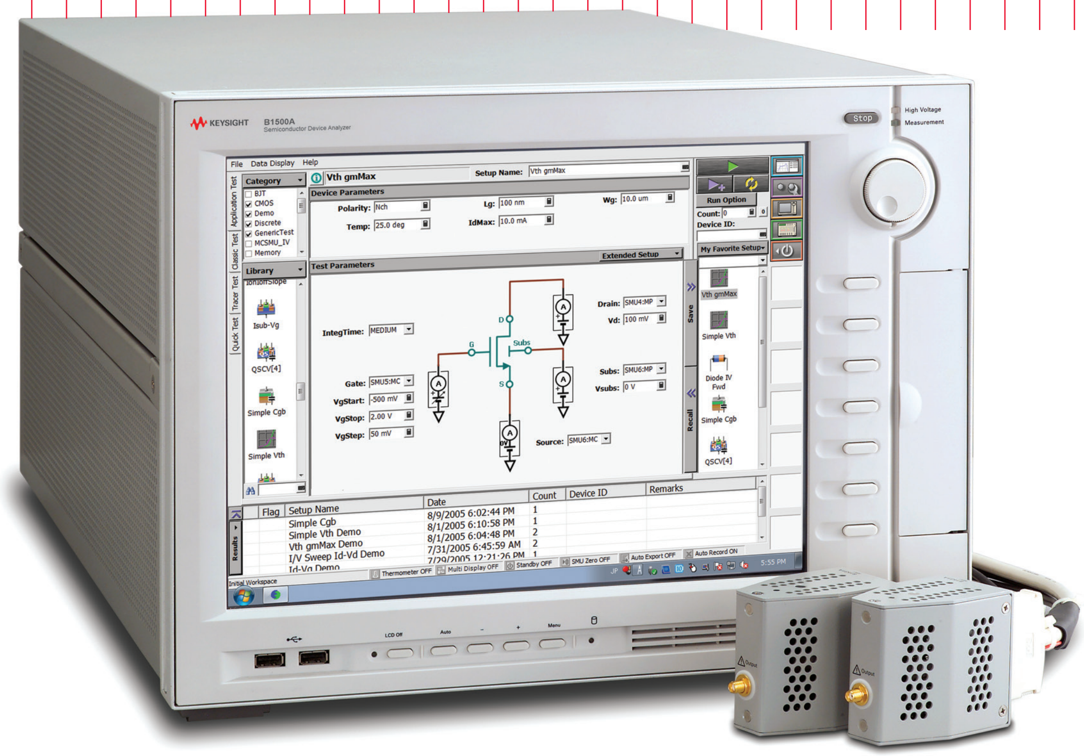
Keysight Technologies
B1500A Semiconductor Device Analyzer
Ultra-Fast 1 µs NBTI Characterization Using the B1500A’s WGFMU Module

Application Note



Introduction

Reducing the time required to characterize the reliability of new process technologies continues to become more and more important. The use of new materials such as high-k gate dielectrics coupled with the push for ever-smaller device geometries make achieving this goal more difficult, since they present new reliability challenges that did not exist a few years ago. In particular, negative bias temperature instability (NBTI) and positive bias temperature instability (PBTI) induced threshold voltage (Vth) degradation in MOSFETs under high gate bias and high temperature is an area of critical concern for advanced semiconductor processes. Many NBTI studies have shown that measured Vth degradation is strongly dependent upon how the test is performed (such as the type of stress applied to the gate or the elapsed time between removal of the stress and the Vth measurement). This makes it important for any NBTI measurement hardware to be able generate various types of AC stress (in addition to DC stress) and for it to be able to make measurements within 1 μs after removal of the stress (to avoid dynamic recovery effects).

To achieve more accurate and realistic data there is also a strong desire to measure the Vth using an Id-Vg sweep rather than through a series of drain current (Id) sampling measurements at a single gate bias voltage. The characterization of dynamic NBTI recovery effects after stress removal requires that a series of sampling measurements from sub-microseconds to one thousand seconds or more be taken at logarithmically spaced intervals, for both Id spot and Id-Vg sweep measurements. In addition, extracting accurate lifetime estimates from measured Vth and Id shifts after a short stress period (~1000 seconds) requires a low measurement noise floor. These are challenging requirements, but the Keysight Technologies, Inc. B1500A Semiconductor Device Analyzer's new waveform generator/fast measurement unit (WGFMU) module can meet all of these needs in a straightforward fashion. This application note will show how the B1500A's WGFMU can provide solutions that meet the needs of ultra-fast NBTI measurement.

Basic NBTI Testing Issues

What is NBTI degradation?

Vth and Id degradation due to NBTI is a well-known phenomenon that was first observed in the early 1990's in PMOS FETs; however, the exact physical mechanism behind this behavior is still being debated to this day. Figure 1 gives a brief overview of NBTI degradation. When the gate voltage is negatively biased with respect to the drain, source and substrate for a period of time (as shown in Figure 1a), the FET characteristics will change (as shown in Figure 1b). As can be seen, the gate threshold voltage (Vth) increases and the drain current (Id) decreases (as compared to before the stress was applied). Experimental data also shows that NBTI degradation gets worse at higher temperatures and thinner gate oxides, which means that advanced semiconductor processes are strongly impacted by this phenomenon. Thus, obtaining an accurate estimate of the effect of NBTI on device lifetimes is essential to insure that they meet their reliability criteria.

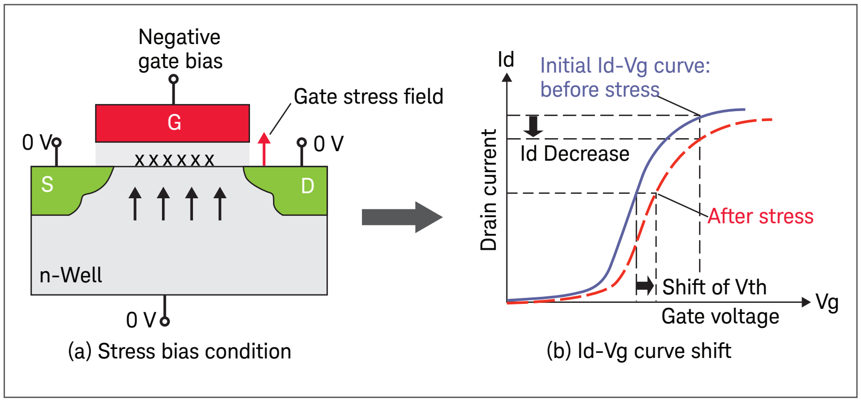


Figure 1. NBTI degradation in PMOS FETs.

NBTI test issues

As previously mentioned, there is no firm consensus among researchers as to the exact physical cause or causes of NBTI degradation. Prudence dictates that IC process engineers allow for some extra NBTI reliability margin to prevent premature device failure due to uncertainty in the physical device model. There is widespread agreement that NBTI degradation consists of two components: a permanent degradation component (although this also does show some slow recovery) and a recoverable degradation component that exhibits very fast dynamic recovery. These two NBTI components are shown in Figure 2 as dotted lines, with the sum of these two effects shown as a solid line that represents the net NBTI measurement result. To predict accurate device lifetimes, the best procedure is to extrapolate the permanent degradation component out to the desired stress time. However, this requires a lot of stress time and (as can be seen from Figure 2) the measured NBTI degradation curve and permanent NBTI degradation line coincide when extrapolated to large stress times.

Dynamic recovery

It is not desirable or realistic to perform long device stresses, but the NBTI dynamic recovery effect makes it difficult to extrapolate device lifetimes from the NBTI degradation measured after relatively short stress periods. The thick and thin dotted lines labeled "Dynamic recovery component" in Figure 2 show that different plots are obtained for the dynamic component depending upon the time between the release of the gate stress and the measurement of Vth or Id. The thick dotted line represents data taken with a short delay between stress release and measure, whereas the thin dotted line represents data taken with a long delay between stress release and measure.

