

# Pulse/Waveform Generation with Integrated Measurement Capability

# B1500A's Waveform Generator/Fast Measurement Unit

## Product Overview



# Introduction

The ability to perform current or voltage measurement at any point along a voltage pulse or arbitrarily generated voltage waveform has long been a highly desired measurement capability. In many measurement applications, especially those involving cutting-edge materials and devices, not only the DC current versus voltage (IV) characteristics but also the AC characteristics (such as pulsed IV, stepped IV or ramped IV) are required for accurate characterization. In addition, the ability to perform noise current analysis in both the time and frequency domains continues to take on increased importance for advanced device characterization in a variety of applications.

Previous pulsed measurement solutions have consisted of user-configured instrument setups, usually consisting of a pulse or function generator, a current to voltage convertor, and an oscilloscope (or voltage sampler). However, these types of measurement solutions have difficulty producing stable and consistent measurement results. This is mostly due to poorly calibrated components and to the lack of calibration of the entire system. In addition, measurement solutions constructed from multiple instruments can easily generate substantial 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 data, an off-the-shelf, self-contained solution with guaranteed specifications is highly desirable.

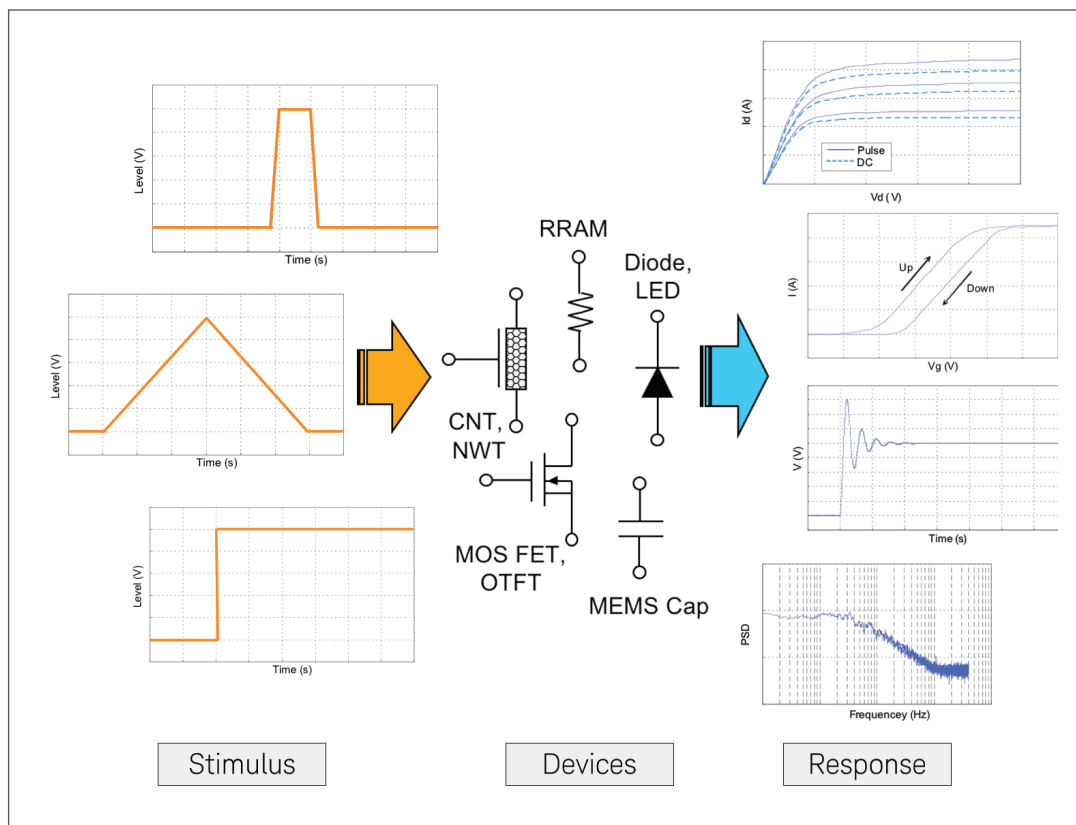


Figure 1. Variation of time domain measurement

## Introduction (continued)

To meet these needs Keysight Technologies, Inc. developed the B1530A waveform generator/fast measurement unit (WGFMU) module for the B1500A semiconductor device analyzer. The WGFMU module combines pulsing and arbitrary linear waveform generation (ALWG) capabilities with current and voltage measurement functions in a single unit. The WGFMU module can measure current or voltage at sampling rates up to 200 Mega-samples/s and it possesses a 16 MHz bandwidth. Its ALWG function has a minimum programmable timing resolution of 10 ns and its bandwidth is about 45 MHz. These features enable the WGFMU to meet the measurement challenges posed by advanced materials and devices mentioned above.

In this product note, the key features of the WGFMU are introduced first. Then the measurement applications are explained based on practical examples with some technical hints to use it more efficiently. This product note includes the following contents:

## Key features of the WGFMU

- ALWG function
- Fast I/V measurement
- Software for ease of use and data handling
- Other B1500A measurement capabilities

## Applications

- Pulsed measurement
  - Pulsed IV measurement
    - Intrinsic  $I_dV_g$ ,  $I_dV_d$  measurement of FET made silicon on insulator (SOI) substrate
    - Write/erase measurement of resistive memory
    - L-I-V test of light emitting diode (LED) and photo diode (PD)
  - Pulsed sampling measurement
    - $I_dV_g$  hysteresis measurement of FET made of high-k gate stack
    - Dynamic write/erase characterization of Flash memory
- Step response measurement
  - Accumulated charge measurement
  - Fast C-t measurement
- Ramp response measurement
  - Displacement current measurement
  - Ultra fast CV measurement
  - Carrier generation measurement of Organic Field Effect Transistor (OFET)
- High speed, precision and long term current sampling measurement
  - Random Telegraph Noise (RTN) measurement
  - Progressive transition measurement
  - Progressive breakdown of gate dielectrics
  - Current transportation of quantum dot array
- Sequence of multiple measurements
  - Stress-measure-stress sequence of reliability test
    - Negative or Positive Bias Temperature Instability (NBTI/PBTI) test
    - Hot Carrier Injection (HCI) test
  - Time domain dielectric breakdown (TDDB) of Magneto Tunneling Junction (MTJ) device

## Key Features of the WGFMU

### Overview

Figure 2 shows a simplified circuit diagram of the WGFMU and the remote-sense and switch unit (RSU). The waveforms created using the WGFMU's ALWG voltage generation capability output through the RSU. The RSU is also where the actual current or voltage measurement is performed. 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. In fast IV mode five fixed current measurement ranges (from 1  $\mu$ A to 10 mA) are available, and you can dynamically switch between ranges during a measurement.

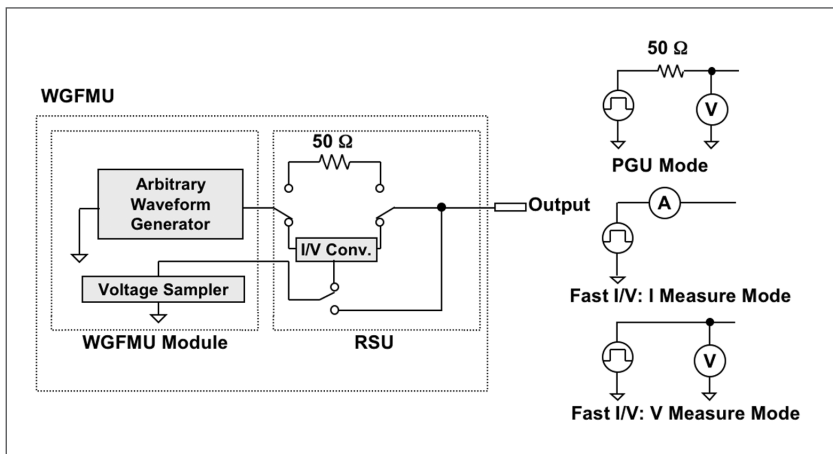


Figure 2. Simplified circuit diagram of the WGFMU showing its operation modes

Using the WGFMU module, a conventional pulsed or transient measurement can be made very easily as shown in Figure 3 on page 5.

The conventional system has difficulty producing stable and consistent measurement results due to poorly calibrated, user-created components and to a lack of calibration of the entire system. In addition, 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. In contrast, the WGFMU is a single module with guaranteed specifications. By placing the RSU close to the device under test (DUT), the WGFMU's cabling is also kept very short and simple.

The key features and specifications of the WGFMU module that are relevant to pulsed or transient measurement are described below. (For more details, please refer to the technical data sheet of the B1500A Semiconductor Device Analyzer).

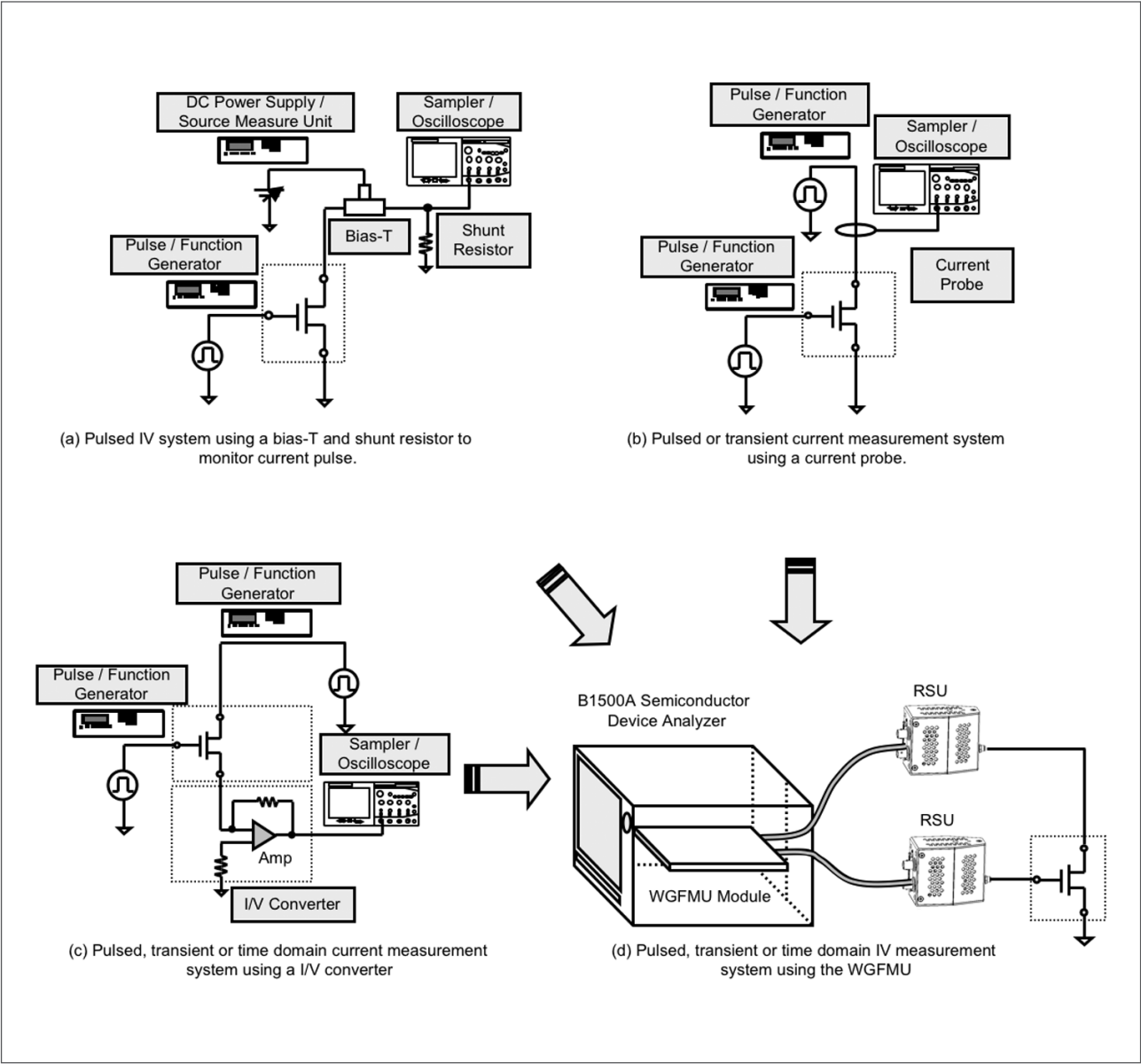


Figure 3. WGFMU simplifies system configuration of time-domain, pulse, transient and ramp IV measurement system

## ALWG function

The ALWG function of the WGF MU can generate waveforms as a series of linear segments of variable length (from 10 ns to 10,000 ns with 10 ns resolution). The memory depth of the waveform vector is 2,048, and the WGF MU has a sequence memory that allows it to create an output sequence consisting of up to 512 waveforms. In addition, a burst counter with a burst count of up to 1012 is available for each waveform included in the output sequence that supports the generation of long-duration AC signals. These capabilities allow the WGF MU to generate waveforms of long duration yet also support sections with very rapid changes (please see Figure 4).

The WGF MU module supports the following output voltage ranges:  $\pm 3$  V,  $\pm 5$  V,  $-10$  V to 0 V and 0 V to  $+10$  V. The resolution of the output voltage is also much better than conventional pulse and function generators:  $96\text{ }\mu\text{V}$  for the  $\pm 3$  V range and  $160\text{ }\mu\text{V}$  for the other ranges; this supports the creation of the very precise stimuli that are required to observe subtle device responses.

As previously mentioned, the WGF MU has a sequence memory that allows it to create an output sequence consisting of up to 512 waveforms (please see Figure 5). The sequence memory allows waveform data to be reused, thereby minimizing waveform memory consumption.

Also as previously mentioned, a burst counter with a burst count of up to 1012 is available for each waveform included in the output sequence.

