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WHITE PAPER

Achieving Accurate On-Wafer Flicker Noise Measurements Through 30 MHz

Mark Hansen
Design Engineer

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ABSTRACT

Low frequency noise performance for many solid state devices is dominated by flicker (1/f) noise. Smaller device geometries and lower operating voltages, coupled with higher operating frequencies and higher data rates, have raised the importance of accurate flicker noise testing. In fact, modern device simulation software requires flicker noise criteria in a complete device model. To obtain meaningful and accurate models, many devices are probed and measured. The most economical method for testing multiple devices is on-wafer testing.

While traditional flicker noise testing was done in the kHz region, new devices have smaller geometries and a higher flicker noise frequency corner, which has mandated testing well into the MHz region. While low frequency testing was straightforward, measuring higher frequencies in a high impedance environment presents several new challenges. A system level approach is discussed as a solution to these challenges.

This paper will present a summary of the science behind flicker noise, describe the challenges of accurately measuring flicker noise, explain the value of a systematic approach to on-wafer flicker noise measurement with a 30 MHz bandwidth, and present real-world data taken from such a system.

BACKGROUND

Noise is fundamental to all active and passive electrical circuits. The use of an electrical component in a circuit generally adds some noise to a circuit. This noise is the result of randomness in the flow or motion of charges or holes in a solid state device. This noise is usually classified into three different types of noise. [1]

- 1] Thermal noise
- 2] Shot noise
- 3] Flicker noise

The general presentation of electrical noise as it affects different frequencies is shown in Figure 1.

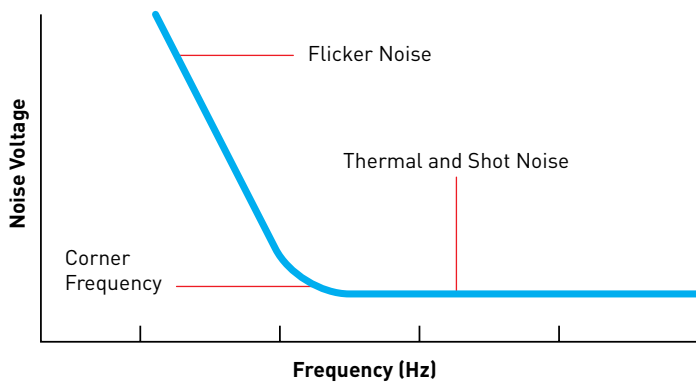


Figure 1: Noise vs. frequency in an electrical component

Thermal noise, also referred to as Johnson noise or kTB noise, is the dominant noise at high frequencies; generally greater than several MHz. In addition to being worse for some devices than others, it is proportional to the temperature of the device. For RF circuits, the noise figure (NF) is partially the result of thermal noise; where NF is the ratio of the signal-to-noise ratio (SNR) of the input of the device divided by the SNR of the output of the device. Normally, NF is expressed in dB. Because the intensity of the thermal noise is independent of frequency, it is often referred to as white noise. The equation below defines why this noise is often referred to as kTB noise:

$$P_N = kTB$$

where P_N is the resultant noise power in Watts from a perfect resistor, k is the Boltzmann constant, T is the temperature of the device in Kelvin, and B is bandwidth of the observed noise in Hz. [2]

Since the thermal noise power of a perfect resistor at room temperature (300K) is -174 dBm/Hz, one can

easily determine the noise figure for an amplifier (or other imperfect device) by using this handy equation:

$$NF = P_o - G_A - (-174 \text{ dBm/Hz}) - 10 \log(BW)$$

NF is the amplifier noise figure in dB, P_o is the amplifier output baseband noise in dBm, G_A is the gain of the amplifier in dB, and BW is the bandwidth of the measured power in Hz. Often the bandwidth of the measured power is the resolution bandwidth of a spectrum analyzer used for the measurement. However, if a spectrum analyzer is used for this measurement, a small correction factor is needed which corresponds to the shape of the filter of the instrument. This correction factor is usually available from the manufacturer of the analyzer.

Shot noise results from the fact that direct current is not a continuous function, but rather a large set of moving discrete charges. These moving charges have a statistical nature to them. The value of these discrete charges varies with time, and causes a noise referred to as "shot noise." Shot noise does not vary with temperature, and remains constant in amplitude up to a frequency which is determined by the amount of time taken for a charge to travel through the conductor from which the noise originates. Shot noise is proportional to the amount of current flowing in a conductor. The shot noise phenomenon can be particularly troublesome when current crosses a junction, such as the P-N junction of a bipolar transistor, or diode. Because MOSFETs have an insulated gate, any shot noise produced is a result of the current flowing from the drain to the source, and not from the gate of the device. The shot noise from a semiconductor is usually minor compared to thermal noise and flicker noise, and is often disregarded.