Dynamic recovery (continued)

Figure 3 shows some sample NBTI dynamic recovery data that illustrates how the stress time duration, the amount of dynamic recovery and the stress recovery time constant all

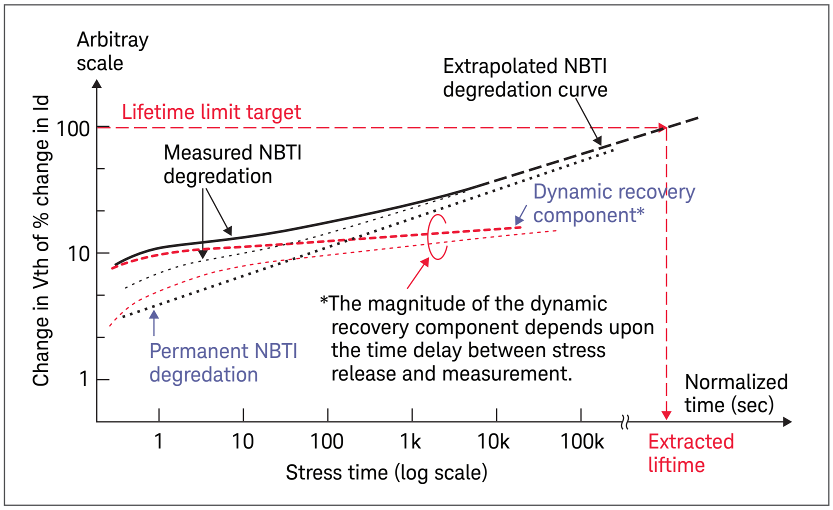


Figure 2. NBTI degradation components and the interaction of dynamic recovery effects and measurement delay.

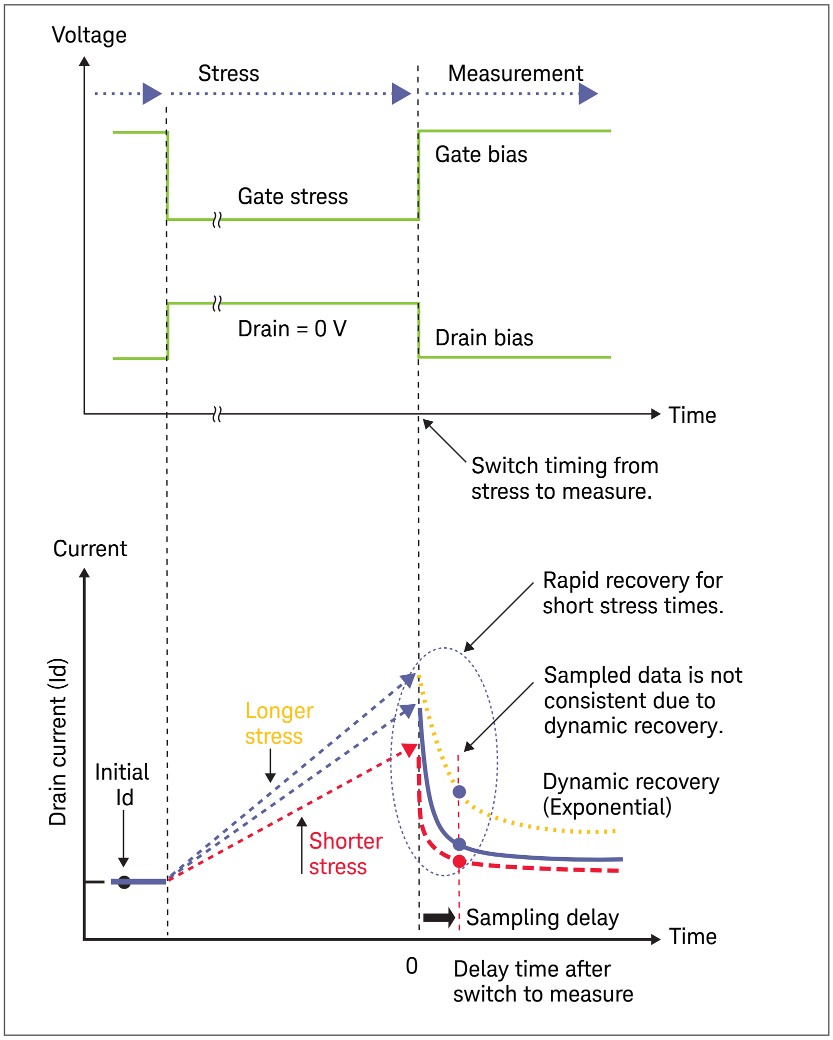


Figure 3. Sample NBTI data showing the dynamic recovery effect.

Dynamic recovery (continued)

interact with one another. Although this is just one example, it does show the difficulties with getting consistent and repeatable NBTI measurement data using different test parameters on different test systems being operated by different users. Therefore, it is critical to reduce the time delay from stress removal to parameter measurement as much as possible to minimize the dynamic recovery effects.

Lifetime extraction in AC operating condition

In addition to the aforementioned issues, there is another important factor that can have 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 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.

NBTI Test Requirements and B1500A's WGFMU Solution

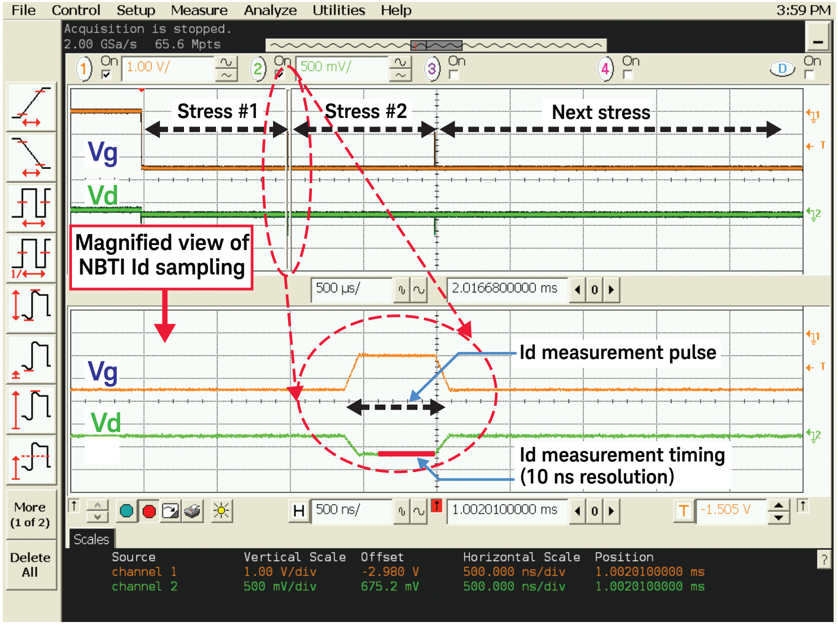
There are following general requirements when performing the NBTI test;

- Fast measurement
  - Id sampling within 1 µs
  - Id-Vg sweeps at 1 µs per point for Vth determination
- Low noise Id measurement*
  - A noise level equivalent to 0.1 mV rms (Vth resolution)
  - Less than 1 nA effective resolution in the 1 µA current measurement range
- Wide time sampling range for dynamic recovery analysis
  - Sampling from sub-microseconds to one-thousand seconds (log sampling interval)
- AC pulsed stress with fast sampling test

*Note: These noise levels assume an appropriate integration time.

