

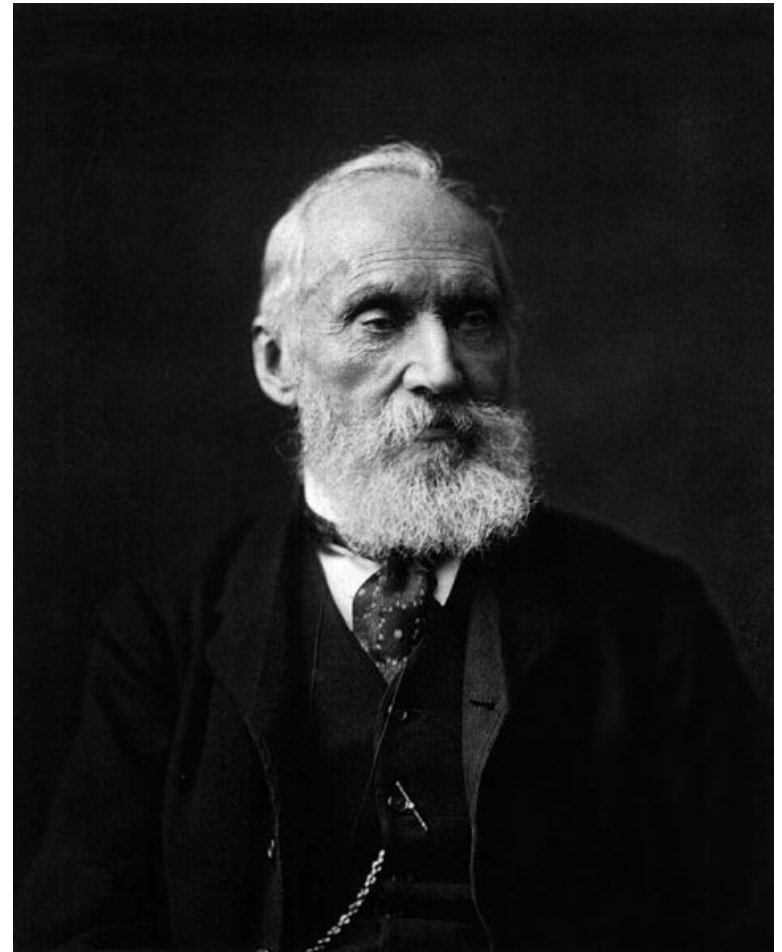
Kelvin Contactors – A Tutorial

Jim Brandes, Multitest, j.brandes@multitest.com

What is a Kelvin Connection?

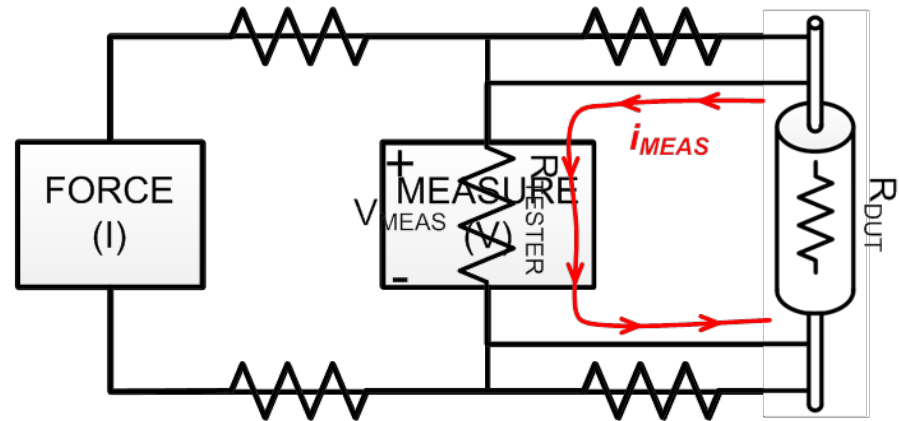
It is not a new idea:

Four-terminal sensing is also known as Kelvin sensing, after William Thomson, Lord Kelvin, who invented the Kelvin bridge in 1861 to measure very low resistances. Each two-wire connection can be called a Kelvin connection. A pair of contacts that is designed to connect a force-and-sense pair to a single terminal or lead simultaneously is called a Kelvin contact.