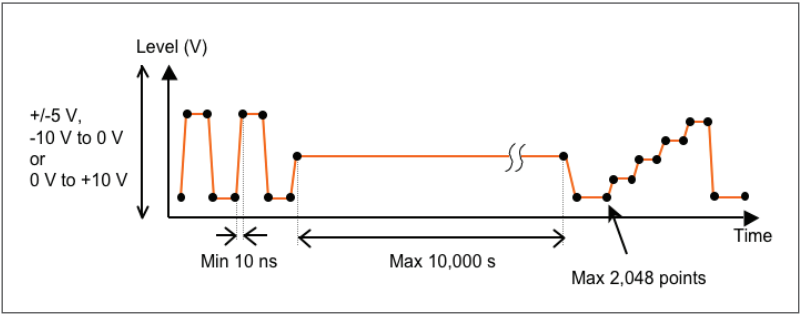


Figure 4. Variable sampling interval of the ALWG function

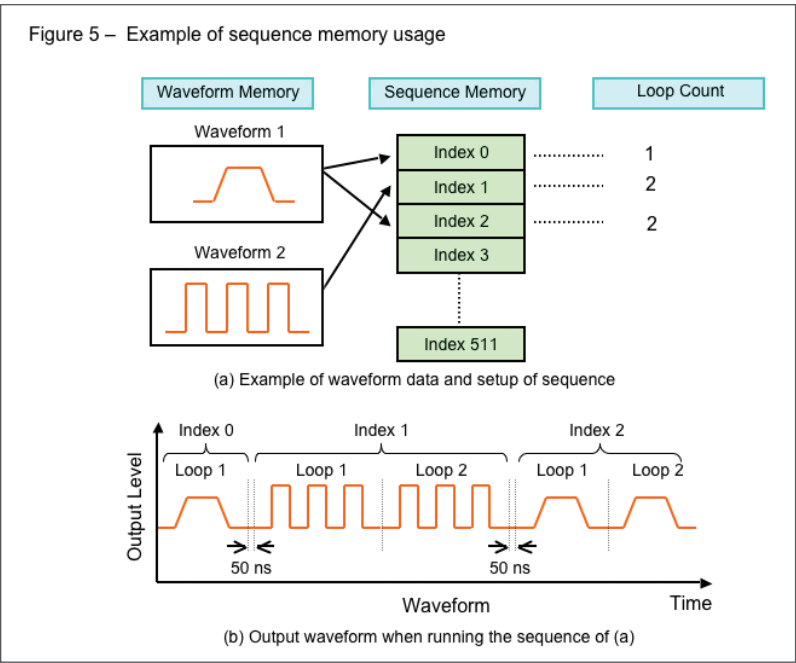


Figure 5. Example of sequence memory usage

ALWG function (continued)

This enables the generation of long-duration AC signals by simply repeating a single pulse. Although there is 50 ns of overhead associated with the transitions between the indexes, there are no glitches. Thus, the WGFMU can generate waveforms with long durations that also include sections with very rapid changes.

The WGFMU can also generate a sequence of pulses using its ALWG function. The minimum pulse rise and fall times and pulse widths depend on several factors, including the output mode, the current measurement range and the load connected to the output of the RSU. Table 1 shows the minimum rise and fall times (defined as the time it takes the pulse to go from 10% to 90% of its initial and final values). By maintaining these rise and fall times, waveform overshoot and distortion are minimized.

For reference, Table 2 shows the minimum achievable pulse widths for a 0 V to 5 V programmed pulse with the condition that the pulse level be within ±0.3% of the programmed value.

Operation mode	Current measurement range	Minimum rise/fall time			Load condition
		0 to 1 V	0 to 5 V	0 to 10 V	
PG	N/A	30 ns	30 ns	N/A	25 pF, open
Fast I/V	10 mA	80 ns	80 ns	80 ns	25 pF, 1 MΩ
	1 mA	250 ns	250 ns	250 ns	
	100 μA	600 ns	600 ns	1.5 μs	
	10 μA	2 μs	4.5 μs	7 μs	
	1 μA	6 μs	-	-	
		-	35 μs	75 μs	25 pF, open

Table 1. Minimum rise time and fall time of the WGFMU

Operation mode	Current measurement range	Minimum pulse width	Load condition
PG	N/A	170 ns	25 pF, open
Fast I/V	10 mA	180 ns	25 pF, 1 kΩ
	1 mA	500 ns	25 pF, 10 kΩ
	100 μA	1.6 μs	25 pF, 100 kΩ
	10 μA	14.5 μs	25 pF, 1 MΩ
	1 μA	115 μs	25 pF, 10 MΩ

Table 2. Minimum pulse width with ±0.3% settling (0 V to 5 V)

## Fast current/voltage measurement

In addition to the ALWG function, the WGFMU has a built-in current to voltage sampling circuit that allows the WGFMU module to measure current or voltage within a very short time interval while simultaneously applying an arbitrary voltage waveform.

The WGFMU module has five fixed current measurement ranges: 1  $\mu\text{A}$ , 10  $\mu\text{A}$ , 100  $\mu\text{A}$ , 1 mA and 10 mA, which enable the WGFMU module to cover a wide range of measurement requirements. In addition, the measurement resolution is 0.014% of range and the noise floor is 0.2% of range. The analog to digital converter (ADC) in the WGFMU has 14 bits of resolution, giving it a wider dynamic range than a comparable solution using a separate oscilloscope that typically only has an 8-bit ADC.

The minimum sampling interval of the WGFMU is 5 ns. In addition, it is variable from 10 ns to 10,000 s with 10 ns resolution. The measurement memory depth is approximately 4 million measurement points per channel.

To reduce measurement noise and utilize measurement memory more effectively, the WGFMU also has a hardware averaging function. The averaging time can be varied from 10 ns to 20 ms, with 10 ns resolution. Figure 6 shows how averaging works and how it can reduce measurement noise.

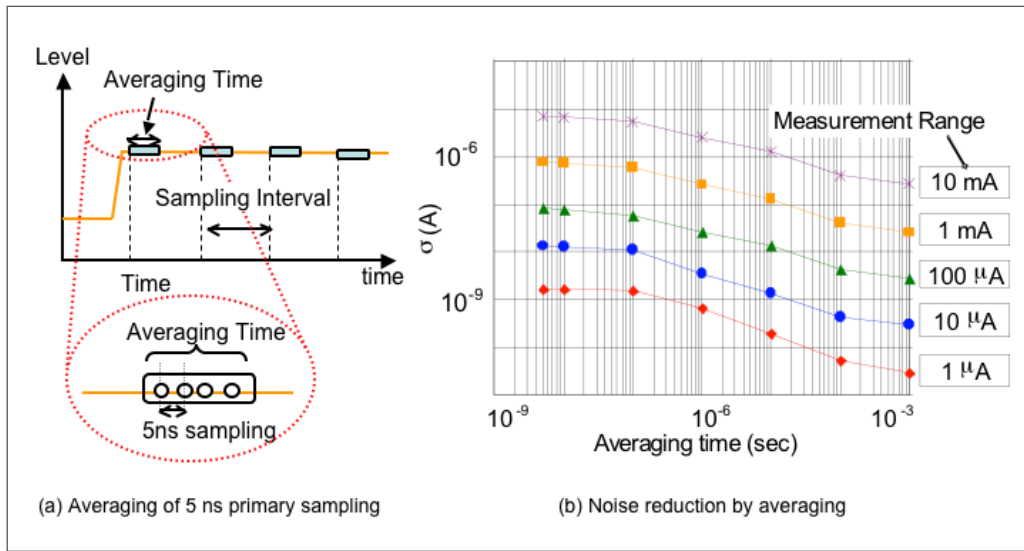


Figure 6. Theory of averaging and example of noise reduction by averaging



## Fast current/voltage measurement (continued)

The aforementioned features give the WGFMU module both high speed and high precision measurement capabilities, along with providing the user the ability to specify the optimal measurement conditions.

Another important WGFMU feature is its ability to measure anywhere on the waveforms it generates. (please see Figure 7).

For example, measurements can be done on the edge of a step to capture the transient response. Measurements can also occur at specific timing points on the waveform. These capabilities significantly reduce the amount of instrumentation memory required and the amount of effort needed to extract data from a long waveform as compared to measurement schemes utilizing an oscilloscope to capture the waveform.

Although the WGFMU only supports fixed measurement ranging, the user can specify the measurement range to be used at every measurement point (also known as controlled measurement ranging). In addition, multiple sampling rates can also be specified within a single waveform. These unique features enable the WGFMU to capture both quick and large-signal and slow and small-signal responses with equal accuracy. Moreover, this can be achieved with minimal consumption of instrument memory.

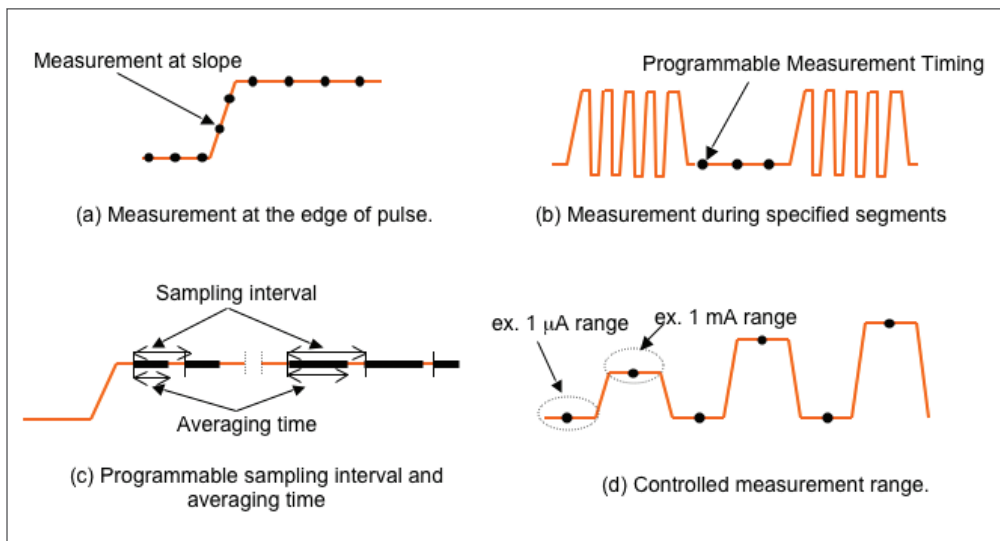


Figure 7. Flexible measurement timing, averaging and range changing are supported by WGFMU

## Furnished software provides ease of use and simplifies data handling

Keysight supplies a “WGFMU instrument library” software driver for the WGFMU. This driver can control all of the WGFMU’s functionality, and it can manage the waveform and measurement data.

The instrument library supports a variety of programming platforms including those listed below.

- Microsoft Visual Studio .Net (C, C++, C#, Visual Basic)
- Microsoft Visual Basic for Application (VBA)
- TransEra HTBasic for Windows
- Keysight VEE
- National instrument LabVIEW

For more details on the supported programming environments, please refer to the “B1530A User’s Guide” (P/N: B1530-90001).

To reduce the learning curve and decrease startup time, Keysight provides sample software for the WGFMU. This consists of two types of sample programs: sample application tests for use with EasyEXPERT, and sample programs for use with the common programming platforms.

The sample programs for the common programming platforms include the source code to permit user customization. A list of the sample software is shown below.

- EasyEXPERT application tests
  - Pattern Editor
    - Supports the creation of arbitrary waveforms and the specification of measurement points on those waveforms.
  - NBTI/PBIT testing with DC stress
    - Supports both fast Id sampling and  $I_d V_g$  measurement.
  - NBTI/PBTI testing with AC stress
    - Supports both fast Id sampling and  $I_d V_g$  measurement.

Figure 8 shows a screen capture of the pattern editor sample application test.

- Common programming platform sample software
  - Fast sampling measurement
    - Supports dual measurement setup on a single waveform.
    - Supports both linear and log sampling.
  - Fast sweep measurement
    - Supports staircase sweep, ramp sweep, and pulsed sweep.
    - Supports single sweep and dual sweep measurement.
  - Pulsed sampling measurement
    - Supports dual measurement setup on a single waveform.
    - Supports both linear and log sampling.
  - Supports both single pulse and linearly increasing pulse steps.

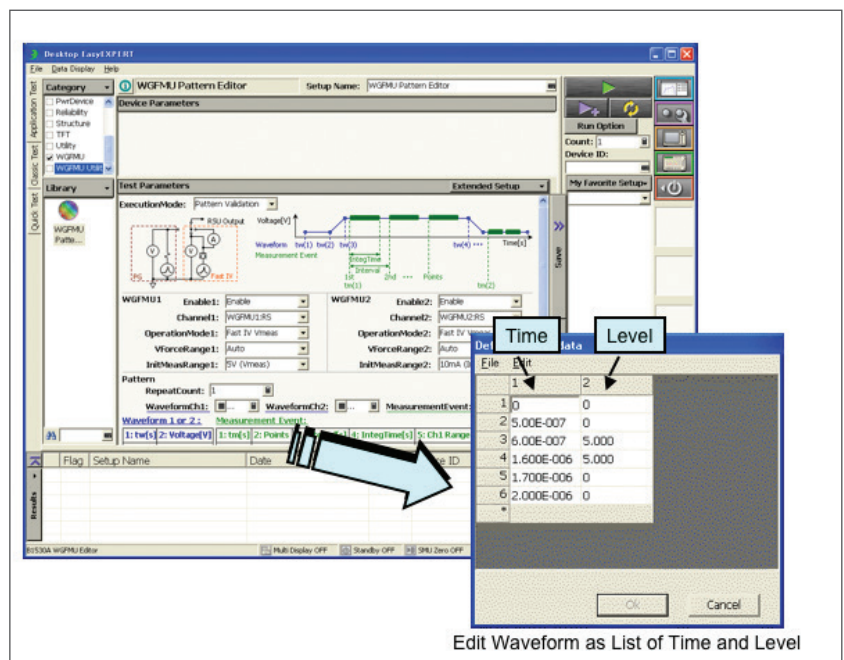


Figure 8. EasyEXPERT pattern editor application test

## Furnished software provides ease of use and simplifies data handling (continued)

- Time domain data recorder  
For noise analysis in conjunction with the RTN data analysis tool.
- NBTI/PBTI  
Supports both DC and AC stress.  
Supports fast  $I_d$  sampling, staircase sweep, ramp sweep, pulsed sweep and on-the-fly measurements.  
Supports reference measurement before applying stress bias and repetitive measurement after stress to evaluate recovery effect.

In addition to the above, an analysis tool for random telegraph noise (RTN) is also included. (Note: The common programming environment sample programs require that an external PC be used as the controller. These programs cannot run directly on the B1500A).

For more information about sample programs for the WGF MU, please refer to the following documents:

- B1530A User's Guide (P/N: B1530-90001)
- B1530A Sample Program Learning Kit User's Guide (P/N: B1500-90503)

The WGF MU's instrument library manages waveform data and measurement data by name and index. This feature allows the user to extract the exact measurement data that they need. Figure 9 shows an example of how measurement data from specific measurement segments can be retrieved.

In this example the segments are given the logical names of “Edge” at the measurement edge, “Top” at the top of the pulse and “Base” at the base of the pulse. As can be seen, this sequence is repeated multiple times. Using this scheme measurement data at (for example) the second edge of the pulse can be retrieved by specifying its name and index (e.g. “Edge2”). This feature greatly simplifies measurement analysis by reducing the effort needed to extract desired measurement data from various segments of the waveform during post-processing data analysis.

