Agenda for Today

• Parametric Test: Some Perspective
• Overview of Fast Pulsed Measurement Solutions
• Practical High-Speed Measurement Issues
• High Speed Measurement Examples
• Summary and Conclusions
PARAMETRIC TEST: A PERSPECTIVE
Parametric Test Measures 4 Basic Device Types:

- Transistors
- Diodes
- Resistors
- Capacitors

Most measurements are either current versus voltage (I-V) or capacitance versus voltage (C-V) measurements.
What is a Source/Measure Unit?
Simplified Equivalent Circuit:

Consider how many rack & stack instruments you would have to combine together to get equivalent functionality!
What Does Parametric Test Involve?

Semiconductor parametric test involves the measurement of voltage and current very accurately and very quickly. It also involves the measurement of capacitance.

MOSFETs have 4 terminals:
4 SMUs \(\rightarrow\) Magic Number!
DC Versus Fast (Transient) IV Measurement

DC Measurement (Milliseconds)

- Basically “static” measurement
- Can wait for the system to settle down before making the measurement
- Long measurement times allow sufficient averaging / integration time for high accuracy

Fast I/V Measurement (Microseconds and below)

- Dynamic measurement
- Must make measurement during the transient response
- Trade-offs must be made between speed and accuracy
Why Is High-Speed Measurement Becoming Critical to Parametric Test?

• Lower operating voltages
  • Some phenomena (such as NBTI/PBTI) have more impact than in the past due to smaller operating margins

• Expanded use of new and exotic materials
  • Some materials (SOI, high-k gate dielectrics) are more sensitive to heating effects or experience other issues requiring fast pulsed measurement

• Random telegraph signal noise (RTN)
  • As lithographies shrink, MOSFET drain current variations due to RTN can affect the stability of SRAM cells
  • RTN measurement requires fast (nanosecond) sampling rates

• Circuits and devices are operating hotter
  • High temperatures generally exacerbate the above effects

→ Fast measurement is necessary to obtain the accurate device parameters
OVERVIEW OF FAST PULSED MEASUREMENT SOLUTIONS
What is a Pulsed IV Measurement?

- IV measurement made using pulses (not DC signals)
- Pulse widths can vary from milliseconds to nanoseconds

<table>
<thead>
<tr>
<th>DC IV measurement</th>
<th>Pulsed IV measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apply voltage (or current)</td>
<td>Pulse width</td>
</tr>
<tr>
<td>Measure current (or voltage)</td>
<td>Pulse period</td>
</tr>
</tbody>
</table>

**Spot**
- Measurement can be slow.
- Timing dependency is low.

**Sweep**
- Measurement must be relatively fast.
- Timing dependency is high.
- Pulse widths vary from ms to ns
- Different equipment is needed depending on the pulse width requirements
How Much Bandwidth is Needed?

A pulse (square wave) is the superposition of sine waves (odd harmonics).
- The base line frequency is determined by pulse period.
- The practical maximum frequency is determined by the width and transition time.
- The DC components only determine the pulse offset.

10 ns pulse width
2 ns edges
100 μs period

Can easily need a system with GHz of bandwidth!
Using Standard SMUs for Pulsed Measurement

- Easy extension from DC measurement.
- Can make pulsed IV measurements down to 500 μs using the same DC measurement setup.
- Intrinsic hardware based timing control for pulse width, period and wait time parameters.
- Three standard SMU modules are supported on the B1500A device analyzer.
  - B1510A High Power SMU (200V/1A, 10fA resolution)
  - B1511B Medium Power SMU (100V/0.1A, 10fA resolution)
  - B1517A High resolution SMU (100V/0.1A, 1fA)

Note:
1. Measurement range and DUT impedance may limit the achievable pulse width.
2. Trade-offs need to be made between effective resolution and pulse speed.
50 μs Pulsing Using Medium Current SMU (MCSMU)