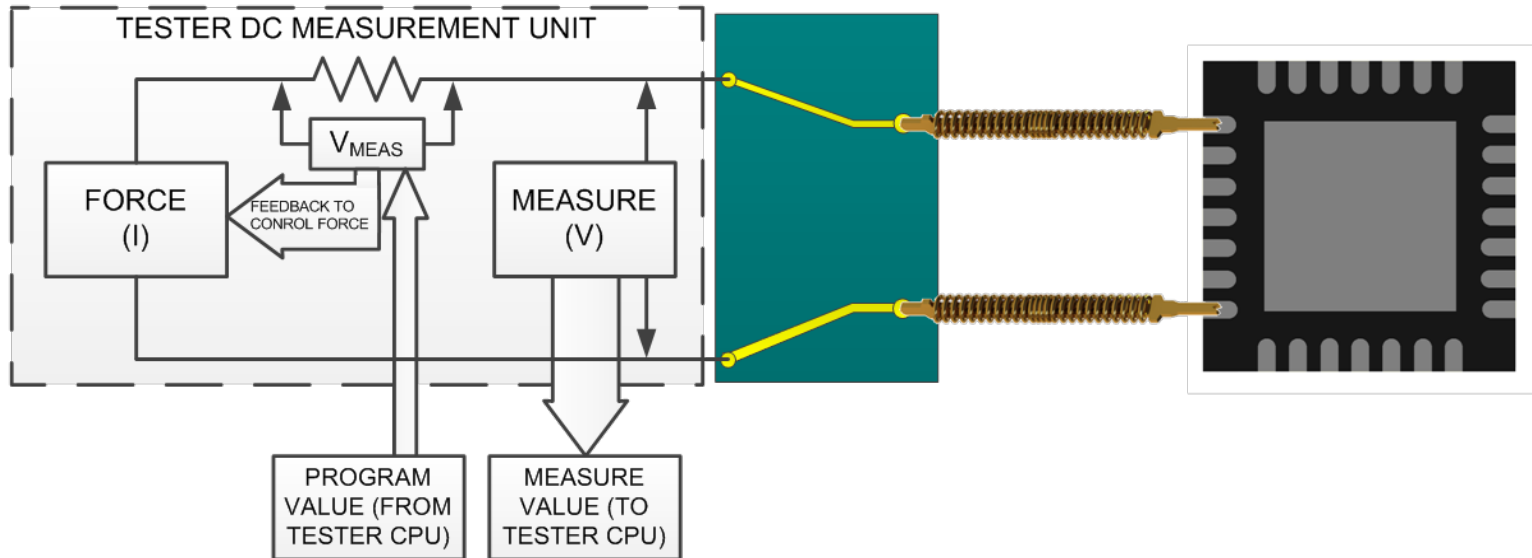


How does a Kelvin Connection Work?

- > Current to device is supplied by one pair of wires (FORCE)
- > The resistance of the device is determined by measuring the voltage drop
- > The current also creates a voltage drop in path to device
- > To avoid including this voltage in the measurement, a separate pair of wires (SENSE) is connected directly to the device
- > Accuracy dependent on measurement impedance being very high
 - > Negligible current on sense path
 - > Negligible voltage drop on sense path

