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On-The-Fly Threshold Voltage Measurement for BTI Characterization

Paul Meyer, Keithley Instruments, Inc.

Advances in traditional CMOS scaling techniques are reaching their limits, bringing up the need for new materials and novel device designs. Along with these new materials and designs comes a new emphasis on latent failure mechanisms and the need for more reliability testing. Failure mechanisms such as bias temperature instability (N-BTI and P-BTI) require high speed source and measure capability to resolve fast recovery affects. An examination of measurement techniques, including on-the-fly measurements, will aid in implementing effective measurement solutions with the proper instrumentation.

Text Bias temperature instability (BTI) refers to instability in the threshold voltage (V_{TH}) when a MOSFET is subjected to temperature stress. With analog applications such as matched transistor pairs, small shifts can lead to circuit failure. Many of the process variations that affect matching of FETs can be mitigated by increasing the area of the transistor, which leaves BTI as the limiting factor.

The need to monitor and control bias temperature instability—both negative (NBTI) and positive (PBTI)—in both scaled CMOS and precision analog CMOS technologies is growing. The current JEDEC standard for NBTI identifies "NBTI recovery during interim measurements" as the concern that motivates reliability researchers to continue to refine test techniques. Experimental data reveals that the time slope of measured degradation is strongly dependent on measurement delay and measurement speed.

Several measurement techniques have been developed to minimize measurement delay and increase measurement speed while monitoring process-induced BTI shifts. Each of these techniques has benefits and drawbacks. Here we examine some of these techniques including on-the-fly measurements and discuss the instrument requirements related to effective implementations of BTI application.

On-the-fly (OTF) techniques

BTI characterization is becoming a critical test in semiconductor design and fabrication. Denais et al. have proposed a method to minimize recovery during interim measurements by using an indirect measurement that could be correlated to V_{TH} shifts. The interim measurement was designed to reduce the "off-stress" time by using only three measurements, as shown in ***Figure 1***. Almost any parametric measurement system can support this technique. However, most GPIB-controlled instruments lack flexibility and are limited by GPIB communication time and the internal speed of the instrument. As a result, the device can remain unstressed for roughly 100ms during the measurement. These limitations can obscure visibility into degradation and recovery within the 100ms time limit.

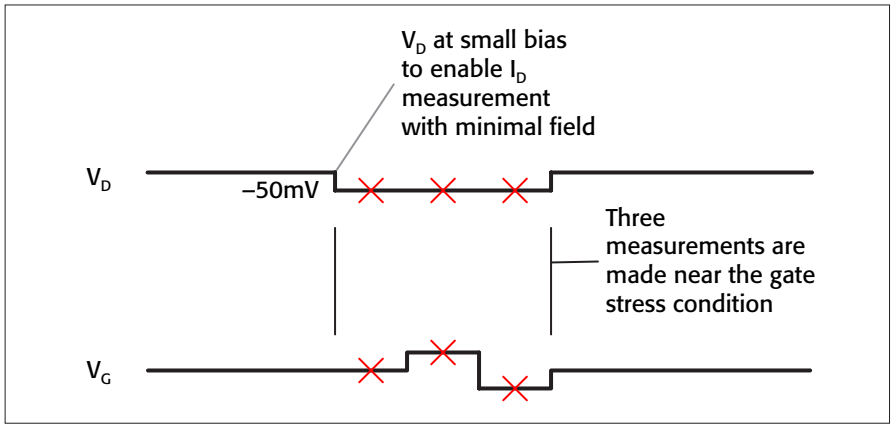

Figure 1. Off-stress time is greatly reduced using the on-the-fly (OTF) technique. Rather than performing exhaustive I_D–V_G sweeps (I_{Dlin} and I_{Dsat}) and extracting V_{TH}, the OTF technique keeps the gate stressed and the drain voltage near ground.

The most critical element in the implementation of OTF techniques is the use of a high speed source-measure unit, or SMU. The high speed SMU provides a number of crucial capabilities. Perhaps the most important of these is fast continuous measurement rates with less than 100µs between successive measurements, which limits the effects of BTI. Fast source settling also maximizes source-measure speed as well as increasing measurement throughput. Another critical capability is a microsecond resolution time stamp. This ensures proper timing analysis and helps improve accuracy. Having a precision voltage source addresses the need for low voltage bias of the drain, which also helps ensure accurate measurements. Lastly, large data buffers help ensure continuous monitoring of device degradation and recovery.