The origins of **flicker noise** are somewhat less understood compared to thermal noise and shot noise. [3] It is interesting to note that flicker noise frequently appears in physical nature. For example; a $1/f$ spectral density is found for the fluctuations in the earth's rate of rotation, and undersea currents. A study of a common hourglass demonstrated that the flow of sand fluctuates as $1/f$. [4] Flicker noise is a special case of $1/f^n$ noise, when $n=1, \pm 0.5$. [5] In an electrical circuit, flicker noise is always related to a direct current. For a semiconductor, this noise with a $1/f$ spectrum results from a variety of effects, such as impurities in a conductive channel, generation and recombination noise in a bipolar transistor due to base current.

In the case of a MOS device, flicker noise is the result of traps in the gate oxide. The effect on current as the traps are filled and emptied randomly produces noise on the current. The effect from randomly trapped charges can be modeled as a random voltage source at the gate of the device. The magnitude of this noise is given by:

$$V^2 = \frac{K}{f * L_{eff} * C_{ox}}$$

where V is the noise voltage referred to the gate, K is a process dependant constant frequently found by measurement, f is the frequency of the noise, L_{eff} is the effective gate length, and C_{ox} is the gate oxide capacitance. [6] From this equation, one can immediately see the diminishing magnitude of the noise as f is increased.

Mathematically, flicker noise is a sum of Lorentzians, where a Lorentzian in physics is a distribution often used to describe resonant behavior. A Lorentzian distribution is shown in Figure 2. When many Lorentzian distributions are summed together, the resulting frequency domain representation is a $1/f$ spectrum. This mathematical result fits in well with the trap theory, since the trap theory represents flicker noise as the sum of the effect of a number of traps. [7]

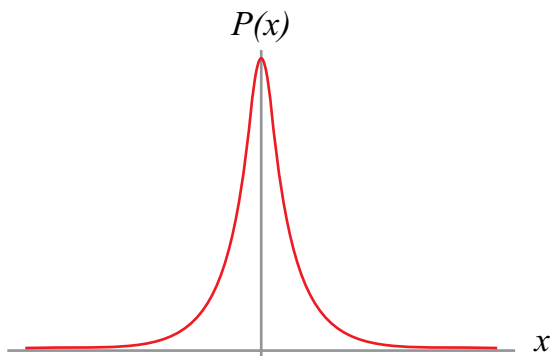


Figure 2: Lorentzian function

FLICKER NOISE CHALLENGES IN VARIOUS DEVICES AND CIRCUITS

Flicker noise can affect many types of analog and digital circuits. As solid state devices become smaller and smaller, flicker noise becomes more pronounced. For low-voltage digital circuits, flicker noise is the dominant cause of logic errors. [8] In the case of an SRAM chip, flicker noise can result in a stored soft

bit error. Flash memory exhibits a random retention error, which is caused by flicker noise. In low light conditions, image sensors are more prone to errors and distortion which are caused by flicker noise. [9]

Flicker noise is well known to cause accuracy issues in higher bit A/D devices. In fact, flicker noise is a major concern for many circuits which have analog blocks. [10]

Although flicker noise generally is not a concern at higher frequencies, flicker noise in transistors is the main cause of phase noise for an oscillator or a phase lock loop. This noise can lead to channel capacity problems for a communications system. The resulting phase noise also leads to jitter in a digital transmission system, which limits the error-free bit rate in the system. [11]

For silicon MOS wafers with no other means of obtaining a band gap voltage reference, a parasitic transistor can be formed to provide the band gap. [12] This parasitic transistor exhibits flicker noise, which will cause noise for the entire circuit's voltage reference. Measuring the flicker noise output for this transistor is helpful in determining the success of the band gap reference.

