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**The Most Common Mistakes Made in
Parametric Test***

***And How to Avoid Them**



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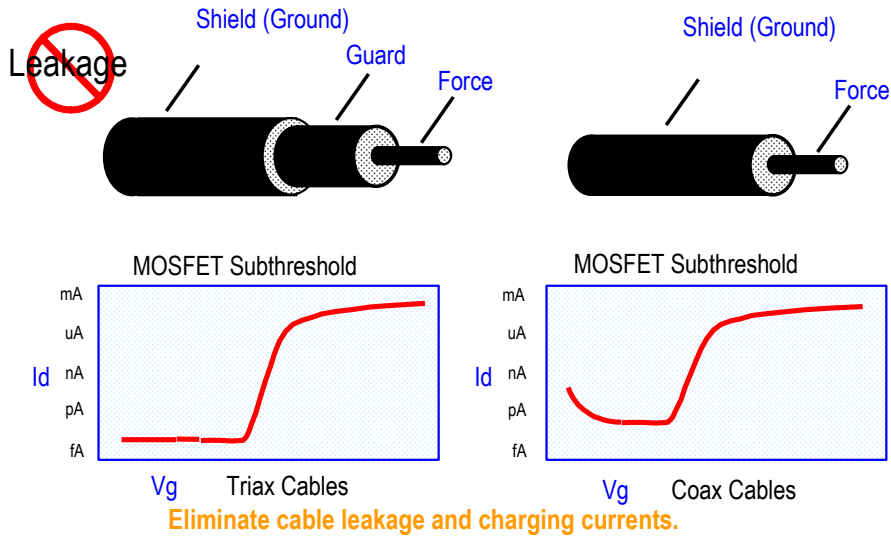


**Mistake #1: Improper triaxial to
coaxial adapters**



Why Use Triax Cables?

Required For Measurements $< 1\text{nA}$.



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The triax cable is a special low dielectric loss, high impedance cable. This cable may be used down to fA levels when properly used with a guarded probe. The guard voltage tracks the force voltage exactly, so that no voltage drop can exist between guard and force. This eliminates the current leakage that would otherwise limit low current measurements.

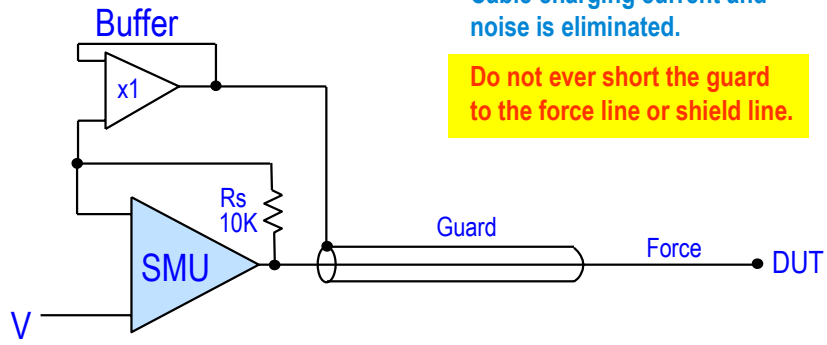
If low impedance coax cables are used with outer layer at ground potential, two limitations will be immediately apparent. The cable leakage will limit the low current measurement floor. In addition, when the voltage is swept, the sudden change will cause additional cable charging. This distorts the low current portion of a MOS Subthreshold curve as shown.

RULES:

Unguarded coax cable is OK for measurements above 1nA.

Triax cable or coax with outer layer at guard potential should be used for measurements below 1 nA.

Triaxial Guard Connection Simplified Diagram



The guard voltage tracks the force voltage exactly.

Cable charging current and noise is eliminated.

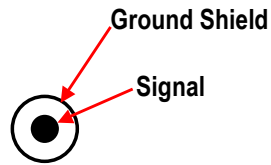
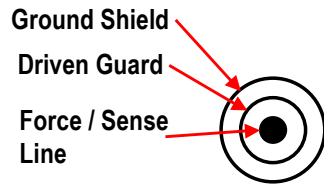
Do not ever short the guard to the force line or shield line.

Driven guard isolation is needed for measurements below 1 nA. For measurements below 1 nA, a regular BNC coaxial cable will leak sufficient current between the center conductor and the outer ground shield to affect the accuracy of the measurement.

The driven guard also has the added benefit of improving the measurement speed. The above diagram shows how the cable capacitance is eliminated with a triaxial cable. The guard is driven at the same voltage as the force center conductor. No current can flow between guard and force when they are held at the same potential.

Please note that the guard and force lines are isolated by a buffer amplifier. They should NEVER be shorted together.

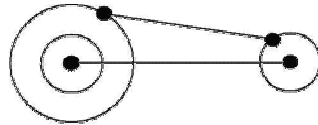
How Do I Connect Triaxial and Coaxial Connections?



- What do I do with the driven guard?
- Does the current I am measuring affect how I connect to a BNC connector?
- Where can I get the necessary TRIAX to BNC connectors?

Sometimes it is necessary to connect triaxial cables to coaxial cables. However, doing so raises some questions as to how this connection should be done.

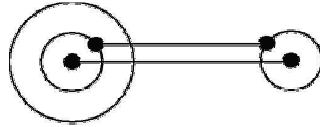
Triaxial to Coaxial Adapters: Measuring Currents > 1 nano-Amp



In this case it is OK to float the guard connection, since current leakage between the center conductor and the outer ground shield does not significantly impact the measurement.

The case where the measured current is above 1 nA is the easiest and simplest. Here you can simply connect the center conductors and outer ground shields together.

Triaxial to Coaxial Adapters: Measuring Currents < 1 nano-Amp



Warning! Shock Hazard!

The only way to maintain low-current measurement accuracy in a coaxial environment is to connect the driven guard to the outer shield of the coaxial connector. This presents a potential safety hazard and must be done with great care.

The case where the measured current is less than 1 nA is tricky. There are a couple of things to keep in mind here:

To maintain measurement integrity, the center signal conductor needs to be surrounded by a driven guard. This means that the BNC outer shield cannot be grounded, but instead must be floating. Special connectors and adapters are often needed to accomplish this.

Another important consideration is that the outer BNC shield can be at 100 V (for the case of a HRSMU or MPSMU) or 200 V (for the case of a HPSMU). This presents a potential safety hazard, and requires that great care be taken with the measurement setup to insure that no accidental electrocution can take place.

Summary of Agilent Connectors

Agilent Part Number	Description		
1250-2652	Triax(F) - BNC(M)		Safe. Not suitable for low-current measurements.
1250-2653	Triax(M) - BNC(F)		
Agilent Part Number	Description		
1250-2650	Triax(M) - BNC(F)		WARNING!!!! Shock Hazard!!!! Required for low-current measurements.
1250-2651	Triax(F) - BNC(M)		
1250-1830	Triax(F) - BNC(F)		

Agilent makes a variety of triaxial to coaxial adapters. In addition, Trompeter also sells these types of adapters as well.



**Mistake #2: Connecting SMUs up
using the 'Sense' line instead of
the 'Force' line**



Most SMUs Have Both Force & Sense Outputs – Which Do I Use?



SMU Force Output

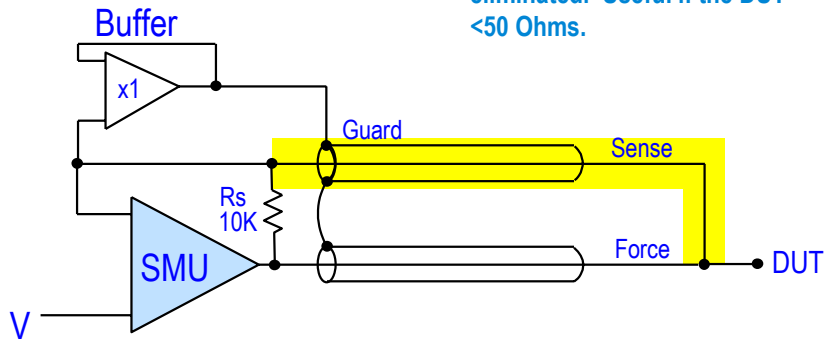
SMU Sense Output

- If making Kelvin measurements, use both the Force and Sense outputs
- If not making Kelvin measurements, always use the Force output (never use the Sense output by itself)

All Kelvin SMUs have both a Force and a Sense output, but many people are confused as to exactly which connection to use when.

Guard and Kelvin Connection Simplified Diagram

The sense line is added.
Cable resistance error is eliminated. Useful if the DUT <50 Ohms.



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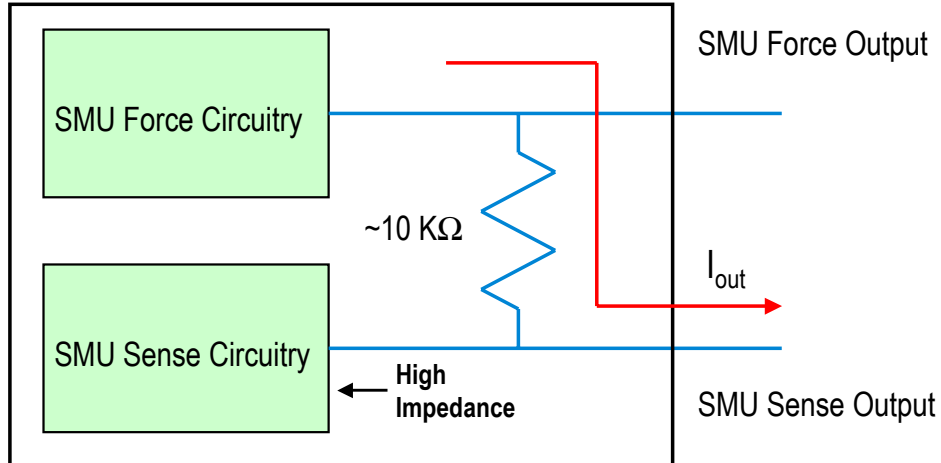
The only difference between the 4155 and 4156 cable configuration is the addition of the sense line. In this case, sensing is done at the DUT, eliminating the fraction of an ohm of cable resistance. The internal sensing resistor R_s is the only feedback path in the 4155.

Note that the 4156 operates just fine without the sense cable. Then it operates just like the 4155. This is important to know because in general you do not need the sensing Kelvin connection. Most MOS measurements are high impedance and the residual cable loss is insignificant.

The E5260 Series and E5270B/4157B SMUs are all Kelvin SMUs (just like the 4156C), meaning that they possess both a Force and a Sense output.

Do Not Use SMU Sense Output by Itself!

Source / Monitor Unit (SMU):



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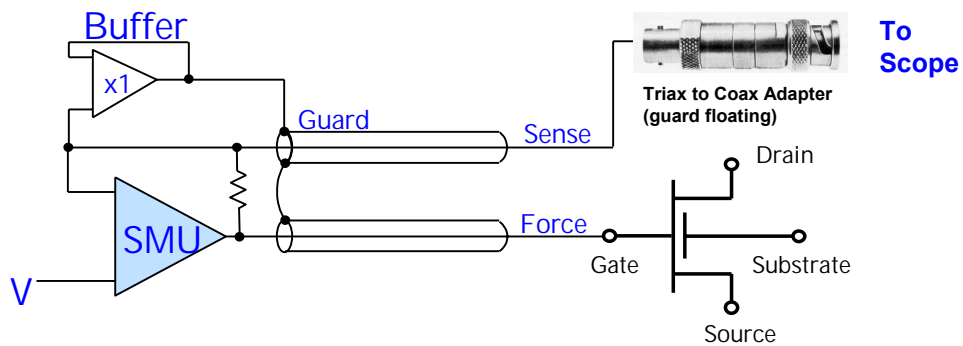


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If you use the Sense line of a Kelvin SMU only, then all of the force current must pass through the $\sim 10\text{ K}\Omega$ resistor that connects the Force and Sense lines. This will distort your measurement results.

Note that it is OK to use the Force line by itself. The Sense circuitry is high-impedance, so the $\sim 10\text{ K}\Omega$ resistor is immaterial to the function of this portion of the SMU circuitry.

Nifty Trick: Use the Sense Line as a High Impedance Scope Probe!



Measure Gate Voltage versus Time Accurately

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The sense line need not be used only for Kelvin connections.

It is ideal for monitoring the voltage on your device with an oscilloscope.

The sense line tracks the force line within 1mv.

All you need is a floating guard coax adapter attached to the sense line at the back of the 4156. Then use any BNC cable to direct connect the SMU sense line to the oscilloscope input.

The adapter shown is the Trompeter Electronics AD-BJ20-E2-PL75.