- Specialized SMU supporting 50 μs pulsing (10 times faster than other SMUs)
- Power output of 30 V@1 A (pulse mode)
- Software supports unique Oscilloscope view that enables you to monitor voltage & current waveforms directly on B1500A without any additional equipment
- Oscilloscope view permits waveform verification and timing parameter optimization

![Oscilloscope view](image)

- Risk that measurement is performed before pulse reaches its peak.
- Actual waveform does not match programmed waveform due to capacitive loading, etc.
- Actual waveform can be monitored.
The Traditional Solution for Fast Pulsed Measurement

SMUs for DC bias

Pulse Generator

DC Bias Source and System Controller

Shunt Resistance

Gate bias pulse

Voltage drop due to $I_d$

$Id = \frac{\text{Voltage drop due to } I_d}{\text{Shunt resistance (R)}}$

Oscilloscope

A seemingly simple measurement technique, but…

This is not simple to implement!
Challenges When Implementing a Pulsed IV System Using Discrete Instruments

- **System accuracy**
  - The overall error is the sum of the individual instrument errors
  - Basic scope resolution is only ~ 8 bits

- **Requires precision components & connectors**
  - The shunt resistance must be very precise
  - The cabling needs to be matched and calibrated
  - Connections need to be tightened to known a torque using a torque wrench

- **Software**
  - The amount of time and effort needed to create the software to integrate everything together is not trivial

- **Compensation for Id Voltage Drop**
  - Actual Vd applied to transistor varies with Id, so compensation routines are needed if a constant Vd is desired
Agilent’s Solution for 10 ns Pulsed IV Measurement

Agilent 81110A Pulse Generator

Agilent B1500A Semiconductor Device Analyzer

Agilent DSO Digital Storage Oscilloscope

Gate Pulse Output Ch

Gate Pulse Monitor Ch

Drain Current Monitor Ch

DC Bias Ch from SMU

DUT

Optional 11713B Switch Controller:
Provides easy switching between DC and Pulsed Measurements.

Convenient EasyEXPERT GUI
Correlation to DC Measurement @ 10ns pulse width using a bulk NMOS transistor w/o self heating

**Id-Vd: DC vs. PLSDIV @ 10ns**

**Id-Vg: DC vs. PLSDIV @ 10ns**

IV curves measured using a 10 ns pulse width correlate well with IV curves measured at DC (as they should).
Id-Vd, Id-Vg measurement with pulsed gate bias.

- Pulse bias sweep measurement using a single pulse.

Variable pulse width

- 10 nsec to 1 μsec.
- Pulse period is fixed as 100 μsec (10 KHz)

Pulse level

- -4.5 V to +4.5V
- Maximum amplitude is up to 4.5V
- Positive pulse for NMOS FET and negative pulse for PMOS FET

Vd Range

- Maximum 10 V

Id measurement range.

- Maximum 80 mA
- Minimum 1μA resolution (depends on measurement range)
An Alternative: Dedicated Hardware for Fast IV Measurement

Waveform Generator/Fast Measurement Unit (WGFMU)

- Remote-sense and Switch Unit (RSU)
  - Located near DUT to minimize signal delay
  - Buffered output monitor function
  - Can switch between SMU and WGFMU

- SMU connection: Triaxial
  DC measurement or debug using SMUs

- Output: SMA to/from DUT

- Furnished Cables

- Voltage Monitor: BNC
  Monitor waveforms using oscilloscope

B1500A mainframe w/B1530A modules
WGFMU: Basic Functionality and Specifications

Equivalent circuit of one WGFMU channel (2 channels / module):

Voltage ranges supported
- PG mode: -5 V to 5 V
- Fast IV mode: -5 V to 5 V, 0 V to 10 V, -10 V to 0 V

Current measurement ranges (fixed)
- 1 µA, 10 µA, 100 µA, 1 mA, 10 mA

Settling times for current measurement (0.6%)
- 10 mA Range: 125 ns
- 1 mA Range: 200 ns
- 100 µA Range: 820 ns
- 10 µA Range: 5.8 µs
- 1 µA Range: 37 µs

Measurement resolution
- 14 bit ADC

Noise
- Max. 0.1 mVrms (V force)
- Max. 0.4 mVrms (V measure)
- <0.2% of Range (I measure)

Sampling rate
- 200 MSa/s (Interval: 5 ns or 10 ns to 1 s w/avg.)

