

Characterizing Random Noise in CMOS Image Sensors

RTS noise measurement using the B1500A's WGFMU Module Application Note B1500-11

Introduction

A random telegraph signal (RTS) is a random process that switches between ± 1 and that has the number of zero crossings it makes in any time interval described by a Poisson process. RTS noise (sometimes also called burst or popcorn noise) exhibits RTS behavior and typically appears as a low-level signal superimposed on a much larger signal. In CMOS image sensors (also known as active pixel sensors) RTS noise can generate erroneous white spots in what should otherwise be dark areas. As feature sizes continue to decrease, the impact of RTS noise on the MOSFETs used to read out pixel data has become more serious.

Until now, RTS noise measurement solutions have consisted of user-configured instrument setups, usually consisting of components such as a low noise power supply, current to voltage convertor and oscilloscope (or voltage sampler). However, these measurement solutions have difficulty producing stable and consistent measurement results. This is mostly due to poorly calibrated components or to the lack of calibration of the entire system. In addition, RTS noise measurement solutions constructed



from multiple instruments can easily generate measurement errors due to their complicated cabling and the overall error arising from the cumulative errors of the individual instrument components. Therefore, in order to acquire consistent RTS noise data, an off-the-shelf, self-contained RTS noise solution with guaranteed specifications is highly desirable.

The B1530A Waveform Generator/Fast Measurement Unit (WGFMU) is an available module for the B1500A Semiconductor Device Analyzer. It possesses the ability to make RTS measurements without the need for 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 of up to 4 million points per channel combines with these measurement capabilities to enable the B1500A's WGFMU module to measure RTS noise over a wide frequency range. In addition, sample RTS noise analysis software is supplied with the WGFMU module so that the user can start RTS noise analysis immediately.

In this application note, RTS noise measurement using the B1500A's WGFMU module will be described and actual measurement examples will be shown.



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Random noise in CMOS image sensors

In contemporary CMOS image sensors, RTS noise is generally the dominant noise source affecting the pixels. Each CMOS image sensor pixel has a readout amplifier that amplifies the photoelectric current generated by a photo diode (please see Figure 1). In order to increase the pixel density the amplifier size has to be reduced in order to maximize the size of the photo diode and in-turn improve the signal-to-noise ratio. This reduces the size of the MOSFET used in the amplifier, which makes it more susceptible to RTS noise.

The physics of RTS noise

RTS noise 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 V_{th} shift caused by a single electron captured at the trap is approximated by equation 1 shown below.

$$\Delta V_{th} = \frac{q}{L \cdot W \cdot C_{ox}} \dots (1)$$

Here, q is electron charge, L is gate length, W is gate width and C_{ox} is gate capacitance. This equation clearly shows that the V_{th} 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 RTS noise in the amplifier may be perceptible by the human eye.

RTS noise 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 RTS noise over a frequency range that extends from less than 1 Hz to many Mega-Hz.