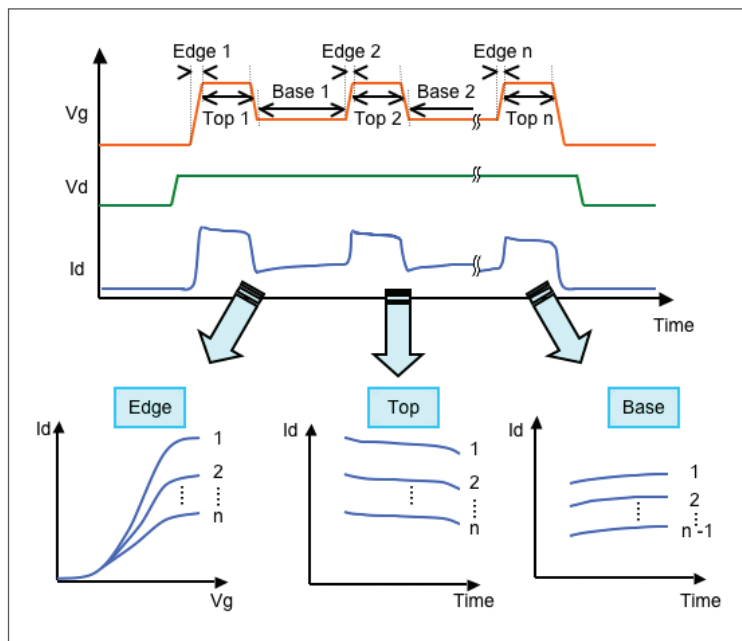


Figure 9. Retrieving measurement results using the measurement event name

## Other B1500A measurement capabilities

The B1500A semiconductor device analyzer can perform a wide variety of measurements in addition to those supported by the WGFMU module. The B1500A supports a variety of source monitor units (SMUs) as well as a multi-frequency capacitance measurement unit (MFCMU). The maximum output range of the SMUs is 200 V/1 A (high power SMU), and the minimum measurement resolution of the SMUs is 0.5  $\mu\text{V}$ /100 aA (high resolution SMU using the atto-sense and switch unit). The MFCMU supports multiple measurement frequencies from 1 kHz to 5 MHz, and it can supply 100 V DC bias when used in conjunction with the medium power or high-resolution SMUs and the SMU CMU unify unit (SCUU). When these modules are installed in the B1500A mainframe along with the WGFMU module the B1500A becomes a very versatile solution for the electrical characterization of cutting edge materials and devices. In addition, a high voltage semiconductor pulse generator unit (HV-SPGU) is available; this module can generate pulses with amplitudes of up to  $\pm 40$  V and it has a minimum pulse width of 50 ns.

For more information on these additional modules, please refer to the B1500A technical datasheet (P/N: 5989-2785EN).

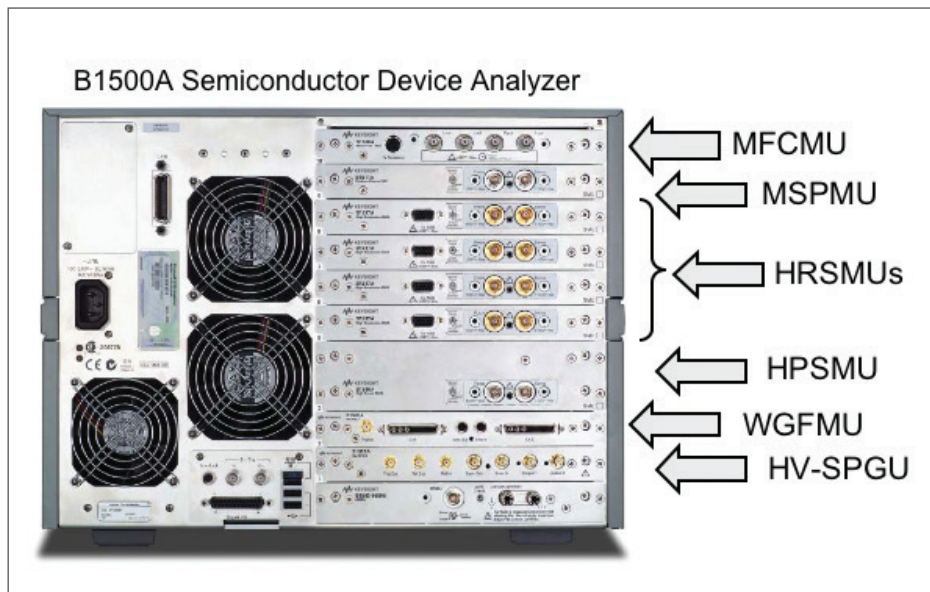


Figure 10. Rear view of the B1500A showing all of the available modules

## Application Examples

In this section some practical measurement examples using the WGFMU will be explored to illustrate how the WGFMU module can solve otherwise difficult measurement challenges.

### Pulsed measurement (pulsed IV, pulsed sampling measurement)

Current measurement in conjunction with a pulsed voltage bias is one of the techniques used to evaluate devices made of novel materials. There are several types of pulsed bias measurements, such as pulsed IV and pulsed sampling measurements.

#### Pulsed IV measurement

In pulsed IV measurement, current is measured at a specified timing on the pulsed bias. The actual IV curve is generated by applying a series of pulses of increasing or decreasing its level.

In the case of a metal oxide semiconductor field effect transistor (MOS FET) with a high dielectric constant (high-k) gate insulator, the drain current drive capability measured using conventional DC equipment such as SMUs is lower than that measured using pulsed bias techniques due to hole and electron trapping at the boundary defects (please see Figure 11).

Since the transistor is driven by a clock pulse under actual operating conditions, IV characteristics measured with pulsed bias are the only means to determine if the device is functioning properly under real-world conditions.

The situation is similar for devices made from materials such as organic thin film transistors (OTFTs) or poly-Si thin film transistors (TFTs) used to drive flat panel display (FPD) pixels.

Pulsed bias IV measurements are also useful to evaluate the intrinsic IV characteristics of TFTs fabricated on insulators, such as SOI (Silicon On Insulator) technologies or CG (Crystal Grade) silicon TFTs made on LCD glass substrates. In these cases the thermal resistance of the insulating substrate is substantially larger than that of silicon. This lowers the drain current measured by DC equipment because of device self heating. To understand the intrinsic IV characteristics under actual operating conditions, pulsed measurements are necessary to enable the drain current to be measured before the transistor heats up.

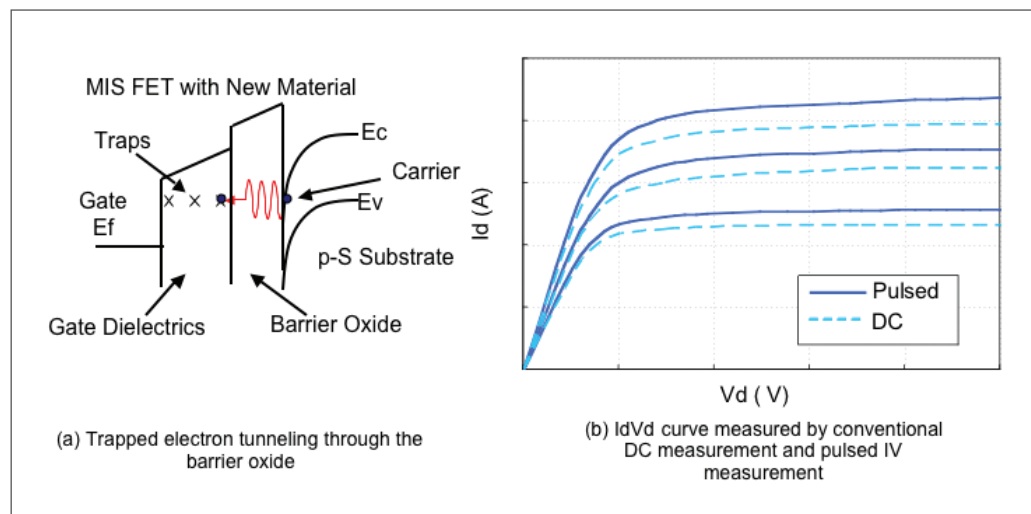


Figure 11. Example of  $I_dV_d$  curve of FET with high-k gate stack measured by DC and pulsed bias

Pulsed IV measurement (continued)

The WGFMU can perform pulsed IV measurement without any additional equipment. Figure 12 shows the connection diagram and bias sequence for a pulsed IV measurement using the WGFMU. Since the WGFMU can force a pulsed voltage bias and measure current simultaneously, pulsed bias can be applied both on the gate and drain terminals cannot be duplicated using the pulsed IV system consists of a bias-T to measure the drain current.

The settling time and the measurement equipment bandwidth are also important considerations for pulsed or transient measurements, since they determine the minimum pulse width and rise time that can be achieved.

Table 3 shows the current measurement settling time of the WGFMU module. The settling time is defined as the time it takes for the measured value to settle within  $\pm 0.3\%$  of its final value after the output voltage is changed from its initial value.

Measurement range	Settling time (s)
10 mA	100 ns
1 mA	250 ns
100 $\mu$ A	1 $\mu$ s
10 $\mu$ A	10 $\mu$ s
1 $\mu$ A	80 $\mu$ s

Table 3. Current measurement settling times

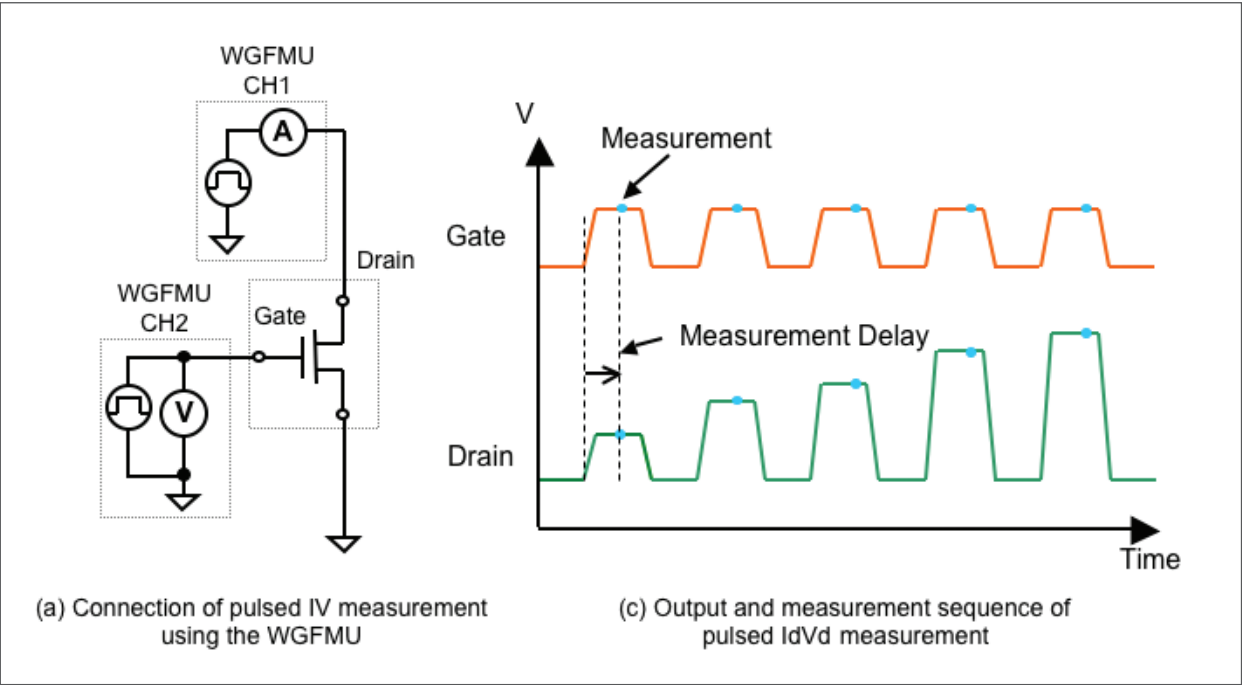


Figure 12. Connection and output sequence of pulsed IdVd sweep measurement using the WGFMU

## Pulsed IV measurement (continued)

A simple example illustrates these ideas. In the 10 mA measurement range, the settling time is given in Table 3 as 100 ns. From Table 1 we can see that the minimum rise time in Fast I/V mode for the 10 mA measurement range is 80 ns. Therefore, the minimum wait time is as follows:

Equation 1

$$100 \text{ ns} + 80 \text{ ns} \times \left( \frac{100 \%}{90 \% - 10 \%} \right) \\ = 200 \text{ ns}$$

This result means that in the case of a pulsed measurement with a 1  $\mu\text{s}$  wide pulse, 800 ns are available for measurement averaging after subtracting out the required 200 ns wait time. From the chart in the Figure 6, the standard deviation of a current measured with 800 ns of averaging time is around 3  $\mu\text{A}$ . It is also possible to use a lower current range to improve the repeatability of the measured current. For example, in the 1 mA range the settling time is 250 ns and the rise time is 250 ns. This leaves 400 ns for the averaging time, which for the 1 mA range implies a measurement current standard deviation of less than 500 nA. This means that the WGF MU module can measure current with a standard deviation of less than 1  $\mu\text{A}$  for the case of a 1  $\mu\text{s}$  pulse width.

Pulsed IV measurement is also useful to avoid self-heating effects when measuring light current voltage (I-L-V) on laser diodes (LDs), light emitting diodes (LEDs), and photo diodes (PDs) (please see Figure 13).

In addition to simple pulses, the WGF MU's AWLG function can output complex pulse combinations with different pulse parameters. This capability is especially useful when characterizing the write/erase characteristics of novel new types of non volatile memory (NVM), such as resistive random access memory (RRAM), phase change RAM (PRAM) or magneto-resistive RAM (MRAM). These types of memory cells can require a complex series of pulses, reset pulses, programming pulses and measurement pulses for proper characterization. Moreover, it is also necessary to measure current during the programming pulse and measurement pulse to understand the details of the cell write/erase process (please see Figure 14). The WGF MU's integrated ALWG and fast I/V measurement capabilities can easily meet these requirements, and it does this without creating any switching delays or glitches.

