On-Wafer Measurement and Analysis of Flicker Noise and Random Telegraph Noise

September, 2014
Outline

– Importance of low-frequency noise
– Measurement and analysis techniques
– Design of Advanced Low-Frequency Noise Analyzer (A-LFNA)
– Device modeling for flicker noise
– Conclusions
Low-Frequency Noise
- 1/f Noise and Random Telegraph Noise

- Minute fluctuation of DC voltage and current observed in an electronic device at the low frequencies

- Its power spectral density usually exhibits 1/f behavior – known as 1/f noise

- Random telegraph noise – noise represented in the time domain exhibiting two or a limited number of stable levels
Physical Origins

– Fluctuations of the number of carriers and mobility fluctuation

– The trapping/de-trapping of carriers is now widely accepted as the main reason for low-frequency noise in semiconductor devices

– Effective indicator of material quality

Advanced Low-Frequency Noise Analyzer
Importance and Increasing Impact on Circuit Performance

- Analog circuits
  - Low-noise operational amplifiers

- RF circuits
  - Phase noise in VCOs, frequency dividers, active mixers

- Logic circuits
  - Read and Write Static Noise Margins in SRAM cells

- Increasing importance
  - Device scaling \((1/L_{eff})^2\) leads to higher noise
  - Voltage scaling leads to larger impact of noise
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Measuring 1/f Noise and RTN

– Either voltage LNA or trans-impedance (current) LNA can be used
**Quality Check on 1/f Noise Data**

- **Valid data**
  - Needs to be above system noise floor and thermal noise of load resistance and measured before roll-off frequency.

- **System noise floor**
  - Determined by LNA's spec and measurement environment.

- **Roll-off frequency**
  - Frequency where the gain of the voltage LNA quickly deteriorates because of equivalent resistance and capacitance on the output node.

- **Invalid data**
  - Ignore after roll-off frequency.

- **Thermal noise of**
  - $4kT R_{LOAD}$
Analysis of RTN Data

- Various data analysis techniques exist to determine trap properties

Measuring Capture and Emission Times from RTN Data

Current Fluctuation over Time  Histogram of Current Values

Example of Calculation of Capture and Emission Time Constants

Challenges for Low-Frequency Noise Measurement

- Low-current/low-noise measurement
- Desire to have data in as broad a frequency range as possible
- Measurement throughput (for statistics)
- Needs for specialty technologies (ex. high-voltage/high-power, ultra-low frequency)
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Advanced Low-Frequency Noise Analyzer

PXIe Chassis
- Embedded PC
- Interface Module
- Digitizer (ADC)

Input Module
- Input Resistor
- LPF
- SG

Output Module
- Output Resistor
- LPF
- VAMP
- CAMP

Substrate Module
- LPF
Custom-Designed Modules

- Interface Module
- Input Module
- Output Module
- Substrate Module
Design of Input, Output, and Substrate Modules
Measurement Setup

Advanced Low-Frequency Noise Analyzer

B1500A

PXI Chassis

Digitizer (ADC)

SMU1

SMU2

SMU3

Input Module

Output Module

Kelvin-Triaxial

Control Signal

Source

Gate

Drain

BG

Substrate Module

Embedded PC

Interface Module

GP-IB
Benefits of Unique Modular Design

- Shortest possible cables to reduce parasitic capacitances and increased roll-off frequency
- Small footprint and portability
  - Easy to mount on and remove from the prober surface through magnetic attachment
State-of-the-art Custom-Designed LNAs
- 3 VAMPs + 1 CAMP

<table>
<thead>
<tr>
<th>LNAs</th>
<th>ULF</th>
<th>LF</th>
<th>Wideband</th>
<th>LNA-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Voltage AMP</td>
<td>Voltage AMP</td>
<td>Voltage AMP</td>
<td>Current AMP</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>0.03Hz – 1MHz</td>
<td>1Hz – 1MHz</td>
<td>1Hz – 40MHz</td>
<td>0.03Hz – 100KHz</td>
</tr>
<tr>
<td>Input Voltage Density</td>
<td>0.67nV/√Hz @10KHz</td>
<td>0.67nV/√Hz @10KHz</td>
<td>1.5nV/√Hz @1MHz</td>
<td></td>
</tr>
<tr>
<td>Input Current Noise Density</td>
<td>&lt;100fA/√Hz @10KHz</td>
<td>&lt;100fA/√Hz @10KHz</td>
<td>&lt;100fA/√Hz @10KHz</td>
<td>&lt;1pA/√Hz @1KHz</td>
</tr>
<tr>
<td>Corner Frequency</td>
<td>20Hz</td>
<td>200Hz</td>
<td>200Hz</td>
<td>200Hz</td>
</tr>
</tbody>
</table>

**Comparison of LNA Noise Floor in A-LFNA with Other Systems**

**Graph:**
- **dBV^2/Hz** vs. Frequency (1Hz, 10Hz, 100Hz, 1KHz, 10KHz, 100KHz, 1MHz)
- **Frequency** on the x-axis
- **Input Noise Voltage** on the y-axis

- **Keysight Advanced Low-Frequency Noise Analyzer**
- **Other System**
- **Keysight Previous System**

**Graph Details:**
- **20Hz**
- **10KHz**
- **200Hz**

**Graph Labels:**
- **Comparison of LNA Noise Floor in A-LFNA with Other Systems**
Unique Capabilities

- High-voltage/high-current handling capabilities at 200V and 0.1A
- Ultra-low frequency measurement and ultra-wide frequency band 0.03 Hz to ~40 MHz
- Circuit 1/f noise measurement (Op Amps, Comparators)
- Built-in signal generator for convenient system calibration and lower cost of ownership