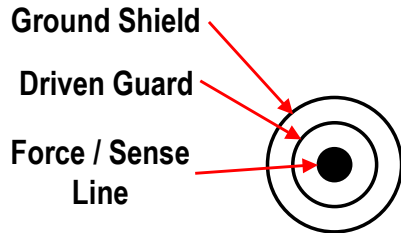


**Mistake #3: Improper connection
on ground unit (GNDU)**

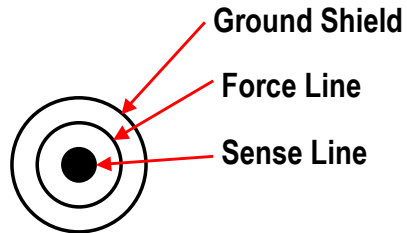


What is the Ground Unit (GNDU) Configuration?

Standard Triaxial Connection:

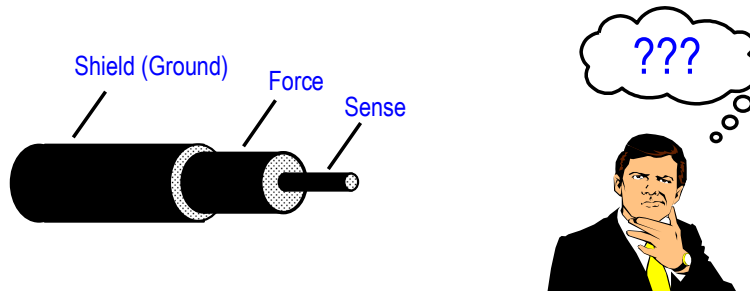


Ground Unit Connection:



Please look carefully at the above diagrams. Many people do not understand that the ground unit (GNDU), while triaxial, does not have the same configuration as a standard triaxial cable. Failure to connect to the GNDU properly will result in improper measurement results.

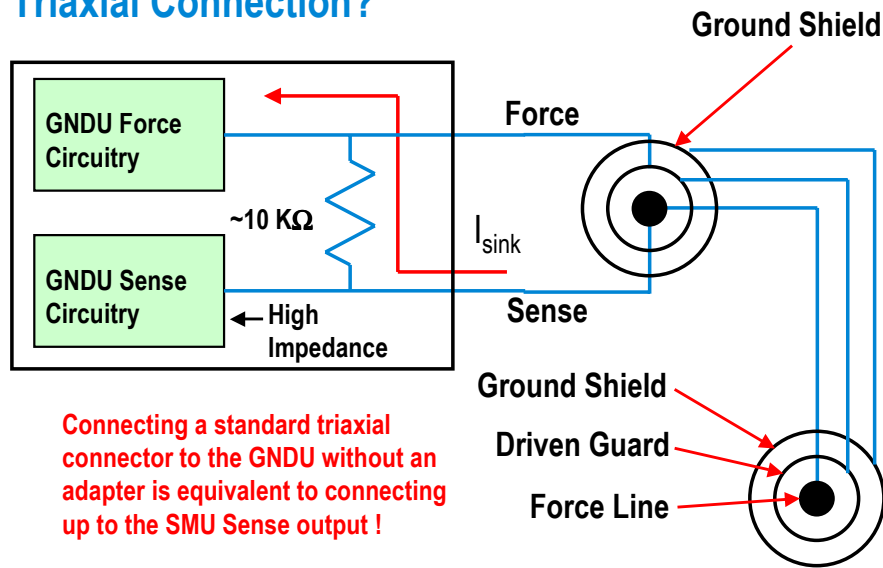
Why is the GNDU Configuration the Way It Is?



- In standard triaxial connections the middle conductor is a driven guard, which eliminates any cable leakage current by always keeping the driven guard the same potential as the center Force/Sense line.
- In the case of the ground unit the potential of the Force and Sense lines is always at zero volts, so there is no need to shield it from the outer ground shield to prevent leakage currents.

The GNDU is can keep the Force and Sense lines together without a driven guard because the Force and Sense lines are always at 0 Volts potential.

What Happens if I Connect the GNDU to a Standard Triaxial Connection?



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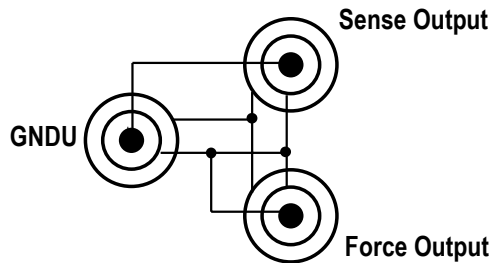
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Please note that if you just connect up a triaxial cable to the ground unit without splitting the ground unit's Force and Sense lines into separate connectors, then it is equivalent to connecting up an SMU using only the Sense line!

Proper GNDU Connection

Unless your equipment is designed to handle the GNDU connection, you must use an adapter that splits out the GNDU Force and Sense lines into standard triaxial configurations.



The **Agilent N1254A-100 Ground Unit to Kelvin Adapter** will split the Force and Sense lines into the proper Kelvin configuration.

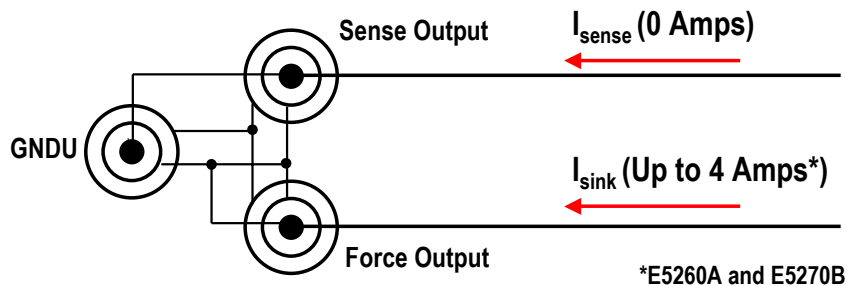
Agilent also make a special GNDU to Kelvin Triaxial cable (16493N) that has a triaxial connection on one end, and a Kelvin Triaxial connection on the other. This cable will perform the same function as the ground unit adapter shown above.

Note: The N1254A-100 is designed to be used with the E5260 Series and E5270B/4157B GNDU. However, it can be used with the GNDU found on the 41501A/B expander box for the 4155/4156 by removing the banana plug from the N1254A-100.

Connections to the GNDU Should be Kelvin



Remember! Pumping large currents through cables will cause an Ohmic drop unless this is compensated via a Kelvin measurement configuration. Since assumedly the reason you are using the GNDU is to sink large currents, you should always connect up both the Force and Sense lines.



*E5260A and E5270B

Note: Agilent makes a special triaxial cable that can handle the 4 Amps of current flow through the GNDU Force output (16493L).

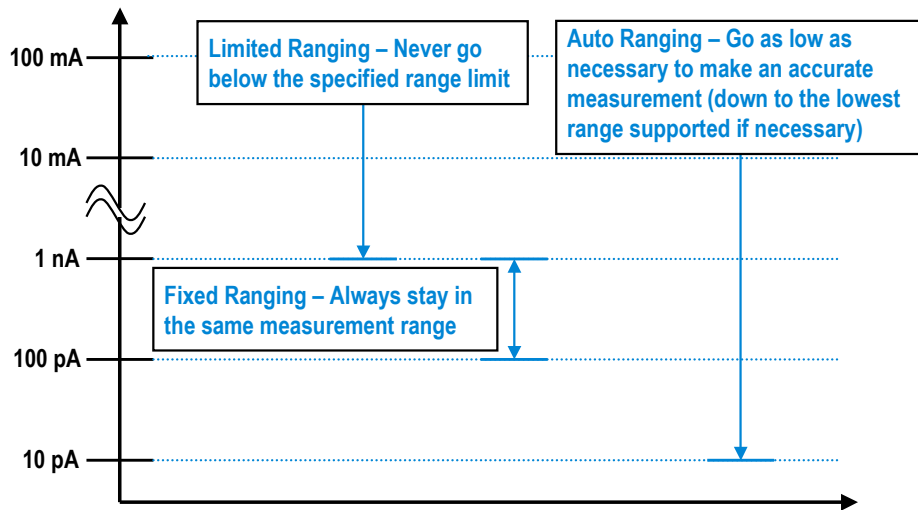


**Mistake #4: Using 'Limited Auto'
ranging instead of 'Auto' ranging**



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Ranging – What is It?



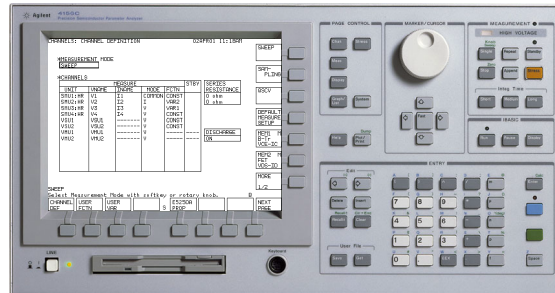
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The differences between Fixed, Limited, and Auto ranging are not difficult to understand. However, many people have never had this adequately explained to them.

4156 Example



- The 4156 has two additional low-current measurement ranges not available on the 4155: 100 pA & 10 pA
- The 4156 boots-up like a 4155C (all SMUs set to Limited 1 nA ranging)
- Unless these are changed, you cannot get the full low-current measurement capability of the instrument!

Many people do not understand that the 4156C actually boots up into a state that makes it look like the 4155C! In order to get the additional low-current measurement accuracy of the 4156C, you must change the range settings.

ID-VG Low-level Subthreshold Measure Setup Page - Default

MEASURE: MEASURE SETUP

02MAY16 10:53AM

***MEASUREMENT RANGE**

UNIT	NAME	RANGE	ZERO	CANCEL	ON
SMU1:HR	Id	LIMITED 1nA	ON	[	10pA]
SMU2:HR	Is	LIMITED 1nA	ON	[	10pA]
SMU3:HR	Ig	LIMITED 1nA	ON	[	10pA]
SMU4:HR	I _s b	LIMITED 1nA	ON	[	10pA]

(*:Old data is used.)

***INTEG TIME**

	TIME	NPLC
SHORT@	640us	0.0384
MED	16.7ms	1
LONG	133ms	8

***WAIT TIME**

1 *(DEFAULT WAIT TIME)

LIMITED

Select Range Mode with softkey or rotary knob.

SWEEP SETUP	MEASURE SETUP	OUTPUT SEQ	S	PREV PAGE	NEXT PAGE
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AUTO

FIXED

LIMITED AUTO

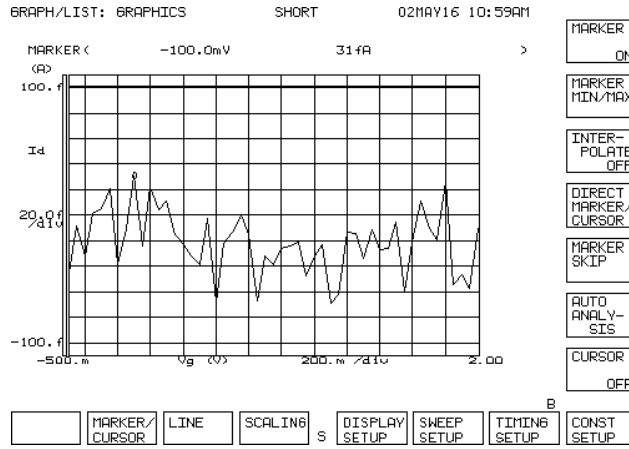
These are 4156 default settings at "boot-up"

Measurements are made quickly but noise level is high.

Notice the LIMITED 1nA settings. These are 4155 defaults.

You need to go the "MEASURE SETUP" page of the 4156C.

ID-VG Low-level Subthreshold Probes Up - Default Range Setting



Noise level is high.
Current measurement
is limited to the 1nA
range.

If you keep the boot-up Range settings of the 4156C and try to measure low-current, then you will get results similar to those shown above.

ID-VG Low-level Subthreshold Measure Setup Page - AUTO range

MEASURE: MEASURE SETUP

02MAY16 10:52AM

*MEASUREMENT RANGE

UNIT	NAME	RANGE	ZERO	CANCEL	ON
SMU1:HR	Id	AUTO	ON	[	10pA]
SMU2:HR	Is	LIMITED	ON	[	10pA]
SMU3:HR	Ig	LIMITED	ON	[	10pA]
SMU4:HR	Isb	LIMITED	ON	[	10pA]

(*:Old data is used.)*

*INTEGRATION TIME

SHORT@	TIME	NPLC
SHORT@	640us	0.0384
MED	16.7ms	1
LONG	133ms	8

*WAIT TIME

1 *(DEFAULT WAIT TIME)*

AUTO

Select Range Mode with softkey or rotary knob.

SWEPT SETUP		MEASURE SETUP	OUTPUT SEQ	S			PREV PAGE	B	NEXT PAGE
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AUTO

FIXED

LIMITED

AUTO

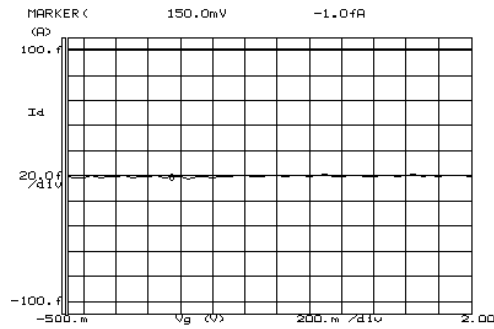
Set the drain SMU range setting to AUTO.

