1MHz
- Noise figure: requires noise source, de-embedding
- Direct observation of a corner frequency (under DC bias) is important.
Why measure high-frequency noise?

Shannon’s equation

\[ C = B \log_2 \left( 1 + \frac{S}{N} \right) \]

- **C**: Channel capacity in bits/s
- **B**: Channel bandwidth in Hz
- **S**: Signal power
- **N**: Noise power

Phase noise at high offset frequencies (∝B) is assuming greater importance

**Phase noise originates from devices (thru up-conversion), circuit, power supply, and outside**

**Ideal**

**Actual spectrum with phase noise**

**Oscillator output power**

**Frequency**

**Offset freq.**

### Standards

| Standard               | max B     |
|------------------------|-----------|
| 4G                     | 20 MHz    |
| 5G                     | 400 MHz   |
| WiGig (802.11ad)       | 2.16 GHz  |
| THz (802.15.3d)        | 69.12 GHz |

Why measure high-frequency noise?

- Phase noise at high offset frequencies (∝B) is assuming greater importance
Accurate noise model a must for Beyond 5G

Influence of White LO Noise on Wideband Communication

Jingjing Chen, Member, IEEE, Dan Kuylenstierna, Member, IEEE, Sten E. Gunnarsson, Member, IEEE, Zhongxia Simon He, Member, IEEE, Thomas Eriksson, Member, IEEE, Thomas Swahn, Senior Member, IEEE, and Herbert Zirath, Fellow, IEEE

- Adverse effects of white noise on mm-wave have experimentally been confirmed [1][2]
- High-frequency device noise is not merely a theoretical concern!
- Measurement-based predictive device noise model is vital to success of Beyond 5G

[1] Chen et al., “Influence of white LO noise on wideband communication,” IEEE Microwave Theory Tech., vol. 66, no. 7, pp. 3349–3359, July 2018.
[2] Chen et al., “Does LO noise floor limit performance in multi-gigabit millimeter-wave communication?,” IEEE Microwave Compon. Lett., vol. 27, no. 8, pp. 769–771, Aug. 2017.
Origins of Noise

- 1/f (flicker) noise, random telegraph noise
  - Materials property
  - trapping/de-trapping between oxide traps and channel electrons
  - number/mobility fluctuation

- Thermal (Johnson) noise
  - phonon scattering
  - resistance

- Shot noise
  - Carrier transport
  - Discrete nature of conducting electron number

Trap/detrap probability

\[ P \propto \text{Exp} \left( \frac{-2d}{\alpha} - \frac{\Delta E}{kT} \right) \]

- \( d \): distance between a trap and an electron
- \( \alpha \): localization length of wave-function
- \( \Delta E \): the energy difference between the trap and the electron
Measurement of thermal and shot noise

- Phenomena with ultrafast relaxation time (e.g., phonon scattering)
- Y-factor method on wafer
  - a noise source
  - complicated de-embedding processes
  - above 10 MHz

Noise figure (Y-factor method)

Agilent Application Note 57-1
Low-frequency noise measurement systems

- **ProPlus Design Solutions**
  - 9812D Advanced 1-f Noise Analyzer
  - Maximum frequency: **10 MHz**
  - Current LNA noise floor: $3.6 \times 10^{-23} \text{ A}^2/\text{Hz} @ 5 \text{ kHz}$

- **Keysight Technologies**
  - E4727B Advanced Low-Frequency Noise Analyzer
  - Maximum frequency: **100 MHz**
  - LNA noise floor: $1 \times 10^{-28} \text{ A}^2/\text{Hz}$
High-frequency noise probe

- Proof of concept: high-frequency noise probe [1-2]
  - Very wideband LNA
  - Locate the LNA as close to DUTs as possible
- Detailed measurement-based calibration of LNA
  - Solid theoretical foundations
  - No fudge factors
  - Amplifier noise accounted for
- Now commercially available as Entrope®