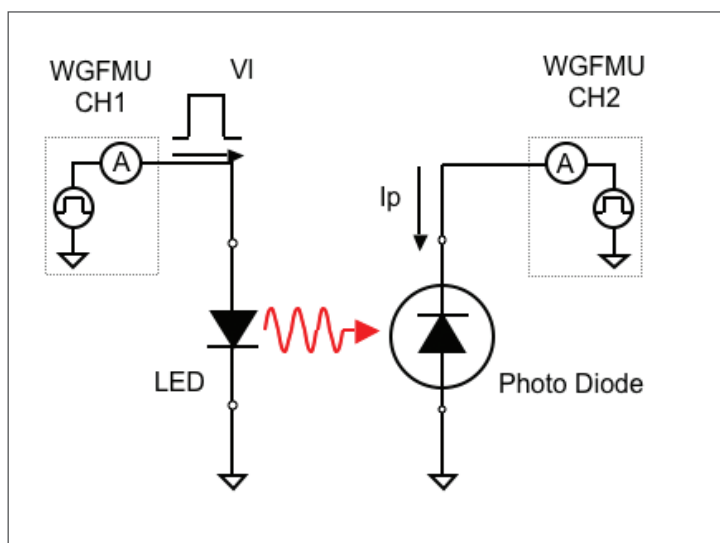


Figure 13. Pulsed L-I-V measurement of photo diode

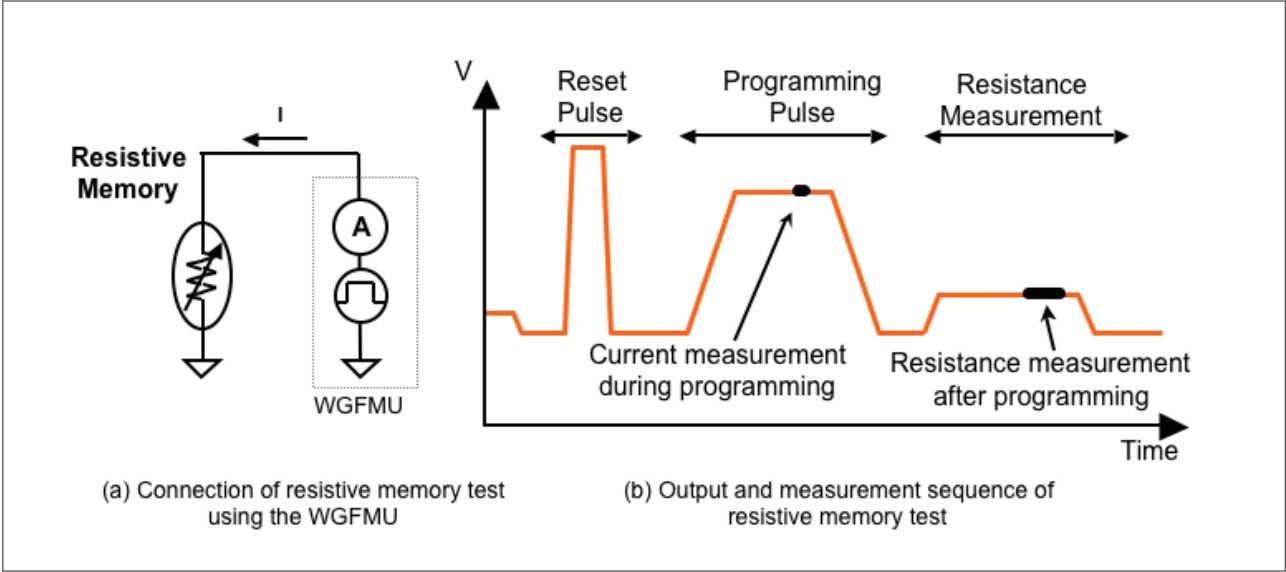


Figure 14. Example of resistive memory measurement with the WGFMU

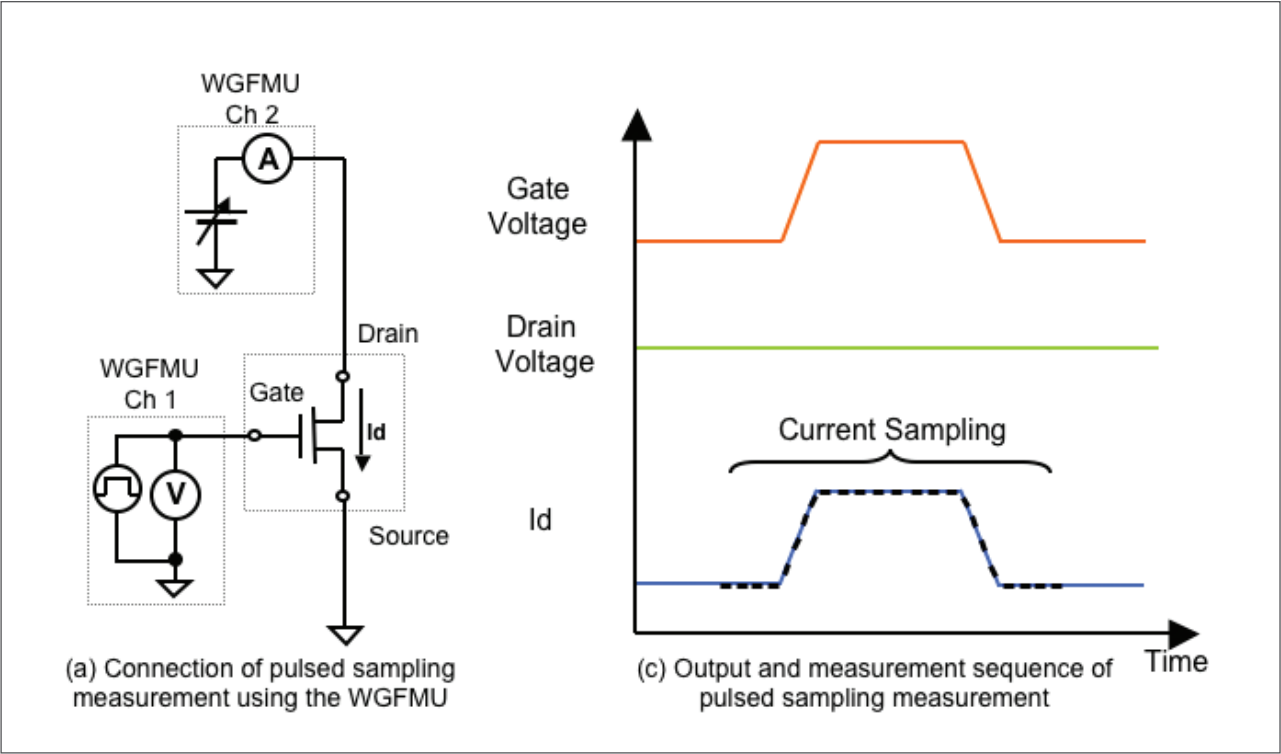


Figure 15. Example of pulsed sampling measurement



## Pulsed sampling measurement

Pulsed sampling measurements are another common measurement technique involving measuring current while a voltage pulse is applied to the device under test (please see Figure 15).

Pulsed sampling measurements can be used to observe the time dependent characteristics of a device as a function of pulsed bias. In the case of high-k gate dielectric MOS FETs, electron trapping in the gate dielectric impacts the threshold voltage and reduces the drain current. Standard DC measurement methods do not yield accurate  $I_dV_g$  characteristics for these devices, so performing a series of pulsed measurements where the drain current is measured during each pulse is necessary in order to accurately characterize these devices. If the gate dielectric trap density is large, then the drain current on an  $I_dV_g$  curve will show hysteresis as shown in the Figure 16 due to the degradation caused by the trapped electrons. This is a good indication that the defect density of the gate dielectrics is large. From the time constant of the lowered drain current, the time constant of the electron traps can be estimated.

In Figure 16 the  $I_dV_g$  curve is captured at the rising/falling edge of the pulse. This requires careful selection of the ramp rate and current range so as not to exceed the response rate of the WGFMU.

When measuring at a rising/falling edge, understanding the delay at each sampling points is key to determining the sampling interval, averaging time and measurement range.

The WGFMU's measurement delay is due to the inherent delay of the measurement circuitry as shown in Figure 17.

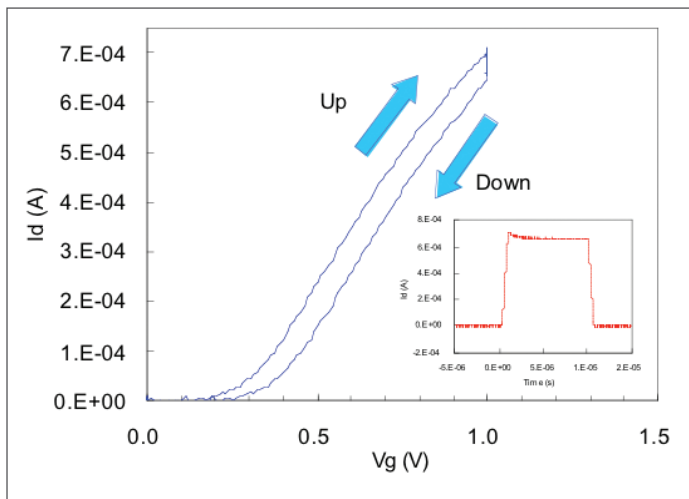


Figure 16. High-k gate dielectric MOS FET  $I_dV_g$  hysteresis curve captured using the single pulse technique

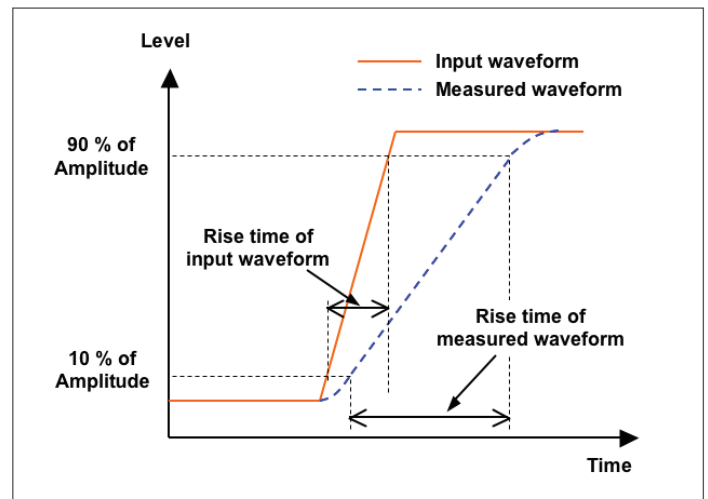


Figure 17. Rise time measurement error due to instrumentation limitations

## Pulsed sampling measurement (continued)

Delay time is determined by the bandwidth of the measurement equipment. Table 4 shows the current measurement bandwidth (-3 dB point) for the WGFMU for each of its measurement ranges.

In general the measurement circuit delay time,  $t_{rs}$ , can be estimated using the following equation:

Equation 2

$$t_{rs} = \frac{0.35}{BW}$$

Here “BW” is the bandwidth of the measurement equipment defined by the -3 dB attenuation point. The total delay time can be calculated using the following equation:

Equation 3

$$t_{rm} = \sqrt{t_{ri}^2 + t_{rs}^2}$$

Here  $t_{ri}$  is the rise time of the input signal,  $t_{rs}$  is the delay time of the equipment, and  $t_{rm}$  is the measured delay time. For the WGFMU module's 10 mA range, the current measurement bandwidth is around 16 MHz from Table 4. This bandwidth value and Equations 2 and 3 yield an equipment delay time of approximately 22 ns. This means that the WGFMU can measure gate delays down to 160 ns with an error of less than 1%.

For sampling measurements made at the edge of the pulse, the sampling interval is equivalent to the rise time determined using the above technique. This means that if the desire is to take 10 samples at the edge of pulse then the minimum rise time/fall time is 1.6  $\mu$ s to achieve an error of less than 1% in the 10 mA measurement range.

This technique is also applicable to the measurement of the dynamic write/erase characteristics of flash memory cells. Due to the increasing demand for high-density solid state memory such as solid state disk drives (SSDs), flash memory manufacturers are increasingly using multiple bit or multilevel cell (MLC) technologies.

MLCs require multiple programming states that must coexist within a limited voltage range. Therefore, accurate control of the threshold voltage ( $V_{th}$ ) is necessary to maintain sufficient margin between the programming states so that the memory cell status can be read correctly (please see Figure 18).

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

Table 4. Current measurement bandwidth for each measurement range

## Pulsed sampling measurement (continued)

Program and verify (P&V) schemes are used to reduce the  $V_{th}$  distribution of the different states so that sufficient margin can be maintained to correctly read the programmed state (please see Figure 18). In a P&V scheme, verification is performed immediately after programming.

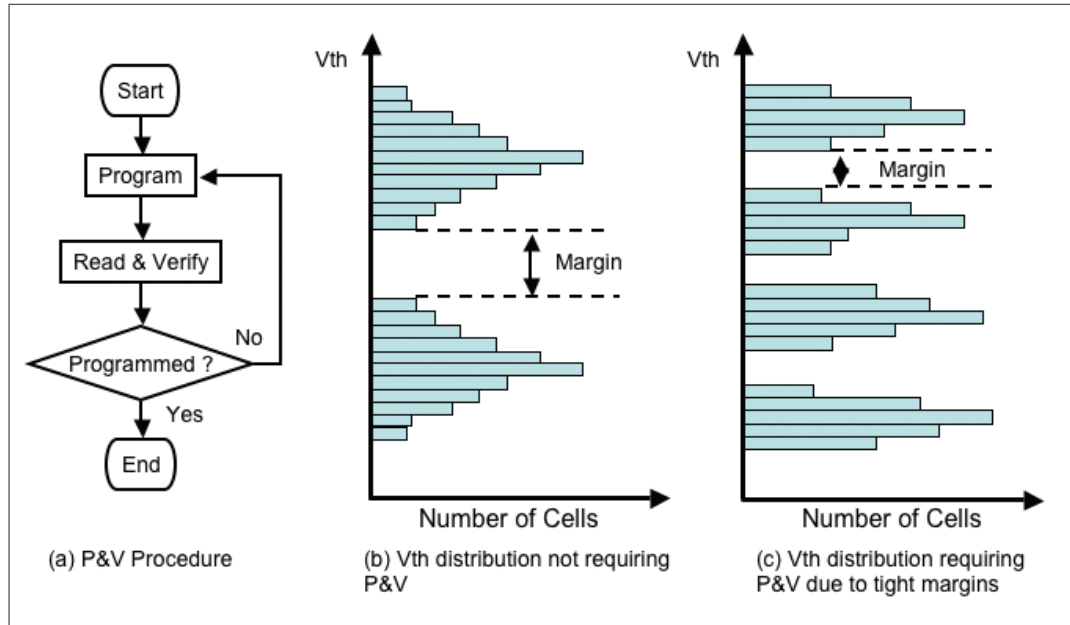


Figure 18. Program & verify (P&V) scheme for tight  $V_{th}$  control

However, there is the possibility of  $V_{th}$  shift after programming due to charge injection or degradation recovery as shown in the Figure 19.

If the  $V_{th}$  of the memory cell shifts after the P&V scheme has verified it to be within the target range, then the P&V scheme may not work as expected and the  $V_{th}$  distribution may exceed the desired limits. Consequently, it is important to verify that the drain/source current is stable after programming. The WGF MU enables you to do this by supporting the evaluation of microamp current levels at a sampling rate of less than 1  $\mu s$  (please see Figure 20).

For more details on testing flash memory using the WGF MU, please refer to application note AN B1500-12, "1  $\mu s$  IV Characterization of Flash Memory Cells using the B1530A" (P/N: 5990-3636EN).

## Step response measurement

The WGFMU can measure the current flow into a device during the application of a step voltage. One application of this step response measurement is to measure delay (please refer to Figure 17 on page 17).

Another use of this WGFMU step response measurement capability is measuring time varying capacitance or C-t characteristics. The WGFMU can perform C-t measurements with microsecond timing resolution.

The charge injected into a capacitor by a step voltage is described by the equations shown below:

Equation 4

$$Q = C \times V$$

Equation 5

$$i = \frac{dQ}{dt} = \frac{d(C \times V)}{dt} = C \frac{dV}{dt} + V \frac{dC}{dt}$$

If C is constant then for a small bias voltage variation ( $\Delta V$ ) Equation 5 reduces to:

Equation 6

$$\Delta Q = C \times \Delta V$$

Here  $\Delta Q$  is injected charge, C is capacitance and  $\Delta V$  is amplitude of the step voltage. From these results one can see that time varying capacitance (C-t) measurement is possible using the variation of the injected charge. C-t measurement can be used to evaluate the boundary trap densities of the gate or interlayer dielectrics used in semiconductor devices. It can also be used to measure the response of capacitive micro electro mechanical systems (MEMS) such as microphones or acceleration sensors.