This uses the two lower ranges of the 4156 and decreases the noise floor by 100x.

To get the full measurement accuracy of the 4156A/B/C, you need to change the measurement range setting on the SMU actually making the low-current measurement from "LIMITED" to "AUTO".

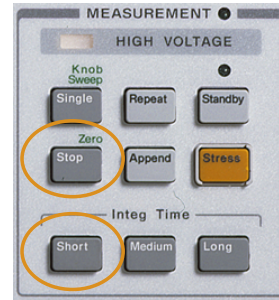
ID-VG Low-level Subthreshold Probes Up - ZERO Check

GRAPH/LIST: GRAPHICS **SHORT** 02MAY16 11:01AM



MARKER/CURSOR LINE SCALING S DISPLAY SETUP SWEEP SETUP TIMING SETUP B CONST SETUP

+/- 2fA variation is the typical noise floor of the instrument by itself (no cables attached).



Integration time can be short.

Wait 30 minutes after boot up of 4156.

If the trace is not centered at 0 fA, press the "GREEN" key and "Zero" key to remove offset error.

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For the 4156C, the Range setting has a much greater impact than the integration time. Using AUTO ranging, you should be able to get good low-current measurements most of the time using SHORT integration.

Extend Resolution 100X 4156C Display Page

DISPLAY: DISPLAY SETUP

*DISPLAY MODE
[GRAPHICS]

*GRAPHICS

	Xaxis	Yaxis	Zaxis
NAME	Vg	Id	
SCALE	LINEAR	LOG	
MIN	-500.0000mV	1.0fA	
MAX	2.0000000 V	100.0000000uA	

*GRID
[ON]

*LINE PARAMETER
[ON]

*DATA VARIABLES

*DATA DISPLAY RESOLUTION
[EXTEND]

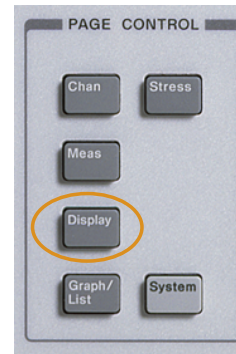
EXTEND

Select Data Resolution with softkey or rotary knob.

DISPLAY ANALYSIS S PREV NEXT
SETUP SETUP PAGE PAGE

1 fA resolution

0.01 fA resolution



This feature is only available in the 4156C. You can upgrade a 4156B to a 4156C.

The Most Common Mistakes Made in Parametric Test

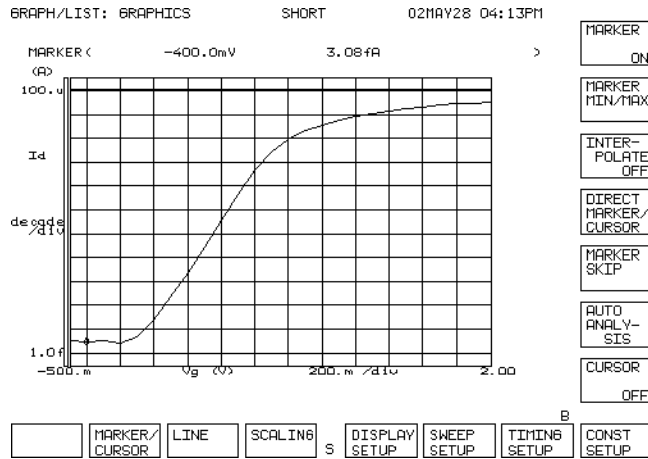


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It is possible to extend the measurement resolution of the 4156C to 0.01 fA by changing the parameter setting shown on the “DISPLAY SETUP” page to “EXTEND”. However, this is considered to be “Readable Resolution” as opposed to the instrument’s basic “Resolution”. “Readable Resolution” gives the full resolving capability of the instruments ADC (analog-to-digital converter); however, it does not perform the averaging that is done when you specify simple “Resolution”.

Please note that if you want current measurement resolution better than 1 fA, then the E5270B/4157B high-resolution SMU (HRSMU) does accept an optional atto-sense & switch unit (ASU) capable of achieving true 100 attoamp (0.1 femtoamp) measurement resolution.

ID-VG Low-level Subthreshold Curve Probes Down - 4156C Graph Page



Low leakage characteristics of a 40 Angstrom thick oxide n-channel MOSFET.

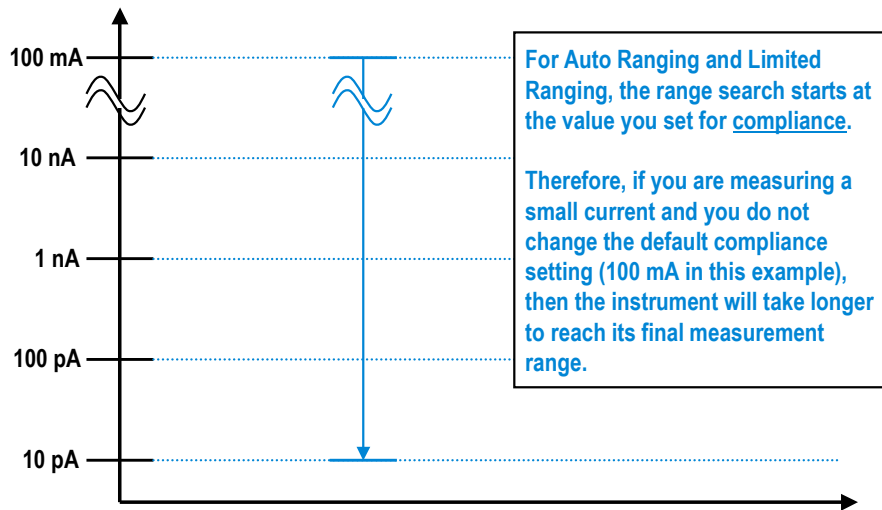
Resolution is .01 fA (10⁻¹⁷ Amps)

This is a sample low-current measurement performed on the 4156C using AUTO ranging.

**Mistake #5: Using Default
(Maximum) Current Compliance
When Making Measurements in
'Auto' or 'Limited Auto' ranging**

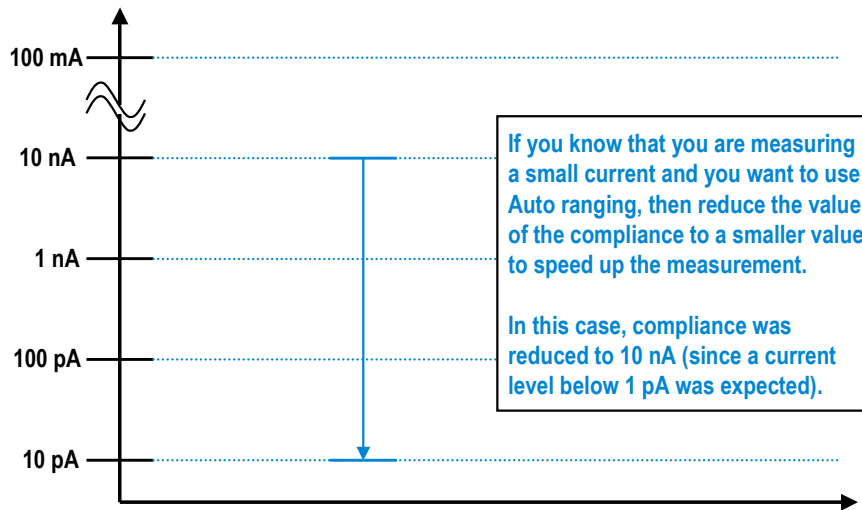


Where Does the Range Search Start?



Many people ask the question: Where does the range search start when I use Limited or Auto ranging? The answer is that it starts at the value that you specify for measurement compliance.

How Do I Change This?



Lowering the specified compliance value will change the point from which Limited and Auto ranging will begin their range search.

Changing the 4155/4156 Compliance Settings

MEASURE: SWEEP SETUP

*VARIABLE	VAR1	VAR2
UNIT	SMU3:HR	
NAME	Vg	
SWEEP MODE	SINGLE	
LIN/LOG	LINEAR	
START	-500.0mV	
STOP	2.0000 V	
STEP	100.0mV	
NO OF STEP	26	
COMPLIANCE	1.0000mA	
POWER COMP	OFF	

*TIMING			
HOLD TIME	3.00 s		
DELAY TIME	0.0000 s		

*SWEEP CONTINUE AT ANY Status

*CONSTANT	SMU1:HR	SMU2:HR	SMU4:HR
UNIT	Vd	Vs	Vsb
NAME	V	V	V
MODE	V	V	V
SOURCE	500.0mV	0.0000 V	0.0000 V
COMPLIANCE	1.0000mA	1.0000mA	1.0000mA

0.001
Enter SMU Compliance Value (-0.1 to 0.1).

SWEEP SETUP MEASURE SETUP OUTPUT SEQ S PREV PAGE NEXT PAGE

Reduce the compliance settings to speed up your low-current measurements

For example, on the 4156C you can change the compliance setting from the “SWEEP SETUP” window. You can also do this under computer control using I/CV automation software.

Remember! Need AUTO Ranging for Low Current

MEASURE: MEASURE SETUP

*MEASUREMENT RANGE			
UNIT	NAME	RANGE	----
SMU1:HR	Id	AUTO	
SMU2:HR	Is	LIMITED	1nA
SMU3:HR	Iq	LIMITED	1nA
SMU4:HR	Isb	LIMITED	1nA

ZERO	CANCEL	ON
ON	[	10pA]
ON	[	10pA]
ON	[	10pA]
ON	[	10pA]

(*:Old data is used.)*

*INTEG TIME

	TIME	NPLC
SHORT	640us	0.0384
MED @	16.7ms	1
LONG	1.33ms	8

*WAIT TIME

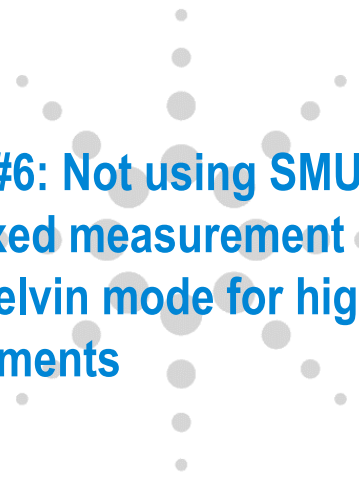
1 * (DEFAULT WAIT TIME)

AUTO
Select Range Mode with softkey or rotary knob.

SWEEP SETUP	MEASURE SETUP	OUTPUT SEQ	S	PREV PAGE	NEXT PAGE
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Keep in mind that reducing the compliance speeds up your measurement, but you still need to be using AUTO ranging in order to measure low currents (fA level)

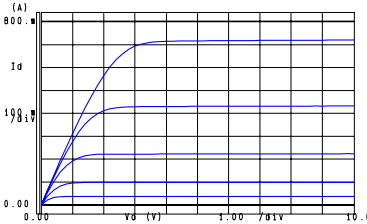
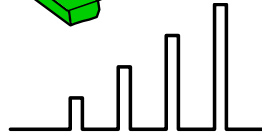
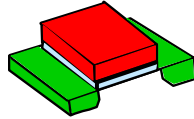
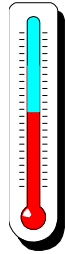
Remember that even if you lower the compliance value, you still need to select "AUTO" ranging in order to measure low currents.



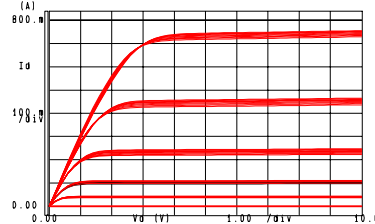
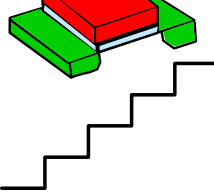
Mistake #6: Not using SMU pulse mode, fixed measurement range, and/or Kelvin mode for high-power measurements



SMU Pulsed Mode Reduces Thermal Heating Error



Pulse = Device Stays Cool



Staircase = Device BBQ'd

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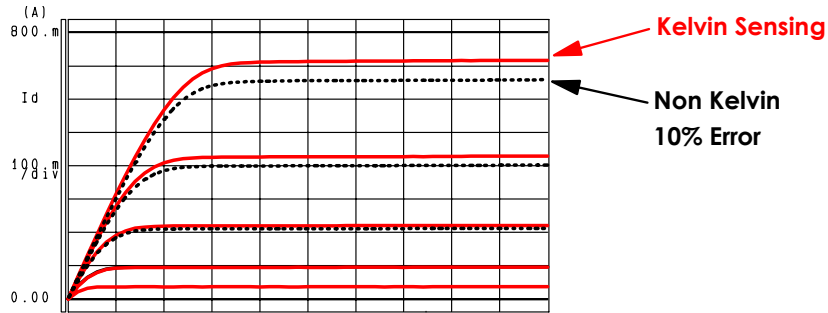
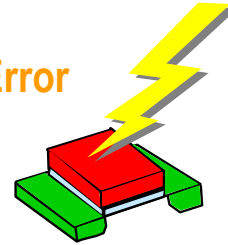
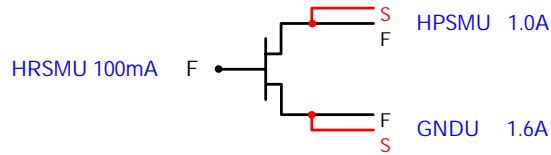
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High-power devices require special measurement considerations. This section will address a couple of important measurement considerations for power MOSFETS and Bipolar transistors.