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supported Devices</td>
<td>BJT, FET, Diode, Resistor, Circuit</td>
</tr>
<tr>
<td>LNAs</td>
<td>VAMP (ULF, LF, HF) x3, CAMP x1</td>
</tr>
<tr>
<td>Max Frequency range</td>
<td>0.03Hz - 40MHz</td>
</tr>
<tr>
<td>VLNA Noise Floor</td>
<td>-183dB V²/Hz @10KHz</td>
</tr>
<tr>
<td></td>
<td>0.7e-26 A²/Hz @10KHz</td>
</tr>
<tr>
<td>CLNA Noise Floor</td>
<td>1e-24 A²/Hz @10KHz</td>
</tr>
<tr>
<td>Max Bias Voltage/Current/Power</td>
<td>200V / 0.1A / 10W</td>
</tr>
<tr>
<td>Input Resistor</td>
<td>0Ω -100MΩ (25 selections)</td>
</tr>
<tr>
<td>Output Resistor</td>
<td>0Ω -100MΩ (25 selections)</td>
</tr>
</tbody>
</table>
Enhanced Throughput

- Wafer map support for automatic on-wafer measurement
- Support of special bias modes such as current-based and threshold-voltage offset based biasing
- Optimized I-V meter driver
- Streamlined measurement routines and settings
- Optimized target search algorithms

<table>
<thead>
<tr>
<th>Device</th>
<th>NMOS W/L=40um / 0.05um</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bias</strong></td>
<td><strong>V_{DS}</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6V</td>
<td>0.3V</td>
</tr>
<tr>
<td>1.2V</td>
<td>1.2V</td>
</tr>
<tr>
<td><strong>LNA</strong></td>
<td><strong>VAMP-HF</strong></td>
</tr>
</tbody>
</table>
Measurement Results – MOSFET in different regions

### Linear region

<table>
<thead>
<tr>
<th>Device</th>
<th>PMOS W/L=1um / 0.05um</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>$V_{DS}$</td>
</tr>
<tr>
<td></td>
<td>-0.05V</td>
</tr>
<tr>
<td>LNA</td>
<td>VAMP-HF, CAMP-LF</td>
</tr>
</tbody>
</table>

### Saturation and sub-threshold regions

<table>
<thead>
<tr>
<th>Device</th>
<th>NMOS W/L=16um / 0.12um</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>$V_{DS}$</td>
</tr>
<tr>
<td></td>
<td>1.2V</td>
</tr>
<tr>
<td></td>
<td>1.2V</td>
</tr>
<tr>
<td>LNA</td>
<td>VAMP-HF</td>
</tr>
</tbody>
</table>

Advanced Low-Frequency Noise Analyzer
Measurement Results – Can handle more devices

Theoretical Thermal Noise 9.2E-23A²/Hz

Device | Poly-Si Resistor 180Ω
LNA | VAMP-ULF

Device | PN Diode
LNA | CAMP-LF
Measurement Results – Large bandwidth

1 Hz -> 40 MHz

Device

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<tr>
<th>Device</th>
<th>NMOS W/L=40um / 0.05um</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>$V_{DS}$</td>
</tr>
<tr>
<td></td>
<td>1.2V</td>
</tr>
<tr>
<td>LNA</td>
<td>VAMP-HF</td>
</tr>
</tbody>
</table>

30 mHz -> 10 MHz

Device

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>$V_{DS}$</td>
</tr>
<tr>
<td></td>
<td>-0.05V</td>
</tr>
<tr>
<td>LNA</td>
<td>VAMP-HF, VAMP-ULF</td>
</tr>
</tbody>
</table>
Measurement Results – Circuit: Op Amp

**Figure 31. Voltage Noise Density vs. Frequency**

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**KEYSIGHT TECHNOLOGIES**
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– Importance of low-frequency noise
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Integral Part of the End-to-End Flow for Device Modeling

- IC-CAP
- IC-CAP WaferPro
- WaferPro Express
- Adv. Low-Frequency Noise Analyzer

- IC-CAP/MBP Bundle
  - User Programmable Solution
  - Turn-key Modeling Solutions

MQA

Automated Measurements → Data Analysis & Selection → Model Extraction → Model Verification

IC-CAP Database

Adavanced Low-Frequency Noise Analyzer
Ready-to-Use .MDM Measurement Data Files

Work with Noise Data in IC-CAP

Work with Noise Data in MBP
Noise Model Extraction

Noise Data Analysis in IC-CAP

MOSFET Noise Model Extraction in MBP
Outline

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Conclusions

- Increasing importance of low-frequency noise for new process technologies and advanced circuit design

- Advanced Low-Frequency Noise Analyzer (A-LFNA) adopts a modular architecture to minimize hardware footprint, improve its portability, and reduce parasitic capacitances to improve the roll-off frequency

- A-LFNA's state-of-the-art LNAs offer the lowest noise floor for low-current/low-noise measurement

- High-voltage/high-current handling capabilities and ultra-low frequency capability allows for noise characterization for specialty technologies

- Fully automated measurement including wafer mapping to satisfy needs for statistical data acquisition

- A-LFNA – An integral part of Keysight’s solution for end-to-end device modeling flow