Direct measurement of white noise in MOSFETs

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11th International MOS-AK Workshop
Silicon Valley, December 5, 2018
One-page 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 characterizing MOSFETs and neuromorphic devices
Outline

- Noise in MOSFETs
  - Low frequency (1/f, RTN)
  - High-frequency (thermal, shot)
- Measurement systems
  - Conventional system (low-frequency)
  - High-frequency noise probe
- Measurement results
- Comparison with models
- Summary
Schematic diagram of MOSFET noise

- **Conventional measurement (LNA, fast IV) “dc”**
- **RTN**
- **Flicker, Shot noise**
- **Thermal noise, Shot noise**
- **Noise figure measurement “ac”**
- **Capacitive coupling**

- **Practical frequency limit in LFN systems: 100 kHz**
- **Noise figure: complicated, requires noise source**
- **Direct observation of a corner frequency (under DC bias) is important.**

**Thermal noise**

\[ S_{ld} = 4k_B T \Delta f / R \]

**Shot noise**

\[ S_{ld} = 2qI_d \Delta f \]
Origins of Noise

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

- Thermal (Johnson) noise
  - phonon scattering
  - resistance

- Shot noise
  - Discrete nature of conducting electron number

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

- \( d \): distance between a trap and an electron
- \( \alpha \): localization length of wave-function
- \( \Delta E \): the energy difference between the trap and the electron
Why 1/f properties?

- Random telegraph noise: Lorentzian-shaped power spectral density
- 1/f noise: superposition of Lorentzians with various time constants

Phenomena with ultrafast relaxation time (e.g., phonon scattering)

- Y-factor method on wafer requires
  - a noise source and high-frequency setups (probes, test structures for de-embedding)
A significant increase in RF noise compared to PSP prediction was observed for sub-100-nm MOSFETs.

PSP: a compact MOSFET model developed by Arizona State University and NXP Semiconductors Research

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

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

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**Ideal**

**Actual spectrum with phase noise**

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**Offset freq.**  

**Frequency**

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**Oscillator output power**

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**Why measure high-frequency noise?**

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

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Phase noise originates from devices (thru up-conversion), circuit, and outside.

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*Shannon's equation*
Accurate noise model a must for 5G & beyond

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, academic concern!
- Measurement-based predictive device noise model is vital to success of 5G and Beyond 5G

Low-frequency noise (empirical)

McWhorther model
- Number fluctuation

Hooge model
- Mobility fluctuation model

\[
\frac{S_{id}}{I_d^2} = \frac{\alpha_H}{f \cdot N}
\]

\[
qN = WLC_{ox} \left| V_g - V_t \right|
\]
Noise models

1/f noise (SPICE2)

\[ S_{ld} = \frac{KF g_m^2}{C_{ox} W L_{eff}} \frac{1}{f^{AF}} \]

1/f noise (BSIM3)

\[ S_{ld,1/f} = \frac{q^2 k T I_d u_{eff}}{L_{eff}^2 C_{ox} f_{eff} 10^8} \left[ NOI A ln \left( \frac{N_0 + N^*}{N_L + N^*} \right) + NOIB(N_0 - N_L) + \frac{NOIC}{2} \left( N_0^2 - N_L^2 \right) \right] + ... \]

Thermal noise (SPICE2)

\[ S_{ld,therm} = \frac{8}{3} k T (g_{ds} + g_m + g_{mb}) \quad \text{for} \quad V_{ds} > V_{dsat} \]
Low-frequency noise measurement systems

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

- **Keysight Technologies**
  - E4727A Advanced Low-Frequency Noise Analyzer
  - Maximum frequency: 40 MHz
  - Current LNA noise floor: $1 \times 10^{-24} \text{A}^2/\text{Hz} @ 10 \text{kHz}$
Noise floor and frequency limit

Demonstration by Keysight B1530A WGFMU (Fast IV)

- **Id (A/µm)**
  - 10^-2
  - 10^-4
  - 10^-6
  - 10^-8
  - 10^-10
  - 10^-12
  - 10^-14

- **Vg-Vt (V)**
  - 0.0
  - 0.4
  - 0.8
  - 1.2

- **SiO2 3nm**
  - L: 240 nm
  - Vt: 0.01 V

- **Vd: 1 V**
- **Vd: 50 mV**

- **Noise floors**
  - 1mA
  - 100µA
  - 10µA

- **DUT noise**

- **Limitation**
  - Amplifier design
  - Configuration (wiring)
Concept of high-frequency noise probe

- Locate the LNA as close to DUTs as possible
- Very wideband LNA

K. Ohmori et al., 2012 VLSI Technology.
K. Ohmori et al., 2013 VLSI Circuits.
Probe’s built-in amplifier enables high-frequency measurements.

