Random Telegraph Noise (RTN) Measurement of Advanced MOSFET using B1500A WGFMU Module
Introduction

Random telegraph noise (RTN) is a sort of electronic noise observed in advanced MOSFETs. Caused by the capture and emission of carriers trapped in the gate oxide, it is typically observed as a small signal superimposed on a much larger signal. It is getting critical to measure and evaluate RTN precisely across a wafer, because RTN significantly affects device reliability. RTN is critical not only for the reliability of a transistor but also for the reliability of the circuit using CMOS image sensors, flash memories, and so on.

For reliable circuit design, you need to provide an appropriate margin that covers the influence of RTN. If you set the margin too low, RTN can cause device malfunctions. If you set the margin too high, the excessive margin can limit device performance.

Recent advances in low power consumption have reduced the drive voltage of electronics, and the operating margin is decreasing. For that reason, more accurate and detailed RTN measurement and evaluation are required for reliable circuit design.

Until now, RTN measurement solutions have consisted of user-configured instrument setups. These usually are made up of components such as a low-noise power supply, current-to-voltage converter, and oscilloscope (or voltage sampler). However, these measurement solutions have difficulty producing stable and consistent results. This is mostly due to poorly calibrated components or the lack of calibration of the entire system. In addition, RTN measurement solutions constructed from multiple instruments can easily generate measurement errors. That is because of their complicated cabling and the overall error arising from the cumulative errors of the individual instrument components. Therefore, in order to acquire consistent RTN data, an off-the-shelf, self-contained RTN solution with guaranteed specifications is highly desirable.

For advanced devices in the R&D phase, the device is not fabricated stably across the wafer. So, it is necessary to measure and analyze many devices on the wafer in detail, and automated RTN measurement has been strongly desired.

The B1530A Waveform Generator/Fast Measurement Unit (WGFMU) is an advanced module for the B1500A Semiconductor Device Analyzer. It allows you to make RTN measurements without any additional measurement equipment. The WGFMU module has a noise floor of less than 0.1 mV (rms), with current measurement sampling rates from 1 S/s to 200 MS/s and a bandwidth extending from DC to 16 MHz. A deep measurement memory capable of storing up to 4 million points per channel, combined with these measurement capabilities, enables the B1500A’s WGFMU module to measure RTN over a wide frequency range. In addition, the WGFMU module comes with sample RTN analysis software so you can start RTN analysis immediately.

The automated RTN measurement is also available using the E4727E3 software developed for the B1500A with the WGFMU. It enables you to perform on-wafer automated RTN measurement at a low cost, including the wafer prober control. It can improve the efficiency of RTN measurement and data analysis.

This application note describes RTN measurement using the B1500A’s WGFMU module and shows actual measurement examples. It also introduces an on-wafer automated RTN measurement solution using WGFMU with E4727E3.
The physics of RTN

RTN in MOSFETs can be explained as a threshold voltage shift caused by the random capture and emission of thermally excited electrons at a trap existing in the boundary between the gate dielectric and the substrate (Figure 2).

The Vth shift caused by a single electron captured at the trap is approximated by equation 1 shown below.

\[
\Delta V_{\text{th}} = \frac{q}{L \cdot W \cdot C_{\text{ox}}} \quad \text{(1)}
\]

Here, q is electron charge, L is gate length, W is gate width and Cox is gate capacitance. This equation clearly shows that the Vth shift becomes larger as the device shrinks. Since the time constants for the capture or emission of electrons from traps can vary from microseconds to seconds, some of the pixel defects caused by RTN in the amplifier may be perceptible by the human eye.

RTN measurement using the B1500A's WGFMU module

The B1500A's WGFMU module has a low voltage noise floor of less than 0.1 mV (rms), and its current measurement capability supports sampling rates from 1 S/s to 200 MS/s and a bandwidth extending from DC to 16 MHz. These features, combined with a deep measurement memory capable of storing up to 4 million points per channel, enable the B1500A's WGFMU module to measure RTN over a frequency range that extends from less than 1 Hz to many Mega-Hz.