One of the most important techniques for measuring power devices is to reduce the power duty cycle by applying voltage or current pulses during measurement (as opposed to simply applying constant DC voltages or currents).

Kelvin Sensing Eliminates High Power Measurement Error



The Most Common Mistakes Made in Parametric Test



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For high-power devices, it is extremely important to use Kelvin (4-wire) measurement techniques. In this case the measurement error is not coming from any sort of thermal device effect, but rather from the Ohmic drop that occurs in the cables going to the device under test.

Using SMUs in Pulsed Mode

Channel Definition Page

CHANNELS: CHANNEL DEFINITION 02MAY20 03:12PM
 Power MOSFET Id-Vd Characteristics

*MEASUREMENT MODE
 SWEEP

*CHANNELS

UNIT	VNAME	INAME	MODE	FCTN	STBY	SERIES RESISTANCE
SMU1:HR						0 ohm
SMU2:HR	Vg	Ig	VPULSE	VAR2		
SMU3:HR						
SMU4:HR						
SMU5:HP	Vd	Id	V	VAR1		0 ohm
VSU1						
VSU2						
VMU1						
VMU2						
PSU1						
PSU2						
GNUD	Vs		COMMON	CONST		

DISCHARGE OFF

VPULSE
 Select Mode with softkey or rotary knob.

CHANNEL DEF USER FCTN USER VAR S E5250A PROP B NEXT PAGE

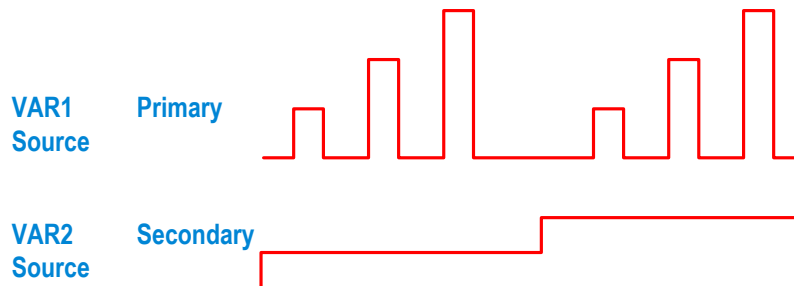
Press the “VPULSE” softkey to define the voltage pulse mode. In this case the gate SMU will be pulsed.

Note: Only ONE SMU can be in pulsed mode.

The 4155 and 4156 allow you to define one of their SMUs to be in pulsed mode. You need to do this on the “CHANNEL DEFINITION” page of the instrument front panel. Of course, this feature is supported in Agilent I/CV as well.

SMU Pulsed Mode

Example of Pulsing The Primary Source



Only one SMU can be pulsed.
Minimum width is 0.5 ms (includes the time to make a 5-digit resolution measurement).

For a sweep measurement, you typically want to pulse the swept source (VAR1). The VAR2 source is varied in order to produce a family of curves, and it does not require pulsing. The minimum pulse width is determined by the time that the instrument requires in order to make a 5-digit measurement.

Using SMUs in Pulsed Mode Power MOSFET Measure Page

MEASURE: SWEEP SETUP 02MAY20 03:11PM
Power MOSFET Id-Vd Characteristics

*VARIABLE	VAR1	VAR2
UNIT	SMU5:HP	SMU2:HR
NAME	Vd	Vg
SWEEP MODE	SINGLE	SINGLE
LIN/LOG	LINEAR	LINEAR
START	0.0000 V	4.500 V
STOP	5.000 V	5.700 V
STEP	50.0mV	300.0mV
NO OF STEP	101	5
COMPLIANCE	1.0000 A	100.00mA
POWER COMP	OFF	OFF

*SMU PULSE	
UNIT	SMU2:HR
NAME	Vg
PERIOD	10.0ms
WIDTH	1.0ms
BASE	0.0000 V

*TIMING
HOLD TIME 0.0000 s

*CONSTANT

UNIT	NAME	MODE	SOURCE	COMPLIANCE

*SWEEP CONTINUE AT ANY status

0.01
Enter SMU Pulse Period (0.005 to 1).

SWEEP SETUP	MEASURE SETUP	OUTPUT SEQ	S	PREV PAGE	NEXT PAGE
-------------	---------------	------------	---	-----------	-----------

A SMU PULSE menu appears.

Here the duty cycle of the pulse is set at 10%.

Change the PERIOD to 100ms to reduce heating further. The device will be powered on only 1% of the time.

If a pulsed SMU is defined on the "CHANNEL DEFINITIONS" page, then an SMU pulse menu will appear on the "SWEEP SETUP" page of the 4155/4156.

Using SMUs in Pulsed Mode

Measure Setup Page

VERY IMPORTANT!

Use **FIXED** ranges.

MEASURE: MEASURE SETUP 02MAY20 03:11PM
 Power MOSFET Id-Vd Characteristics

*MEASUREMENT RANGE				ZERO CANCEL OFF	
UNIT	NAME	RANGE		OFF	OFF
SMU2:HR	Ig	FIXED 1mA		OFF	[10pA]
SMU5:HP	Id	FIXED 1A		OFF	[1nA]

(*:Old data is used*)

*INTEG TIME		
	TIME	NPLC
SHORT@	80us	0.0048
MED	16.7ms	1
LONG	266ms	16

*WAIT TIME
 *(DEFAULT WAIT TIME)

FIXED
 Select Range Mode with softkey or rotary knob.

SWEEP SETUP	<input type="text"/>	MEASURE SETUP	OUTPUT SEQ	S	<input type="text"/>	<input type="text"/>	PREV PAGE	B	NEXT PAGE
-------------	----------------------	---------------	------------	---	----------------------	----------------------	-----------	---	-----------

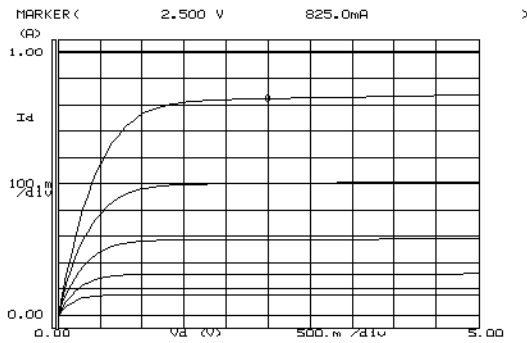
FIXED prevents the SMUs from auto ranging. **AUTO** overrides the pulse settings and could add up to 30ms on each range change.

Here Id is set to the 1Amp range to make use of the HPSMU in the expander box.

When making pulsed measurements, it is VERY important to use FIXED measurement ranging. If you use LIMITED or AUTO ranging, then you can easily over-ride your pulse timing setups. This is because the instrument will also choose accuracy over measurement speed when confronted with a conflict between the two.

Using SMUs in Pulsed Mode Graph Page

GRAPH/LIST: GRAPHICS SHORT 02MAY20 03:12PM
Power MOSFET Id-Vd Characteristic



MARKER/CURSOR LINE SCALING DISPLAY SETUP SWEEP SETUP TIMING SETUP

MARKER ON

MARKER MIN/MAX

INTER-POLATE OFF

DIRECT MARKER/CURSOR

MARKER SKIP

AUTO ANALYSIS

CURSOR OFF

VERY IMPORTANT!

Use **SHORT** integration.

This minimizes heating and assures proper timing.

LONG integration will over-ride your pulse width/length setting. Much more time is required for long integration.

The Most Common Mistakes Made in Parametric Test

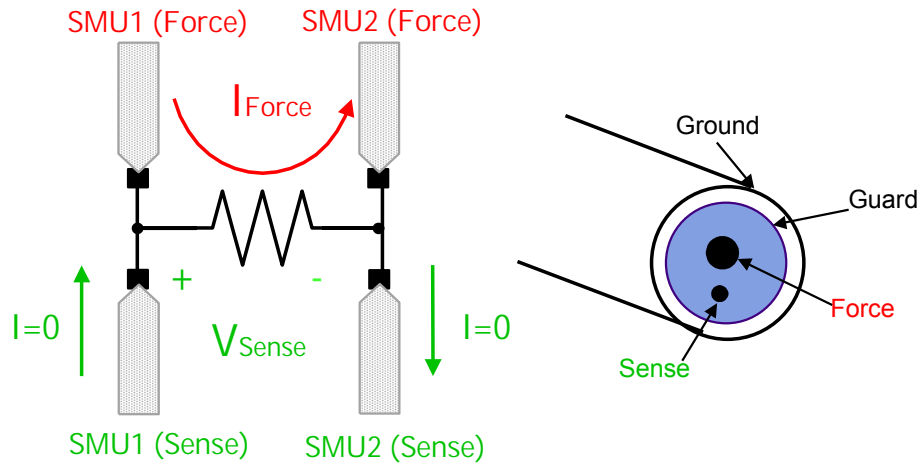


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Besides selecting FIXED ranging, you need to make sure that you are using SHORT integration. The reason is the same: otherwise, accuracy will over-ride your pulse settings.

Kelvin Triax Cable

Ideal for both low current and low impedance applications.



The Most Common Mistakes Made in Parametric Test

 Agilent Technologies

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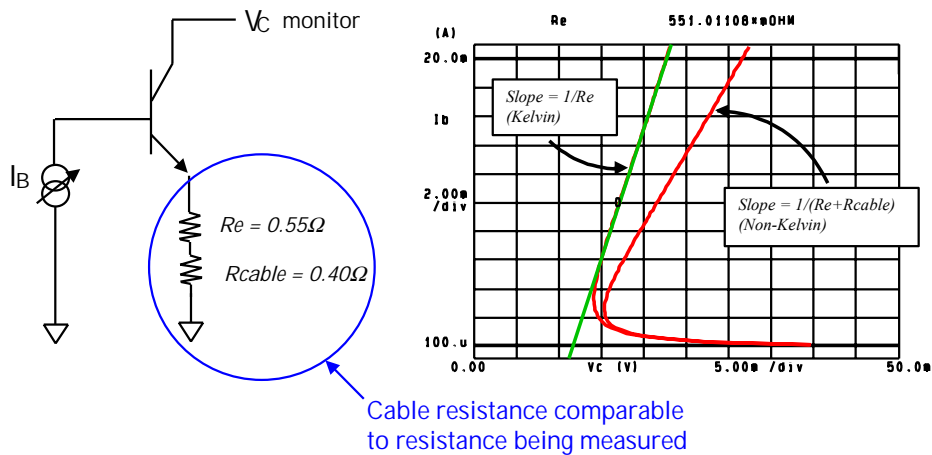
The 4155 uses the same triax cables as the 4142 and 4145. These cables are good for low current measurements. However, two cables are necessary for low resistance Kelvin measurements.

Agilent Technologies designed a special Kelvin triax cable for the 4156, E5260 Series, and E5270B/4157B. This cable is optimized for both low current and low resistance measurement. Both force and sense lines are held rigidly in the same Teflon cable. Friction is reduced and the cable is less sensitive to noise caused by moving the cable.

Kelvin triax cable assemblies are available with two connector options:

16434A	4156 compatible on one end; 4142 compatible on the other end
16493K	4156 / E5260 Series / E5270B compatible on both ends (standard option)

Non-Kelvin Measurements Can Introduce Significant Error



The Most Common Mistakes Made in Parametric Test

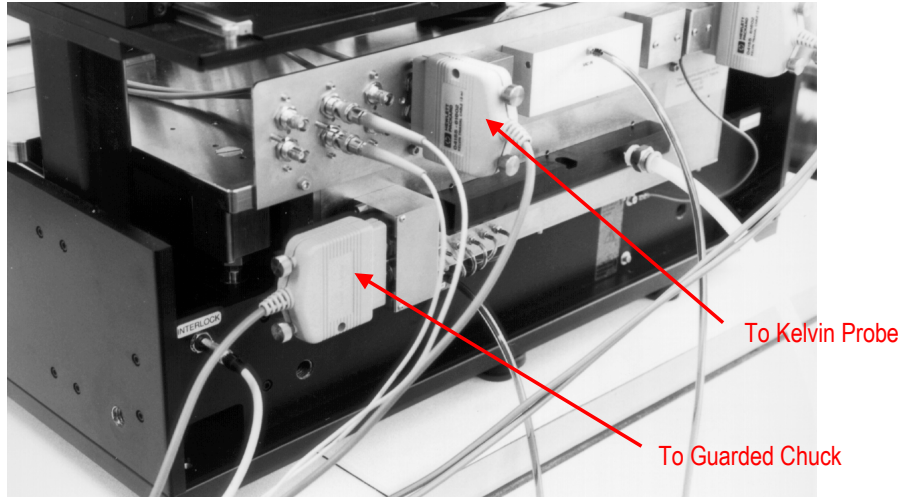


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In the example above, the device is connected with a SMU on the base sweeping current, a voltmeter on the collector, and the emitter is grounded with a Kelvin SMU. The base SMU does not have to be Kelvin since we are only forcing current and do not care about measuring the cable loss in the base. Also, the collector SMU is being used only as a high impedance voltmeter, so there is no cable loss in this lead.