It has been established that increased $1/f$ noise in a transistor manufacturing process can result in a decrease in long-term reliability of the transistor. Since the $1/f$ noise can result from impurities in MOSFET gate oxide materials, and a high content of impurities can lead to eventual failure of the device, monitoring flicker noise during wafer production is becoming increasingly important, as more and more end users of semiconductors are mandating higher and higher reliability. It is expected that many wafer manufacturers will add test structures to their process control monitors for monitoring flicker noise during wafer production. [13]

NEW MEASUREMENT CHALLENGES

Because flicker noise increases with smaller devices, and an increase of flicker noise increases the flicker noise bandwidth, the measurement range required to fully characterize the flicker noise spectrum has been pushed from the kHz range to the MHz range. Therefore, traditional methods of flicker noise measurement are deficient in many ways. First, since the frequency rolloff of the flicker noise system is dominated by the parasitic capacitance in the system, and because the flicker noise is reaching higher frequencies, this rolloff

must move higher. Second, the frequency response of all components in the system must move higher. Third, all electrical noise which might affect the system must be controlled or eliminated. Fourth, the system must be capable of accurate DC measurements on the device under test (DUT). And finally, the system should be capable of multiple device measurement.

1] To increase the system rolloff frequency to a reasonable value, the system capacitance must be minimized. The rolloff frequency is dominated by the elementary equation

$$F_{\text{rolloff}} = \frac{1}{2\pi * R * C}$$

where F_{rolloff} is the rolloff frequency in Hz , R is the Thevenin equivalent of the resistive loads and C is the capacitance in the measuring equipment and cables. As an example; for a system with only 100 pF of capacitance and an equivalent load resistance of 10,000 ohms, the system rolloff is 159 kHz. However, a system with 500 pF would exhibit a system rolloff of only 31 kHz, which would be inadequate for many measurements.

2] The test equipment and components associated with the noise measurement function in the tester must be capable of accurate measurements across the entire measurement spectrum which starts below 3 Hz and has an upper bound of up to 30 MHz. The low noise amplifier (LNA) in particular, must be able to cover the entire bandwidth, as well as the dynamic signal analyzer used in the system.

3] Unwanted electrical noise is another major obstacle for the measurement of flicker noise. Because measurement noise can come from many sources, proper noise design of the flicker noise system is mandatory. This noise may be conducted into the system by means of power mains or other areas where wires, cables, or even metal, air, or vacuum lines enter or exit the system. Even a simple computer network cable can be problematic from a noise standpoint if care is not taken.

Noise from source monitor units (SMUs), which are used to bias the DUT, and other test equipment must be filtered. This filtering is a challenge since both low and high frequencies must be attenuated while maintaining low bias supply impedance across the measurement band. Grounding is a serious concern

for the measurement system. Since the system contains several grounds, it is possible that ground loops or other ground noise will occur. This is more pronounced at 50/60 Hz and multiples of 50/60 Hz, however, other frequencies can be observed on ground lines as well. A potential difference between two grounds at different parts of the system will result in measurement noise and error, and therefore must be carefully managed. Noise on the ground can severely affect the low frequency measurements and will be extremely problematic in a poorly designed measurement system.

For higher frequencies, careful shielding needs to be designed into the system. The shielding not only reduces or eliminates electromagnetic noise from nearby television and AM radio transmitters, but also cell phones, as well as the electromagnetic noise generated by the system's computer and other test equipment. The noise may be conducted into the system, or it may come from a travelling electromagnetic wave. This noise will interfere with measurement results.

The elimination of higher frequency noises, such as the signal emitted from a cellular phone handset, is often overlooked since the 1/f system has a top measurement frequency far below the frequency emitted by the handset. Overlooking this noise is a mistake. As an example, take the case of a GSM handset. Although the signal is transmitted at 800 or 1800 MHz, the signal has a frame rate of 4.615 mS. This frame rate results in a pulsing noise frequency of 217 Hz, which is often rectified in a nonlinear junction of the DUT, or other nonlinear mechanisms, and appears at baseband. It is for this reason that higher frequency shielding must be present.

It is interesting to note that unwanted noise from AM and television transmitting stations is generally stable in magnitude and frequency, and therefore easily recognizable. The noise from cell phones tends to vary widely in frequency and magnitude, making troubleshooting very difficult. Of course, a well-designed system will be immune from all of these noise sources.

For on-wafer measurements, motor noise from the prober must be controlled. Even when the motion is stopped on the prober, some motors are energized for the purpose of maintaining position. Motors must not be located in an area where the noise couples into the measured wafer, such as within a shield enclosure. A

combination of properly located motors and shielding along with filtering is used to combat this issue. A modern prober will not be impaired by any motor noise. Additional electrical noise may originate from mechanical vibrations on the on-wafer probe station. It is for this reason that the system must be located in an area which is free from vibration.