The pull-up resistor, $R_{pu}$, often (but not always) dictates floor noise and the permissible $I_d$ current.
Amplifier calibration for noise measurement

- Detailed measurement-based calibration
  - Solid theoretical foundations
  - No fudge factors
  - Amplifier noise accounted for

![Image of amplifier with labels LNA, Four pins (D,G,S,Sub)]
Hardware components

- Function Generator
- Spectrum Analyzer
- Digital Multimeter
- Semiconductor Analyzer (B1500A)
- Monitor
- Probe Station
- LNA Power Supply
- Entrope™ Noise Probe
- Entrope™ Software (PC)

Entrope™ system

Should be purchased through a local distributor.
## Specification of *Entrope™* Noise Probe

<table>
<thead>
<tr>
<th>Probe type</th>
<th>Frequency</th>
<th>Floor noise (minimum)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Entrope™</em> 101A</td>
<td>100k - 100MHz</td>
<td>(~3\times10^{-23} \text{ (A}^2/\text{Hz}) @ 10 \text{ MHz})</td>
</tr>
<tr>
<td><em>Entrope™</em> 102A</td>
<td>100k - 100MHz</td>
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</tbody>
</table>

### System specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max DUT bias voltage</td>
<td>40 V</td>
</tr>
<tr>
<td>Max drain current</td>
<td>5 mA</td>
</tr>
<tr>
<td>No. of biasing terminals</td>
<td>3 (Source: GND)</td>
</tr>
<tr>
<td><strong>R_{DUT}</strong></td>
<td>&gt; 50 Ω</td>
</tr>
</tbody>
</table>
Sample and measurement conditions

- **Sample**
  - n-MOSFET
  - Technology node: 0.13 µm
  - \( L_g: 120/180/240/300 \) nm

- **Measurement**
  - dc (\( I_d-V_d, I_d-V_g, I_d-V_b \))
  - noise
  - at room temperature

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**Id-Vd (\( L_g: 120 \) nm)**

- \( V_g: 0.6 \) V, \( V_g: 0.7 \) V, \( V_g: 0.8 \) V
- Biases for noise measurement

![Id-Vd Graph](attachment:image.png)
Noise measurement (Vgs: 0.6V, Lg: 120 nm)

Vgs: 0.6V

Vds (V): 0, 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.3, 0.5, 0.6, 0.7, 0.8

Sid (A^2/Hz)

Frequency (Hz)
Noise measurement (Vgs: 0.7/0.8V, Lg: 120 nm)

Vgs: 0.6, 0.7, 0.8 V
Vds: 0, 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.3, 0.5, 0.6, 0.7, 0.8 V
Variability (Lg: 120 nm)

Device-to-device variability seems to be large in the lower frequency region.

RTN appears even in the higher frequency region.
Sid extraction in saturation (Lg: 120 nm)

- Sid values at 300 MHz
- Saturation region (Vds > 0.2 V)

\[ S_{ld,\text{therm}} = \frac{8}{3} kT(g_{ds} + g_m + g_{mb}) \quad \text{for} \quad V_{ds} > V_{dsat} \]

SPICE2

Conductance (gds, gm, gmb)

Model: only thermal noise

Excess noise confirmed!

Vgs: 0.6, 0.7, 0.8 V
Vds: 0.2, 0.3, 0.5, 0.6, 0.7, 0.8 V
Measurement-based predictive white noise model is vital to success of 5G and Beyond 5G

By using Entrope™ Noise Probe, we demonstrated higher frequency noise measurement
- Clear direct observation of white noise
- Simple reliable approach for predictive noise models