The emitter on the other hand, must be connected to a Kelvin SMU. Because of this, we can compensate for the 0.40 ohm path through the cable and fixture. From the graph we can see the emitter resistance is 0.55 ohm when compensated using the Kelvin connection. Non-Kelvin resistance is 0.95 ohm, due to the extra 0.40 ohm cable and fixture resistance error.

Wafer Prober Kelvin Cable Connections Optimized For Measurement Accuracy



The Most Common Mistakes Made in Parametric Test



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Photo of SMU cable connection to a Cascade Microtech Summit probe station.

Kelvin triaxial cables mate directly to up to six probes top side and a guarded Kelvin chuck (substrate) connection. There is even a provision for mating to the Agilent GNDU configuration

This station uses the Micro Chamber (TM) design for a small volume shielded box enclosing only the probes and wafer; not the entire probe station. The rigid mechanical design with guarded chuck provides an ideal environment for fA current, fF capacitance, and μV voltage measurements.

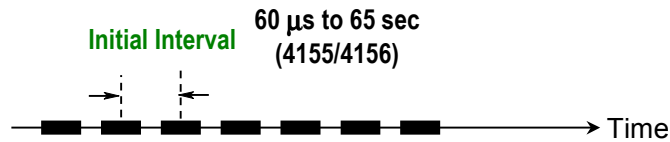


**Mistake #7: Using 'Auto' ranging in
Time Sampling Mode (4155/4156)**



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What is Time Sampling?

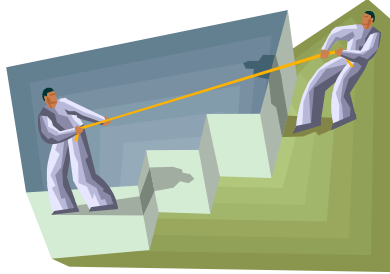


Time sampling involves measuring a voltage or current at regular intervals over time.

Useful for certain types of reliability stress measurements such as Time Dependent Dielectric Breakdown (TDDB)

Time sampling is one of three available measurement modes on the 4155/4156. The other two are Sweep and Stress.

Specifying a Small Sampling Interval and Auto Ranging Creates a Conflict!

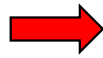
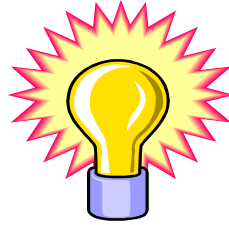


- Time sampling inherently requires that the measurement occur within a certain time period. Otherwise, the sampling rate cannot be met.
- Auto ranging requires the instrument to start at the specified compliance value and work its way down to the correct measurement range, which takes time.
- Specifying both a short sampling time (fast sample rate) and auto ranging creates a conflict for the instrument!

Remember! Whenever Agilent instruments are confronted with a conflict between measurement speed and measurement accuracy, accuracy will always win-out.

How Does this Conflict Get Resolved?

- Accuracy always wins out over speed
- The instrument will take as long as necessary to auto range, ignoring the specified measurement interval settings
- The end result is that the instrument will not measure at the interval you specified!



**NEVER USE AUTO-RANGING WHEN MAKING
FAST TIME SAMPLING MEASUREMENTS**

Many times people call in with support questions as to why they are not getting the time sampling rate that they specified. In virtually every case, we find that they are using AUTO ranging, which creates a conflict when specifying fast sampling rates.

How Do I Optimize My Time Sampling Measurements?



Besides using **FIXED** ranging, what else do I need to do to optimize my **Time Sampling** measurements?

- Minimize active units
- Measure on only one resource
- Disable the STOP condition
- Minimize the compliance setting

There are several other requirements to obtain the sampling rate that you specify (in addition to using **FIXED** measurement ranging). ALL of these conditions must be met. For more information, please refer to the 4155/4156 data sheet.

Optimizing Time Sampling Measurements - 1

CHANNELS: CHANNEL DEFINITION 97AU601 04:07AM

*MEASUREMENT_MODE
SAMPLING

*CHANNELS

UNIT	VNAME	INAME	MODE	FCTN	STBY	SERIES RESISTANCE
SMU1:HR	UGATE	IGATE	V	CONST		0 ohm
SMU2:HR	VSUB	ISUB	COMMON	CONST		0 ohm
SMU3:HR						
SMU4:HR						
VSU1						
VSU2						
VMU1						
VMU2						

DISCHARGE ON

SAMPLING
Select Measurement Mode with softkey or rotary knob. B

CHANNEL DEF	USER FCTN	USER VAR		S	E5250A PROP			NEXT PAGE
-------------	-----------	----------	--	---	-------------	--	--	-----------

Minimize the number of active resources to only those that you need.

It is a good idea to minimize the number of measurement resources that you have active in the "CHANNEL DEFINITION" page.

Optimizing Time Sampling Measurements - 2

MEASURE: SAMPLING SETUP

*SAMPLING PARAMETER		*STOP CONDITION	
MODE	LINEAR	ENABLE/DISABLE	DISABLE
INITIAL INTERVAL	1.04ms	ENABLE DELAY	0.0000000 s
NO. OF SAMPLES	101	NAME	
TOTAL SAMP. TIME	AUTO	THRESHOLD	0.00000000
		EVENT	Val > Th
		EVENT NO.	1
HOLD TIME	0.000000 s		
FILTER	OFF		

*CONSTANT			
UNIT	SMUL:HR		
NAME	UGATE		
MODE	V		
SOURCE	20.000 V		
COMPLIANCE	1.0000mA		

LINEAR
Select Sampling Mode with softkey or rotary knob.

SAMPLING SETUP MEASURE SETUP OUTPUT SEQ S PREV PAGE NEXT PAGE

For intervals < 2 ms, **must** have STOP CONDITION set to DISABLE

For intervals < 2 ms, can only have one measurement channel

Make sure that compliance is set as low as possible

The Most Common Mistakes Made in Parametric Test



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Another very important condition is that you only have one measurement channel defined. Specifying more than one measurement channel is not allowed for time intervals less than 2 ms.

Also, for time intervals less than 2 ms you must have the "STOP CONDITION" set to "DISABLE".

Optimizing Time Sampling Measurements - 3

MEASURE: MEASURE SETUP

UNIT	NAME	RANGE	ZERO CANCEL	OFF
SMU1:HR	IGATE	FIXED 1mA	OFF	[10pA]
SMU2:HR	ISUB	FIXED 1mA	OFF	[10pA]

(*:Old data is used.)

*INTES TIME

	TIME	NPLC
SHORT@	640us	0.0384
MED	16.7ms	1
LONG	266ms	16

*WAIT TIME
1 *(DEFAULT WAIT TIME)

OFF
Select Zero Cancel Mode with softkey or rotary knob.

SAMPLING SETUP MEASURE SETUP OUTPUT SEQ S PREV PAGE NEXT PAGE

For intervals < 2 ms, **must** used **FIXED** measurement range (never use **AUTO** ranging).

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As previously mentioned, you **MUST** use **FIXED** measurement ranging for measurement intervals less than 2 ms.

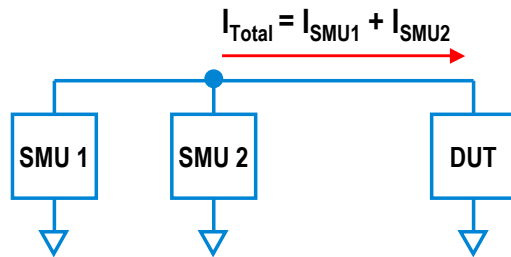


**Mistake #8: Improperly connecting
SMUs in parallel**



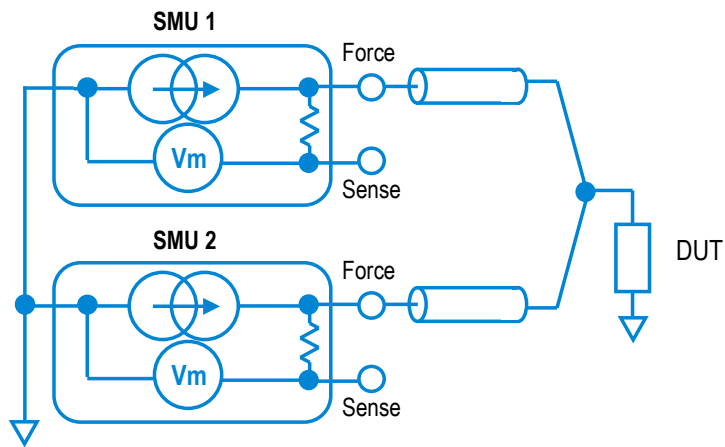
Why Would I Connect SMUs in Parallel?

- Connecting SMUs in parallel allows you to increase the total current delivered to a DUT



Connecting SMUs in parallel has many practical benefits. However, the actual implementation must be done carefully due to practical limitations of the SMUs.

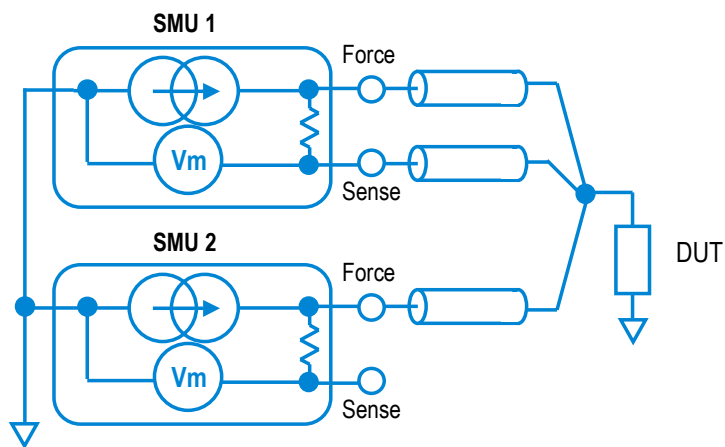
I Force, V Measure (Non-Kelvin Connection)



- Easy to do: Can control with I/CV
- Voltage measurement accuracy is relatively poor

This shows a simple case where the two SMUs are both in current force mode (non-Kelvin connection).

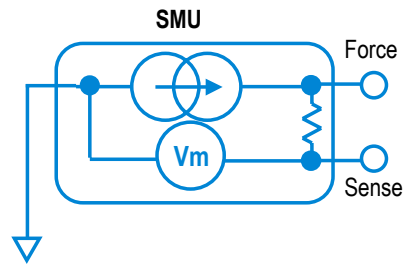
I Force, V Measure (Kelvin Connection)



- Easy to do: Can control with I/CV
- High voltage measurement accuracy

This shows a slightly more complicated case where both SMUs are in current force mode, but one SMU is connected in a Kelvin configuration to improve the voltage measurement accuracy.

Current Force Mode is not Always Useful

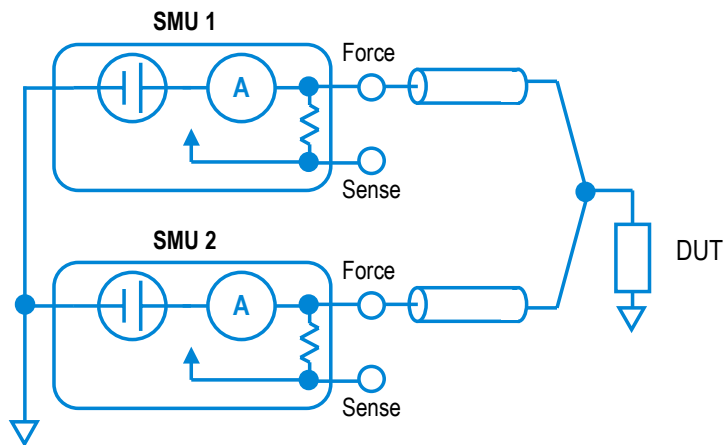


Paralleling SMUs in current source mode is easy, BUT:

- **Not all applications can be covered this way**
- **It begs the question of how to parallel SMUs in voltage force mode**

Connecting SMUs in parallel in current force mode is relatively trivial. However, the usefulness of this procedure is limited. Most of the time we want to force a voltage, and we want to place SMUs in parallel in order to improve the the current sourcing capability of our voltage source.