Figure 1. Charge trapping caused by energy band shift generates RTN.
The B1500A’s WGFMU solution consists of the WGFMU module as well as two remote-sense and switch units (RSUs). The WGFMU module contained in the mainframe generates the arbitrarily waveforms, and these waveforms are then transmitted through a cable to the RSU. The RSU, which performs the actual current or voltage measurement, is separate from the WGFMU module so that it can be placed near the device under test (DUT) to minimize cable lengths and guarantee accurate high-speed measurement. Since each WGFMU module supports two RSUs, RTN on a MOSFET can be measured with a single WGFMU module by connecting one RSU to the gate and one RSU to the drain. In this case, the substrate (or bulk) and source terminals should be connected to the common (ground) level of the outer shield of the coaxial cable (please see Figure 2). Up to five WGFMU modules can be installed in a single B1500A, for a total of ten channels maximum.

Sample software to measure and analyze RTN are bundled with the B1500A’s WGFMU module (please see Figure 3). Using this sample software, users can start RTN evaluation immediately using the WGFMU module.
Figure 4 shows a simplified circuit diagram of the WGFMU and RSU. The WGFMU has arbitrary linear waveform generator (ALWG) voltage generation capability, with the waveform generated by the ALWG output through the RSU. The RSU is where the actual current or voltage measurement is made. The WGFMU has two operation modes: PG mode and Fast IV mode. The PG mode combines a very fast voltage measurement capability with 50 Ohm output impedance to minimize waveform reflections. The Fast IV mode has a slightly slower measurement speed and slower waveform rise/fall times than the PG mode, but it can measure both current and voltage.

![Simplified circuit diagram of the WGFMU module.](image)

The key specifications of the B1500A’s WGFMU module are shown below.

**Voltage force**
- Output Range:
  - ± 5 V
  - 0 V ~ +10 V
  - −10 V ~ 0 V
- Noise floor:
  - Less than 0.1 mV (rms) \(^1\)

**Current measurement**
- Measurement range:
  - ± 10 mA fixed
  - ± 1 mA fixed
  - ± 100 μA fixed
  - ± 10 μA fixed
  - ± 1 μA fixed
- Measurement resolution
  - 0.014 % of range \(^2\)
- Noise floor
  - 0.2 % of range \(^3\)
- Sampling interval
  - 5 ns, 10 ns to 1 s Variable
- Hardware averaging
  - 10 ns to 20 ms variable
- Measurement memory depth
  - About 4 million data points per channel \(^4\)

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1. Theoretical value (100 ns to 1 ms).
2. Display resolution. Can vary at most 5% based on the result of calibration.
3. Supplemental information. Effective value, without averaging at 0 V into an open load.
4. Typical value.
RTN data analysis software

This software can perform time domain and frequency domain analysis of the drain current measured by the B1500A's WGFMU module and automatically display extracted parameters.

- Visualized time domain data and digitized data
- Power distribution
- Histogram of the level and appearance
- Histogram of the capture and emission time constants and their ratio

Practical measurement considerations

To perform accurate RTN measurements, a variety of factors including measurement equipment performance, characteristics of the DUT and environmental noise have to be taken into account. In the following sections, we will explain how to mitigate these factors.

Measurement equipment and environmental noise

If the RTN being measured is below the current measurement noise floor, then the RTN cannot be observed. Figure 5 shows the noise floor for the current measurement ranges of the B1500A's WGFMU module. To make the RTN measurement possible, it is important to chose an appropriate measurement range.

Note: This is supplemental data and it is not a guaranteed specification of the module.

In addition, other environmental factors such as vibration and electromagnetic interference can impact RTN measurement. To eliminate vibration related noise, a semiautomatic wafer prober with proper vibration isolation should be used. To eliminate electromagnetic interference, the current measurement loop should be kept as small as possible. The current loop can be minimized by tying the cables between the WGFMU module and the RSU in a bundle and by creating a current return path near the DUT by connecting the MOSFET substrate and source pads to the shield of the signal lines going to the gate and drain.