Memory length
- 4,000,000 points/channel

Note: Fast IV mode eliminates load line effects

PG mode: Minimum 50 ns pulse width (50 Ω Load)
Fast IV mode: Minimum 145 ns pulse width
Fast IV Sweep Measurement Made Using the Agilent’s WGFMU

- A staircase sweep with 100 μs per step (50 μs delay) was performed to create a baseline.
- A staircase sweep with 1 μs per step (500 ns delay) correlates well with the 100 μs measurement.
- A 1 μs pulsed IV sweep (100 ns rise/fall time, 500 ns delay, 2 μs period) also correlates well with the other two measurements.
- Averaging time: 50 ns.
- Current measurement range: 10 mA.

This data shows that there is no dependency on step size or pulsing; all measurements yield the same results.
Rack & Stack Solution vs. Integrated Module

Discrete Instrument Solution:
• Extremely fast pulsing (2 ns rise/fall, 10 ns width)
• Complex calibration issues
• Requires very sophisticated software
• Can be subject to load line effects
• Can be expensive

Integrated Module:
• Easy to use
• No calibration issues (off-the-shelf product)
• Slower pulsing capability (10 ns rise/fall, 50 ns width)
• Eliminates load line effects
• Relatively less expensive
PRACTICAL HIGH SPEED MEASUREMENT ISSUES
Proper Structure Design is Crucial to Achieving Clean Pulses on Pulses <200 ns in Width

Structure for conventional DC measurement

Large overshoot and ringing

Structure optimized for RF measurement

Clean pulse shape
Pad Arrangement Good Down to ~200 ns

Long, non-50 Ohm current path distorts the pulse shape.
Note that a minor change in pad layout significantly improves measurement results.
Pad Arrangement Good Down to $\leq 10$ ns

Minimize the loss in the gate pulse path

Minimize the loss in the drain current path

Minimize the voltage offset caused by the high-frequency impedance mismatch between the source and substrate
Important! Keep the Signal Path Clean

DC bias, ground and control pads (if needed)

• Separate probes by at least 200 μm to avoid cross-talk
• All grounds should be connected together

Minimum pad size: 50 μm x 50 μm (Infinity Probes)
Using DC Probes for High-Speed Measurements

Advantages:
• Cheaper than RF probes
• Bandwidth OK for WGFMU module
• Flexible pad layouts

Disadvantages:
• Minimum achievable pulse width ~100 ns
• Mechanical tension created on probes
• Not supported by all prober companies

Cable Accessories

Establishes return path for Gate Pulse
Terminates Well and Source
Establishes return path for Drain Current

To measurement equipment

16493R-202 SSMC (Plug) – SMA(m) 200 mm
16493R-101 or 102
16493R-202 SSMC(Plug) – SMA(m) 200 mm
Using RF Probes for High-Speed Measurements

Advantages:
• More than sufficient bandwidth
• Impossible to improperly connect

Disadvantages:
• Cost
• Fixed pad layout

RF Probe
(ex. Cascade Microtech Infinity Probe)

SMA Connectors

To measurement equipment

Advantages:

Disadvantages:

- More than sufficient bandwidth
- Impossible to improperly connect

- Cost
- Fixed pad layout
Can SMUs be Used as Bias Sources in High-Speed Measurements?