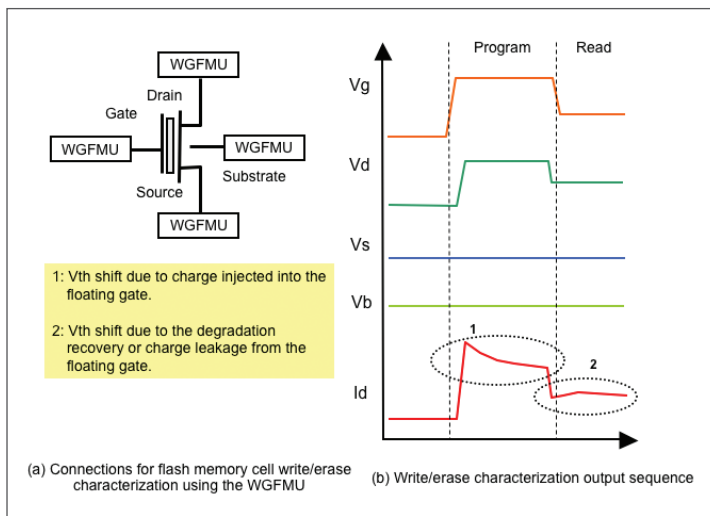


Figure 19. Dynamic Vth shift during and after flash memory programming

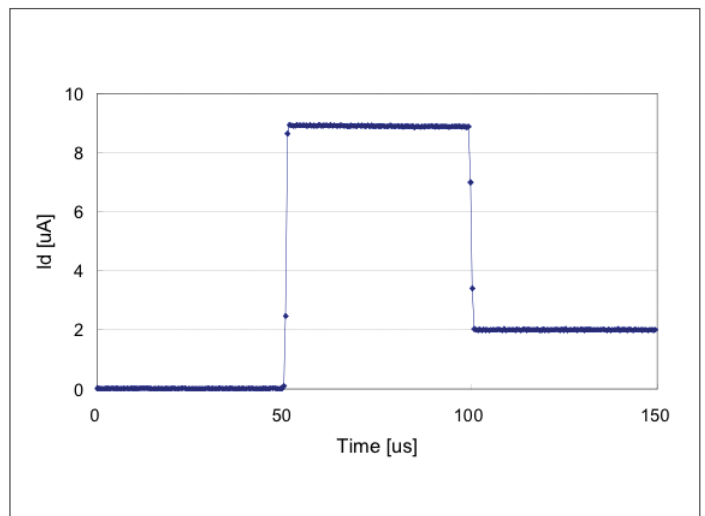


Figure 20. Example of  $I_d$  measurement with 500 ns sampling rate performed using the WGFMU

## Step response measurement (continued)

The current when applying a step voltage to a time varying capacitance is described by the equation shown below:

Equation 7

$$I_C(t) = \frac{dQ(t)}{dt} = \frac{dC(t)}{dt} \times \Delta V$$

Here  $I_C$  is the current flowing into the capacitor. From Equation 7,  $C(t)$  can be calculated using the following equation:

Equation 8

$$C(t) = \int_0^t I_C(t) dt / \Delta V$$

The WGFMU can measure current with a 5 ns sampling interval and it can return the measured current's averaged value. This capability allows us to replace the integral in Equation 8 with a summation approximation created by multiplying the sampled current with the sampling interval as shown below:

Equation 9

$$C(t) = \sum_{n=1}^{n=N} (I_{cn} \times \Delta t) / \Delta V$$

Here  $t$  is the period of integration,  $N$  is the total number of samples taken during this period,  $I_{cn}$  is the current measured in interval “ $n$ ” and  $\Delta t$  is the sampling interval. For optimum accuracy, the sampling interval should be the same as the averaging time to avoid any measurement current discontinuities.

For this type of measurement it is also important to choose the appropriate current range, sampling rate, averaging time and step voltage rise time, which need to be selected based on the capacitor and its response time.

Figure 21 shows  $C$ - $t$  measurement results for a capacitor with both fast and slow components.

The fast component can be simulated by a single capacitor ( $C_p$ ) and the slow component can be simulated as the series combination of a capacitor ( $C_s$ ) and a resistor ( $R_s$ ).  $C_p$  is approximately 104 pF,  $C_s$  is 100 pF and  $R_s$  is 1 M $\Omega$ . This makes the time constant of slow component about 10  $\mu$ s.

The amplitude of the applied step voltage ( $V_{step}$ ) is 50 mV and the rise time of its edge ( $T_{edge}$ ) is 1  $\mu$ s. This allows us to estimate the maximum current charging  $C_p$  at about 5  $\mu$ A. In this case the current measurement range is 10  $\mu$ A, the sampling interval is 100 ns and the averaging time is the same as the sampling interval.

Figure 21b shows that  $C_p$  dominates the initial portion of the step response and that subsequently the response is determined by the parallel combination of  $C_p + C_s$  with the expected time constant of 10  $\mu$ s.

The ability of the WGFMU module to accurately measure an extremely fast step response enables you to gain information not accessible using conventional LCR meters employing the auto balancing bridge measurement technique.

## Step response measurement (continued)

There are several factors that need to be considered to achieve accurate C-t measurement.

At the step edge the displacement current charging the capacitor is determined by the following equation:

Equation 10

$$I_c = C \frac{V_{step}}{T_{edge}}$$

Here  $V_{step}$  is the amplitude of the step voltage and  $T_{edge}$  is the duration of the rising edge. For the measurement to work this current has to be less than the measurement range used.

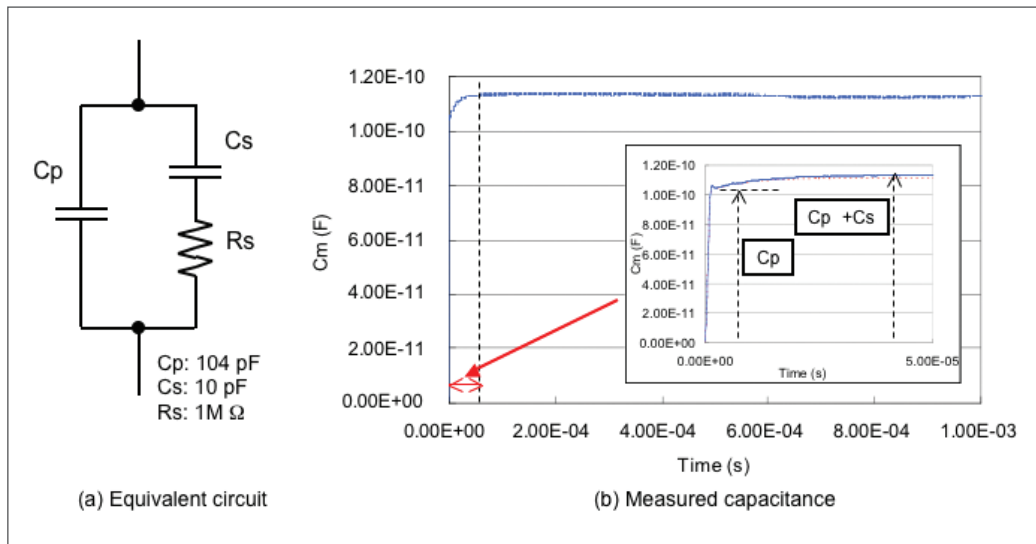


Figure 21. C-t measurement results for a capacitor with both fast and slow components

The bandwidth of the current measurement as shown in Table 4 determines the response time of the WGF MU. For example, the 10  $\mu$ A range has a bandwidth of 600 kHz. Combining this with delay time Equations 2 and 3 yields a timing resolution of approximately 4  $\mu$ s as shown below:

Equation 11

$$\sqrt{\left(\frac{0.35}{600 \text{ kHz}}\right)^2 + (4 \mu\text{s})^2} = 4.042 \mu\text{s}$$

If the device can withstand a larger step voltage, then a faster response time could be achieved by using a higher current measurement range.

## Step response measurement (continued)

In addition, for accurate measurement the instrument offset current component of the measured current has to be taken into account. Figure 22 shows an example of offset current measured by the WGFMU at 10  $\mu\text{A}$  range.

In this example, the measured offset current and variation are well within the specifications. Since charge is calculated by integrating the measured current, drifts in the value of the measured current are critical for long duration measurements. Taking the offset current into account, the current measured by the WGFMU can be expressed by the equation shown below:

Equation 12

$$\text{Error} = \frac{I_{\text{offset}} \times t}{V_{\text{step}}}$$

Here  $I_{\text{meas}}$  is the total current measured by the WGFMU,  $I_c$  is the current actually flowing into the capacitor and  $I_{\text{offset}}$  is the instrument offset current (i.e. current not actually flowing into the capacitor). Since on average  $I_{\text{offset}}$  can be approximated as a constant, the error in the calculated capacitance due to offset current is given by the equation shown below:

Equation 13

$$I_{\text{meas}} = I_c + I_{\text{offset}}$$

Here  $t$  is the time from the start of measurement. It is important to remember that the capacitance measurement error is not related to the size of capacitor being measured. This means that proper offset cancellation becomes critical when measuring relatively small values of capacitance.

For example, suppose we are measuring a 100 pF capacitor using a 100 mV step voltage. In this case the error caused by the 1 nA offset current equals 10% of the measured value when we are 1 ms away from the rising step edge.

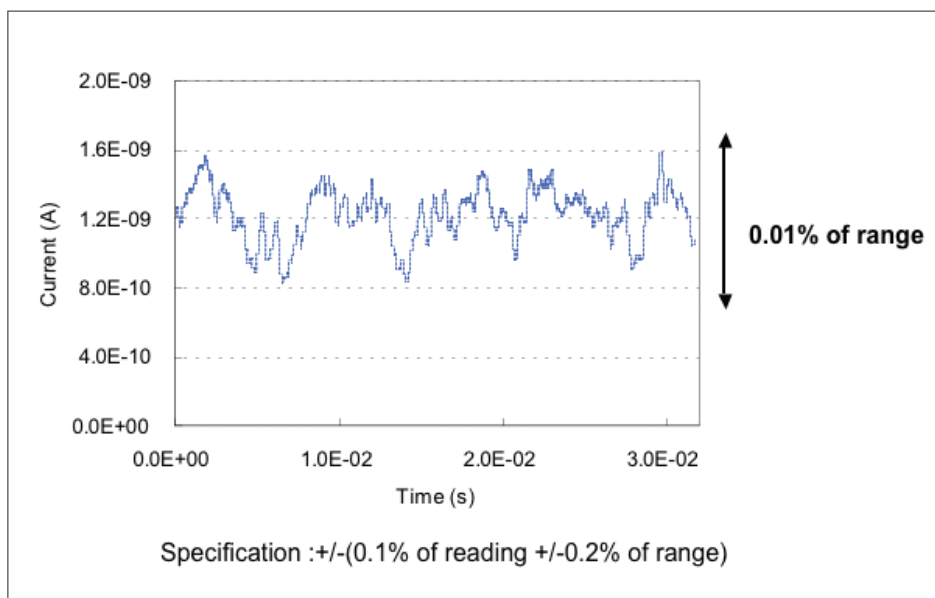


Figure 22. Offset current data for the 10  $\mu\text{A}$  range showing measurement variation

## Step response measurement (continued)

Figure 23 shows the measurement sequence necessary for capacitance measurement with offset cancellation.

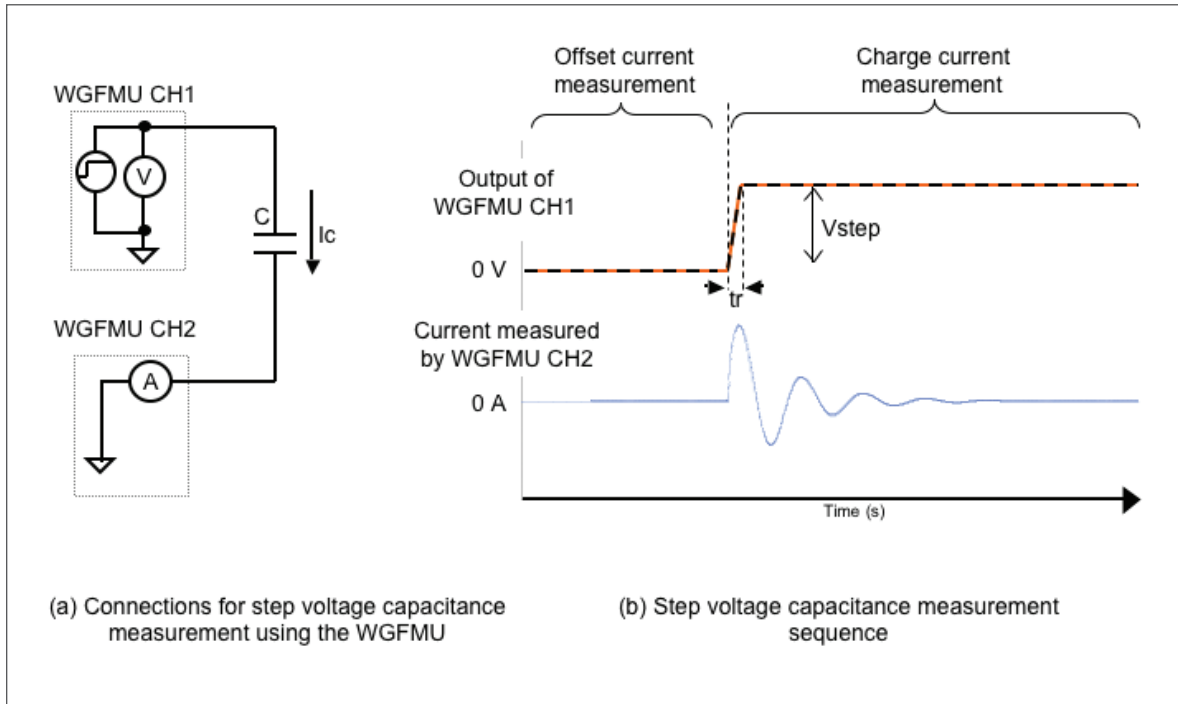


Figure 23. Step voltage capacitance measurement sequence with offset cancellation

The instrument offset current is measured at 0 V immediately prior to the charge measurement to eliminate error due to offset current drift. The charge injected by the step voltage is described by the equation shown below:

Equation 14

$$Q = \sum (I_c + I_{\text{offset}}) \times \Delta t = C \times V_{\text{step}} + \sum I_{\text{offset}} \times \Delta t$$

Here  $I_c$  is the current needed to charge the capacitor at the step, and  $\Delta t$  is the sampling interval.

By using the offset current ( $I_{\text{offset}}$ ) previously measured using Equation 12, the capacitance can be calculated using the following equation:

Equation 15

$$C = \frac{Q - I_{\text{offset}} \times t}{V_{\text{step}}}$$

In this case, the measured capacitance is stable until 1 ms even though the offset current was about 1.2 nA (less than 0.1 % of full scale range). This demonstrates that offset cancellation works. In the case of a long term measurement, the offset current drifts (please see Figure 22). This means that the fast C-t measurement technique using the WGFMU is suitable for measuring the fast response of capacitors in less than a few milliseconds.



## Step response measurement (continued)

Since  $I_{\text{offset}}$  is a constant, the influence of this error becomes smaller when measuring larger capacitances because  $Q$  in Equation 15 becomes larger. Also, if the device under test can withstand larger step voltages then the error on the measured capacitance is reduced relative to the increased step voltage.

## Ramp response measurement

Applying a ramp voltage to measure current is a well-known technique to measure displacement current. For capacitive loads the displacement current flowing through the load is described by the familiar equation shown below:

Equation 16

$$I_c = C \frac{dV}{dt}$$

Here  $I_c$  is current flowing into the capacitor,  $C$  is the capacitance and  $dv/dt$  is the ramp rate (v/s). A constant ramp rate implies a constant value for  $dv/dt$ . This means that the measured current will become constant after a transition period determined by the time constant of load.