Figure 5. Noise floor for the WGFMU module’s various current measurement ranges.
**Sampling rate**

The measurement current noise can be reduced by measurement averaging. Figure 6 shows an example of how averaging can reduce this noise. Increasing the averaging time further reduces the noise of the measured current. However, if the sampling rate is longer than the time constant of electron capture or emission, then the RTN will not be observed on the measured current.

![Figure 6. Noise reduction of measured current as a function of averaging.](image)

Using a lower current measurement range also reduces the measurement current noise floor. In this case, the bandwidth of the current measurement circuit determines the upper limit of the frequency components of the RTN.

**Current measurement bandwidth**

Table 1 is supplemental information showing the bandwidth (defined by the ~3 dB point) of the B1500A's WGFMU module's current measurement circuit (with a 25 pF load).

(Note: Actual bandwidth may be further degraded due to additional capacitive load from cabling and the device).

Since the bandwidth of the lower current ranges is lower than that of the higher current ranges, when choosing a current measurement range make sure that you have sufficient bandwidth to detect the RTN that you are trying to measure.

In addition to the measurement equipment, the characteristics of the DUT also need to be considered.

<table>
<thead>
<tr>
<th>Measurement range</th>
<th>Bandwidth (~3 dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mA</td>
<td>~16 MHz</td>
</tr>
<tr>
<td>1 mA</td>
<td>~8 MHz</td>
</tr>
<tr>
<td>100 µA</td>
<td>~2.4 MHz</td>
</tr>
<tr>
<td>10 µA</td>
<td>~600 kHz</td>
</tr>
<tr>
<td>1 µA</td>
<td>~80 kHz</td>
</tr>
</tbody>
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Measurement conditions

Since the boundary traps that are capturing electrons and generating the RTN have spatial and energy distributions, the time constants and (in-turn) the level of RTN strongly depend on the bias voltages applied to the MOSFET gate and drain.

Figure 7 shows examples of the RTN with different applied gate voltages.

The above example is an NMOS FET with dimensions of 0.44 μm (W) by 0.24 μm (L) and an oxide thickness of 4 nm. This example shows that the level and time constant of the RTN and the number of peaks in the histogram vary in conjunction with changes in the gate voltage.

As this result illustrates, it is necessary to measure RTN under a variety of combinations of bias conditions, current ranges and sampling rates. In this way, the measurement data can yield valuable insights into the distribution and the time constants of the boundary traps.

Figure 7. Graph showing variations in RTN as a function of gate bias voltage.
Efficient RTN Measurement on Wafer

As described in the introduction, advanced devices in the R&D phase are not fabricated stably across the wafer. So, it is necessary to measure and analyze many devices on the wafer in detail and automated RTN measurement has been strongly desired.

For automated RTN measurement on wafer, the user needs to program to control B1500A and wafer prober. In addition, wafer mapping is also required. The E4727E3 software enables automated RTN measurement on wafer quickly without programming and supports the analysis and wafer map capabilities. It also provides a benefit to make an automated RTN measurement system or upgrade from existing B1500A cost-effectively.

![E4727E3 can control WGFMU and wafer prober.](image)

Key features of E4727E3:
- Automated measurement without programing
- Auto prober control
- Wafer mapping
- Single data display for multi decade in frequency domain
- Upgradeable from your existing B1500A

To learn more about E4727E3, please see the links below.
Conclusion

RTN measurement and analysis is getting very important, according to the device innovation. The B1500A’s WGFMU module is the best solution for the advanced MOSFET RTN measurement.

In addition, E4727E3 enables you to perform on-wafer automated RTN measurement with an automated wafer prober. It saves the introduction cost and improves the efficiency of device development.

B1500A Now Supported in Windows 10

B1500A PC platform has been renewed. It includes Windows 10 OS, faster CPU, 8 GB of memory and a solid state drive (SSD). The latest PC platform enables you to perform your software tasks easily while improving your total computing performance.

Windows 10 upgrade option is also available.

For more detail: https://literature.cdn.keysight.com/litweb/pdf/5991-3327EN.pdf