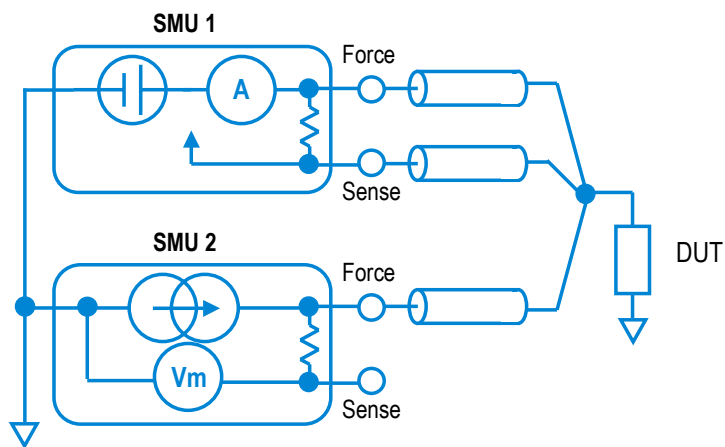
V Force, I Measure (Non-Kelvin Connection)



- Voltage force accuracy is poor
- Easy to use in concept, BUT requires great care to prevent two voltage sources from interfering with one another

This is the simplest case of paralleling two SMUs in voltage force mode. Since this is a non-Kelvin connection, the current measurement accuracy is rather poor. In addition, as we shall see this configuration is quite tricky if we want to keep the two SMUs from conflicting with one another.

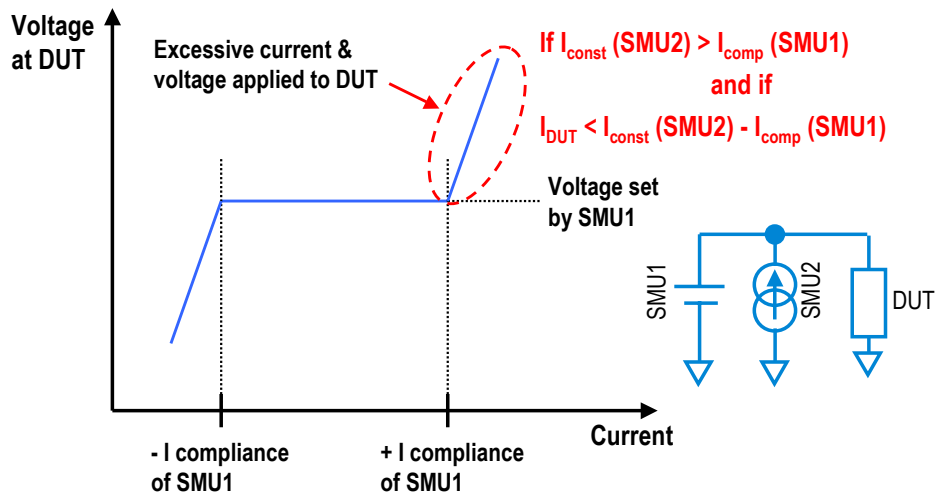
V Force, I Measure (Kelvin Connection)



- High voltage force accuracy
- Requires sophisticated measurement control software

In this situation, one SMU is forcing voltage and measuring current, while the other is acting as a current source. This configuration can work well, but it has some limitations as is shown in the next slide.

Issues with Voltage Force Solution Just Shown:



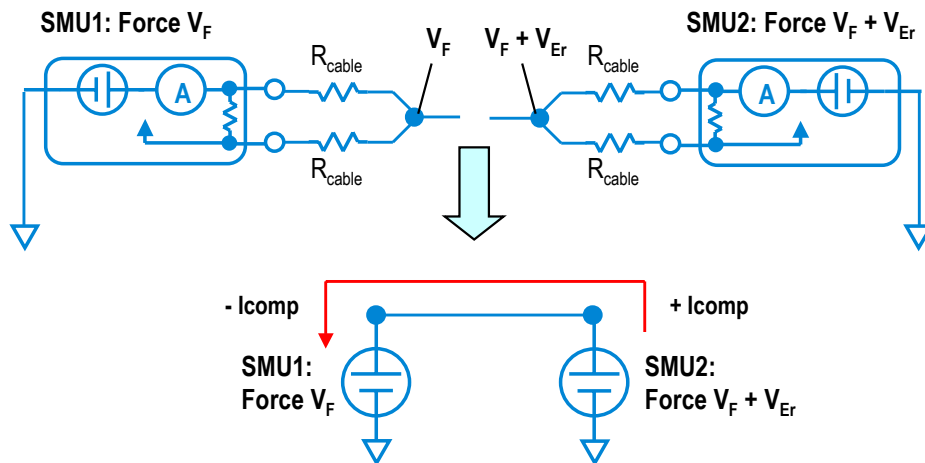
The Most Common Mistakes Made in Parametric Test



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For the case shown in the previous slide, if the measured current deviates from the +/- I compliance range of the SMU in voltage force mode, then erroneous measurement results will be obtained.

Problem with Connecting two V Force Mode SMUs in Parallel (Kelvin Configuration)



The Most Common Mistakes Made in Parametric Test

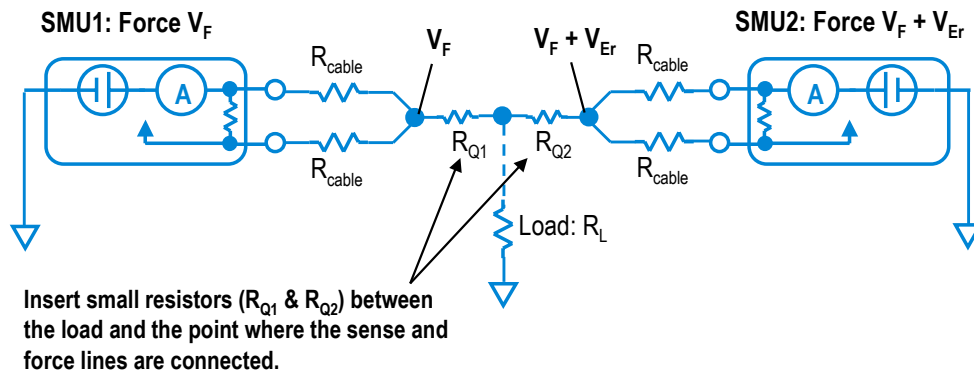


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Let us examine the case of placing two SMUs in parallel in voltage force mode with a Kelvin configuration.

The problem with this approach is that, even if you specify the exact same voltage for both SMUs, in practice there will be some voltage force error between the SMUs. This will cause one SMU to source current into the other SMU and very quickly one or both SMUs will hit their current compliance limit.

Solution: Quasi-Kelvin Mode with 2 SMUs in Parallel



The Most Common Mistakes Made in Parametric Test

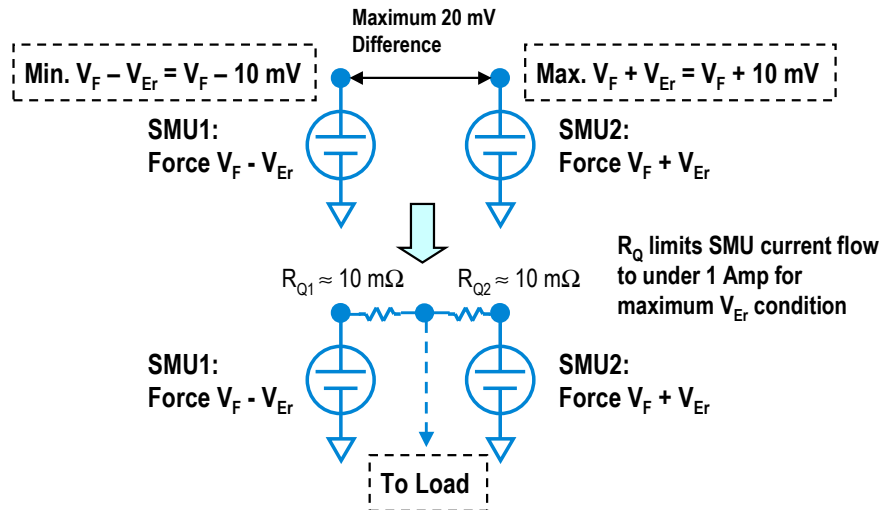


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To prevent the situation shown on the previous slide, we create a “quasi-Kelvin” configuration using two small resistors. These resistors limit the current flow to keep the SMUs from hitting compliance.

Determining R_Q Value for Quasi-Kelvin Configuration

Maximum Force Voltage Error in 20V Range: $\pm 0.03\% \times 20 \text{ V} + 4 \text{ mV} = \pm 10 \text{ mV}$



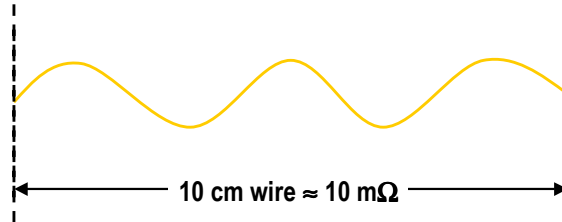
The Most Common Mistakes Made in Parametric Test

 Agilent Technologies

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This slide calculates the values of the resistors required in order to limit the current flow from one SMU to another.

How Do I Create a 10 mΩ Resistance?



A 10 cm wire has an equivalent resistance of about 10 mΩ, so this is usually the simplest means to insert this resistance.

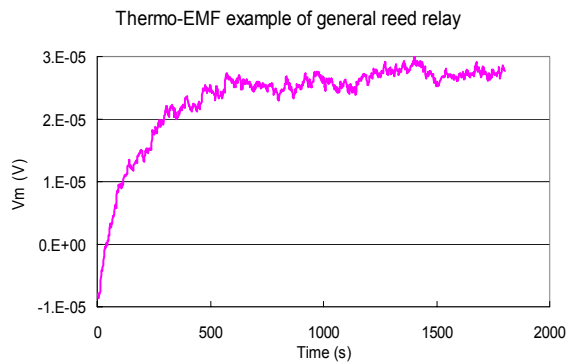


**Mistake #9: Failure to account for
electro-motive force (EMF) on
sensitive voltage measurements**



Thermo Electro-Motive Force (EMF): What is It?

- A transient voltage pulse that is associated with reed relay switches.



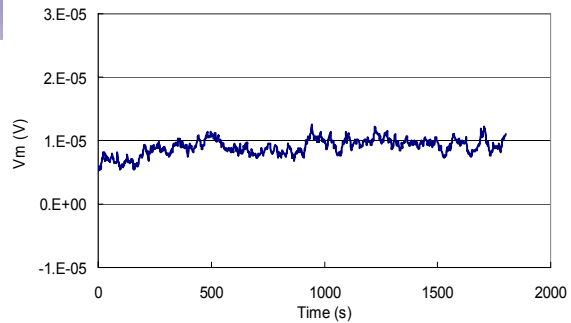
Note: This is NOT an example of the relays used in our instrumentation.

Conventional reed relay switches, which can be obtained from a variety of sources, typically generate a thermo-EMF (electro-motive-force) ranging from a few tens of micro-volts to a few hundreds of micro-volts after the relay activation current is turned on or off. This voltage drift, which can continue for several minutes before dying out, is usually not acceptable when making precision measurements such as those required for BJT matching characterization. The above figure shows an example of the thermal-EMF generated by a commercially available reed relay.

Agilent 4073A/B Relays Eliminate Thermo-EMF



Agilent 4073A example through the switching matrix



The Most Common Mistakes Made in Parametric Test

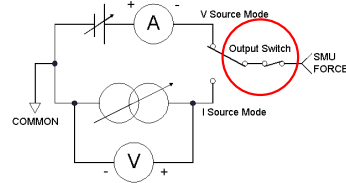


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The Agilent 4073A and 4073B test systems use a proprietary reed relay that almost completely eliminates the thermo-EMF problem. The above graph illustrates the dramatic difference between the performance of the 4073A/B relays versus those shown on the previous slide. As you can see, the relays in the 4073A/B act as near ideal switches.

Managing the Use of a Reed Relay Switch

- **Wait until the thermo-EMF has stabilized to its final value.**
 - For the 4156C and E5270, set the SMU output relay to its on (closed) state after warm-up and keep it there.
- **Complete the measurement as quickly as possible.**
 - Complete the measurement within 10 seconds. This keeps the total drift to less than a few micro-volts.

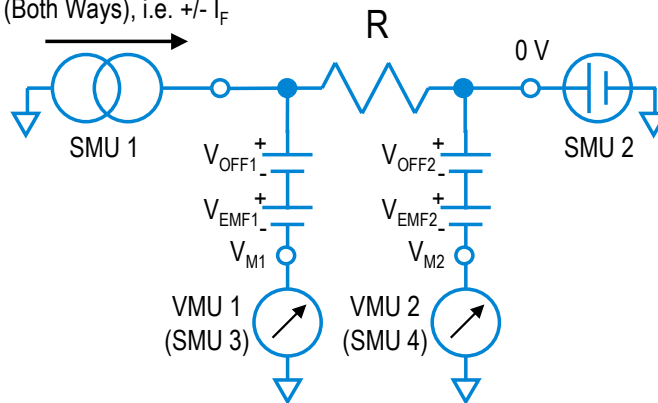


The reed relays used in semiconductor parameter analyzers and switching matrices are not as close to the ideal case as are those used in the 4073A/B. The data sheet specifications of the parameter analyzer SMUs take the thermo-EMF effects into account so users do not have to worry about this effect for normal applications. However, when performing measurement for matching applications that require extremely high levels of accuracy beyond the normal specifications, the guidelines shown above can minimize or eliminate the thermo-EMF effects.