The WGFMU can force a ramp voltage with a constant ramp rate even if the impedance of the load fluctuates (as in the case of the WGFMU's fast I/V mode). The WGFMU can also measure current during the ramp, so it can be used for capacitance measurements with varied biases such as CV measurements of MOS capacitors (please see Figure 24).

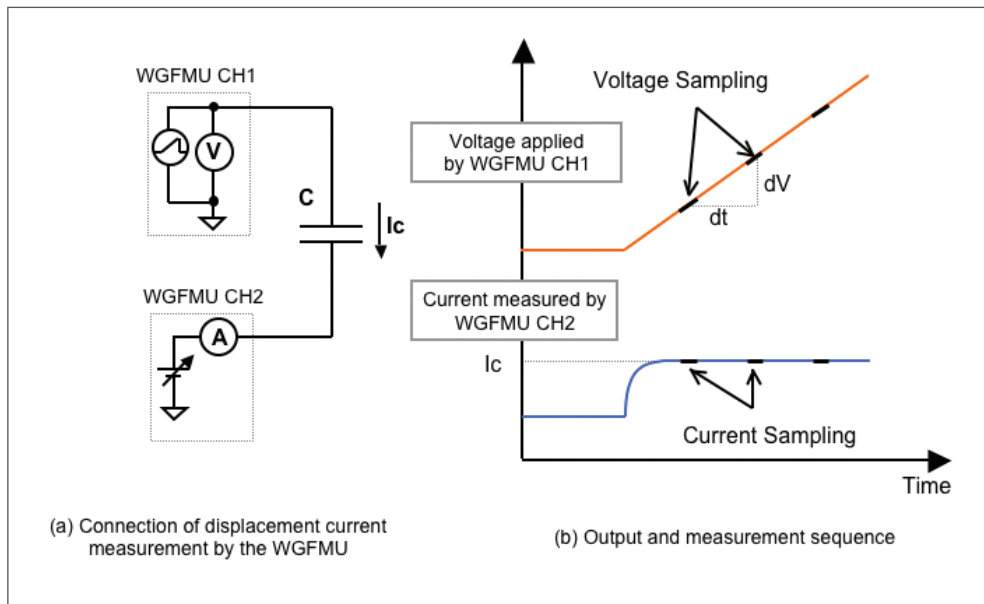


Figure 24. Measuring capacitance using a ramp voltage

Since the WGFMU's measurement speed is very fast, it is easy to capture a CV curve in a very short time period using the single ramp sweep measurement technique.

## Ramp response measurement (continued)

Figure 25 shows a measurement sequence for performing ramp sweep measurement.

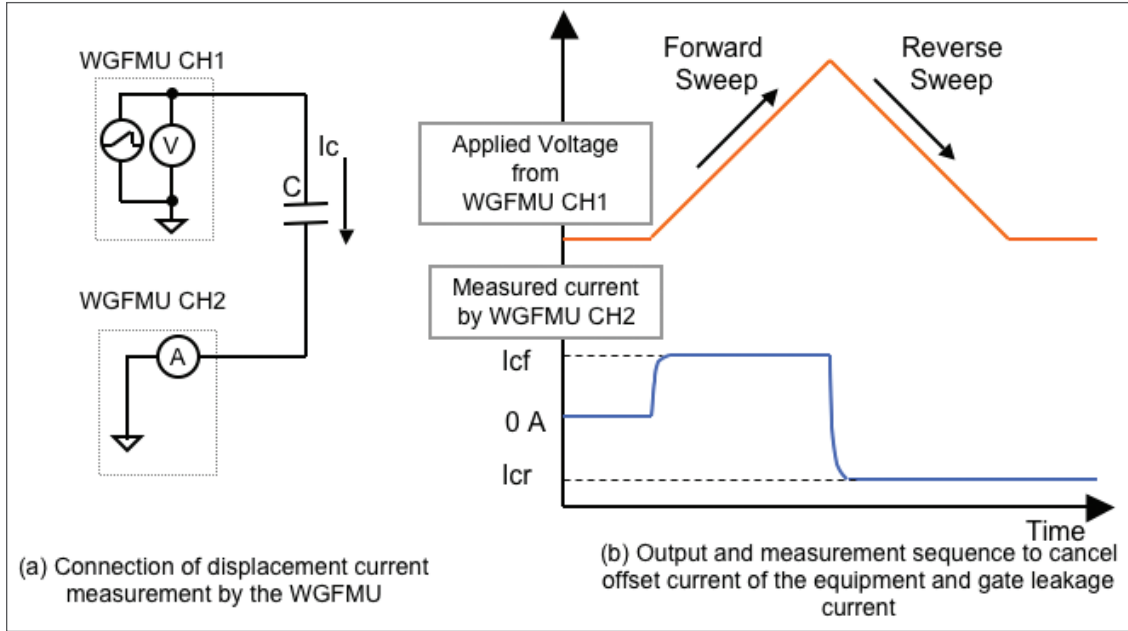


Figure 25. Fast CV measurement sequence example

The value of the capacitor is 100 pF. The voltage is swept from 0 V to +4 V with 1,000 steps. The measurement current range is 10  $\mu$ A, and the measurement interval and averaging times are both set at 10  $\mu$ s. The ramp rate is 400 V/s and the measured current is about 40 nA. To eliminate drift due to the offset and gate leakage currents, the capacitance is calculated by subtracting the current at reverse sweep from the current at forward sweep as shown below:

Equation 17

$$C = \frac{(I_{cf} - I_{cr})}{2} \frac{dV}{dt}$$

Equation 18

$$I_{cf} = C \frac{dV}{dt} + I_{offset} + I_{leak}(V)$$

Equation 19

$$I_{cr} = -C \frac{dV}{dt} + I_{offset} + I_{leak}(V)$$

Here  $I_{cf}$  is the current measured during the forward sweep and  $I_{cr}$  is the current measured during the reverse sweep.  $I_{offset}$  is the offset current of the instrument.  $I_{leak}$  is the gate leakage current, which is assumed to be a function of the gate voltage. Figure 26(a) shows the results of the measurement.

Note that periodic spikes occur during the capacitance measurement. These spikes are caused by integrated non-linearity (INL) in the digital to analog converter (DAC) as shown as Figure 26(b). In the case of the WGFMU this INL is about 0.02% of the full scale, which is negligible for normal measurements. However, for displacement current measurements it causes a large error due to the fast ramp rates used when measurements have to occur in a very short period of time.

### Ramp response measurement (continued)

One method to eliminate these spikes is to attach a low pass filter to the output of the RSU. However, you can also remove these spikes digitally because the ramp rate error in the non-spiking portion is still less than 1%. The simplest procedure is to take the gradient (derivative) of the measured values to detect the peaks, and then remove them.

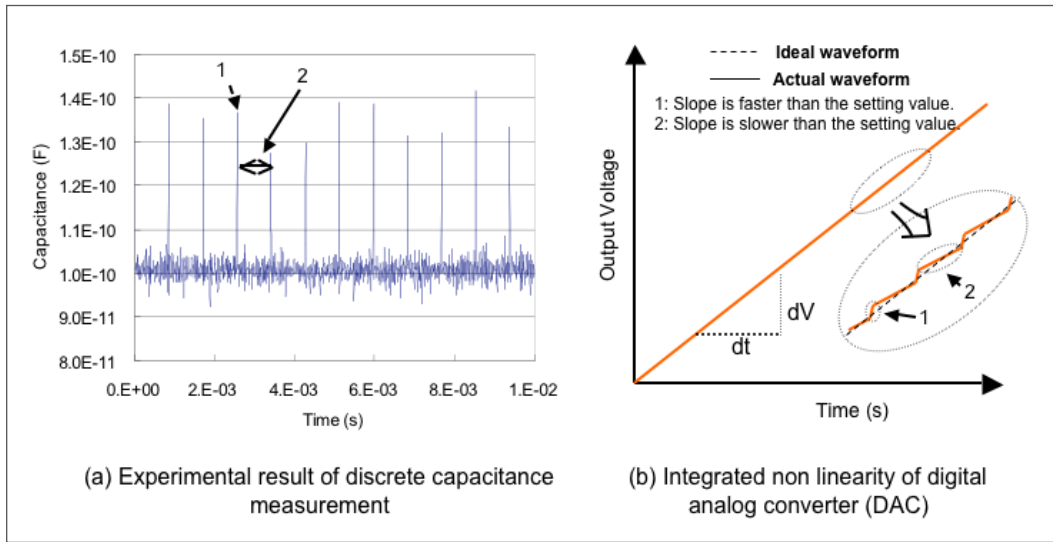


Figure 26. Integrated non linearity (INL) of DAC and its effect on the capacitance measurement

Figure 27 shows the experimental results of measuring a CV curve of a MOS FET.

In this example  $V_g$  is swept from -4 V to +4 V with 1,000 points. The measurement current range is 10  $\mu$ A, and the measurement interval and averaging times are both set at 10  $\mu$ s. This data shows that the WGFMU can measure an entire CV curve with 1,000 points in 10 ms, which is significantly faster than conventional LCR meters using conventional auto balancing bridge techniques.

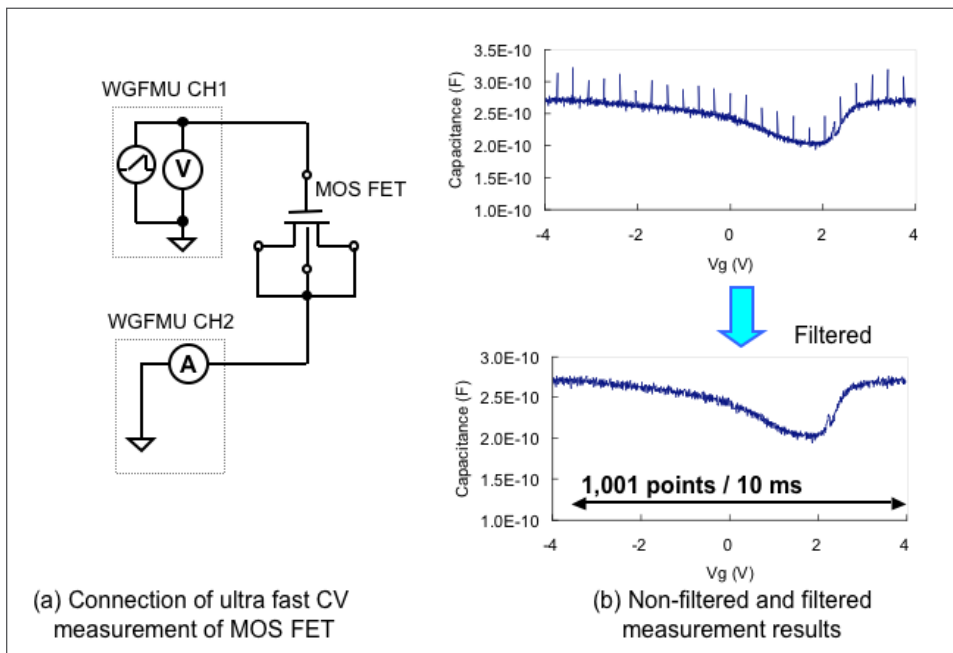


Figure 27. Using digital filtering to remove spikes on ultra fast CV measurements

### Ramp response measurement (continued)

Displacement current measurement can also be used to investigate the carrier generation mechanisms of organic filed effect transistors (OFETs). As shown in Figure 28, many researchers are investigating OTFT current generation processes by analyzing the forward sweep and reverse sweep displacement currents.

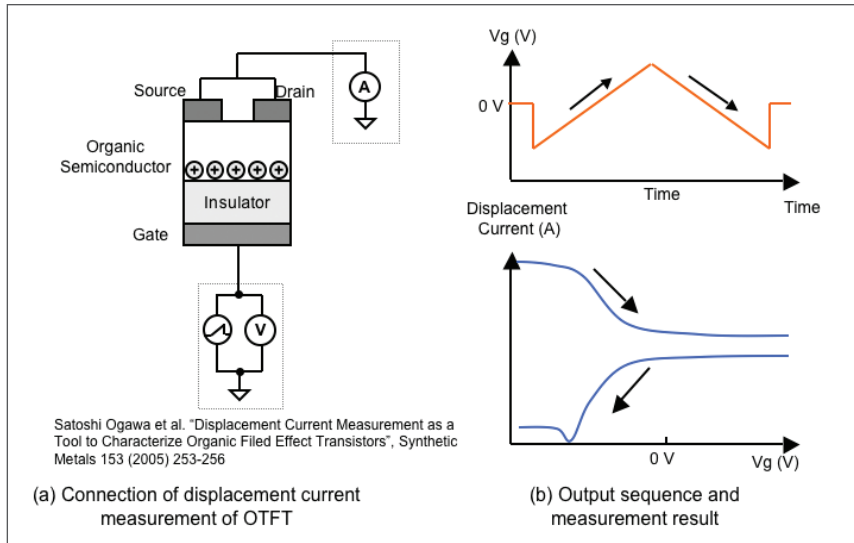


Figure 28. Organic transistor carrier generation mechanisms evaluated using displacement current mechanisms

### High speed, precision and long term current sampling measurement

The WGFMU can store about 400 million points of measured data per channel in addition to the fast and precision measurement capability. It extends a usage of the WGFMU to observation of small and fast phenomenon occurring over the long term like a random noise measurement and progressive transition measurement.

### Random telegraph noise (RTN) measurement

The twin factors of aggressive logic device scaling and lower the operating voltages reduce operating margins and increase the impact of noise-related errors. Starting at the 22 nm technology node, random telegraph noise (RTN) is being studied as a serious bottleneck for device functionality. RTN has the greatest impact on static random access memory (SRAM). In addition to its obvious presence in memory ICs, SRAM circuits are also a key component of many logic device such as central processor units (CPUs). SRAM cells exist in either a state of "0" or "1", and if the SRAM cell does not have sufficient noise margin then RTN can cause random state changes as shown in Figure 29.

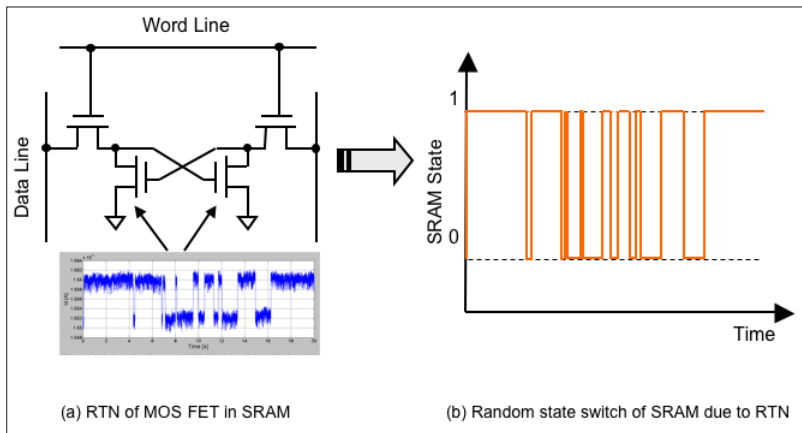


Figure 29. Random SRAM state change caused by RTN

## Random telegraph noise (RTN) measurement (continued)

Also, in CMOS image sensors (also known as active pixel sensors) RTN can generate erroneous white spots in what should otherwise be dark areas. As feature sizes continue to decrease, the impact of RTN on the circuits used to read out pixel data has become more serious (please see Figure 30).