**NO!** SMUs cannot respond fast enough when the FET is driven by a fast pulse.

- It is best if you can keep the non-switching nodes at ground.
- If you need to vary the voltage on all nodes, then use only high-speed equipment (e.g. WGFMU) even if the node is held at a constant voltage.
- If you must use SMUs, then only connect them to terminals where there is little or no current flow.
- Also if using SMUs, make sure that they are set to their maximum current range for fastest response.
Wafer Chuck Considerations

Difficult to change chuck voltage quickly

Alternative method

If left open the chuck will charge up and the substrate potential may not be stable during measurement (important if performing long-duration reliability test)

If the WGFMU module is connected to the chuck then it will have a very long settling time due to the large chuck capacitance

Use a shorting plug to ground the wafer chuck (do not leave it open!)

If the chuck must be biased, keep the voltage constant throughout your measurement
Probe Contact Resistance

Maintaining low contact resistance is critical for pulsed measurements

• High contact resistance combines with stray capacitance to degrade pulse shape (sometimes quite significantly)
• High contact resistance also reduces both the amplitude of the pulse voltage and the current flowing into the DUT
Cable Capacitance Can Also Affect Measurement Results

One way to avoid this issue (other than making your cables as short as possible) is to measure current at the source, since it is usually at a stable voltage (i.e. zero volts).
Issues Caused by Fixed 50 Ω PGU Output Impedance

Conventional Pulse Generator

1. Voltage applied to DUT changes when device impedance changes
2. Voltage applied to DUT does not match programmed value even when device impedance becomes constant

WGFMU Module (Fast IV Mode)
No load lines effects
Electromagnetic Induction Noise

Magnetic Flux: $B_{\text{noise}}$

Noise current

Loop Area: $S_{\text{loop}}$

Electromagnetic noise is proportional to the loop area

To reduce noise, make the signal loop as small as possible

$$V_{\text{noise}}(t) = \frac{d}{dt} \oint_{\text{loop}} B_{\text{noise}}$$
Twist Cables to Minimize Noise
(B1500A WGF MU Module Example)

Twist long cables between the RSUs and the B1500A to minimize signal area.

Must properly connect probe shields.

Cable accessories to connect probe shields.

To make current return path for gate pulse signal.

To make current return path for drain current signal.

To shorten the well and source.

RSU

16493R-202 SSMC (Plug) – SMA(m) 200 mm

16493R-101 or 102
Connecting with multiple cables reduces the residual resistance, but it increases total area of ground/signal loop.
Solution to Ground Loop Issue

You may need to disconnect the instrument common from earth (chassis) ground and/or do the same for the wafer prober.
Filtering Noise (If Necessary)

• Ferrite cores are an effective means of eliminating noise
• Cut-off frequencies need to be chosen carefully to avoid removing the high-frequency components of the signal being measured
HIGH-SPEED AND PULSED MEASUREMENT EXAMPLES
Negative Bias Temperature Instability

- Phenomena:
  - Shift in $V_{th}$ and degradation (reduction) of $I_{on}$ under negatively biased gate voltage
  - Dynamic recovery
    - The shift partially recovers if the stress is removed
  - More severe in PMOS transistors
- Accelerated under:
  - High temperature
  - High $V_g$ bias
Why Has NBTI Become a Major Issue?

• Process Vdd is lower
  – At Vdd ≤ 1.2 V, even a 20-50 mV shift in Vth has a big impact

• Many ICs are running much hotter than in the past (circuit self heating)

• Advanced processing issues exacerbate the NBTI mechanism
  – Dependent on gate dielectric material
    ➢ High-k gate dielectrics have more defects than standard materials
  – Dependent on gate insulator thickness
    ➢ Effect grows exponentially worse as thickness decreases
NBTI Dynamic Recovery

Fast recovery from the stress condition

The defects generated by the stress recover rapidly after removal of the stress:

- The total number of defects consists of the combination of permanent defects and fast recovering defects (different defect mechanisms).
- It is difficult to estimate the number of fast recovery defects prior to measurement because they depend upon a variety of factors (gate material, process factors, bias voltage and stress time).
Ultra-fast NBTI Measurement Requirements

At the 2006 IRPS H. Reisinger (Infineon) questioned the NBTI data taken via conventional methods. He stated that the dynamic recovery time of charge trapped in the insulator or surface greatly affects the results of the NBTI characterization.