Kelvin Resistance Measurement

$$R = (V_{M1} - V_{M2})/I_F$$

Force Current Twice
(Both Ways), i.e. $\pm I_F$



Key Points:

- 1) Make sure that you eliminate Joule self-heating effects
- 2) Measure twice and average the two resistances

The Most Common Mistakes Made in Parametric Test



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A resistor can be measured accurately in two ways: using the Kelvin (or 4-terminal) measurement method with a precision resistance meter, or using SMUs and VMUs as shown in the above figure. To obtain a successful resistance measurement, two things are important: 1) elimination of the Joule self-heating effect, which will increase the temperature of the device, and 2) measuring twice, which requires applying current in both directions by switching the polarity of the force current (I_F). By measuring twice, you can take the average of the two resistances to cancel the offset voltage of the VMU (or voltage sense) and the thermo-EMF of the connection terminal. The easiest way to measure resistors is by using the SMU/VMU method, because the current (effectively the power) applied to the resistor can be controlled.

In the case of the E5270B/4157B, the MPSMU and HRSMU both have a voltage measurement resolution of $0.5 \mu\text{V}$, which is almost as good as the voltage measurement resolution of the 4155C/4156C VMUs (which is $0.2 \mu\text{V}$).

Note: It is left as an exercise for the reader to convince yourself that by applying Kirchoff's current law and voltage law to the above circuit for the two different cases involving the force current and then averaging the two calculated R values, the effects of the thermo-EMF and voltage offset are eliminated.

VBScript for Kelvin Resistance Measurement

```
Kelvin_R.vbs - WordPad
File Edit View Insert Format Help
Kelvin_R.vbs - WordPad
' Kelvin Resistance Measurement Using VMUs:
' Must use Agilent FLEX Programming Mode:
call NTUtils.CommWrite (linklabel, "US " & Chr(13) & Chr(10), 10)
' ASCII w/header <,>:
call NTUtils.CommWrite (linklabel, "FMT 5" & Chr(13) & Chr(10), 10)
' Spot measurement:
call NTUtils.CommWrite (linklabel, "MM 1,23" & Chr(13) & Chr(10), 10)
' Set auto-calibration mode to OFF:
call NTUtils.CommWrite (linklabel, "CM 0" & Chr(13) & Chr(10), 10)
' Set Integration Time to Long:
call NTUtils.CommWrite (linklabel, "SLI 3" & Chr(13) & Chr(10), 10)
call NTUtils.CommWrite (linklabel, "SIT 3,10" & Chr(13) & Chr(10), 10)
' Set the VMU mode to differential:
call NTUtils.CommWrite (linklabel, "VM 23,2" & Chr(13) & Chr(10), 10)
' Connect the pins:
call NTUtils.CommWrite (linklabel, "CN " & Chr(13) & Chr(10), 10)
' Wait for the Thermo-EMF to settle:
call NTUtils.CommWait ((emfdelay*1000) & Chr(13) & Chr(10))
' Set up voltage measurement conditions:
call NTUtils.CommWrite (linklabel, "RV 23,10,2" & Chr(13) & Chr(10), 10)
' Perform Measurement Twice Using Iforce +/-:
For i = 0 to 1 Step 1
' Set up the dc current/voltage sources:
call NTUtils.CommWrite (linklabel, "DI " & Chr(13) & Chr(10), 10)
call NTUtils.CommWrite (linklabel, "DV " & Chr(13) & Chr(10), 10)
' Wait for circuit to stabilize:
call NTUtils.CommWait (1000 & Chr(13) & Chr(10))
' Execute the measurement:
call NTUtils.CommWrite (linklabel, "XE" & Chr(13) & Chr(10), 10)
' Check if operation is complete:
call NTUtils.CommWrite (linklabel, "*OPC?" & Chr(13) & Chr(10), 10)
call NTUtils.CommRead (linklabel, B_str, 100, 10)
' Check if error(s) occurred:
call NTUtils.CommWrite (linklabel, "ERR?" & Chr(13) & Chr(10), 10)
call NTUtils.CommRead (linklabel, A_str, 100, 10)
' Get the first error message:
A_str_lth = Len(A_str)
For j = 1 to A_str_lth

```

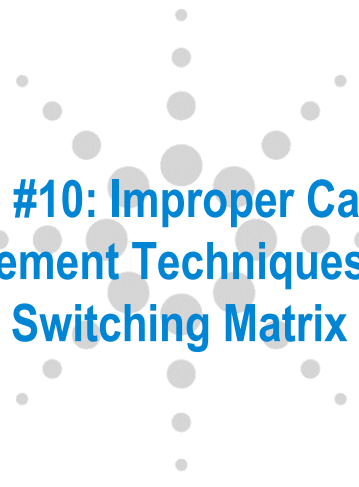
To obtain the fine control over the instrument measurement resources necessary to make accurate matching measurements when using ICS or I/CV, it is usually preferable to create a Visual Basic Script (VBScript) algorithm. The VBScript option gives the ability to precisely control all of the instrument measurement resources. A sample script is shown above (many such sample algorithms are available from Agilent).

VBScript Measurement Results

The screenshot shows the ICS software interface for a Kelvin resistor measurement. The main window displays a table of results for two force cases. A red box highlights the 'RAVG' column, which contains the value 99.56540. A callout box points to this value with the text: "Algorithm automatically calculates the averaged R value." Below the table, a circuit diagram shows a resistor connected between terminals A and K. The 'Measure' panel on the right includes buttons for 'Single', 'Repeat', 'Append', 'History', 'Auto Seq', and 'Stop'.

	IFORCE1	VMEAS1	RCALC1	IFORCE2	VMEAS2	RCALC2	RAVG
1	-1.00000m	-0.09956	99.56480	1.00000m	0.09957	99.56600	99.56540
2							

This page shows the measurement results for a ~ 100 Ohm resistor measured using the previously shown algorithm. Data for both the (+) and (-) Iforce cases is shown. Of course, the algorithm could be modified to only return the averaged value.

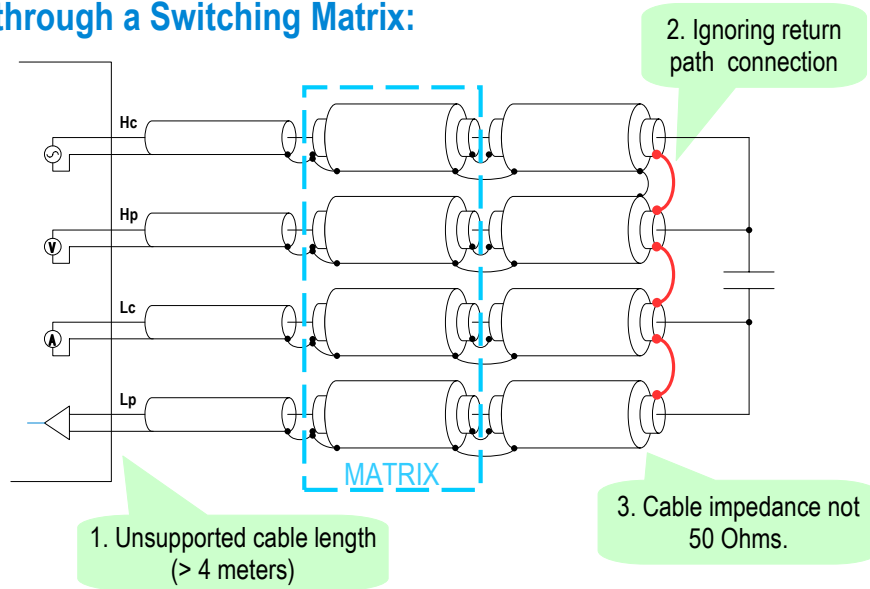


**Mistake #10: Improper Capacitance
Measurement Techniques When
Using a Switching Matrix**



Agilent Technologies

Three Most Common Mistakes Using a Four terminal pair through a Switching Matrix:



The Most Common Mistakes Made in Parametric Test



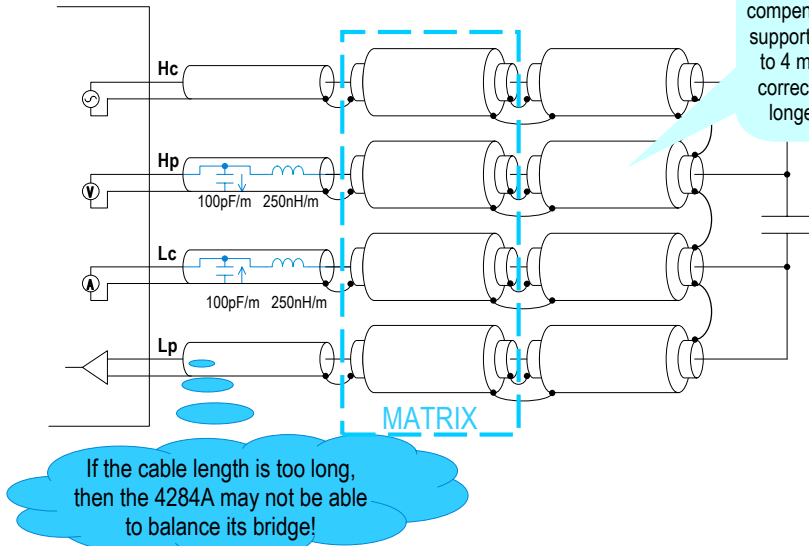
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Many users make one or more of these mistakes when connecting up a capacitance meter through a switching matrix. We will look at each of these in-turn.

Mistake 1: Unsupported Cable Length Causes Error

The 4284A can only compensate cable lengths up to 4m

The innate 4284A compensation routine only supports cable lengths up to 4 meters. Additional correction is needed for longer cable lengths.



The Most Common Mistakes Made in Parametric Test

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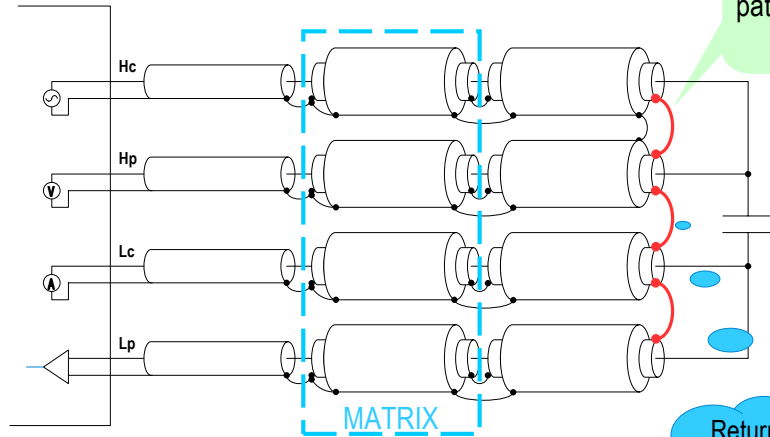
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As will be shown, proper cable length is critical for the bridge of the capacitance meter's measurement circuitry to balance.

Mistake 2: No Return Path Wire Causes Error

→ Return wire stabilizes the cable inductance.

Make return path near the device.

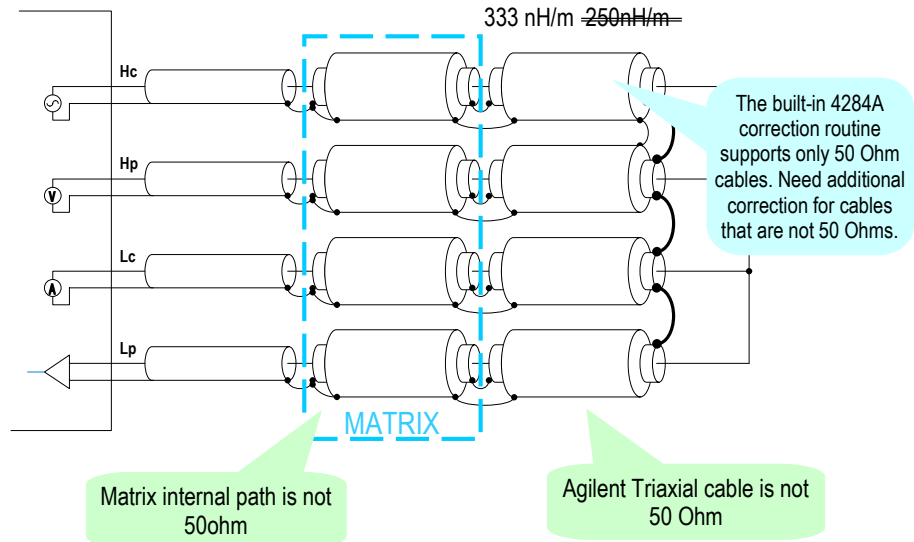


Cable inductance can change from 250 nH/m to more than 400 nH/m by removing return wire.