The nature of the noise and the containment techniques used to combat the noise mandates that a system approach be taken to the flicker noise measurement system. An enormous number of interactions occur which cannot possibly be modeled or predicted. It is for this reason the advantage goes to an integrated measurement solution as opposed to a rack and stack solution.

4] DC characterization of a device is necessary before flicker measurements can be performed. Flicker noise measurements are closely tied to the DC bias on a device. The noise is proportional to the DC current through the device. The DC measurements are used to calculate transconductance [G_m], and the channel conductance [R_{ds}], which are used in the 1/f data presentation. A flexible 1/f system will be able to take multiple DC measurements on each die without changing the setup. To maintain signal and probing integrity, and to minimize the introduction of noise, no changes in cabling should be made between DC and flicker noise measurements.

5] Another major trend for flicker noise systems is the need to test multiple devices, not only to obtain statistical significance, but also to observe variations of flicker noise among different sites across a wafer. Because multiple devices need to be measured on a wafer, a semi-automatic prober is necessary, as manually locating each site is highly impractical. In many cases several different devices need to be measured on a single die, as well as measurements on multiple die across a wafer. This necessitates advanced step-and-repeat probing functions. The software associated with a modern flicker noise system should provide graphical tools for observing the flicker noise of multiple sites on a wafer by means of wafer mapping.

A MODERN FLICKER NOISE MEASUREMENT SYSTEM

To achieve the necessary measurements and overcome the challenges associated with flicker noise measurements up to 30 MHz, a complete system

was developed in which each part of the system was designed for optimal performance. In addition, a system integration approach was taken such that undesirable interactions between components of the system were eliminated. The system is capable of high frequency rolloff response, measurements out to 30 MHz, accurate DC measurements and multiple device testing. Diagrams of the modern flicker noise setup are shown in Figures 3 and 4.

Figure 3 shows the necessary setup for the DC characterization. Quite simply, the transistor is biased, and measurements are made with an SMU. For a single die measurement, the die is characterized for DC performance before noise testing is started. This sequence is straightforward. For the testing of multiple die on a wafer, each individual die should be characterized for DC performance. Only after data is collected from this measurement should flicker noise testing be executed.

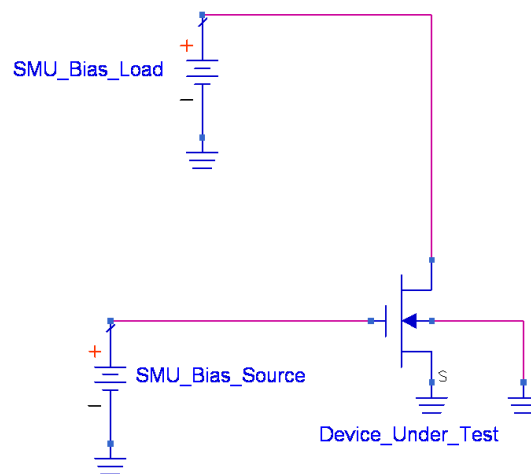


Figure 3: DC measurement setup for MOS transistor

All DC measurements should be guarded measurements such that DC current measurements can be made down to the femto-ampere range. Most modern source monitor units provide a guard signal, and this guard signal must be maintained all the way down to the probe at the wafer to obtain an accurate DC measurement. Without the guard in place, a leakage will occur between the force signal from the SMU and ground. Although this leakage is normally quite small, it will disallow small current measurements. It is optimal that the flicker noise system has the ability to switch between DC measurements and flicker noise without having to change any cabling or probes (Cascade Microtech patent pending). Integrating this

functionality into a flicker noise system presents a unique set of challenges.

Figure 4 shows the configuration for the flicker noise measurement. Note the addition of filtering, as well as a mechanism to measure the noise on the drain or collector of the device under test.

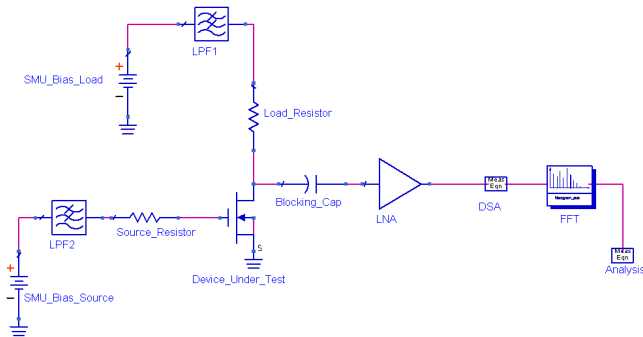


Figure 4: Modern flicker noise test setup

Each block must be carefully designed to enable optimal flicker noise measurements. The filter units block noise, which is generated from the SMUs. These low-pass filters must have a very low cutoff frequency. They incorporate a unique design which has the purpose of only passing the DC from the SMU. The filters are designed to handle the maximum voltages and currents appropriate for the devices under test.