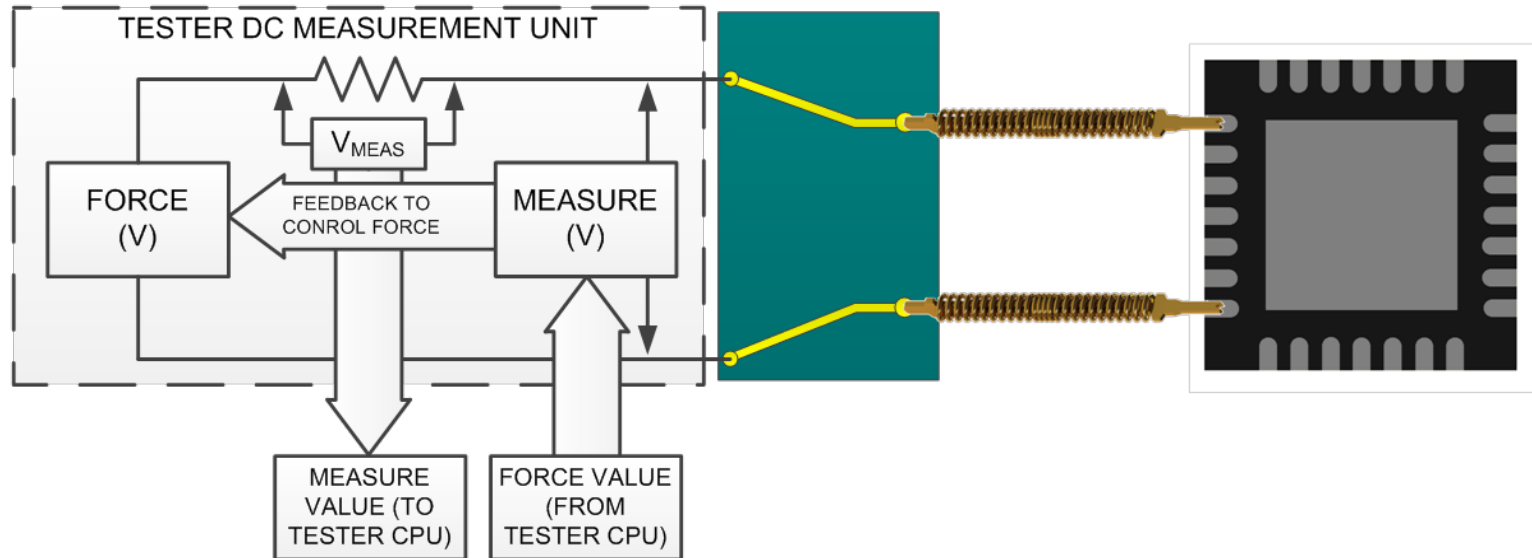


IC Test: Non-Kelvin Voltage Measurement



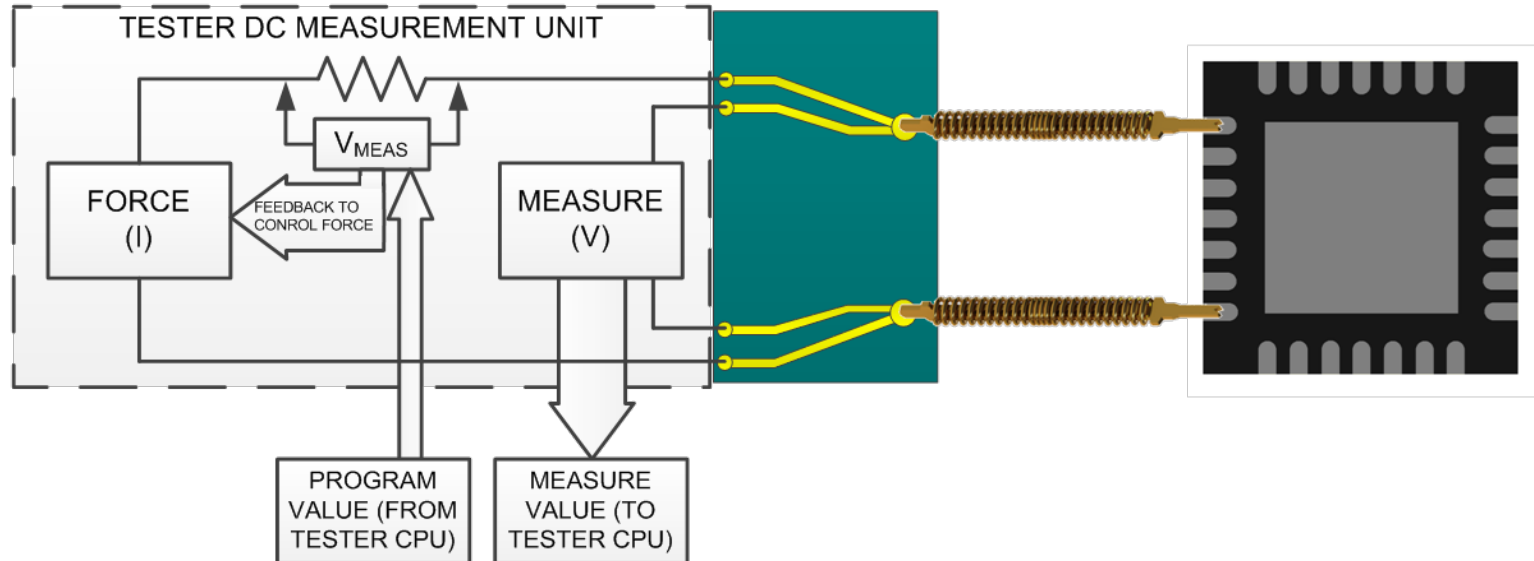
- > Tester CPU sends program force current value to DCMU
 - > Current out of DCMU is sensed as V-drop across small R
 - > Sensed value compared to program value to control force unit
- > Voltage measured at output of DCMU
 - > Measured value sent to tester CPU to compare to limit(s)
- > Measure error due to voltage drop on the path: PCB and Contactor

IC Test: Non-Kelvin Current Measurement



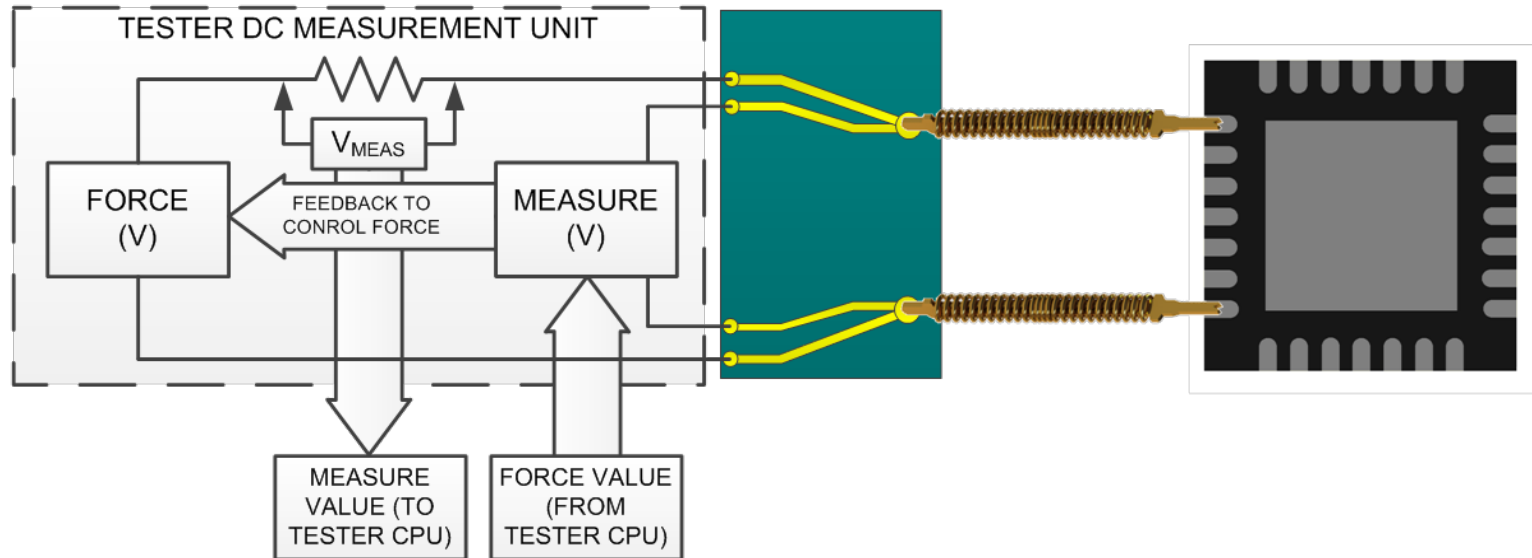
- > Tester CPU sends program force voltage value to DCMU
 - > Voltage at out of DCMU is sensed
 - > Sensed value compared to program value to control force unit
- > Current measured as voltage drop across small R in path
 - > Measured value sent to tester CPU to compare to limit(s)
- > Force error due to voltage drop on the path: PCB and Contactor