Ultra-fast NBTI Id sampling test

Figure 4 shows that the WGFMU module can perform the sub-microamp level Id sampling measurements required for ultra-fast NBTI testing. The upper portion of the oscilloscope trace shows the entire stress/Id measurement/stress cycle. The lower portion of the oscilloscope trace shows a magnified view of the Id measurement. All waveform timings can be specified with 10 ns resolution, including the pulse rise and fall times, the drain pulse delay relative to the gate pulse and the timing of the Id sampling relative to the gate pulse. To support the analysis of dynamic recovery effects, Id can be sampled with linear or log intervals. The gate bias voltage can return to its stress value immediately after completion of the Id measurement.



```
Acquisition is stopped.
2.00 GSa/s   65.6 Mpts
```

```
Source       Vertical Scale  Offset     Horizontal Scale  Position
channel 1    1.00 V/div      -2.980 V   500.000 ns/div    1.0020100000 ms
channel 2    500 mV/div      675.2 mV   500.000 ns/div    1.0020100000 ms
```

Figure 4. Ultra-fast NBTI Id sampling test waveform.

Ultra-fast NBTI Id-Vg sweep test

Sampling Id at a single gate bias is the best way to minimize NBTI data distortions due to dynamic recovery effects; however, it is not possible to directly extract Vth from this measurement. By sweeping Vg it is possible to extract the Vth directly from the Id-Vg plot. Figure 5 shows sample Id-Vg sweep data taken using the WGFMU where Vg is increased by a constant step value under two different conditions: 1 µs and 100 µs step times. The two measurements overlap perfectly, which verifies that the 1 µs Vg-Id sweep measurement gives the correct result when used for ultra-fast NBTI characterization. This approach is

Ultra-fast NBTI Id-Vg sweep test (continued)

valid for all of the WGFMU's current measurement ranges (1 µA to 10 mA) as long as an appropriate integration time is used.

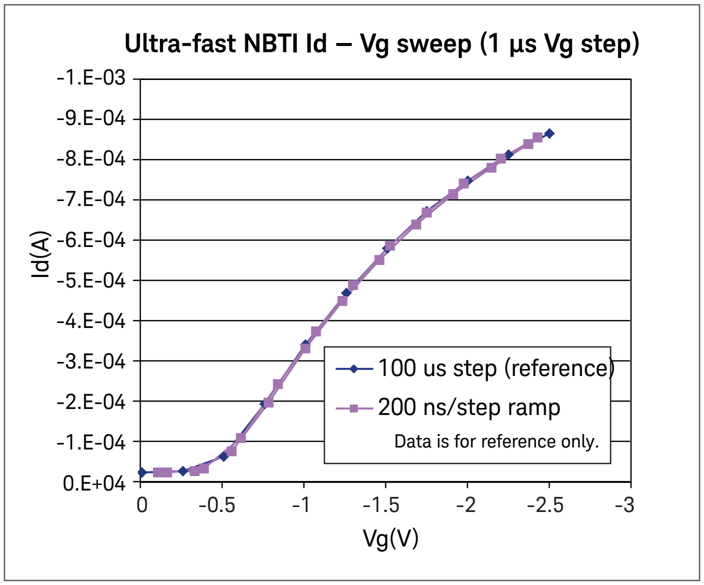
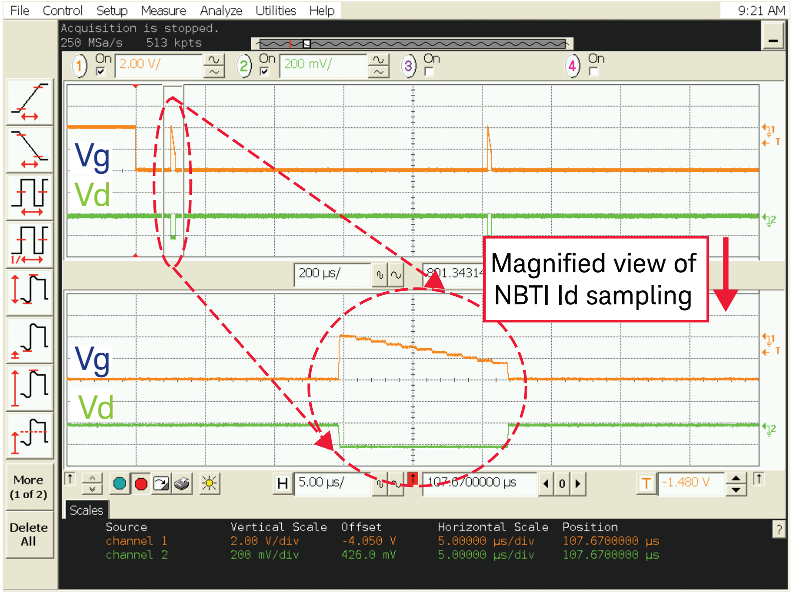


Figure 5. Ultra-fast NBTI Id-Vg sweep data for Vth extraction.

There are several options when performing Id-Vg sweep measurements depending on the user's preference. The most common approach is a basic staircase Vg sweep measurement as shown in Figure 6a. However, the WGFMU can also make sweep measurements while ramping the gate voltage (Vg). Figure 6b shows an example of a ramped gate double sweep measurement where Vg and Id are measured with the exact same timing as in the staircase Vg sweep case, and they produce the same IV curve measurement result. This illustrates that the WGFMU is extremely flexible and that it is capable of meeting the most demanding needs of ultra-fast NBTI characterization.

Figure 7 shows an example of NBTI characterization using the WGFMU's ultra-fast NBTI Id-Vg sweep capability. Figure 7a shows a series of Id-Vg sweep measurements taken in the WGFMU's 10 µA measurement range. In the plot's legend the number following the letter "T" indicates the number of seconds of stress that precede the measurement. For example "T100" means that this Id-Vg sweep measurement was made after 100 seconds of stress time. Figure 7b shows a magnified view of the Id-Vg plots around the area where Id = 1 µA, so that the Vth at this point can be determined. The measurement time for each Vg point in the sweep was set at 2 µs, which is sufficient for the noise level (~1 nA rms) and allows each 71 point curve to be made in 140 µs. Figure 7c shows an NBTI lifetime analysis plot for the Vth extracted at Id = 1 µA using interpolation on the Id-Vg sweep data. The data is reasonable, and the R2 value of the trend line shows that the data is well-correlated and that the measurement data is accurate.

Ultra-fast NBTI Id-Vg sweep test (continued)



```
Acquisition is stopped.
250 MSa/s    513 kpts
```