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

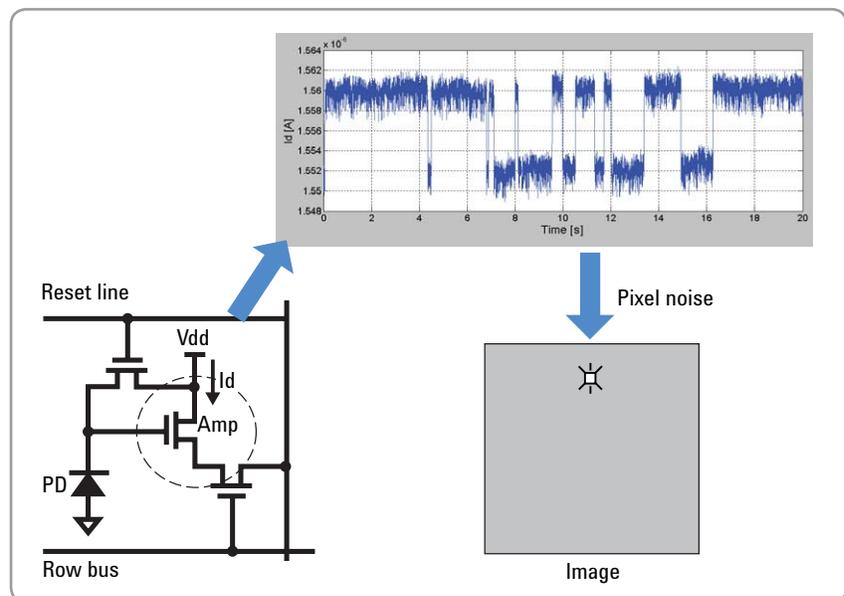


Figure 1. Pixel errors due to RTS noise in the amplifier circuit

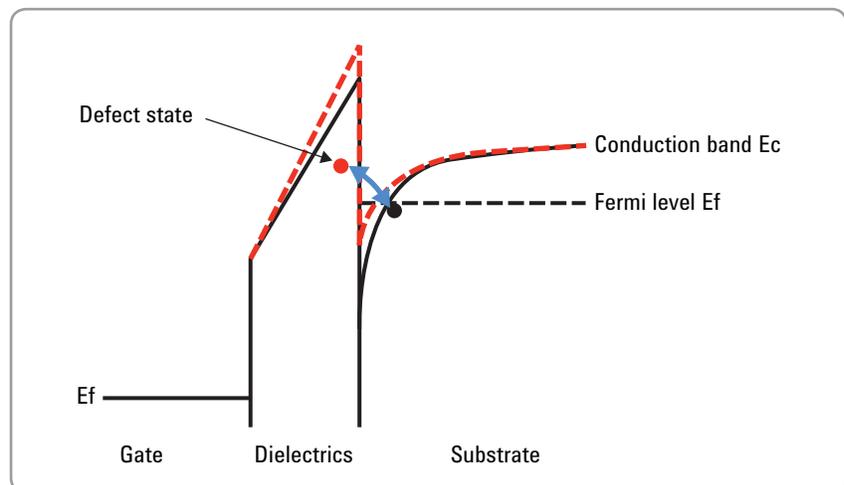


Figure 2. Charge trapping caused by energy band shift generates RTS noise

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, RTS noise 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 3). 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 RTS noise are bundled with the B1500A's WGFMU module (please see Figure 4). Using this sample software, users can start RTS noise evaluation immediately using the WGFMU module.

Figure 5 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.

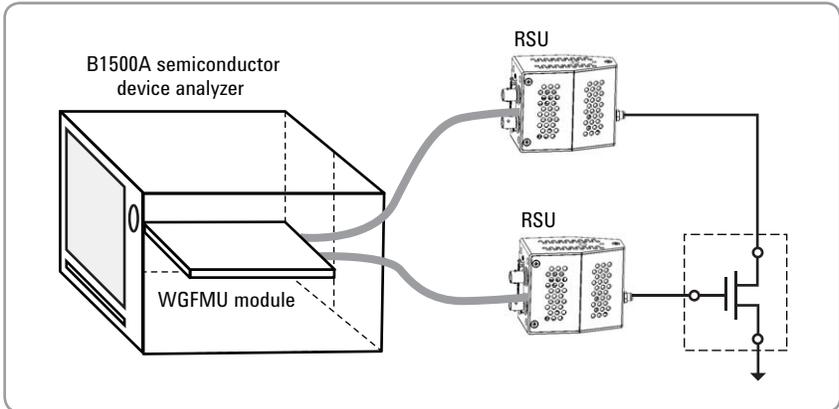


Figure 3. A single B1500A WGFMU module can comprise an RTS noise measurement system