Force I / Measure V with Kelvin across PCB



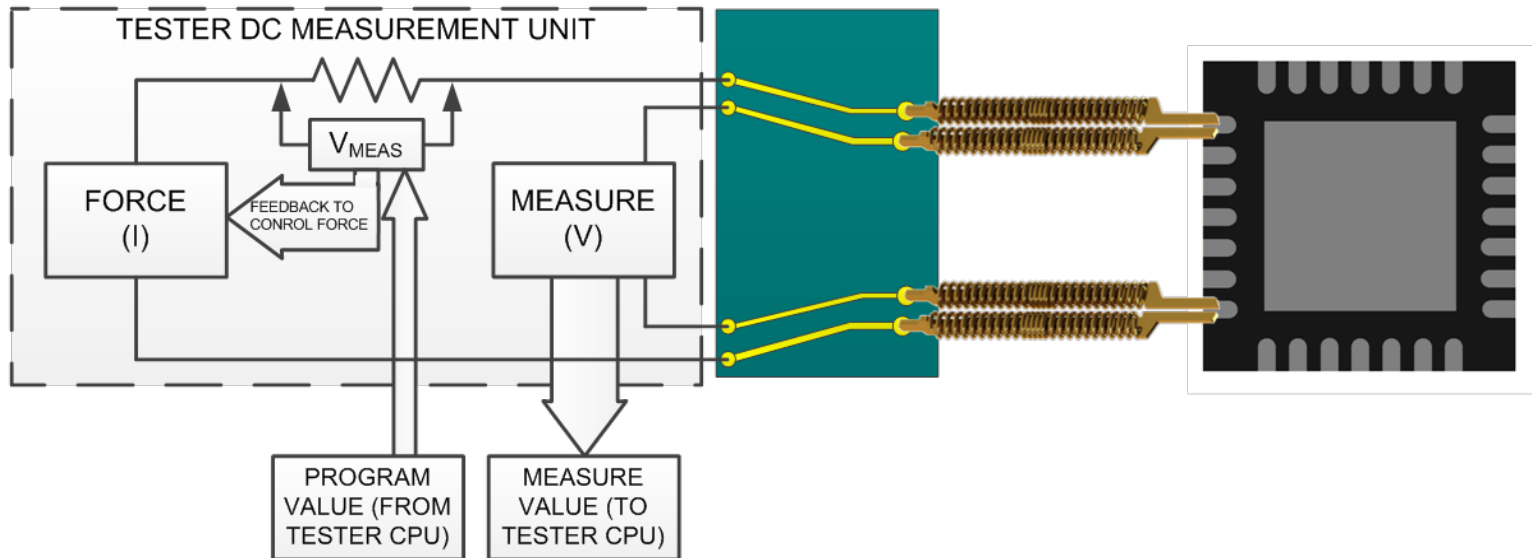
- > This is the situation when Kelvin contactors are not available
- > This is an improvement over sensing at output of DCMU
- > The voltage measured is now accurate at the point F & M are shorted
- > Still an error due to drop through contactor
- > This cannot be resolved mathematically
 - > Mechanical device: R_C varies slightly with each insertion
 - > Wear / contamination point: R_C Varies more over time

Force V / Measure I with Kelvin across PCB



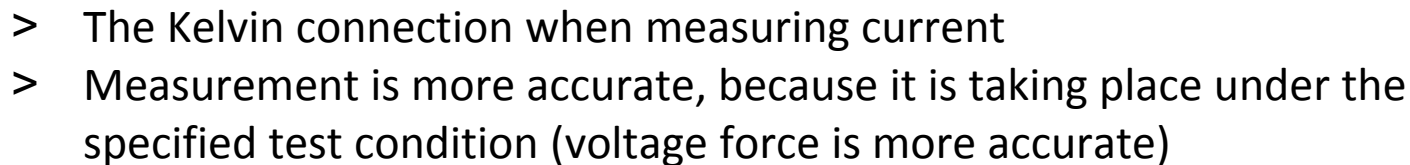
- > This has the same benefit and drawback
- > The forced voltage is accurate at the point of contact on the board
- > The voltage on the device will be different
- > The magnitude of the difference depends on the amount of current
- > The measurement accuracy is only as good as the force accuracy