Magnified view of NBTI Id sampling

```
Source         Vertical Scale  Offset     Horizontal Scale  Position
channel 1      2.00 V/div      -4.050 V   5.00000 µs/div    107.6700000 µs
channel 2      200 mV/div      426.0 mV   5.00000 µs/div    107.6700000 µs
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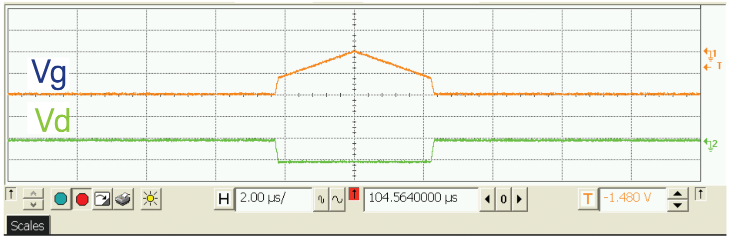
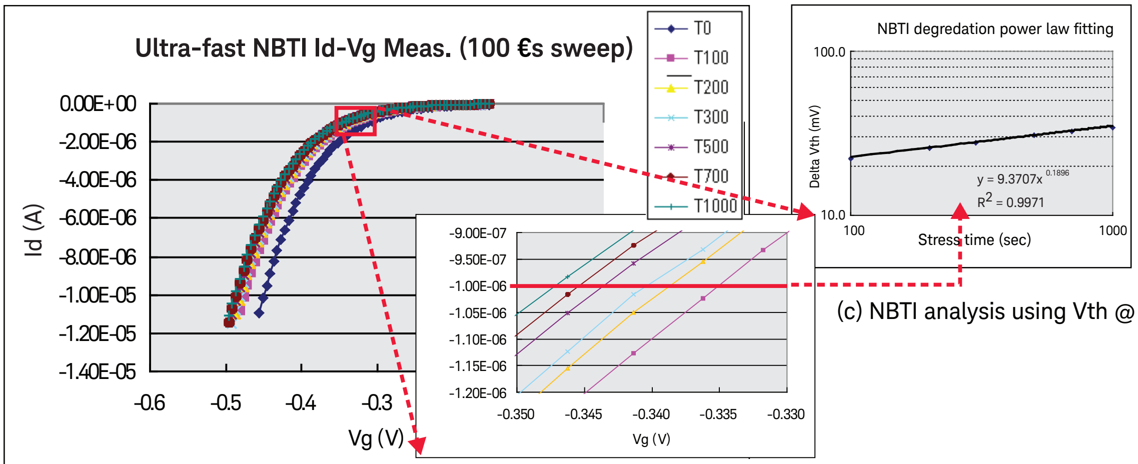
(a) Staircase Vg sweep IV measurement



(b) Example of double-ramp Vg sweep IV measurements

Figure 6. Measurement options for ultra-fast Vg sweep waveforms.



(c) NBTI analysis using Vth @ Id=1 µA.

(b) Magnified view around Id=1 µA.

(a) Id-Vg 100 µs sweep data at 100 ~ 1,000 sec stress time.

Figure 7. NBTI characterization example taken over 1,000 seconds of stress time using Id-Vg sweeps taken at 2 µs per point.

Low noise WGFMU performance in fast sampling

The extraction of NBTI lifetime data requires noise levels of 0.1% (rms) or less for Id measurements (relative to the measured Id value) and noise levels of 0.1 mV (rms) for Vth determination. However, these noise limits are not absolute but depend on several factors including the characteristics of the device itself and how long the NBTI stress was applied before measuring the NBTI degradation. Figure 8 shows an example of how the Vth measurement variation affects the NBTI lifetime estimation. In this plot the center line represents the ideal case of no Vth measurement noise, and the upper and lower lines show cases where 0.1 mV (rms) of noise (equivalent to ±0.3 mV peak-to-peak noise) has been added at a point between the 100 second and 1,000 second stress times. The NBTI degradation is then extrapolated from these three points. Of course this is an extreme example, but this graph does show how noise can have a large impact on the estimated NBTI lifetime. As a rule of thumb, 0.1 mV (rms) of noise in a Vth measurement is acceptable.

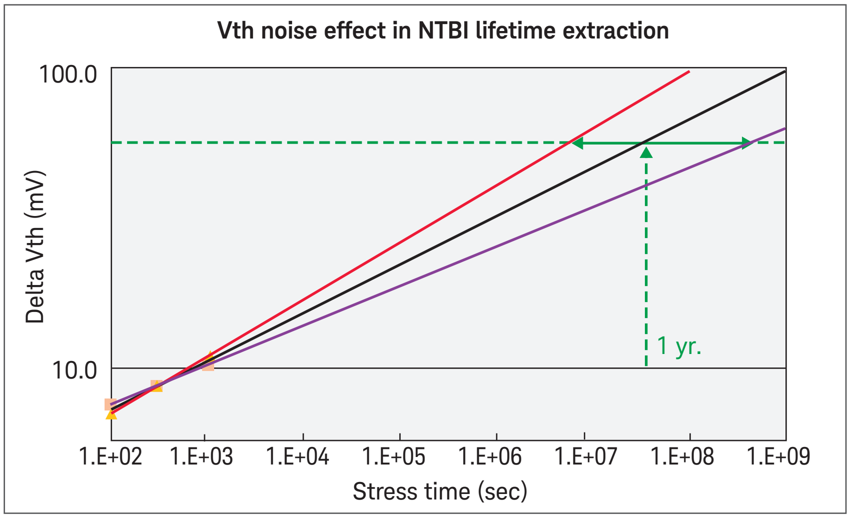


Figure 8. The effect of Vth noise on NBTI lifetime estimation.

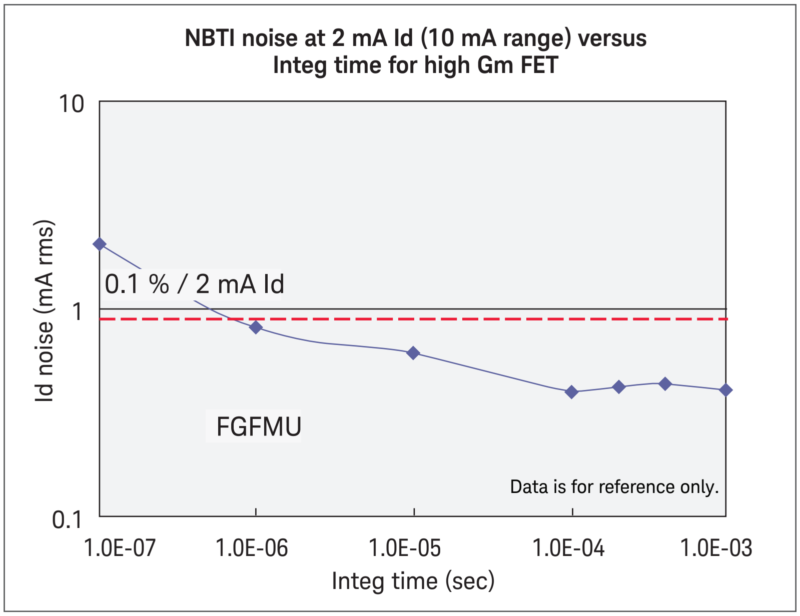


Figure 9. WGFMU NBTI Id measurement noise example for high-Gm FET.

Low noise WGFMU performance in fast sampling (continued)

Figure 9 shows a plot of Id noise for an NBTI measurement made on a high Gm FET using the WGFMU at different integration times. The 0.1% (rms) noise limit is shown in red for reference. Since the measured data is well below the 0.1% (rms) noise limit this shows that the WGFMU can make accurate NBTI measurements with very short integration times, which means that the sampling intervals can be short as well. This gives further confidence that the WGFMU can perform accurate NBTI characterization even using ultra-fast sampling intervals.

Figure 10 shows that the WGFMU exhibits very low noise even in the 1 µA current measurement range. The 1 µA range is frequently needed for Vth extraction in the sub-threshold region, and this plot indicates that good NBTI characterization is possible even when measuring currents at levels that are one tenth of this range (0.1 µA). These low noise levels at low current illustrate another advantage of using the WGFMU for NBTI characterization.

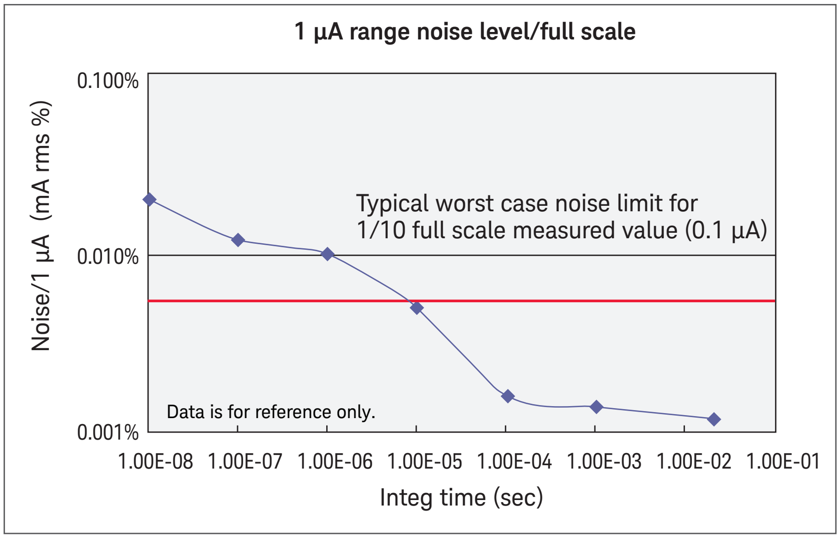


Figure 10. Example showing residual noise of the WGFMU in the 1 µA range.

Wide sampling range for dynamic recovery characterization