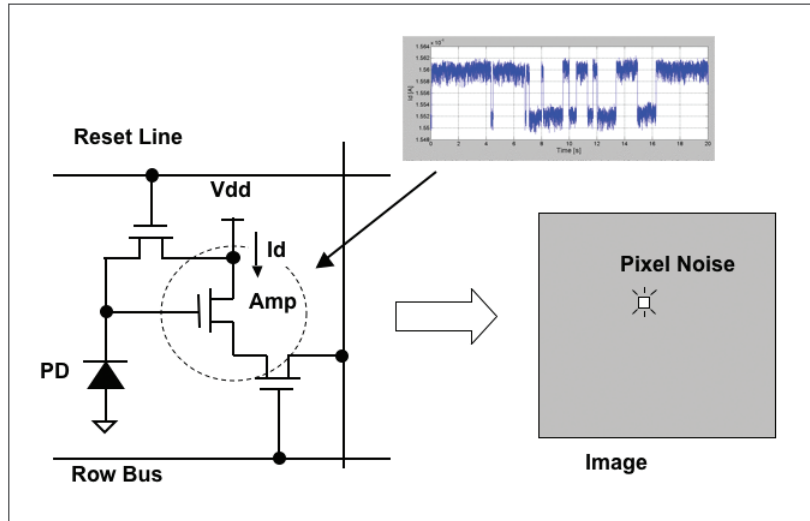


Figure 30. Random CMOS image sensor pixel noise caused by RTN

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 megahertz.

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 31 shows the noise floor for the B1500A WGFMU module's current measurement ranges; obviously, a measurement range with sufficient noise floor has to be selected to make the measurement possible.

Note: This data is part of the WGFMU's supplemental characteristics and it is not a guaranteed module specification.

## Random telegraph noise (RTN) measurement (continued)

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 substrate and source pads to the shield of the signal lines going to the gate and drain.

### – Sampling rate

The measurement current noise can be reduced by measurement averaging. An example showing the use of averaging to reduce this noise is shown back in Figure 6. 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.

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.

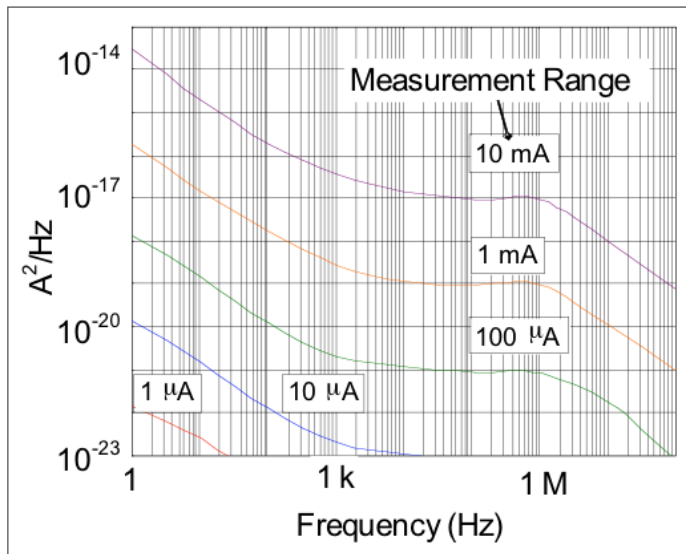


Figure 31. Current measurement noise floor

### – Current measurement bandwidth

The bandwidth of the current measurement determines the maximum frequency range of RTN that can be measured. (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.

## – Measurement conditions

Since the boundary traps that are capturing electrons (or holes) 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 MOS FET gate and drain.

Figure 32 shows examples of the RTN with different applied gate voltages.

The above example is an NMOS FET with dimensions of  $0.44\text{ }\mu\text{m}$  (W) by  $0.24\text{ }\mu\text{m}$  (L) and an oxide thickness of  $4\text{ nm}$ . 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.

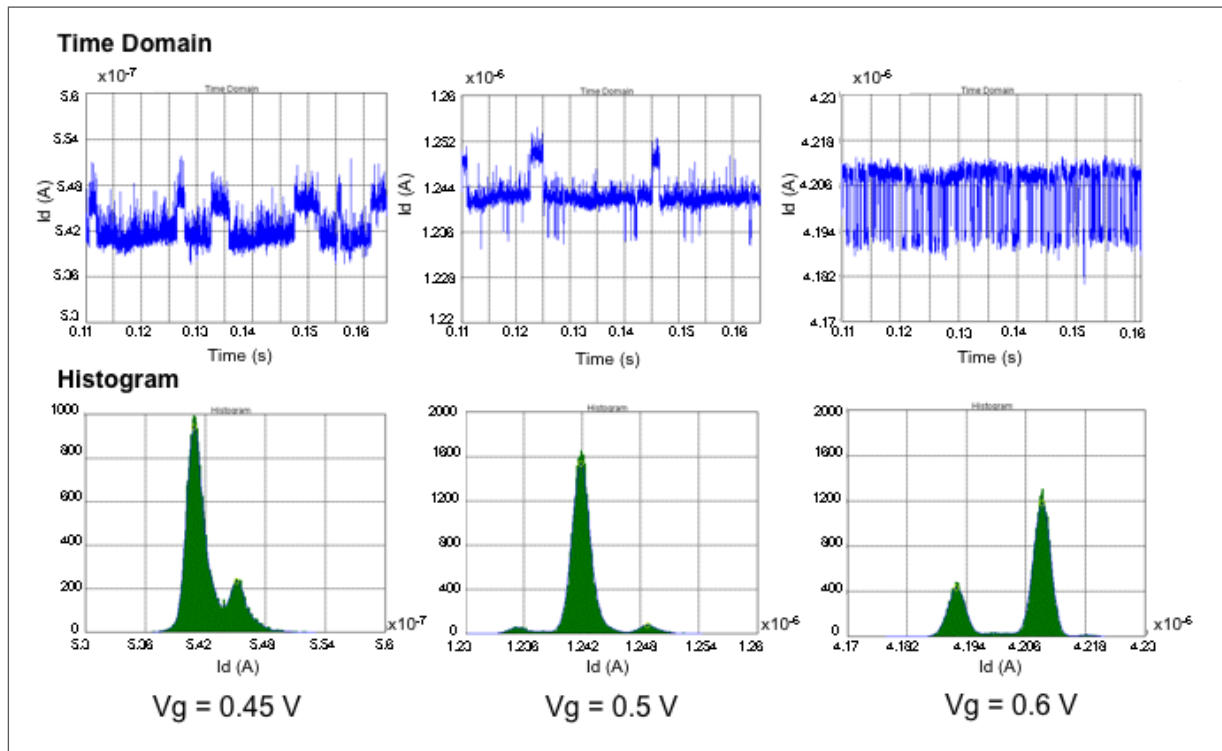


Figure 32. RTN measured under various bias conditions

RTN is also observed on nanoscale devices like a single-walled carbon nanotube transistors (CNTs) or nanowire transistors (NWTs) fabricated on insulator substrates. Since the size of the nanotube is extremely narrow, the threshold voltage is strongly impacted by trapped carriers caused by insulator defects. Also, the threshold voltage can be shifted if molecules attach themselves to the tube (please see Figure 33). These unique characteristics have generated a lot of interest in CNTs and NWTs for use as biochemical sensors.

## Random telegraph noise (RTN) measurement (continued)

Sample RTN analysis software is supplied with the WGFMU module so that the user can start RTN analysis immediately. Figure 34 shows some examples of the data analysis capabilities supported by this tool.

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

- Histograms of the RTN level
- Visualized time domain data and digitized data
- Visualized time constants of electrons (or holes) capture and emission calculated from the digitized waveforms and their ratio
- Power spectrum distribution

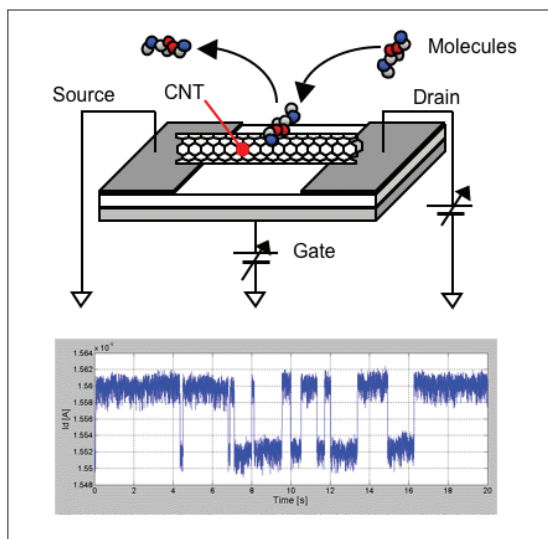


Figure 33. RTN caused by the molecules attaching to the single-walled CNT

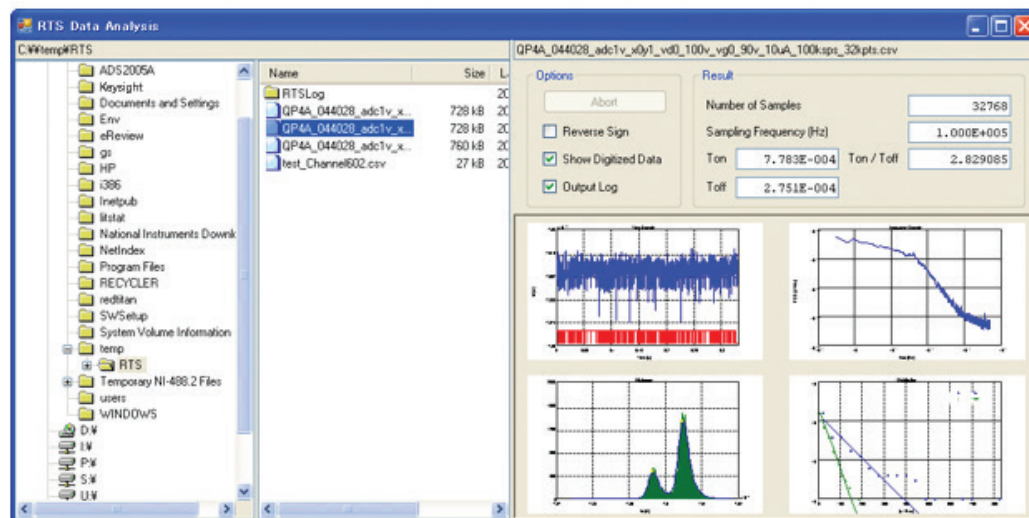


Figure 34. Examples of the RTN data analysis tool's capabilities



## Progressive transition measurement

The WGFMU's high-speed current sampling measurement capabilities and its deep measurement memory can also be used to measure time dependent, transition phenomena like progressive gate or interlayer dielectrics breakdown. During time dependent dielectric breakdown (TDDB) measurements, small current peaks have been observed just before the large current of final (hard) breakdown. This phenomenon is known as “progressive breakdown” and it reflects mechanisms and process that are precursors to the final breakdown.

At the beginning of breakdown, carriers jump into the states nearest to the dielectric defects and then jump into adjacent defects. This is known as “hopping conduction”. As time progresses the current path eventually reaches the opposite electrode. Once a small current path is established between the electrodes, larger currents start to flow until the dielectric breaks down completely (please see Figure 35).

Similar electron/hole hopping conduction is observed in quantum dot arrays fabricated in dielectrics.

The WGFMU's high-speed current sampling capability allows you to observe this kind of transition in real time, which helps in the understanding of the physics of these devices.

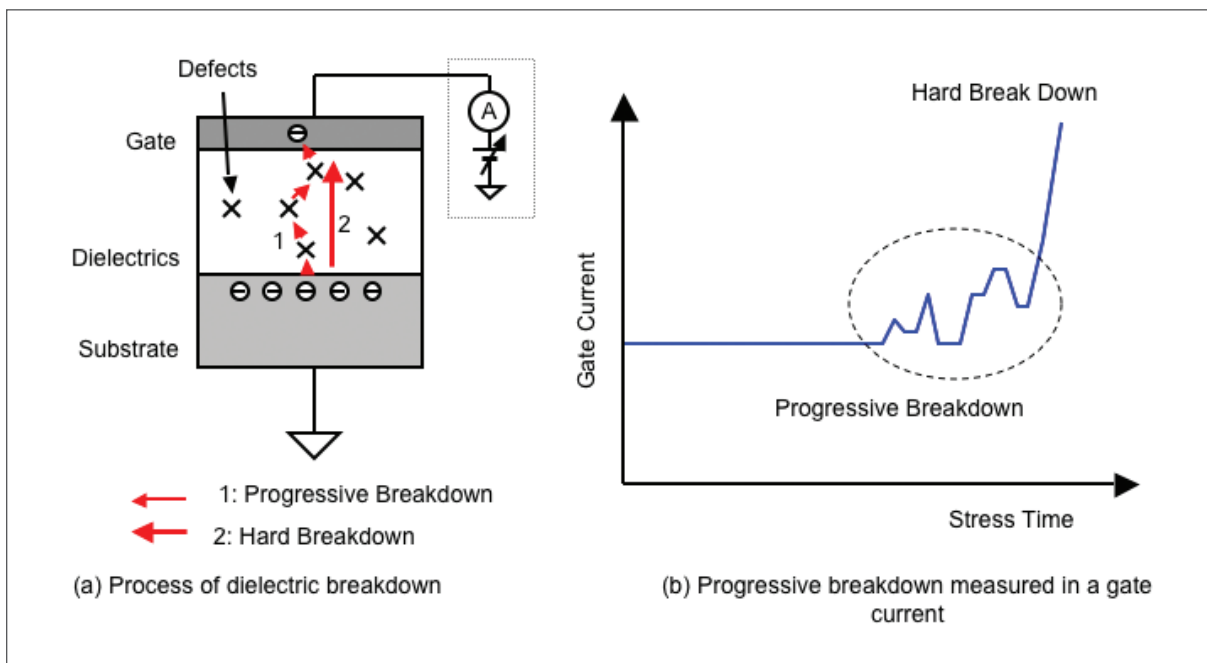


Figure 35. Measurement of the progressive breakdown of a dielectric

## Multiple measurement sequences

The WGF MU's ALWG function can output a combination of long term and short term stimuli by utilizing its wide timing resolution range (from 10 ns to 10,000 s) and its sequence memory capability. These features can be used for reliability testing where IV characteristics are measured after repeated applications of bias stress. This is often known as stress-measure-stress (S-M-S) testing. An S-M-S test sequence is used in several kinds of reliability testing, such as negative bias temperature instability (NBTI) and positive bias temperature instability (PBTI) tests, hot carrier injection (HCI) tests and Time Dependent Dielectric Breakdown (TDDB) tests.

A major challenge facing NBTI and PBTI testing is the dynamic recovery effect, meaning that the device under test can recover from its stressed condition. If this occurs before a characterization measurement can be completed then the data obtained is of no use in predicting device reliability. In some cases the measurement after stress has to be made in one microsecond or less.