[1] K. Ohmori et al., 2012 VLSI Technology.
[2] K. Ohmori et al., 2013 VLSI Circuits.
Simplified diagram of the Noise Probe system

- Probe’s built-in amplifier enables high-frequency measurements.
- The pull-up resistor, $R_p$, often (but not always) dictates floor noise.
## Specification of Entrope® Noise Probe

| Probe type   | Frequency       | LNA noise (minimum)                           |
|--------------|-----------------|----------------------------------------------|
| Entrope® 101A | 10k - 200MHz    | ~3×10^{-23} (A^2/Hz) @ 10 MHz               |
| Entrope® 102A | 10k - 200MHz    | ~5 × 10^{-23} (A^2/Hz) @ 10 MHz             |

### System specification

| Specification                      |                   |
|------------------------------------|-------------------|
| Max DUT bias voltage               | 40 V              |
| Max drain current (I_d)            | 5 mA (30 mA for a high-current model) |
| No. of biasing terminals           | 3 (Source: GND)   |
| Minimum measurable R_DUT           | ~50 Ω             |

- In practice, measurements up to several hundreds MHz are possible.
- Today’s demonstration employs measured noise values at 300 and 500 MHz.
Sample and measurement conditions

- **Sample**
  - n-MOSFET (RF-TEG)
  - Technology node: 130 nm
  - $L_g$: 120 nm, $W_g$: 10 µm

- **Measurements**
  - $D_c$ ($I_{d}-V_{d}$, $I_{d}-V_{g}$)
  - Noise
  - At room temperature
The white noise levels for $V_d = 0$ V are consistent with ideal thermal noise ($4k_B T/R$).
Variability of noise among six DUTs

- Variability of short-channel MOSFETs is large in the low-frequency region.
- Emergence of random telegraph noise (RTN) enhances the variability.
Drain-bias dependent $S_{Id}$

- Entrope® Noise Probe gives you noise spectra of DUT, in which LNA noise is accounted for.
- Broadband characterization from flicker (1/f) noise to white noise is clearly demonstrated.
Evaluation of white noise level $S_w$

$$S_{Id}(f) = A/f^\beta + S_w$$

$-\beta \approx -1$: slope of flicker noise

$S_w$: white noise level

$(A/S_w)^{1/\beta}$: corner frequency

- By using the experimental data above the corner frequency, one can accurately evaluate the white noise level without a residual component of 1/f noise.
- In this study, the values at 300 and 500 MHz were used.
White noise levels $S_w$ as a function of $V_d$

Transition of the dominant factor from thermal noise to shot noise is clearly observed.

A. van der Ziel, *Noise in Solid State Devices and Circuits*. New York, NY, USA: John Wiley & Sons, Inc., 1986.
S. T. Hsu, A. van der Ziel, and E. R. Chenette, “Noise in space-charge-limited solid-state devices,” *Solid-State Electron.*, vol. 10, no. 2, pp. 129–135, Feb. 1967.
The white noise levels $S_w$ as functions of $V_d$ and $V_g$.

The white noise levels for large $V_d$ do not exceed the $2qI_d$ value.
Two viewpoints of white noise: thermal and shot

**Thermal noise**

\[ S_w = 4k_B T \ g_{d0} \times \gamma \]

**Shot noise**

\[ S_w = S_{shot} \times F = 2qI_d \times F \]

**Example of the Fano factor Eq.**

\[ F = S_w / [2qI_d \ coth(V_d/2k_BT)] \]

- F → 1 at V_d → 0 V
- Difficult to use if V_d and I_d are very small.

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Y. Tsividis and C. McAndrew, Operation and Modeling of the MOS Transistor, 3rd ed., Oxford, UK: Oxford University Press, 2011.