Understanding dynamic recovery is one of the most important topics in advanced NBTI characterization, requiring extensive Id sampling or Vth extractions. Fortunately, the WGFMU can meet this need by providing measurement sampling capability with linear intervals, logarithmic intervals or even an arbitrarily specified timing. Figure 11 shows sample NBTI data taken by measuring Id in log time (10 samples per decade) from 0.5 µs to 600 seconds on a PMOS FET at 125 degrees Celsius. This data clearly shows the dynamic recovery behavior of the MOSFET. This same approach can be used to extract the Vth by employing the ultra-fast Id-Vg sweep capability of the WGFMU. In addition, it is possible to perform this dynamic recovery measurement after the completion of the standard NBTI testing. This permits the evaluation of both NBTI degradation and dynamic recovery in a single stress test, which has obvious advantages in terms of cost and efficiency since both types of data can be obtained without having to perform the lengthy stress test twice.

Wide sampling range for dynamic recovery characterization (continued)

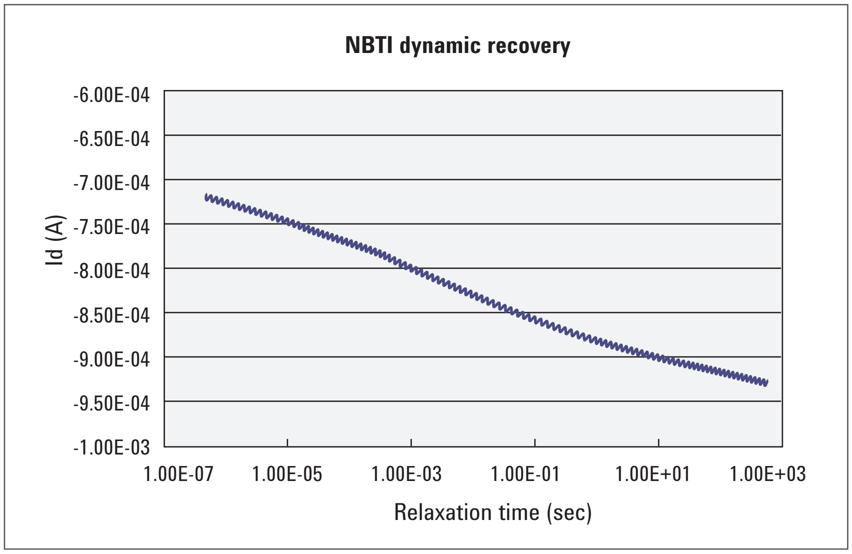


Figure 11. Id sampling dynamic recovery example from 0.5 µs to 600 seconds.

AC Stress for new process qualification

The type of stress applied during the stress phase strongly influences the magnitude of the NBTI degradation and, in-turn, the device lifetime estimates. Figure 12 shows sample DC and AC stresses applied during an NBTI test, where the AC stress is meant to simulate the stress experienced during typical IC operation. In this example a DC drain voltage stress is applied for both cases, although the WGFMU does permit the application of an AC stress to the drain as well.

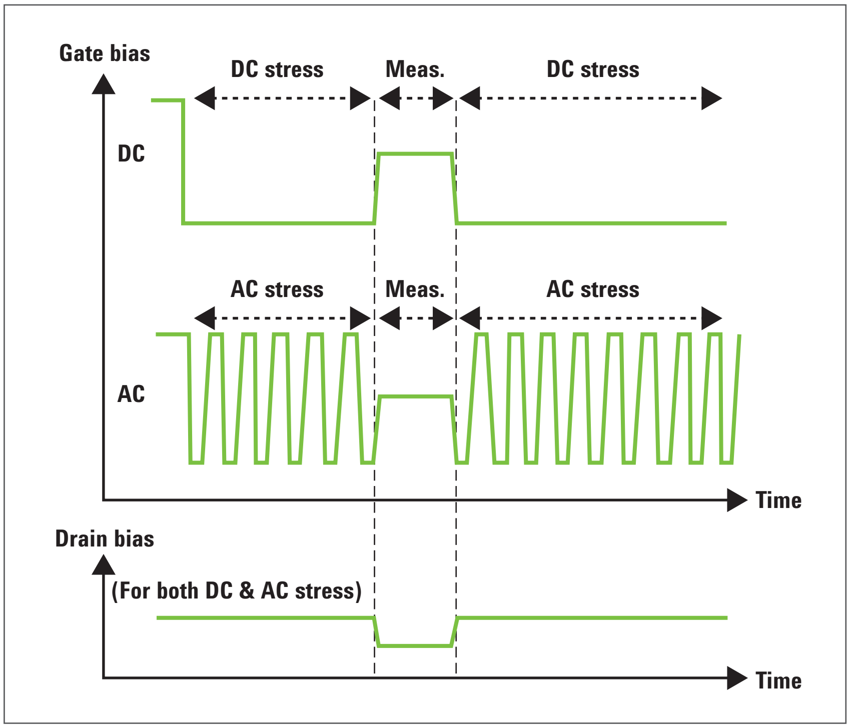


Figure 12. Examples of DC and AC NBTI stresses.

AC Stress for new process qualification (continued)

Figure 13 then shows the percent degradation in Id for both the DC and AC cases (the peak of the AC stress value is the same as the constant DC value). As this data shows, NBTI measurement requires the measurement of AC stress as well as DC stress, since purely DC stress gives an overly pessimistic view of device lifetimes and does not accurately reflect real world conditions. Previously it has been very difficult to obtain accurate AC stress data because of the complexity involved in switching an AC pulsing source at the gate with the DC bias source needed to make NBTI Id measurements using external instruments. Of course, the WGFMU can easily take care of this task through a simple programming procedure.

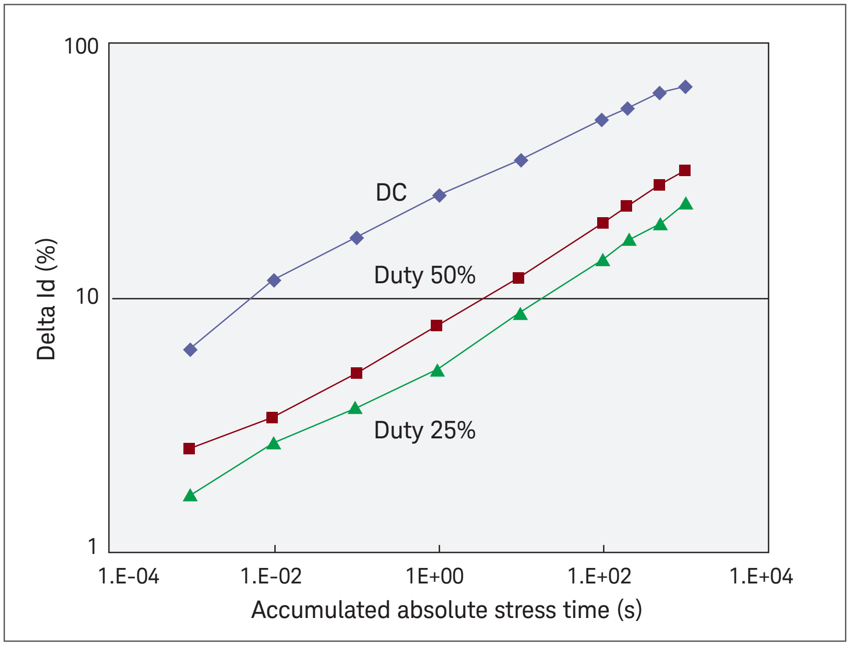
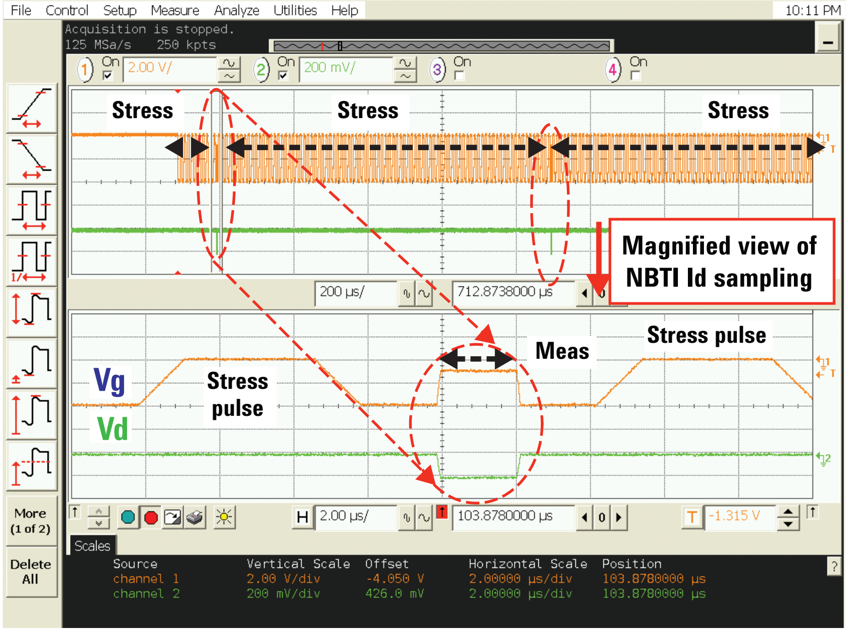


Figure 13. Example showing variations in NBTI degradation caused by DC and AC stress.

AC Stress for new process qualification (continued)

Figure 14 shows the oscilloscope capture of an AC NBTI waveform at 100 kHz and 50% duty cycle created using the WGFMU. It is clear that the waveform is glitch-free and does not exhibit any overshoot. The frequency of the AC pulse can be increased to 1 MHz at a 50% duty cycle without any noticeable overshoot.



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Acquisition is stopped.
125 MSa/s    250 kpts
```

```
Source        Vertical Scale  Offset      Horizontal Scale  Position
channel 1     2.00 V/div      -4.050 V    2.00000 µs/div    103.8780000 µs
channel 2     200 mV/div      426.0 mV    2.00000 µs/div    103.8780000 µs
```