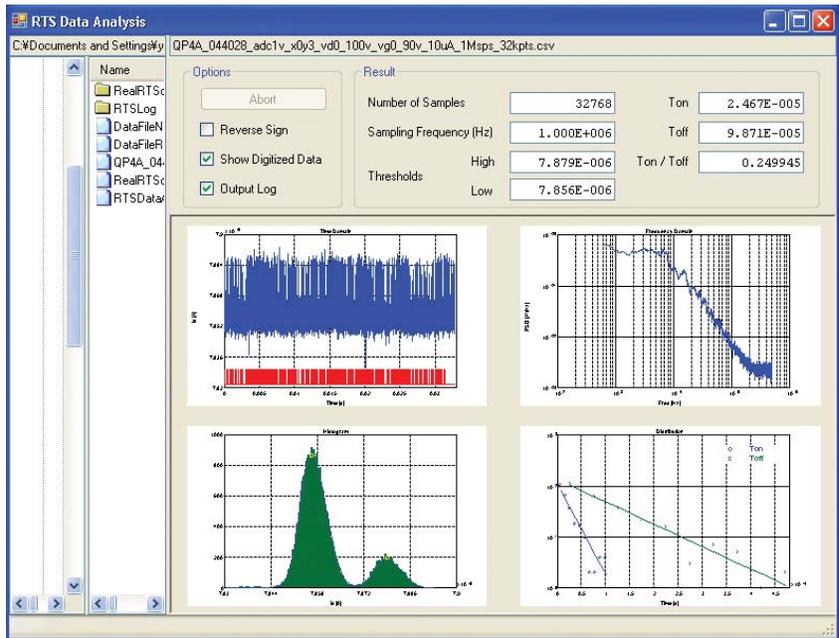


Figure 4. Sample program to analyze RTS noise properties

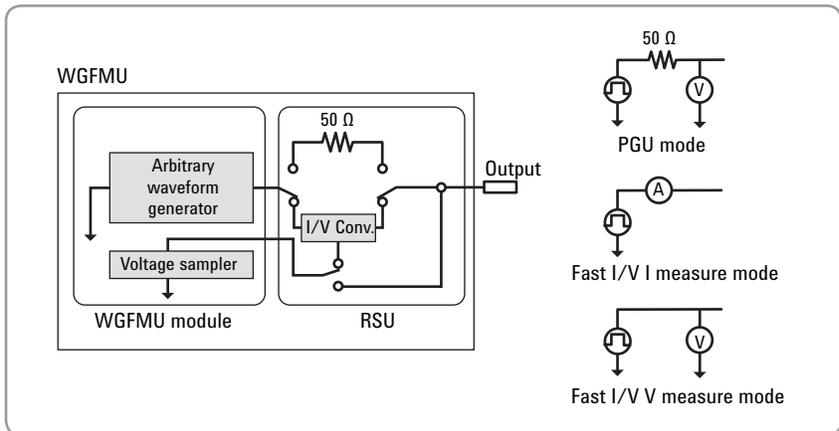


Figure 5. Simplified circuit diagram of the WGFMU module

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 range²
- Noise floor
 - 0.2 % of range³
- 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 channel⁴

RTS 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.

- 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

- 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 RTS 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 RTS noise being measured is below the current measurement noise floor, then the RTS noise cannot be observed. Figure 6 shows the noise

floor for the current measurement ranges of the B1500A's WGFMU module. To make the RTS measurement possible, it is important to choose 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 RTS noise 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.

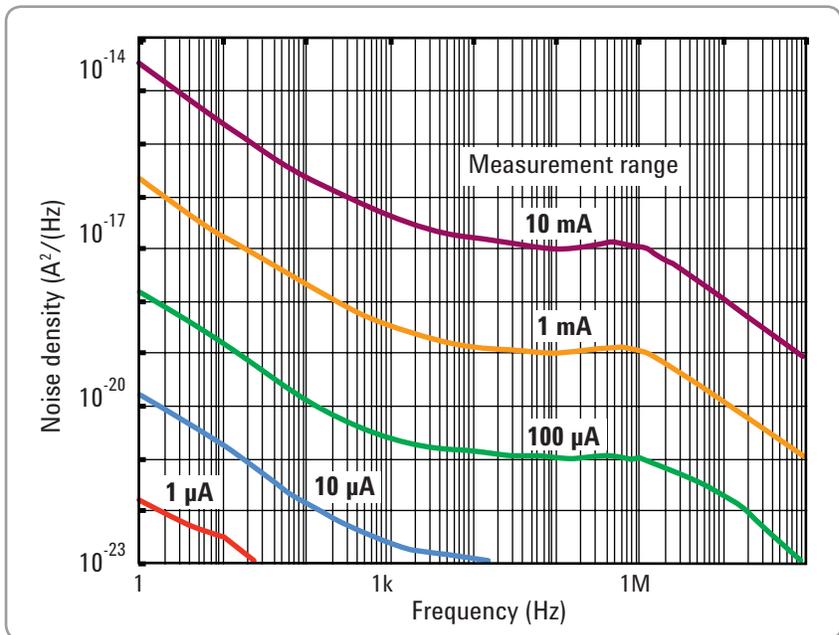


Figure 6. Noise floor for the WGFMU module's various current measurement ranges

Sampling rate

The measurement current noise can be reduced by measurement averaging. Figure 7 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 RTS noise will not be observed on the measured current.