Force I / Measure V with True Kelvin

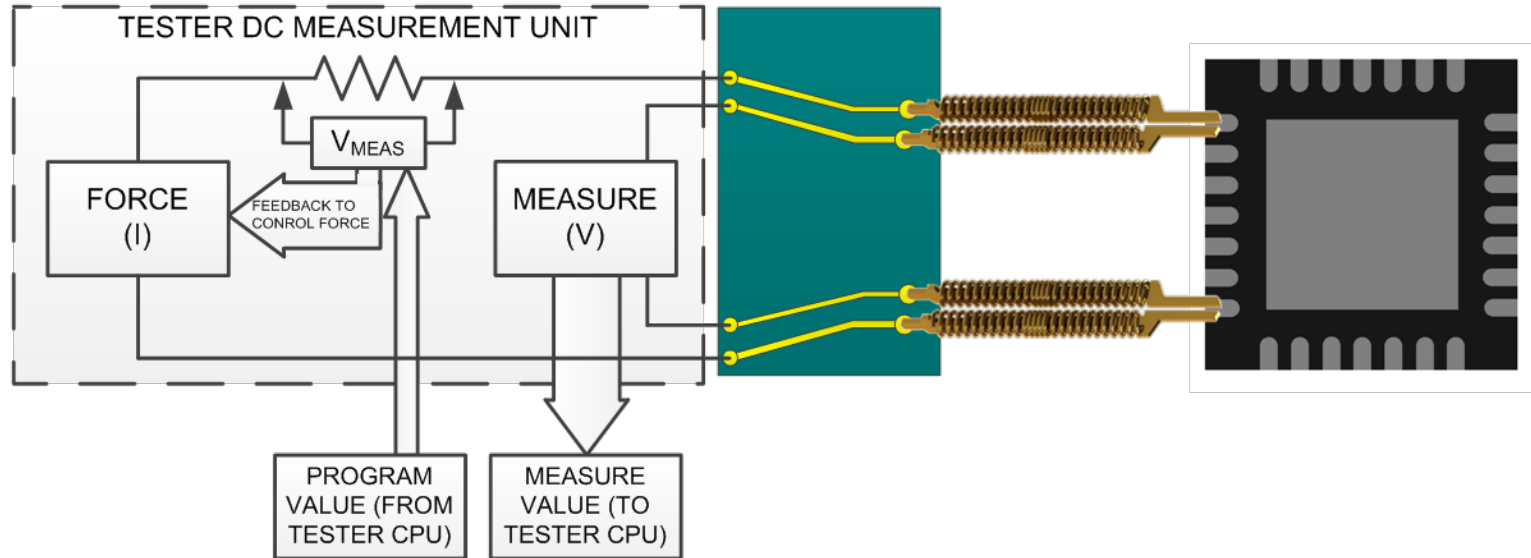


- > Here is an example of a true Kelvin connection
 - > Force and sense all the way to the DUT
 - > Electrically isolated, mechanically independent
- > Provides an accurate voltage measurement at any current flow
- > R_c is eliminated as an issue from DC parameteric measurements
 - > Voltage measurements
 - > Current measurements

Silicon Valley
Test Workshop



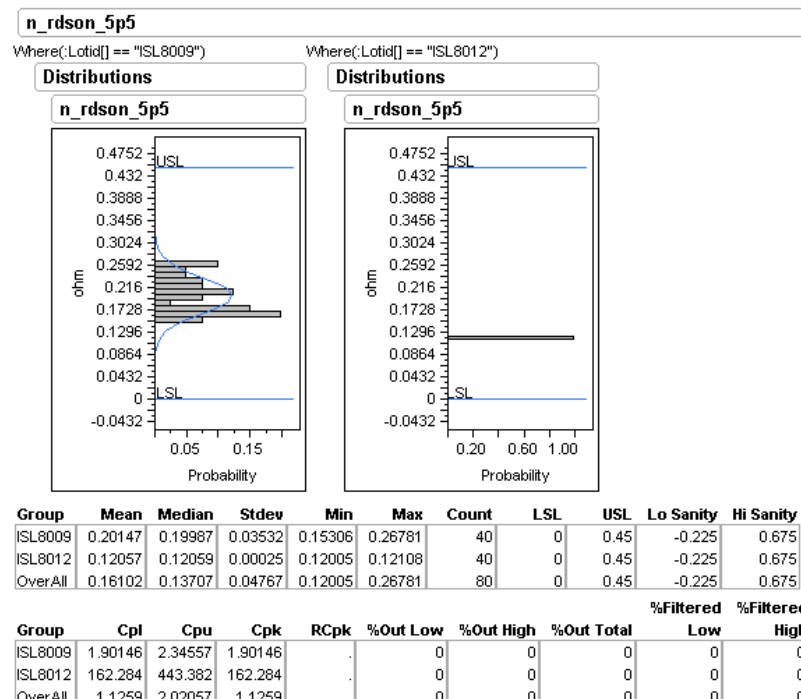
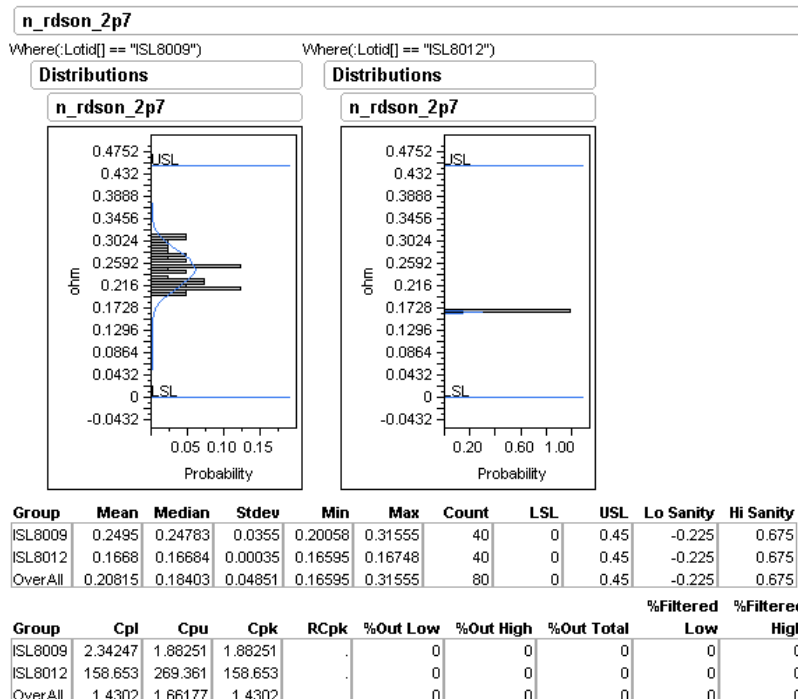
Does it *REALLY* work?