The dynamic recovery time is highly dependent on the gate insulation material:
- Conventional oxide... 200 $\mu$s
- High-k dielectric... <1 $\mu$s

Conclusion: NBTI measurements made within 1 $\mu$s after stress removal are necessary!
Ultra-fast Id Spot Measurement Using WGFMU

Id spot measurement within 1μs after removal of the stress*

*Note: 10 mA and 1 mA ranges. The measurement speed depends upon the measurement range settling time.
Both AC & DC Stressing Capabilities are Needed

- The only difference between the AC and DC cases is the shape of the stress waveforms.
- In both cases there is no delay in transitioning from stress to measure and no glitching during the transition.
The Effects of DC & AC Stress on NBTI Device Degradation Are Dramatically Different

- Pure DC stress causes the largest shift in the Id.
- AC stress is probably a more realistic representation of the stress experienced by devices under normal operating conditions.
Why is RTS Noise* Important?

• As MOSFET device sizes shrink, RTS noise becomes much more prominent at low frequencies
  – RTS noise is believed to be caused by charge trapping/de-trapping
  – If RTS noise occurs it generally dominates all other low-frequency noise components

• Active pixel sensors (aka CMOS image sensors) are especially sensitive to RTS noise
  – In CMOS image sensors RTS noise generates erroneous white spots in what should be dark areas

• SRAM Cell Stability
  – As lithographies and voltage levels have continued to shrink, RTS noise is starting to impact SRAM cell stability.

*Note: RTS noise (RTN) is also known as burst noise or popcorn noise.
What is a Random Telegraph Signal (RTS)?

A random process that has the following properties:

1. $X(t) = \pm 1$
2. The number of zero crossings in the interval $(0,t)$ is described by a Poisson process.
WGFMU RTS Noise Measurement Technique

Output waveform monitor (optional)

(Measured with WGFMU)

Note: Sampling rates need to be in the nanosecond range, and hundreds of thousands (or even millions) of measurement points may need to be recorded.
Sample RTS Noise Measurements Made Using the B1500A WGFMU Module

Measured sampling data

Digitized data

Zoom
RTS Noise Power Spectrum Distribution

Slope is constant at low frequencies.

\[ \text{Slope} \approx \frac{1}{f^2} \]

(At high frequencies)
When are <100 ns Pulses Required?

**Self-heating effect**

- **SOI Transistors**
  - Short pulse width (under 100 ns) to avoid heat generation.
  - Very small duty cycle (< 0.1%) to allow time for the device to cool.

**An ultra short pulse can be used to measure the intrinsic \( I_d \) of a MOSFET.**

**MOSFETs Impacted by electron trapping**

- Short pulse width to measure \( I_d \) before any electrons can get trapped
- Negative gate baseline voltage to remove electrons before next pulsed measurement.
Measurement Example Using 10 ns Pulsing

Charge trapping effects are clearly visible in the measurement results.

SiON device with large interface trap density
SUMMARY AND CONCLUSIONS
What Are the Key Points to Remember for Successful High-Speed Test?

- **Equipment considerations**
  - Make sure you know what your fast measurement or pulsing needs are so that you can choose the proper equipment to meet your requirements.
  - If making on-wafer measurements, make sure that your prober supports the necessary probes and that it has a low enough noise floor for your needs.
  - Follow all suggestions in this presentation for on-wafer probing.

- **Careful planning and device layout can prevent many headaches later**
  - Optimize layouts for high-speed
  - Minimize contact resistance

- **Follow these basic principles if building a system on your own**
  - Calibrate scope and pulse generator using precision meter
  - Use high-quality cables with known delay times
  - Keep cable lengths as short as possible
  - Make sure all connections have the proper torque
Agilent Parametric Handbook Has More Information

You can download the PDF file (Rev 3) from the web: http://www.agilent.com/find/parametrichandbook

You can also request it after completing the evaluation form.
Thank You for Your Kind Attention
Questions