Common OTF techniques

One common OTF technique involves monitoring only the drain current, sometimes referred to as the I_D only technique. It involves providing a small bias on the drain of between 25–100mV and making continuous drain current measurements. Here, the continuous sampling rate is critical.

One advantage is that the recovery dynamics of the BTI mechanism can be captured very shortly after the stress is removed. Experimentation suggests that the recovery dynamics show greater variability and sensitivity to process variation than the degradation dynamics.

Another technique is the OTF single point technique. This is much like the I_D only technique, except that I_D is measured in the linear region. The key point here is to minimize degradation recovery time by shortening the measurement time. ***Figure 3*** illustrates an OTF single point measurement.

Some researchers may be concerned that many OTF techniques use indirect V_{TH} measurement techniques that are too distantly related to the parameter of interest. For instance, monitoring only I_D as the interim measurement may not provide enough visibility into actual V_{TH} shifts, because other parametric shifts, such as mobility degradation due to interface states degradation, might have an impact on I_D that is independent of that due to V_{TH}.

The OTF V_{TH} method simply replaces the three measurements of the Denais OTF technique shown in ***Figure 1*** with a sweep of a few points centered on the gm-max, as shown in ***Figure 2***. The extracted V_{TH} is potentially more accurate than the V_{TH} extrapolated from just three measurements. Its accuracy, however, depends on the noise floor of the test system, the source settling speed, and the measurement integration rate.

Instrumentation solutions

There are a broad range of SMU instruments that could be used to perform various BTI measurements with varying degrees of success. There are attributes that contribute to better BTI measurement including source voltage slew rate, source settling time, measurement speed, measurement repeatability, and temporal repeatability of the test sequence.

Older SMUs tend to require several tens of milliseconds to apply a new set point voltage, settle to an acceptable level, and perform a precision measurement. These SMUs have limited use with respect

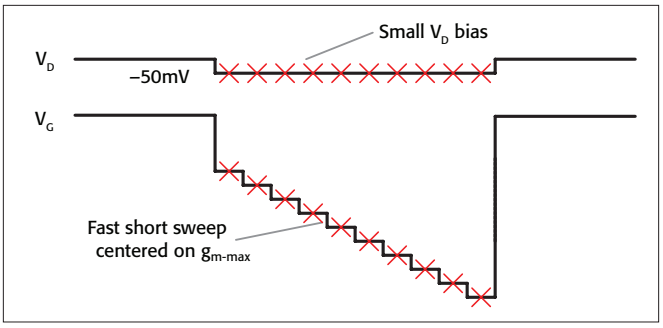

Figure 2. V_{TH} OTF uses a short fast V_G sweep centered on gm-max. This technique allows a 10-point sweep to be completed and the stress conditions returned in less than 5.4ms. If only I_D is measured, the time is reduced to 3.8ms.

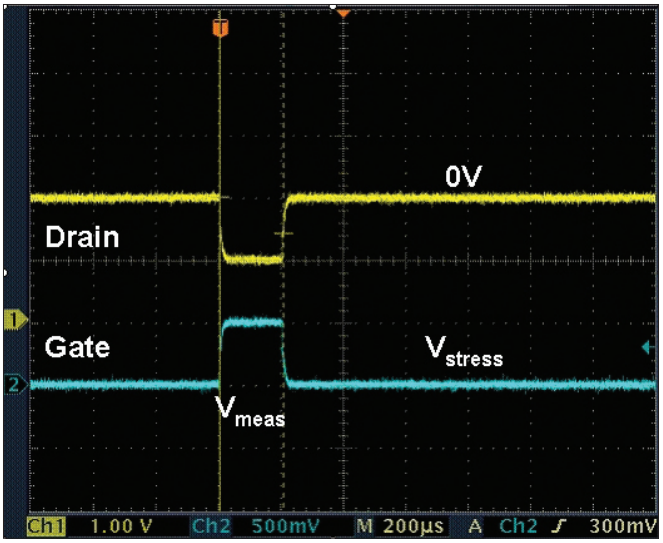

Figure 3. A scope shot of the source and drain voltages on a BTI test structure during a measurement cycle of the OTF single point technique using Keithley's Series 2600 SourceMeter instrument. The structure is measured and returned to stress in 200µs, much faster than what is possible with traditional SMUs.

to BTI measurements. More modern SMUs can perform a source-delay-measure cycle in hundreds of microseconds or two orders of magnitude faster than older units. For best results, an SMU architecture that can execute arbitrary source-delay-measure cycles across multiple channels without speed degradation is best. Additionally, it is paramount that the SMU timing be maintained for every device, even in a parallel test regime.