- > It should be obvious that the RC of the force path has been eliminated as an issue, but what about the sense path?
- > The resistance of the sense path is unimportant because of the miniscule current flow on the path
- > Evidence: Sometimes an isolation resistor is added to the path
 - > Reduces the *stub* on the high-speed path
 - > 10 kΩ looks like **Open** in 50 Ω environment; **Short** to measurement unit



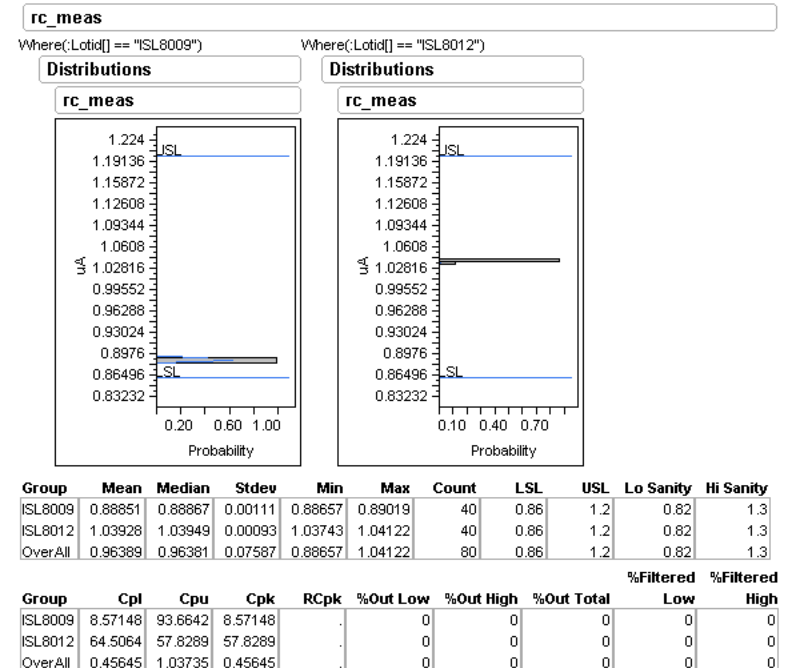
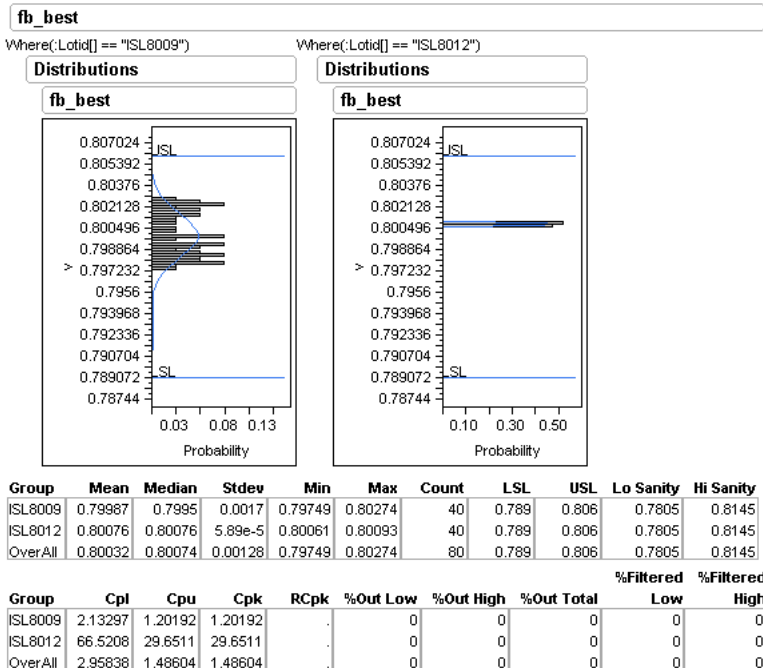
Does it *REALLY* work?



- > Comparison performed by user of single-contact vs. Kelvin
- > Two $R_{DS(on)}$ tests
- > Average resistance drops from 25 mΩ to 17 mΩ (20 mΩ to 12 mΩ on right)
- > Standard deviation drops from 35 mΩ to 350 μΩ (35 mΩ to 250 μΩ on right)



Does it *REALLY* work?



- > Comparison performed by user of single-contact vs. Kelvin
- > Uncertain about test on left, except to show how standard deviation is reduced
- > Test on right appears to be R_C : (Force voltage, measure current)
- > The current increases from 0.89 μA to 1.04 μA , implying 15% lower R_C

When is Kelvin Needed?