Figure 14. AC stress waveform example (100 kHz, 50% duty cycle).

NBTI Software

There are two software options to control the B1500A's WGFMU module. The first option is EasyEXPERT application tests. The second option is furnished sample software that runs on an external Windows-based PC. The sample software can be used interactively or (with user-customization) as part of a larger system to perform parallel NBTI testing using multiple WGFMU modules or to perform automated testing by integrating the WGFMU control into an existing test system.

EasyEXPERT application test software

Figure 15 shows the four NBTI application tests that are furnished to control the WGFMU. These application tests cover the four basic combinations of DC and AC stress and fast Id sampling and fast Id-Vg sweep.

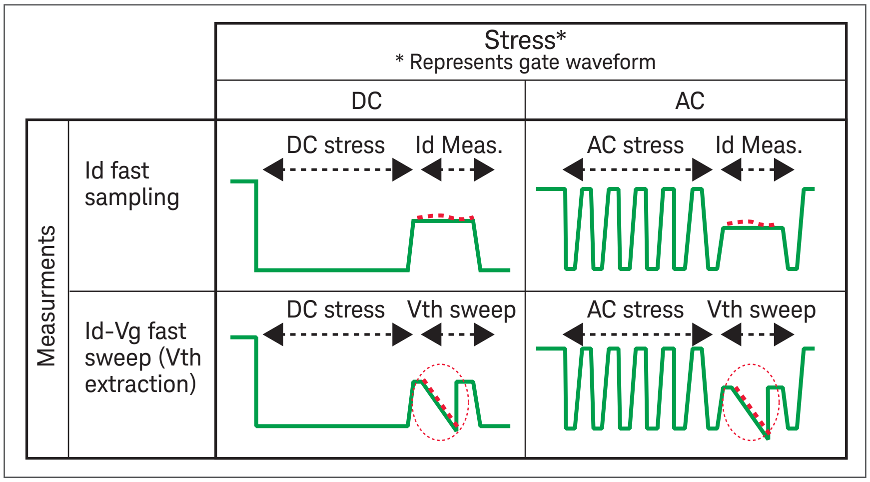


Figure 15. Furnished EasyEXPERT NBTI application test stress/measure combinations.

Figure 16 illustrates the functioning of the EasyEXPERT NBTI application test for the Id sampling case. The user interface is shown on the left, the interim Id sampling data for the various stress/measure timings are shown in the top right and the final NBTI degradation versus stress time plot is shown at the bottom. The final degradation data as well as the interim results are saved in the "Results" window of the EasyEXPERT interface. For the Id-Vg sweep mode case, the Id-Vg sweep data is shown in the interim results as well as the gate voltage corresponding to the Id current selected to define the Vth of the FET. The final NBTI degradation graph shows the extracted Vth plotted against the applied stress time.

EasyEXPERT application test software (continued)

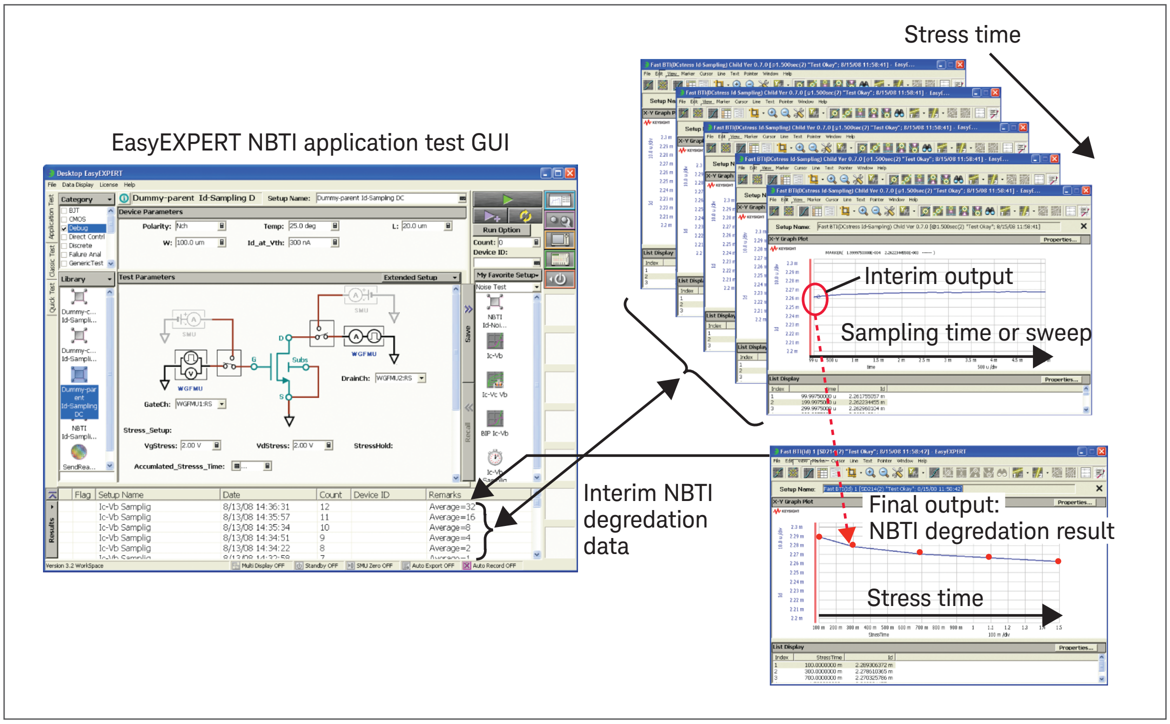


Figure 16. Ultra-fast NBTI EasyEXPERT application test GUI and display.