The Source Resistor (R_{source}) and the Load Resistor (R_{load}) set the impedance conditions for the device under test during the noise measurements. To accommodate a broad range of devices which can be tested, a variety of source and load resistors are set with software control. A software algorithm assists in optimizing the values of the source and load resistors to be used during testing. The R_{load} resistor provides a load for the device such that a voltage divider is constructed from the drain or collector and bias supply. The center of this voltage divider is the point where the voltage is measured by the LNA. The blocking capacitor has a relatively large capacitance. This large capacitance sets a high pass filter, enabling the system to measure flicker noise signals with frequencies of less than 3 Hz. Only the flicker noise generated by the transistor is amplified by the LNA.

The LNA amplifies noise signals from the device under test without adding any (or very little) noise of its own to the signal it's responsible for amplifying. The performance of the LNA is the major factor which sets the system noise floor. The noise floor for this modern flicker noise system is shown in Figure 5.

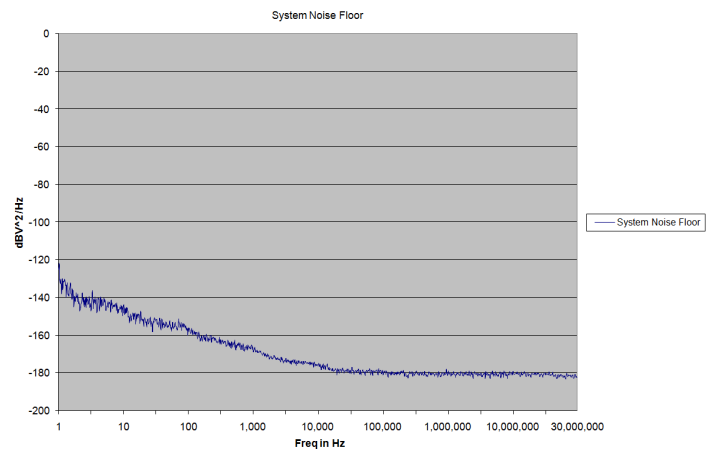


Figure 5: Noise floor of a flicker noise system

The LNA must have very high input impedance such that it does not load down the drain/collector measurement node. The LNA must have a wide bandwidth such that no attenuation occurs at either the low edge or the high edge of the frequency range of interest. The LNA must have enough gain to drive the next stage, which is the digitizer, and the gain must not vary significantly with frequency. In addition, the gain of the LNA must overcome the system noise figure of the dynamic signal analyzer (DSA). For a typical setup, an LNA used for this application might have approximately 40 dB of AC gain.

The DSA collects the signal from the LNA. This instrument has several unique performance characteristics. First, the test signal from the LNA is conditioned. After conditioning, the digitizer converts the AC noise from the LNA to a digital format such that the computer can analyze the noise signal. The DSA has two important specifications. These are the bandwidth and the number of bits used to represent the measured signal. The bandwidth, which is proportional to the sampling rate of the digitizing section, should start at DC and extend to at least 10 MHz, or in some cases, as high as 30 MHz, depending on the device being characterized. Finally, the DSA interfaces to a microprocessor or computer, where the Fast Fourier Transform (FFT) and data analysis is accomplished.

The FFT is implemented in software, and converts the time domain bit stream from the DSA to a frequency domain representation, such that display and further analysis of the noise data can be prepared. Since flicker noise is a frequency domain phenomenon, direct analysis in the time domain does not yield meaningful data. However, a tool to view the time domain signal from the digitizer is needed to capture

random telegraph signals (RTS). RTS noise is closely related to flicker noise in a MOS transistor. While flicker noise is a description of noise with a 1/f spectrum in the frequency domain, RTS is generally described in the time domain, and is also the result of trapped charge in the gate oxide caused by defects in the material. However, small area devices may contain a single defect, which in the time domain results in an observed switching between two voltage levels. This appears as a randomly switched voltage signal, which switches between two quantized levels. [14]

Once the FFT is calculated, data analysis can occur. The data in the FFT represents the voltage squared data taken at the drain or collector of the device under test. Calculations are done which convert this data to the equivalent noise input current of the device. This is done in a multi-step calculation as follows:

$$V_{meas} = \sqrt{10 A/10}$$

where V_{meas} is the noise voltage in volts at the drain terminal of the device under test, and A is the voltage amplitude in dBV^2/Hz measured at the digitizer.