- Measuring low resistance values
 - Any value of a few Ohms should be considered
 - Definitely required if less than one Ohm
 - Power Controllers – $R_{DS(on)}$ parameter
 - Implied low resistance, based on current and voltage parameters
 - Voltage Regulators – V_{DO} parameter
- High accuracy voltage force or measure
 - A to D and D to A converters – small voltage increments
- Voltage measurement under high current loading
 - Power controllers / voltage regulators
- *Users need to establish standards and adhere to them*
 - $R_{DS(on)} < 1 \text{ Ohm}$; V_{OUT} accuracy $< 5\%$ of input value , for example



Gemini Kelvin probe pair

Recognizing the Need for Kelvin

> Low Resistance specifications. Examples:

- R_{DSON} (Common low-R parameter):

		switching		
Output Stage MOSFETs				
R _{DSON,LS}	Drain-to-source resistance, low side	T _J = 25°C, LDMOS only	40	mΩ
R _{DSON,HS}	Drain-to-source resistance, high side	T _J = 25°C, LDMOS only	40	mΩ
I/O Protection				

I/O Protection

- Implied $R = 280 \text{ m}\Omega$ ($280 \text{ mV} / 1 \text{ A}$):

TESTBY	steady current	CE = High, $V_{\text{IN}} = 5.0\text{V}$	170	280	μA
INPUT TO OUTPUT CHARACTERISTICS					
VDO	Drop-out voltage IN to OUT	CE = Low, $V_{\text{IN}} = 5\text{V}$, $I_{\text{OUT}} = 1\text{A}$	170	280	mV
INPUT OVERVOLTAGE PROTECTION					

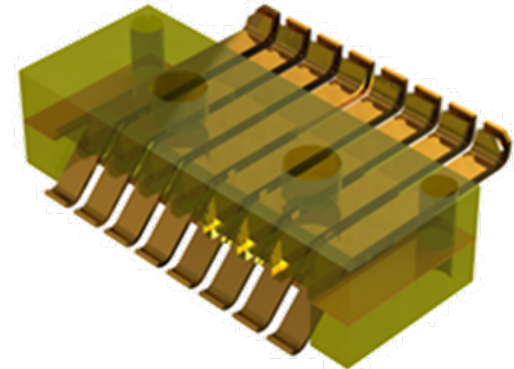
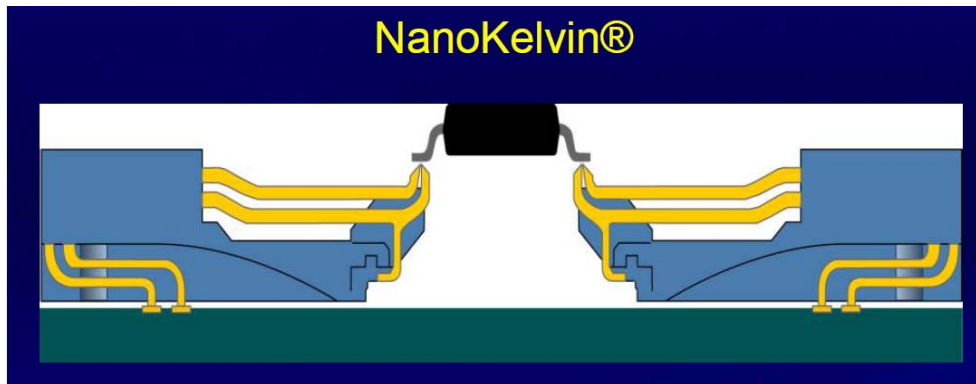
> High maintenance requirements

- Frequent probe cleaning
- Short probe life
- Indicate R_C sensitivity – should be investigated

Establish Standards – Adhere to them

- Kelvin is *initially* more expensive than non-Kelvin
 - More probes (and perhaps more expensive probes) in contactor
 - More-difficult board layout – more traces, finer pitches
 - Might require more tester resources, potentially extending test time
- Non-Kelvin is often *much more expensive* than Kelvin in high-volume production
- Frequent probe cleaning to keep test yield up
 - Reportedly as few as a few thousand insertions!
 - Can significantly cut test cell efficiency– down for cleaning when it could be running!
- Frequent probe replacement to keep test yield up
 - Reportedly as few as a few tens of thousands of insertions
 - Dramatically increases cost per insertion
- Poor yield
 - Multiple re-tests to achieve target yield
- A few thousand dollars up front can save tens of thousands in production
- Issues may not appear during Engineering development – Seen in high volume

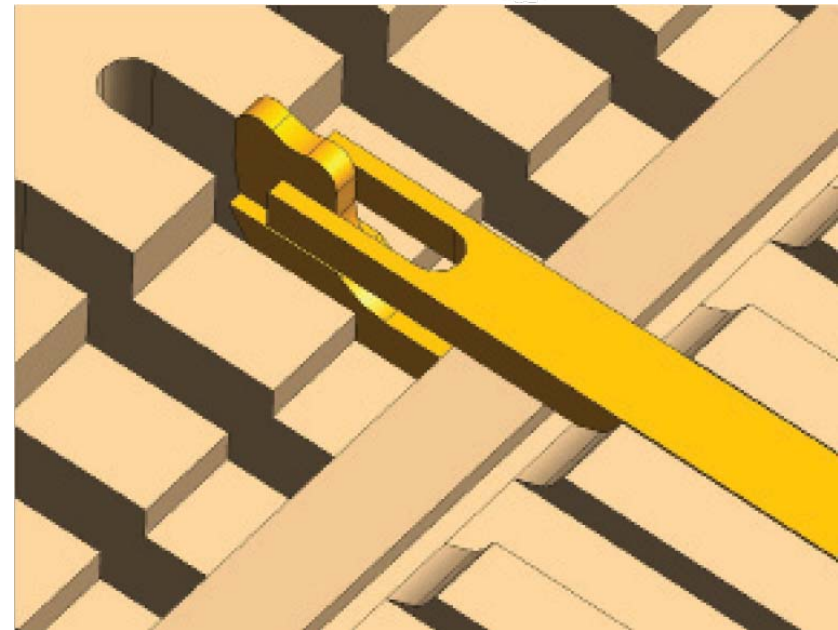
Kelvin Contact Examples (from internet)