The measurements described here can be performed using Keithley's Series 2600 System SourceMeter® instruments. A single Model 2612 incorporates dual four-quadrant source-measure units and an embedded test script processor (TSP®), which allows the instrument to perform a complete BTI characterization independently.

The unique architecture of Keithley's Series 2600 System SourceMeter instruments can typically complete the Denais OTF interim measurement and return the test structure to the stress condition in approximately 2ms. The 2600 System also features a continuous sampling interval of 90µs with up to 50,000 data points stored in the instrument's buffer. In addition, the 2600 System can achieve a short gate voltage disruption of approximately 200µs.

Conclusion

Regardless of the technique employed, the best possible BTI measurements require very fast coordination of source and measure. Using OTF techniques without high speed source measurement instruments casts doubt on the accuracy of the lifetime prediction.

References

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2. M. Denais et al., "On-the-Fly Characterization of NBTI in Ultra-Thin Gate Oxide PMOSFETs," in *Technical Digest of IEDM*, 2004, p. 109.

About the Author

Paul Meyer received his BSE degree from the Missouri Institute of Technology. He is a product marketer in the Semiconductor Labs Group at Keithley Instruments. Meyer's previous experience includes production management, equipment development, and application engineering in the semiconductor industry.

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KEITHLEY INSTRUMENTS, INC. ■ 28775 AURORA ROAD ■ CLEVELAND, OHIO 44139-1891 ■ 440-248-0400 ■ Fax: 440-248-6168 ■ 1-888-KEITHLEY ■ www.keithley.com

BELGIUM
Sint-Pieters-Leeuw
Ph: 02-3630040
Fax: 02-3630064
info@keithley.nl
www.keithley.nl

CHINA
Beijing
Ph: 8610-82255010
Fax: 8610-82255018
china@keithley.com
www.keithley.com.cn

FINLAND
Espoo
Ph: 09-88171661
Fax: 09-88171662
finland@keithley.com
www.keithley.com

FRANCE
Saint-Aubin
Ph: 01-64532020
Fax: 01-60117726
info@keithley.fr
www.keithley.fr

GERMANY
Germering
Ph: 089-84930740
Fax: 089-84930734
info@keithley.de
www.keithley.de

INDIA
Bangalore
Ph: 080-26771071, -72, -73
Fax: 080-26771076
support_india@keithley.com
www.keithley.com

ITALY
Peschiera Borromeo (Mi)
Ph: 02-5538421
Fax: 02-55384228
info@keithley.it
www.keithley.it

JAPAN
Tokyo
Ph: 81-3-5733-7555
Fax: 81-3-5733-7556
info.jp@keithley.com
www.keithley.jp

KOREA
Seoul
Ph: 82-2-574-7778
Fax: 82-2-574-7838
keithley@keithley.co.kr
www.keithley.co.kr

MALAYSIA
Penang
Ph: 60-4-656-2592
Fax: 60-4-656-3794
chan_patrick@keithley.com
www.keithley.com

NETHERLANDS
Gorinchem
Ph: 0183-635333
Fax: 0183-630821
info@keithley.nl
www.keithley.nl

SINGAPORE
Singapore
Ph: 65-6747-9077
Fax: 65-6747-2991
koh_william@keithley.com
www.keithley.com.sg

SWEDEN
Solna
Ph: 08-50904600
Fax: 08-6552610
sweden@keithley.com
www.keithley.com

SWITZERLAND
Zürich
Ph: 044-8219444
Fax: 044-8203081
info@keithley.ch
www.keithley.ch

TAIWAN
Hsinchu
Ph: 886-3-572-9077
Fax: 886-3-572-9031
info.kei@keithley.com.tw
www.keithley.com.tw

UNITED KINGDOM
Theale
Ph: 0118-9297500
Fax: 0118-9297519
info@keithley.co.uk
www.keithley.co.uk

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