The equivalent total load resistance for the device under test is the parallel combination of the load resistor and the channel resistance:

$$R_{eq} = \frac{R_{load} * R_{ds}}{R_{load} + R_{ds}}$$

where R_{eq} is the resulting equivalent loading resistance, R_{load} is the load resistor for the measurement equipment, and R_{ds} is the drain to source resistance for the MOSFET.

The noise current squared, I_D^2 , through the drain to the source of the device under test is calculated as:

$$I_D^2 = \left(\frac{V_{meas}}{R_{eq}} \right)^2$$

where V_{meas} and R_{eq} are defined above.

Finally, the equivalent gate noise voltage squared is calculated as:

$$S = \left(\frac{I_D}{g_m} \right)^2$$

where S is in volts squared, and G_m is the transconductance of the device under test.

As a final step, the data is formatted and saved such that it is ready for further analysis. The flicker noise software must be flexible enough to handle data formats for export into any of the popular model extraction software packages.

FLICKER NOISE MEASUREMENT RESULTS

In this section, the flicker noise results are presented for an NMOS device. Although these results are limited to the NMOS, the system is able to measure a wide variety of devices.

The first step for accurate flicker noise measurement is characterization of the DC parameters of the device under test. In the case of the FET, a DC bias point is characterized by first selecting a drain voltage and then varying the gate voltage. From this information displayed on the left-hand side of Figure 6, the transconductance g_m can be obtained. Next, the drain voltage is varied at a desired gate voltage and the resulting drain-source resistance, R_{ds} , is obtained as shown on the right-hand side of Figure 6.

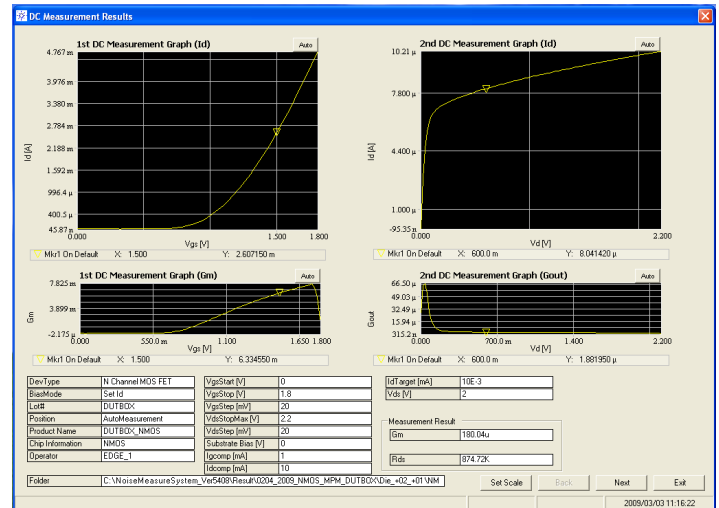


Figure 6: Measured DC parameters

The noise measurement setup includes the selection of the gate voltage, the drain voltage, and the source and load resistors. The selection of the load resistor, along with the parasitic capacitance of the measurement equipment, determines a system rolloff point. The load resistor can be selected to optimize the rolloff frequency, but still provide enough impedance to properly set the drain current. The software, which controls the system, will provide assistance to the user in selecting the load resistor by providing rolloff frequency information for each resistor which might be selected. An automated system will allow the user

to select as many as 20 bias points. Flicker noise data will be collected for each bias point.

Once the flicker noise data is taken, calculations are done such that three graphs are presented. Figure 7 shows the actual voltage taken at the LNA input node. The calculated drain current noise power is shown in Figure 8, and the equivalent input noise power for the device under test is shown in Figure 9. The equivalent noise power data from Figure 9 is the most common presentation of the data.