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 RTS noise.

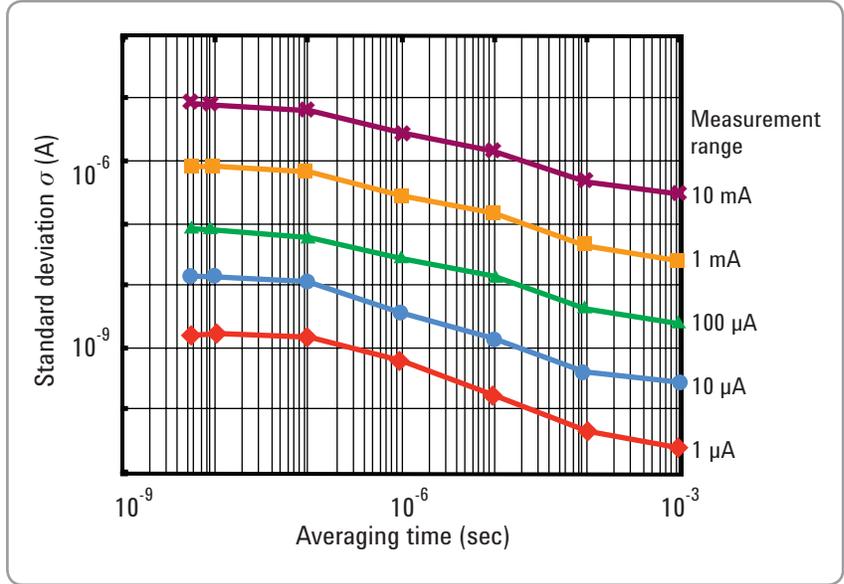


Figure 7. Noise reduction of measured current as a function of averaging

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 RTS noise that you are trying to measure.

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

Table 1

Measurement range	Bandwidth (-3 dB)
10 mA	~16 MHz
1 mA	~8 MHz
100 μ A	~2.4 MHz
10 μ A	~600 kHz
1 μ A	~80 kHz

Measurement conditions

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

Figure 8 shows examples of the RTS noise with different applied gate voltages.

The above example is an NMOS FET with dimensions of $0.44 \mu\text{m}$ (W) by $0.24 \mu\text{m}$ (L) and an oxide thickness of 4 nm . This example shows that the level and time constant of the RTS noise 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 RTS noise 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.