High performance sample software for use with external Windows PC

There is still no definitive consensus as to the best method for NBTI measurement, and researchers at various technical conferences have presented a wide variety of methods to evaluate the NBTI degradation mechanism. Therefore, any software supplied to control the WGFMU for NBTI testing needs to have a great deal of flexibility. In addition, it is important that whatever software is supplied have the ability to be easily integrated into existing reliability test environments.

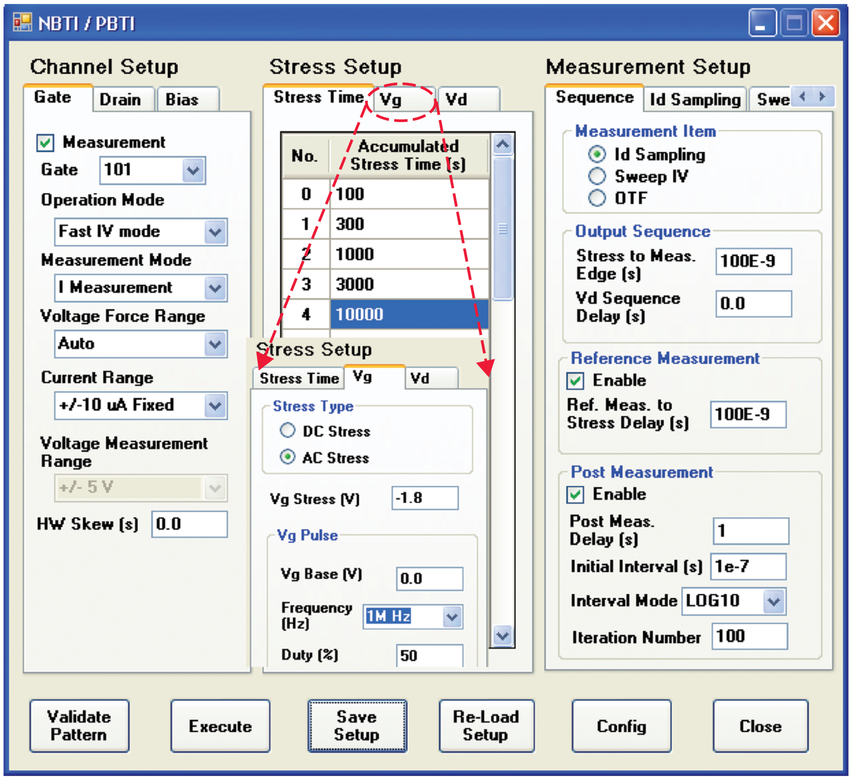
To meet these needs, Keysight provides a Windows-compatible API that supports the programming of the WGFMU in a variety of software environments. Figure 17 shows the GUI of some NBTI sample software written in Visual C# using the WGFMU Windows API library. This software runs on a Windows-based PC and it controls the B1500A via GPIB. The API supports a variety of capabilities that are important for state-of-the-art NBTI measurement. These include:

- Id sampling and Id-Vg sweep in linear or log time starting at sub-microsecond timing
- On-the-fly (OTF) NBTI testing
- Pre and post stress Id or Id-Vg sweep measurement
- Post dynamic recovery testing from sub-microseconds to more than 1,000 seconds that is independent to the middle of NBTI test setup. (Refer Figure 18)
- Choice of the DC or AC stress
- Support for two WGFMU modules (four channels). Note: This allows the MOSFET source and substrate to be connected to WGFMU channels rather than to the circuit common. This greatly increases the measurement flexibility and also supports devices with different pad layouts within the same wafer.

This powerful sample software is furnished with the B1500A's WGFMU module. It can be used without modification to perform interactive evaluation of NBTI device degradation, and it can easily be customized and combined with existing software for users' current

High performance sample software for use with external Windows PC (continued)

reliability test systems. The sample software includes simple sweep measurements for DC and pulsed modes, and ultra-fast sampling measurements in addition to the NBTI application.



☑ Measurement
Gate: 101
Operation Mode: Fast IV mode
Measurement Mode: I Measurement
Voltage Force Range: Auto
Current Range: +/-10 uA Fixed
Voltage Measurement Range: +/- 5 V
HW Skew (s): 0.0

No.	Accumulated Stress Time (s)
0	100
1	300
2	1000
3	3000
4	10000

Stress Setup
Stress Type: ○ DC Stress ● AC Stress
Vg Stress (V): -1.8
Vg Pulse
Vg Base (V): 0.0
Frequency (Hz): 1M Hz
Duty (%): 50

Measurement Item: ● Id Sampling ○ Sweep IV ○ OTF
Output Sequence
Stress to Meas. Edge (s): 100E-9
Vd Sequence Delay (s): 0.0
Reference Measurement
☑ Enable
Ref. Meas. to Stress Delay (s): 100E-9
Post Measurement
☑ Enable
Post Meas. Delay (s): 1
Initial Interval (s): 1e-7
Interval Mode: LOG10
Iteration Number: 100

Figure 17. NBTI sample software GUI for use with external Windows PC.

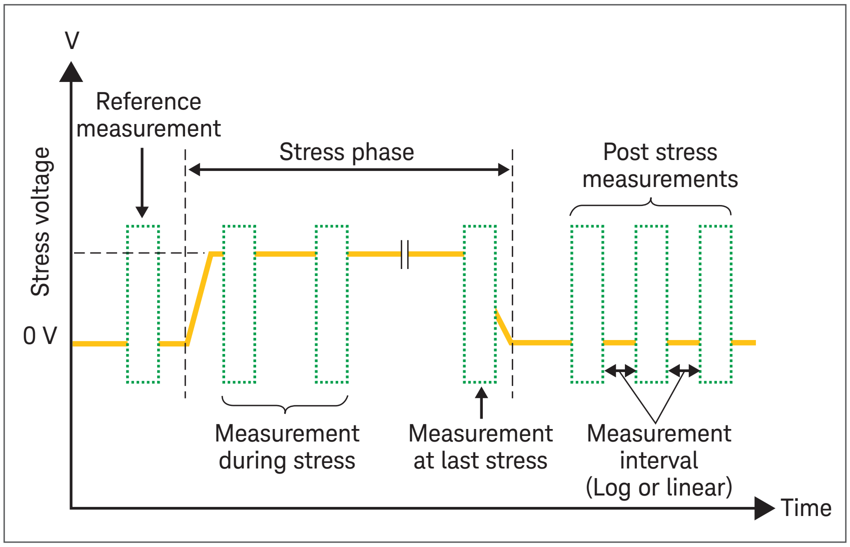
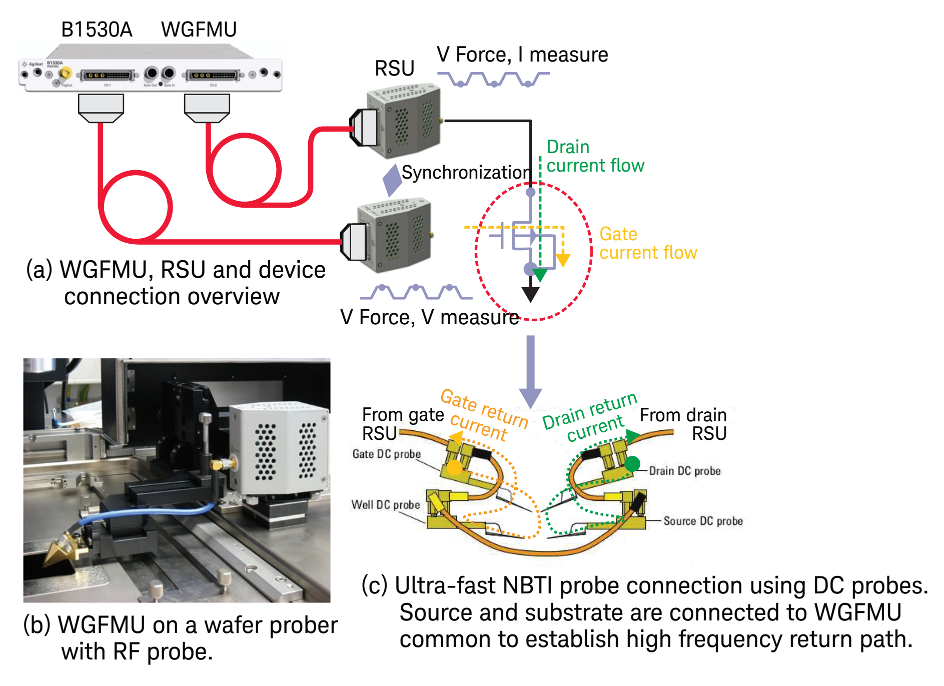