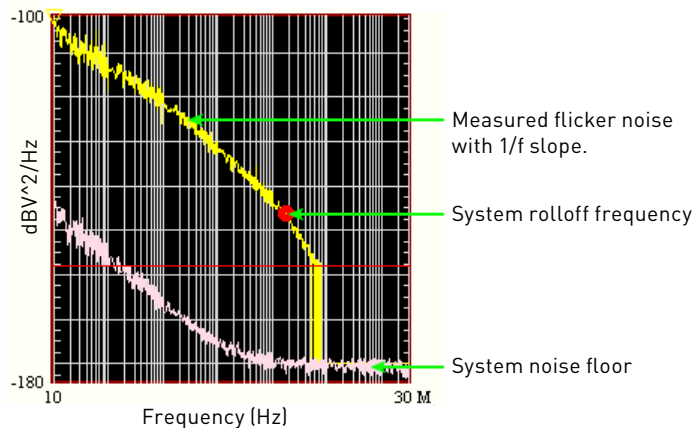


Figure 7: Noise measurement from the digitizer

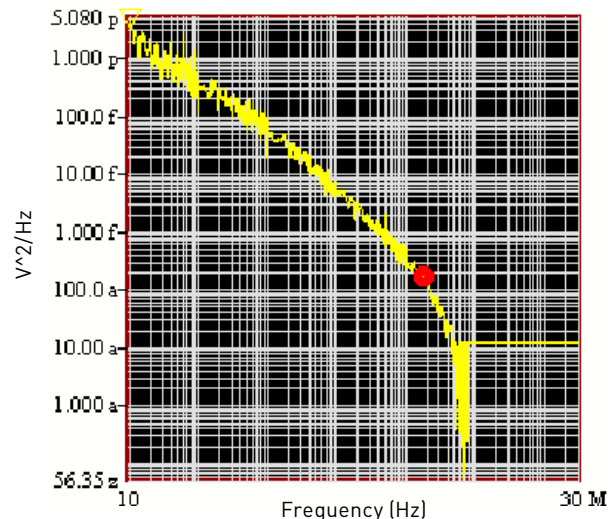


Figure 9: Equivalent input noise power

The system rolloff frequency, due to system capacitance and resistance, is indicated on each plot with a red dot for the user's reference. The flicker noise itself is plotted as the yellow line. As frequency increases, the point where the frequency dependent $1/f$ slope is lost, and the thermal and shot noise become dominate, is referred to as the $1/f$ corner. Noise spikes in the $1/f$ plot should be minimal, or ideally, absent altogether. As an aside, inspection of the resulting power graphs shows the $1/f$ noise to have equal power in each decade where the $1/f$ slope is present.

Since an engineer taking on-wafer measurements will obtain a large amount of data, a graphical method of presentation of the flicker noise data can aid in quickly spotting bad data or data from devices which may not be functional. In addition, the flicker noise trend plot for devices across a wafer can help identify process stability issues across the wafer, which can aid in yield enhancement. Figure 10 shows a graphical output such as the one just described.

