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

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Outline

- Importance of low-frequency noise
- Measurement and analysis techniques
- The Advanced Low-Frequency Noise Analyzer (A-LFNA)
- How to get clean data
- Conclusions
Low-Frequency Noise – Frequency and Time Domain

- 1/f Noise and Random Telegraph Noise

**Power Spectral Density**

- 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 (RTN)

- noise represented in the time domain exhibiting two or more stable levels

![Diagram of 1/f noise and RTN](image)
Analysis of RTN Data

Various data analysis techniques to determine trap properties

Importance and Increasing Impact on Circuit Performance

[Diagram of OCXO]

[Schema of circuit components: AD8671, integrator and zeros, frequency multipliers, etc.]

[Graph showing device noise measurements with labels for Left and Right inverters]

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TECHNOLOGIES

Device Noise Measurements
Page 5
Example Sid Analysis vs Ibias - NMOS Device 2N7002K

\[ S_{iD} = \frac{i_{nD}}{1f} \frac{1}{Hz} = KF \frac{i_{AF}}{D_{DC} f_{EF} COX \cdot Leff^2} \]
Example RTN Data - NMOS Device, 2N7002K
Measurement Results – Resistor and Diode

**Theoretical Noise**

\[ I_{\text{noise}} = \frac{kT}{R} = 1.622 \times 10^{-13} \, \text{A}^2/\text{Hz} \]

<table>
<thead>
<tr>
<th>( I_2 )</th>
<th>( V_2 )</th>
<th>( R_{out} )</th>
<th>AMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m</td>
<td>1.00189</td>
<td>987.9</td>
<td>VAMP_LF</td>
</tr>
<tr>
<td>2m</td>
<td>1.99089</td>
<td>989.6</td>
<td>VAMP_LF</td>
</tr>
<tr>
<td>5m</td>
<td>4.95412</td>
<td>984.6</td>
<td>VAMP_LF</td>
</tr>
<tr>
<td>10m</td>
<td>9.88349</td>
<td>987.9</td>
<td>VAMP_LF</td>
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</tbody>
</table>

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<thead>
<tr>
<th>( I_2 )</th>
<th>( V_2 )</th>
<th>( R_{out} )</th>
<th>AMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1u</td>
<td>0.00836284</td>
<td>28250</td>
<td>VAMP_LF</td>
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<tr>
<td>10u</td>
<td>0.0797556</td>
<td>3413</td>
<td>VAMP_LF</td>
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<tr>
<td>100u</td>
<td>0.163532</td>
<td>418.8</td>
<td>VAMP_LF</td>
</tr>
</tbody>
</table>

**Device Noise Measurements**

\[ i_d^2 = 2 \cdot e \cdot I_d \cdot \Delta f + KF \cdot \frac{I_d^{AF}}{f} \cdot \Delta f \]
Measurement Results – OP07D Op Amp Circuit

Figure 31. Voltage Noise Density vs. Frequency
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Measuring 1/f Noise and RTN

Device Noise Measurements

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New Release
Advanced Low-Frequency Noise Analyzer
now with WaferPro Express

Output Module
- Output Resistor
- LPF
- VAMP
- CAMP

Input Module
- Input Resistor
- LPF
- SG

Substrate Module
- LPF

Test Fixture Module
- Connect to packaged thru-hole device

PXie Chassis
- Embedded PC
- Interface Module
- Digitizer (ADC)
Integration with WaferPro Express!

- Get or receive wafer map to or from Velox software. Control prober from A-LFNA.
- Leverage factory defined measurement routines and settings to suit specific needs.
- Control biasing in many ways: set current, Vgs offset beyond threshold-voltage, Vgs, etc.

→ Measurement platform that is flexible and expandable.
A-LFNA Connections

Source Measurement Unit (SMU)
Bias, Triaxial Shielded Cable

Input Module

Output Module

Substrate Module

Digital Control

Digitizer

Device Noise Measurements
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Input, Output, and Substrate Module Block Diagram

Input Module
- SMU1
- DC
- LPF
- RSOURCE
- Noise
- SG
- Gate

Substrate Module
- SMU3
- LPF
- Back Gate

Output Module
- SMU2
- DC
- Noise
- RLOAD
- LPF
- VAMP
- AMP
- To Digitizer

Device Noise Measurements
1/f Noise Measurements - NMOS Device, 2N7002K

Vds = 2 V

Smoothed Sid vs Frequency and Id

ULF Data

From 0.03 Hz

To 40 MHz
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Don’t Add Instrument Noise to Your Measured Data

Instrument noise needs to be much better than DUT noise

Measured\_noise = √\text{instrument\_noise}^2 + \text{DUT\_noise}^2

Use floating ground.

Noise power adds as RSS.

Noise at output?

![Plot of excess noise caused by reference noise](image)
State-of-the-art Custom-Designed LNAs
3 Voltage Amplifiers (VAMP) + 2 Current-to-Voltage Amplifiers (CAMP)

<table>
<thead>
<tr>
<th>LNA Noise of A-LFNA Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input voltage noise density</strong></td>
</tr>
<tr>
<td>ULF VAMP</td>
</tr>
<tr>
<td>Frequency range</td>
</tr>
<tr>
<td>@ 10 kHz</td>
</tr>
<tr>
<td>Input current noise density (max)</td>
</tr>
<tr>
<td>@ 10 kHz</td>
</tr>
<tr>
<td>Corner frequency</td>
</tr>
<tr>
<td>Maximum input voltage</td>
</tr>
<tr>
<td>Maximum input current</td>
</tr>
<tr>
<td>Output impedance</td>
</tr>
</tbody>
</table>
Quality Check on 1/f Noise Data

Device Noise Measurements

Thermal Noise = $4kT R_{LOAD}$

LOAD Needs to be above system noise floor and thermal noise of load resistance and below roll-off frequency

Valid Data

Determined by LNA's spec and measurement environment

System Noise - VAMP

Frequency where the gain of the voltage LNA quickly deteriorates because of equivalent resistance and capacitance on the output node

Roll-off Frequency

Ignore after roll-off frequency

Invalid Data

Determined by family characterization

Based on family characterization

System Noise - SMU
Shield From Air Currents

Thermoelectric voltage noise caused by uneven airflow from ambient room air turbulence causes significant noise at low frequencies.
Triple Shielding Design to Minimize External Noise

Electromagnetic Shield

2nd Layer GND Shield
Benefits of Unique Modular Design

- Poor Grounding seen with competitor product

Modular design features small footprint

- Easy to mount on and remove from the prober surface through magnetic attachment
- Shortest possible cables to reduce parasitic capacitances and increased roll-off frequency
Hardware Averaging
User may trade off trace noise for measurement speed

Npts = 16384 = 2^{14}
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Conclusions

- Device noise is becoming increasingly important for analog, RF and digital design.
- Measuring noise is hard. Lots of ways data can be corrupted (interference, oscillations, etc.)
- The 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.
- This has now been integrated with WaferPro Express, enabling you to fully automate noise measurements as a part of a larger and broader suite of measurements.