Figure 18. Example of active-stress and post-stress NBTI measurement sequence.

B1500A's WGFMU and RSU system setup

Figure 19 shows an overview of a typical measurement configuration using the WGFMU to perform NBTI testing on-wafer. The setup consists of one WGFMU module and two remote-sense and switch units (RSUs). The RSUs are designed to be located close to the device under test (DUT) at a spacing of less than 20 cm to insure that pulses applied to the DUT are clean even when operating in the 1 µA current range at high speed. To prevent waveform distortions and reflections it is important to provide a current return path between the DUT ground and the coaxial shield of the RSU's BNC cable. When using the RSUs with RF probes, the ground-signal (G-S) or ground-signal-ground (G-S-G) structure insures that there is a proper current return path. When using the RSUs with DC probes, special cables are necessary to achieve this same result. Keysight can supply this necessary cabling, as well as can many wafer prober companies.



(a) WGFMU, RSU and device connection overview

(b) WGFMU on a wafer prober with RF probe.

(c) Ultra-fast NBTI probe connection using DC probes. Source and substrate are connected to WGFMU common to establish high frequency return path.

Figure 19. Ultra-fast NBTI system configuration example.

B1500A's WGFMU and RSU system setup (continued)

Figure 20 shows a block diagram of the WGFMU and RSU. The arbitrary linear waveform generator (ALWG) function operates similarly in both the PG and Fast IV modes. The PG mode supports faster pulses and it has a 50 Ω output impedance; however, the PG mode only supports voltage measurement. The Fast IV mode is slightly slower than the PG mode, but it can measure both voltage and current. Fast IV mode supports five fixed current measurement ranges from 10 mA to 1 µA full scale with effective four digits resolution. Up to five WGFMU modules (ten channels) can be installed in a single B1500A mainframe, which allows for parallel NBTI testing.

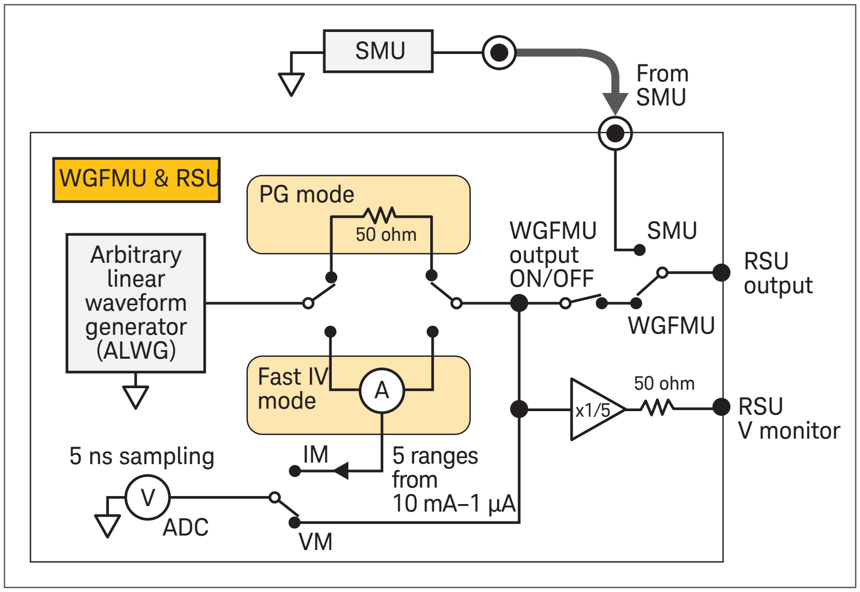


Figure 20. Block diagram of the WGFMU and one RSU channel.

Switching between RSU and SMU

The RSU output can be switched via software commands to a source/monitor unit (SMU) that is connected to the RSU's triaxial input. This allows measurements to be made at the RSU output using the SMU, which has voltage and current output capabilities and voltage and current measurement ranges that are not available on the WGFMU. Figure 21 shows the triaxial (SMU) input and voltage monitor output of the RSU.

Figure 21. RSU picture showing the SMA output, the BNC voltage monitor output and the triaxial SMU input.

Monitoring WGFMU output waveform

There are two ways to monitor the WGFMU voltage output. Of course, one way is to use the built-in voltage measurement capability of the WGFMU. However, the RSU also has a buffered voltage monitor output. The RSU voltage monitor output allows the user to connect an oscilloscope to monitor the WGFMU voltage output, which permits monitoring of the output voltage waveform without interfering with the current measurement capabilities of the WGFMU. This feature is especially useful for detecting a very high speed signal transition that cannot be detected due to bandwidth limitations of the WGFMU's voltage measurement function.

Conclusion

This application note has shown how the B1500A's new WGFMU module can be used to solve ultra-fast NBTI measurement challenges. It can do this without requiring any external equipment (such as custom-built circuitry, oscilloscopes or pulse generators). The key components of the WGFMU solution are a low-noise sub-microsecond sampling capability and an ALWG function that supports complex stress and measurement waveforms.

The WGFMU's new AC pulsed NBTI solution meets the needs of advanced NBTI testing, and its performance is virtually impossible to duplicate by combining off-the-shelf components such as a pulse generator, oscilloscope and external switching circuitry. The WGFMU is the only tool that can determine realistic NBTI lifetimes by duplicating the AC stress actually experienced by devices inside of an IC.

The provided EasyEXPERT ultra-fast NBTI application test library provides an easy-to-use interface to control a single WGFMU module (two channels), and it can be used to build a B1500A-based ultra-fast NBTI test system.

The furnished ultra-fast NBTI sample software and API make it easy to control the B1500A's WGFMU module from an external PC via GPIB, and they provide more measurement flexibility than the EasyEXPERT ultra-fast NBTI application test library. Users can easily expand and customize the sample software to integrate it into existing reliability test and parametric analysis environments. This software gives users the ability to access all of the measurement features of the WGFMU, including its ultra-fast current and voltage measurement capability that can be synchronized with arbitrary waveforms with 10 ns resolution.

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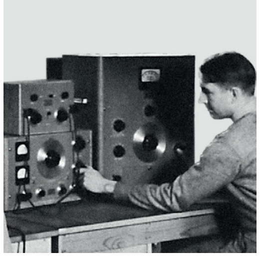

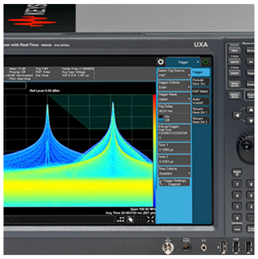

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