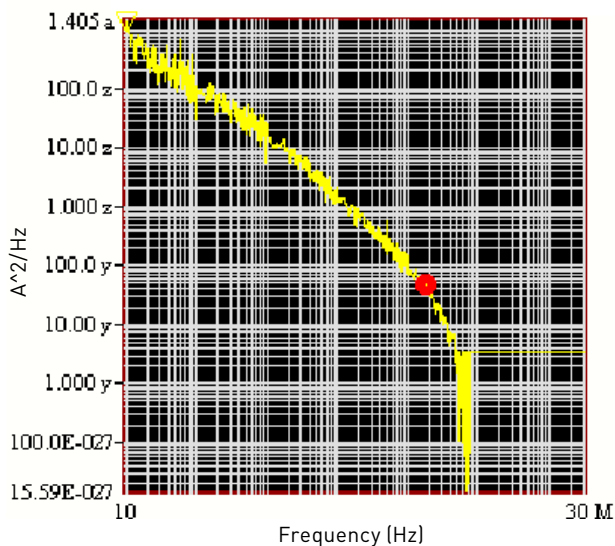


Figure 8: Calculated drain current flicker noise

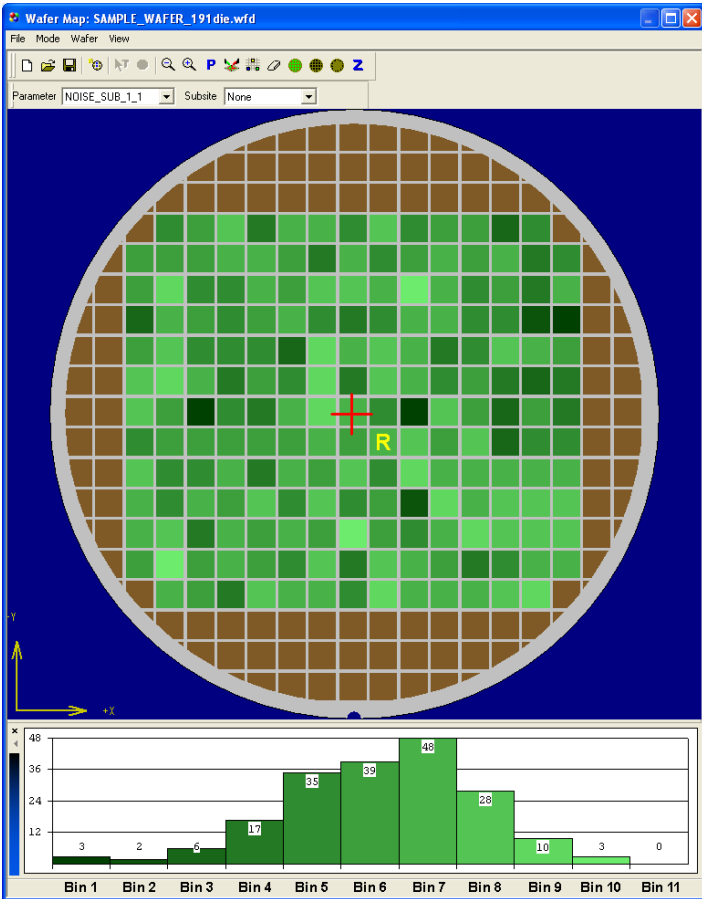


Figure 10: Graphical plot of flicker noise data taken at several sites across the wafer

Once the data is inspected, both the DC data and the flicker noise data can be exported to model extraction tools, where the actual transistor model is generated for use in circuit simulations by circuit design engineers.

A useful tool available on the flicker noise measurement system is the ability to view RTS noise, which was previously discussed. As shown in Figure 11, the RTS noise can be identified in the time domain with some simple signal averaging.

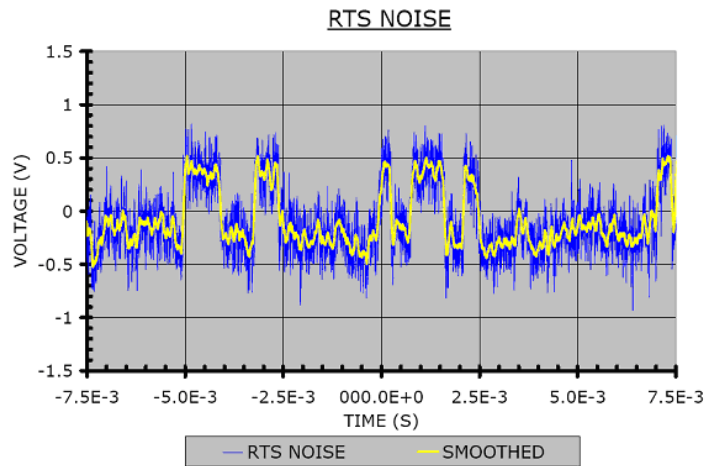


Figure 11: RTS signal in the time domain

The RTS data in the time domain can be saved, and if desired can be processed with Matlab, or even Excel.

CONCLUSIONS:

Three types of noise are produced by an electrical component; thermal noise, shot noise, and flicker noise. Flicker noise measurements have become more important for the semiconductor industry as the technology advances. Because of the higher 1/f corner frequencies and instrument noise concerns, state of the art semiconductor devices require a new approach for the measurement of flicker noise. Obtaining useful flicker noise data can be tricky and has many challenges. Recently, the challenges have been addressed such that valid flicker noise measurements are obtainable with the proper equipment. A modern flicker noise measurement system is able to provide repeatable spur-free measurements through 30 MHz in a commercially available system, and is able to measure DC and flicker noise on a single system. Measured results of a MOS transistor from a modern flicker noise measurement system prove that it is possible to obtain a clean measurement yielding accurate measurement data.

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Cascade Microtech, Inc.

toll free: +1-800-550-3279
phone: +1-503-601-1000
email: cmi_sales@cmicro.com

Cascade Microtech Japan

phone: +81-3-5615-5150
email: cmj_sales@cmicro.com

Cascade Microtech Singapore

phone: +65-6873-7482
email: cms_sales@cmicro.com

Cascade Microtech GmbH

phone: +49-811-60005-0
email: cmg_sales@cmicro.com

Cascade Microtech Shanghai

phone: +86-21-3330-3188
email: cmc_sales@cmicro.com

Cascade Microtech Taiwan

phone: +886-3-5722810
email: cmt_sales@cmicro.com

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