The WGF MU's fast measurement capabilities make it an ideal tool for this purpose.

The WGF MU's ALWG and fast I/V measurement functions allow it to create almost any kind of measurement sequence; this includes fast Id measurements, fast sweep measurements, fast ramp sweep measurements and pulsed IV measurements. The WGF MU can also create S-M-S sequences with any combination of these measurements. Figure 36 shows some examples of the S-M-S sequences that the WGF MU can provide.

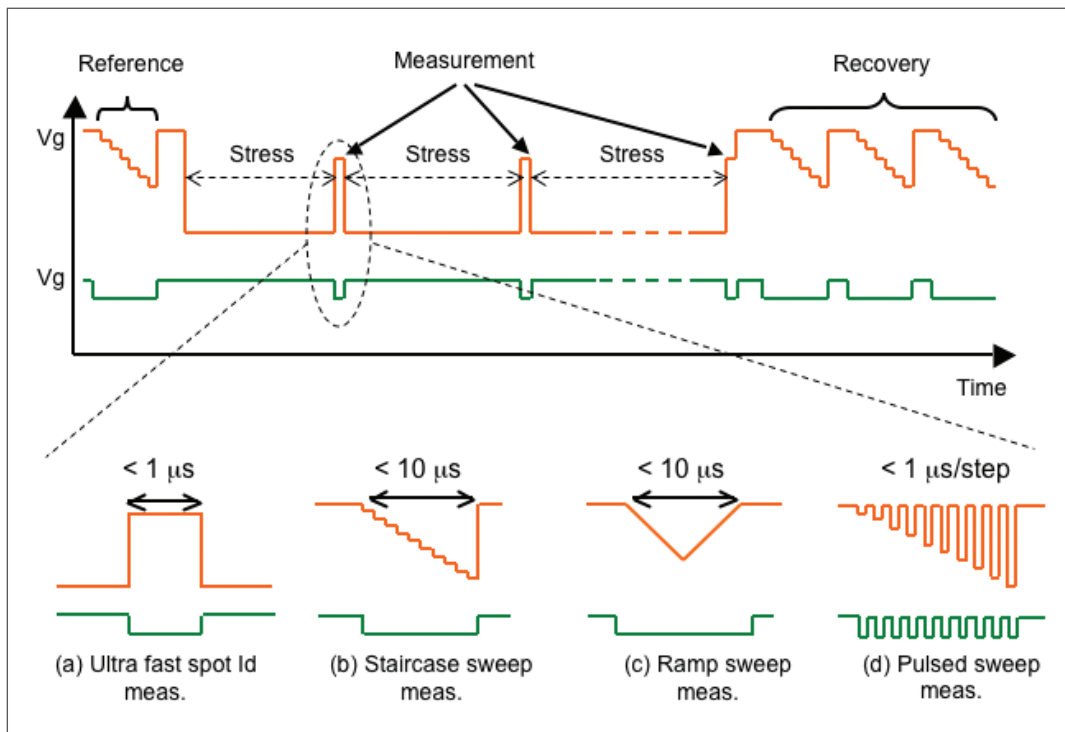


Figure 36. The WGF MU can produce a wide variety of NBTI/PBTI test sequences

## Multiple measurement sequences (continued)

In addition to how quickly the measurement can be made after stress removal, there is another important factor that has a serious impact on device lifetime estimates. NBTI testing performed with a pure DC stress gives device lifetime estimates that are much lower than those performed with AC stresses. However, AC stress is a more accurate representation of the stress that devices will actually experience under real-world conditions. This means that NBTI testing performed with only DC stressing gives overly pessimistic estimates of device lifetimes, and that designing to this criteria will cause the process to be over-engineered with an associated negative impact on profitability. Figure 37 compares the experimental results for a drain current degradation measurement under conditions of both DC stress and AC stress.

These results show that lifetime estimates based on AC stress measurement results are much longer than those based on simple DC stress. One additional benefit of the WGFMU when applying an AC stress is that the frequency of the AC pulse can be increased to 1 MHz at a 50% duty cycle without any noticeable overshoot.

To build an NBTI system that can apply AC stress using conventional components, a rack & stack system composed of pulse generator units (PGUs), source monitor units (SMUs) and a switch unit to switch between stress and measurement are required (please see Figure 38).

This solution has the following serious issues:

- Unstable switching times vary the delay times between stress and measurement.
- Unexpected glitches generated by the switches can impact the degradation or recovery.

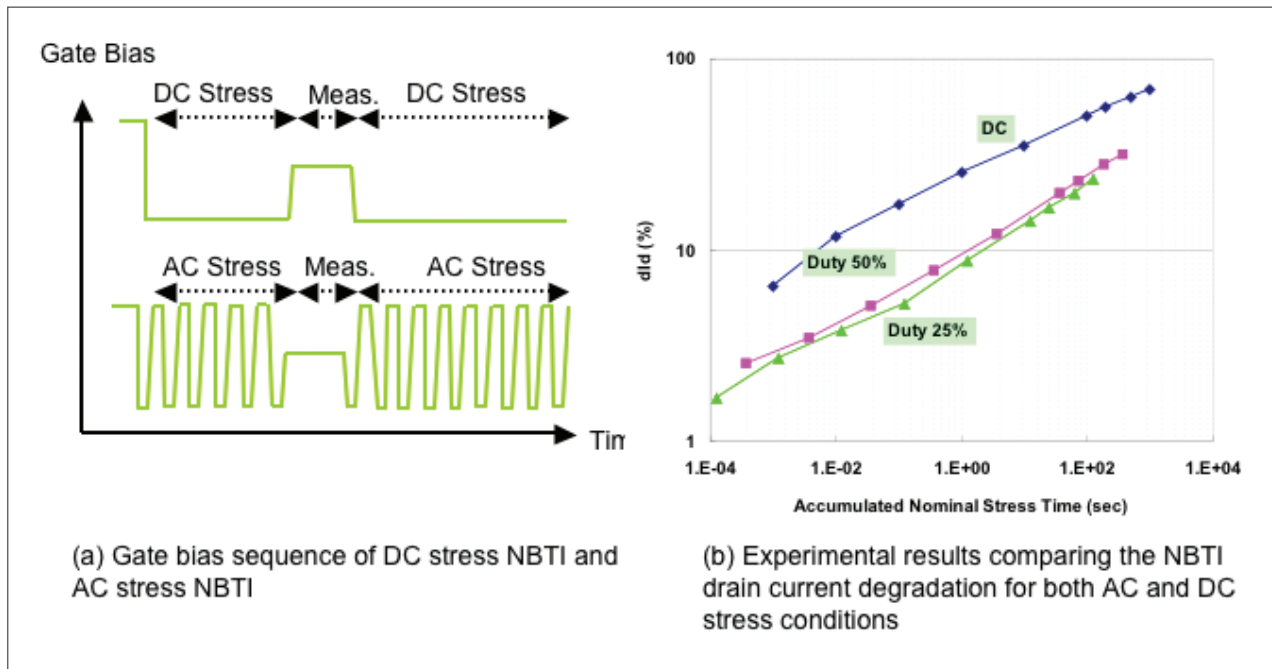


Figure 37. A comparison of DC and AC NBTI stress measurements show that AC stressing is necessary to estimate device lifetimes under practical operating conditions

## Multiple measurement sequences (continued)

The WGFMU not only solves both of these concerns but also simplifies the cabling connections. The WGFMU provides a consistent and constant delay between stress and measurement, as well as glitch free operation. It allows you to investigate variations in device life time estimates as a function of stress bias shape, which is a capability that cannot be duplicated using conventional rack & stack systems.

Similarly, the WGFMU can be used to create S-M-S sequences for reliability tests such as hot carrier injection (HCI), and for TDDDB tests for magneto tunneling junction (MTJ) devices like MRAM employing the test sequence shown in Figure 39.

For more details on NBTI testing using the WGFMU, please refer to application note B1500-10, “Ultra-Fast 1  $\mu$ s NBTI Characterization Using the Keysight B1500A’s WGFMU Module” (P/N 5989-9963EN).

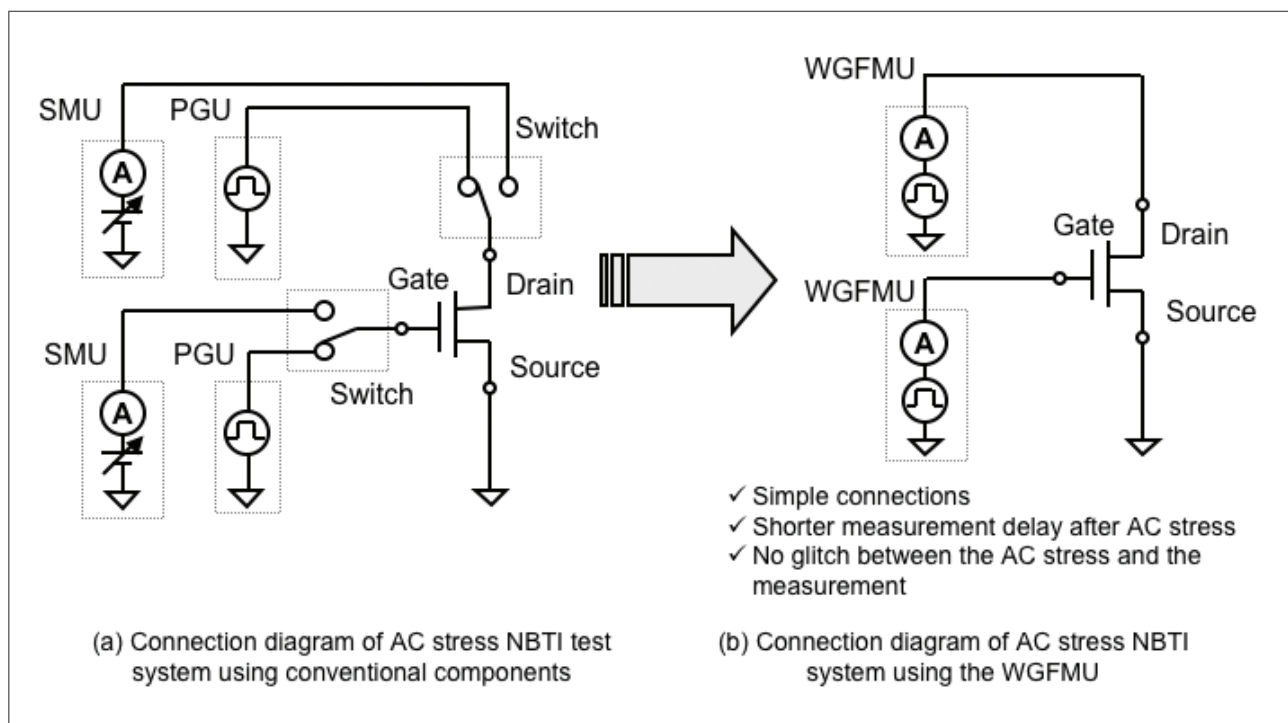


Figure 38. The WGFMU provides a simple NBTI AC stress test solution

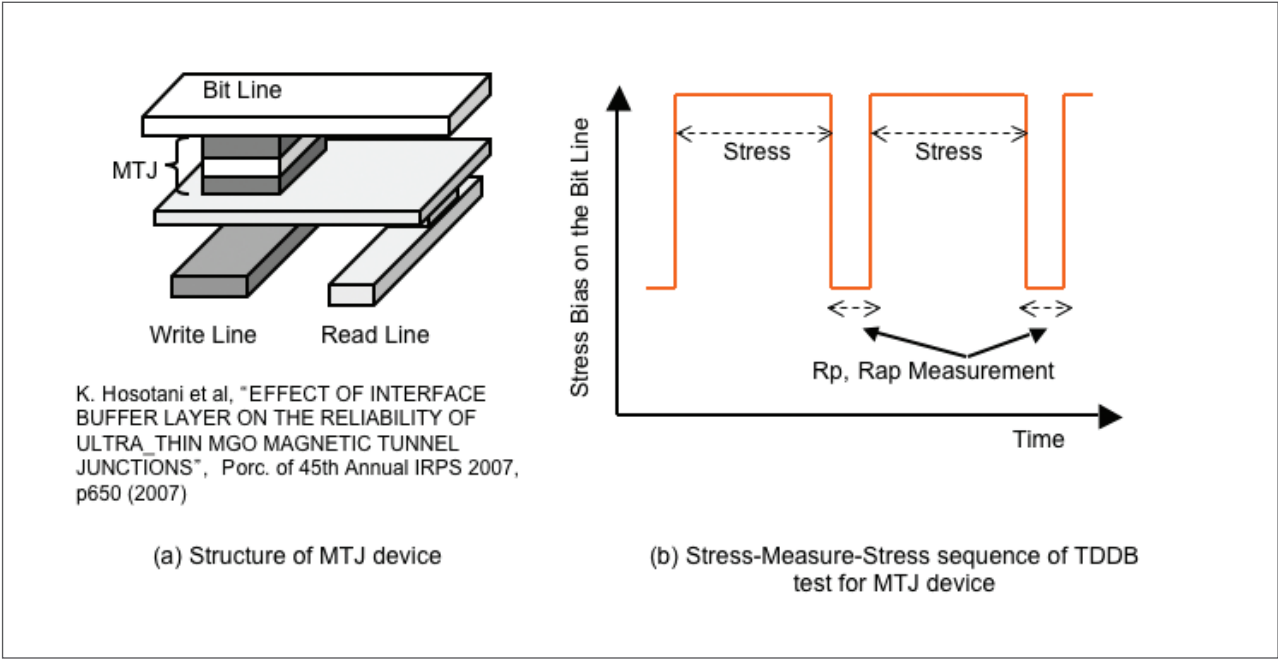


Figure 39. TDDb Stress-Measure-Stress Sequence test for Magneto Tunneling Junction

## Conclusion

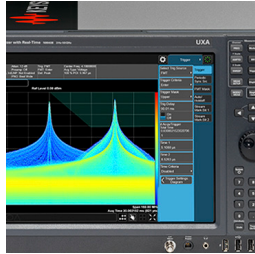
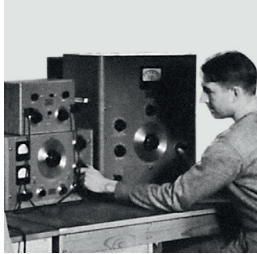
In this product note the key features of the B1500A WGFMU module have been explained. The WGFMU can be used for a wide variety of measurement applications due to its unique combination of pulsed and arbitrary waveform generation functions and high speed current/voltage measurement capabilities. A number of practical measurement examples utilizing these features have been discussed. The WGFMU is a self-contained, off-the-shelf measurement solution providing accurate and repeatable analysis capabilities that can be used to evaluate state-of-the-art devices constructed from the most advanced materials.

The Keysight B1500A semiconductor device analyzer uses the same precision SMU technology as its predecessor, the Keysight 4155/56 series semiconductor parameter analyzer. However, SMUs are not fast enough to meet the needs of many modern devices and process technologies. The B1500A WGFMU module is available to cover the measurement areas that SMUs cannot, permitting the B1500A to become the next de facto industry standard tool for semiconductor parametric test.

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Accelerate Technology Adoption.  
Lower costs.

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Formerly known as Product Note B1500A-1

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