X. Chen, C. H. Chen, and R Lee, “Fast evaluation of the high-frequency channel noise in nanoscale MOSFETs,” IEEE Trans. Electron Devices, vol. 65, no. 4, pp. 1502–1509, Apr. 2018.
Proposed empirical Eq. for the Fano factor

\[ F = \frac{S_w}{2qI_d + S_{th}} \]

All of \( S_w \), \( I_d \), and \( S_{th} \) are measurement-based values.

- The proposed equation is practical for any biases of \( V_g \) and \( V_d \).
- The Fano factor should be affected by various elements such as device structures and dimensions, impurity profiles, and choice of materials. Actual measurement is important.
Published in IEEE TED (Early Access)

Abstract—On-wafer evaluation of white thermal and shot noise in nanoscale MOSFETs is demonstrated by directly sensing the drain current under zero- and nonzero-drain-bias \( (V_d) \) conditions for the first time, without recourse to a hot noise source, commonly needed in noise figure measurement. The dependence of white noise intensity on the drain bias clearly shows thermal noise at \( V_d = 0 \) V and shot noise at \( V_d > 0 \) V with its gate-bias-dependent suppression. An empirical expression for the Fano factor (shot-noise suppression factor) that is well-behaved even at \( V_d = 0 \) V exactly and suitable for measurement-based evaluation is proposed. The direct measurement approach could allow more accurate and predictive noise modeling of RF MOSFETs than has conventionally been possible.

Index Terms—1/f noise, device modeling, MOSFET, shot noise, thermal noise.

I. INTRODUCTION

MOSFETs are known to exhibit flicker (or 1/f) noise at low frequencies (LFs) and white noise at high frequencies (HFs). Physical origins of flicker noise and white range, including the white noise region and the transition region to that region, therefore, are essential not only for elucidating the physics behind but also for developing predictive device noise models for circuit design. Models built only from extrapolated data may well necessitate more silicon respins.

White noise in MOSFETs is typically characterized by noise figure (NF) measurement at RF, where flicker noise is negligible. In the Y-factor method of NF measurement, a known good “hot” white noise source is required to provide two [“hot” and “cold” (room temperature)] reference noise temperatures [15], [16]. The hot or cold white noise is impressed to the device under test (DUT) during the measurement. The method is typically applicable down to 10 MHz at best and usually requires a complicated de-embedding procedure, which adds to measurement uncertainty. LF (flicker) noise measurement, on the other hand, is performed by directly sensing noise generated by the DUT under “cold” dc-biased conditions. Several systems for LF noise measurement are commercially available. Although a typical maximum mea-
Some restrictions apply.

- **Sample**
  - RF-TEG
  - Limited No. of DUTs

- **How?**
  - Bring a wafer with you
  - Ship a wafer to us

Please contact us if you are interested in measurement by using Entrope® Noise Probe.
Peripherals for quantum computing (QC)

Present QC
Peripherals are located at room temperature.

Future QC
Peripherals will be in a cryogenic environment.

Quantum processor (Qubit)

Peripherals (Controller)

Cryogenic CMOS

IND News “Google runs largest chemistry calculation on quantum computer”, Aug 28, 2020.
B. Patra et al., IEEE JSSC 53 (2018) 309.
At present, *in-situ* broadband noise characterization down to 120 K has been successfully achieved.

Aiming for noise characterization at 4 K

IEEE EDTM (to be presented, April 2021)

Nominated for the best paper award

Available at TechRxiv

White Noise Characterization of N-MOSFETs for Physics-Based Cryogenic Device Modeling

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Abstract

We propose a methodology of variable-temperature broadband noise characterization for cryogenic measurements, which includes a broadband low-
Summary of our message

- Measurement-based predictive white noise model is vital to RF modeling and circuit design
- By using Entrope® Noise Probe, we demonstrated uncomplicated higher frequency noise measurement
  - Observed clear direct white noise
  - Proposed practical equation for the Fano factor
  - Simple reliable approach for predictive noise models

Please contact us if you are interested in measurement by using Entrope® Noise Probe