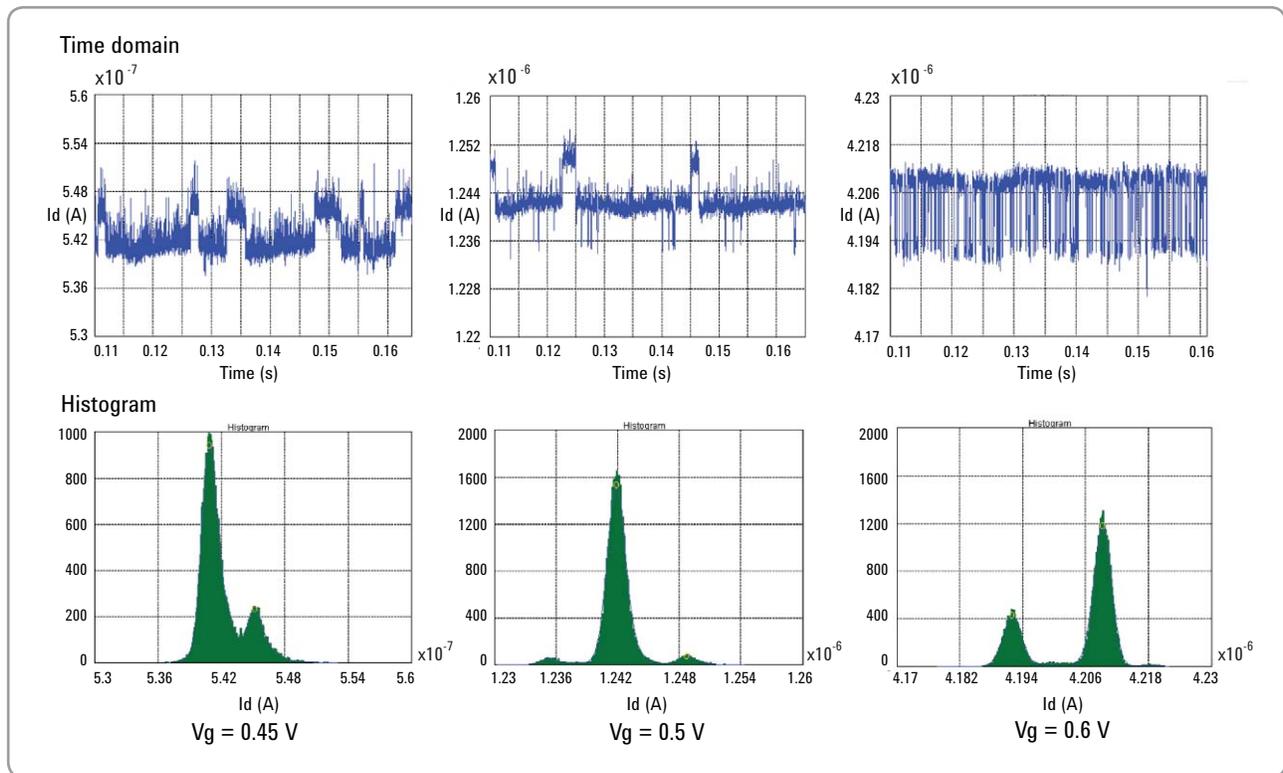


Figure 8. Graph showing variations in RTS noise as a function of gate bias voltage

Distribution on wafer

Since the size of the MOSFETs is very small, depending on the distribution and frequency of defect traps on the wafer some devices will not show any RTS noise while other devices will show significant RTS noise.

From the previous discussion, it is clear that it is necessary to measure multiple devices across a wafer in order to observe RTS noise. Conversely, by evaluating the spatial distribution of the RTS noise across the wafer it is possible to evaluate the distribution of defect densities that correspond directly to the operation of the device.

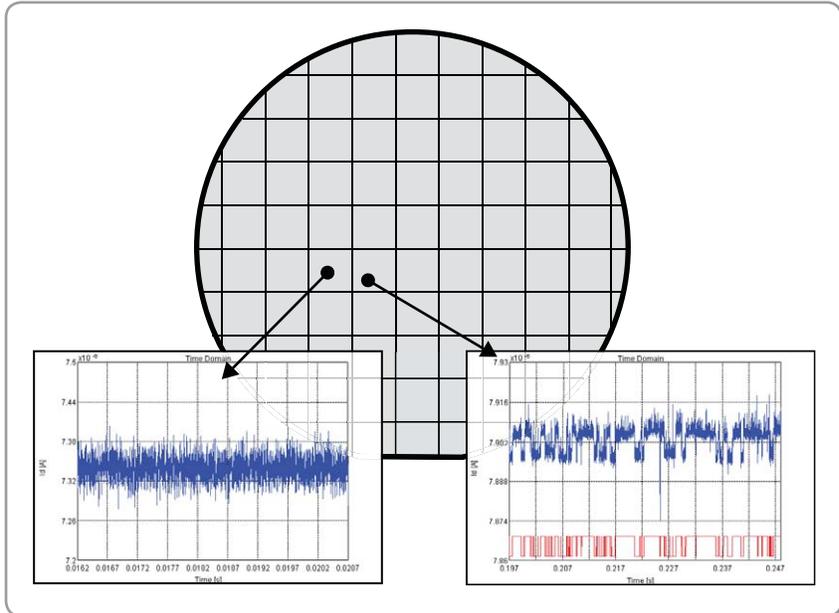


Figure 9. Plot showing variations in RTS noise across a wafer

Conclusion

RTS noise analysis at the readout amplifier of each pixel of modern, high resolution CMOS image sensors is essential to minimize random pixel noise in a captured image.

The B1500A's WGF MU module is a self-contained, off-the-shelf measurement solution for MOSFET RTS noise measurement, making it the ideal solution for the accurate and repeatable analysis of RTS noise in CMOS image sensors.

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