The outer shield of the BNC cables coming from a capacitance meter are actually NOT at ground potential, but are “virtual grounds”. In order to stabilize the inductance of the cables, it is important to supply a “return path” through the BNC shield.

Mistake 3: Wrong Cable Causes Measurement Error

4284A calibration routine expects 50 Ohm cable environment



The Most Common Mistakes Made in Parametric Test



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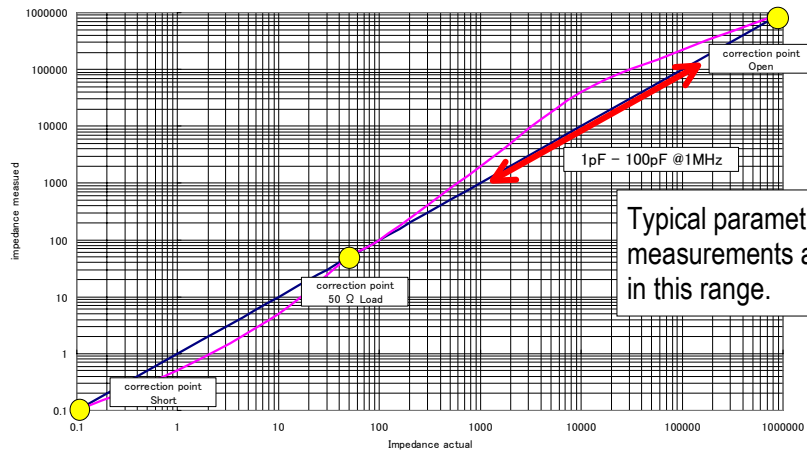
Capacitance meters typically expect a 50 Ohm environment. However, the switching matrix paths and the additional triaxial cable coming from the switching matrix outputs do not have a 50 Ohm characteristic impedance.

Four terminal pair summary

- In order to archive accurate capacitance measurement,
 - Capacitance meter must be used under designed condition, such as specified cable length, impedance and return path.
- However,
 - It is very difficult to use the capacitance meter under the ideal condition, especially through a switching matrix.
- Therefore, we need additional correction to capacitance meter ...

Capacitance meters require some very specific conditions to be met in order to supply accurate measurement results. However, it is very difficult to meet all of these conditions, particularly when measuring semiconductor devices.

Limitation of OPEN/SHORT/LOAD correction

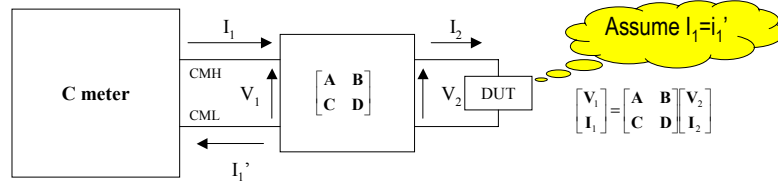


Open/Short/Load correction is not perfect. Load impedance should be same range as the device impedance you want to measure.

Unfortunately, the typical input impedance of a semiconductor device is very much higher than 50 Ohms.

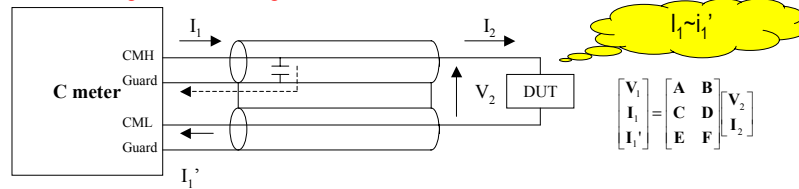
Open/Short/Load Correction Model

Ideal



- The built-in 4284A compensation algorithm extracts four parameters using three (open/short/load) measurements.

If the cable length is too long...



- Cables that are too long invalidate the assumptions. The number of port parameters becomes greater than four and **the built-in 4284A compensation routine does not work.**

This slide shows why it is important to use cables no longer than 4 meters. Although this example deals with the 4284A, the situation with the 4294A is similar.

Open/Short/Load correction summary

- Open/Short/Load correction is not perfect.
- For accurate correction
 - Cable length must be within the CMU design limits.
 - Load impedance must be around the DUT impedance.

SWM connections typically make the length > 4 meters

Not easy!!

DUT impedance values typically vary from 1 KOhm to 1 MOhm

If the above conditions are not met, then the built-in 4284A compensation does not work correctly.

Until now, there have not been too many good ways to switch between CV and IV measurements using a switching matrix.

Our New Solutions Enable Accurate Measurement

- We have new solutions for both positioner-based and prober-card based IV and CV measurement.
- Both solutions provide accurate CV / IV measurement.



The Most Common Mistakes Made in Parametric Test



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Agilent now has solutions for both positioner-based and probe card-base CV/IV measurement.

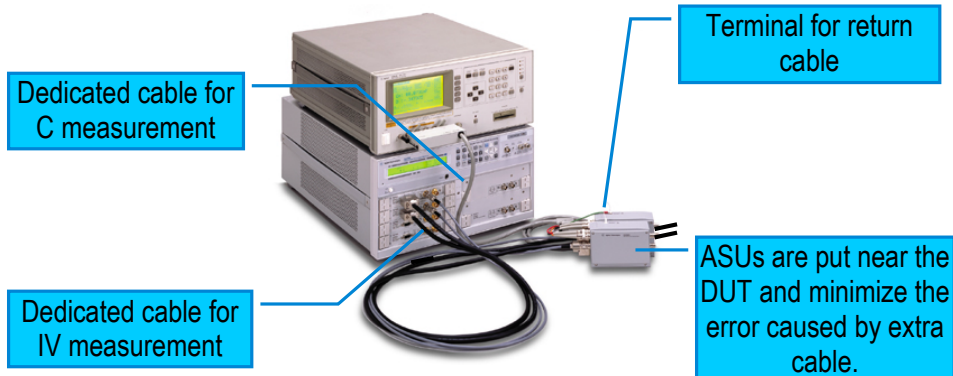
1. For positioner-based measurement, we have introduced the atto-sense and switch unit (ASU), which works with the E5270B high-resolution source/monitor unit (HRSMU). The ASU has two BNC inputs that are optimized for use with a capacitance meter. This allows you to switch between CV measurements (using a capacitance meter) and IV measurements (using the E5270B/4157B) without having to change any cables.
2. For probe card-based measurements, we have introduced the 41000 Series integrated Parametric Analysis and Characterization Environment (iPACE).

Solution #1: E5270B with ASU (Positioner-Based)

- ASU (Atto Sense & Switch Unit) supports both IV and CV measurement. It switches the IV and CV path near the DUT so that the built-in 4284A compensation routine works correctly.

C accuracy: 0.1% @100pF, 1MHz (Preliminary)

Maximum C measurement frequency: Up to 5 MHz



The Most Common Mistakes Made in Parametric Test

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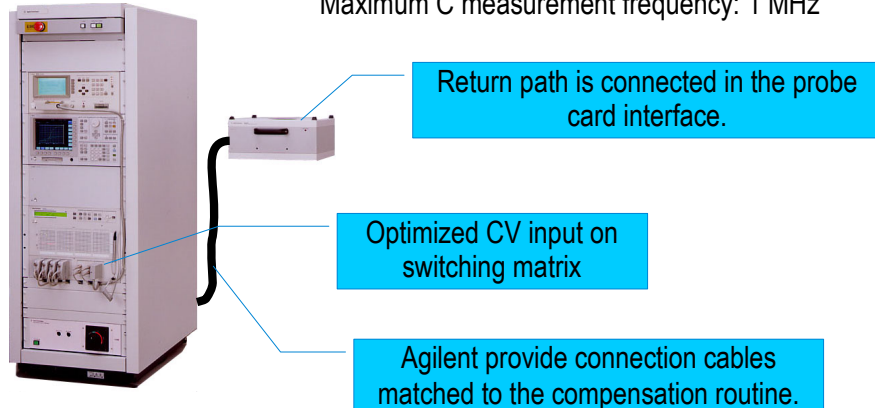
As you can see, for the case of positioner-based measurement the E5270B/4157B ASU solves the problems associated with using a capacitance meter in conjunction with a parameter analyzer. By keeping the CV measurement cable length fixed, the calibration and error correction required with a conventional switching matrix is eliminated.

Solution #2: Agilent 41000 Integrated Solution (Probe-Card Based)

- **Integrated solution provides total measurement environment.**

C accuracy: <0.4% @100pF, 1 MHz

Maximum C measurement frequency: 1 MHz



The Most Common Mistakes Made in Parametric Test



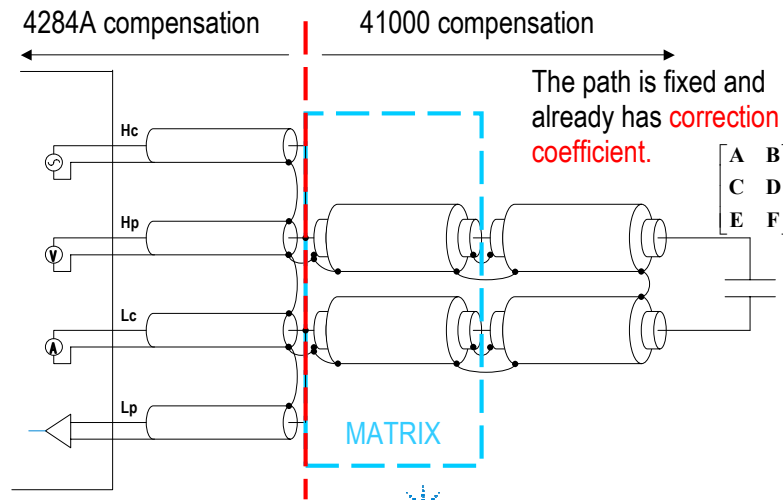
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The 41000 Series solves the CV/IV measurement dilemma for the case of probe card-based wafer probing. The 41000 is shipped already racked and cabled, and all of the connections necessary for accurate CV measurement have already been taken care of for you.

In addition, the B2200A/B2201A switching matrices have built-in compensation routines for compensating capacitance measurements made through them.

Solution #2: Why is the integrated solution effective ?

Specially designed correction routine is provided by the system.



The Most Common Mistakes Made in Parametric Test

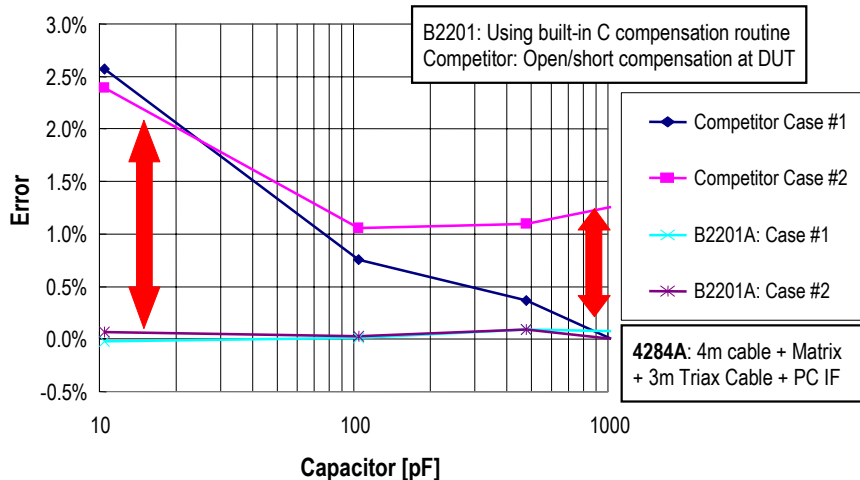
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The 41000 solution breaks the capacitance compensation up into two parts. The first part is taken care of by the capacitance meter. The second part is taken care of by the B2200A/B2201A switching matrices.

Capacitance Measurement Error

Competitor's Matrix Has no Compensation Routine!



B2201: Using built-in C compensation routine
Competitor: Open/short compensation at DUT

4284A: 4m cable + Matrix + 3m Triax Cable + PC IF

This plot shows the capacitance measurement error of Agilent's switching matrix (B2201A) versus that of our competitor. Comparable combinations of input/output connections are shown.

New Capacitance Measurement Solutions - Summary

- CMU built-in correction is only effective under the designed condition and difficult to apply to SWM.
- Agilent can provide new two solutions for CV / IV measurement.

Solution #1: E5270B + ASU : Maintains the CMU compensation limit.

Solution #2: 41000 iPACE : Total correction routine for matrix & cable.



The Most Common Mistakes Made in Parametric Test



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Agilent can supply CV/IV measurement solutions for both positioner-based and probe card-based measurement environments.

Conclusions / Summary



- A little understanding can go a long way towards helping you improve your parametric measurement skills.
- More information is available in our “Parametric Test Assistant CD” (Agilent Publication # 5988-9736EN)
- Live phone-based assistance is available by calling Agilent’s US Customer Care Center at: 1-800-829-4444