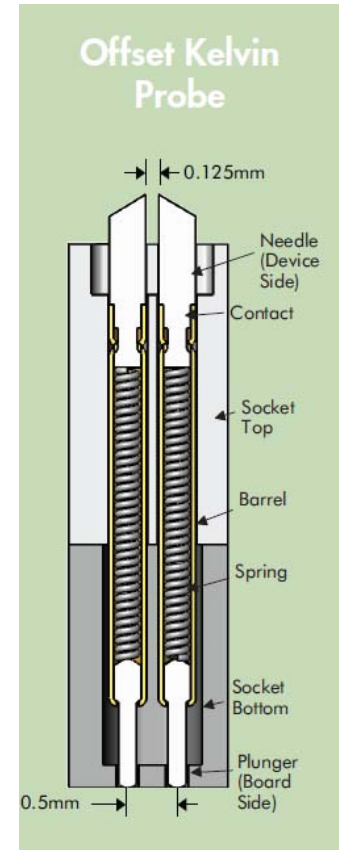
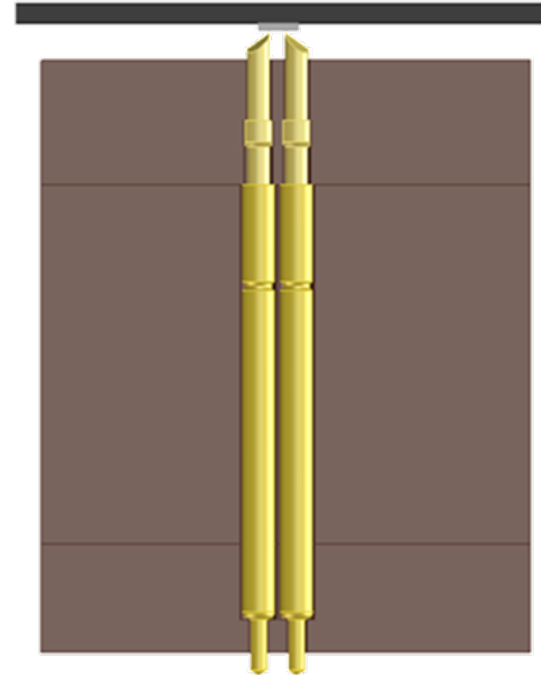
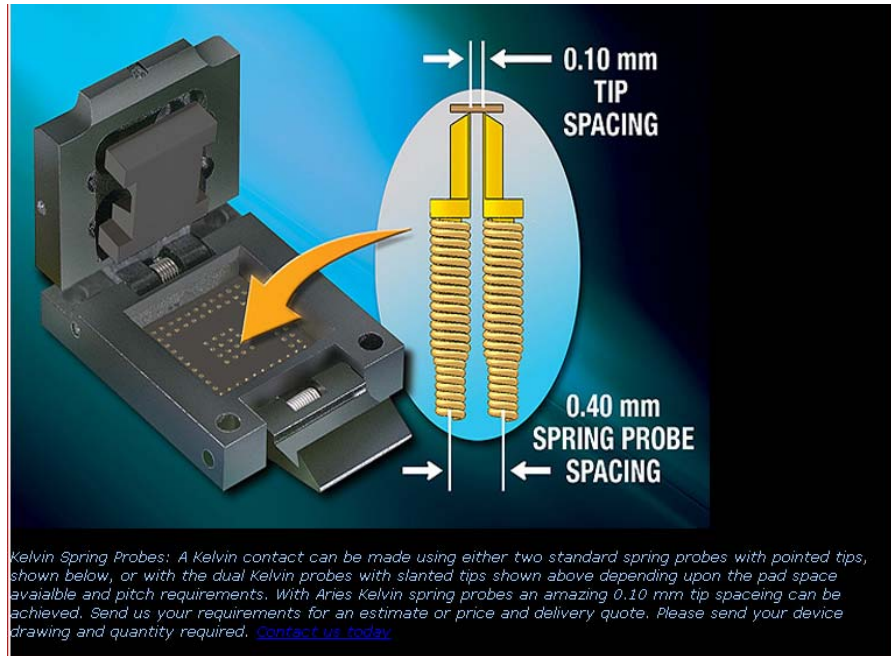
NF1.3S-Kelvin



Cantilevers
and
Rockers

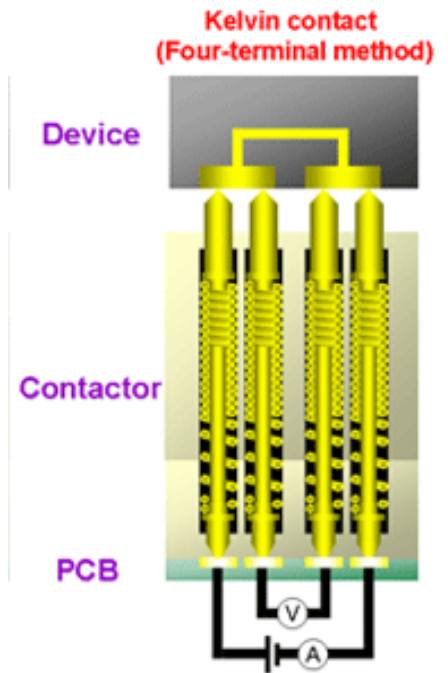
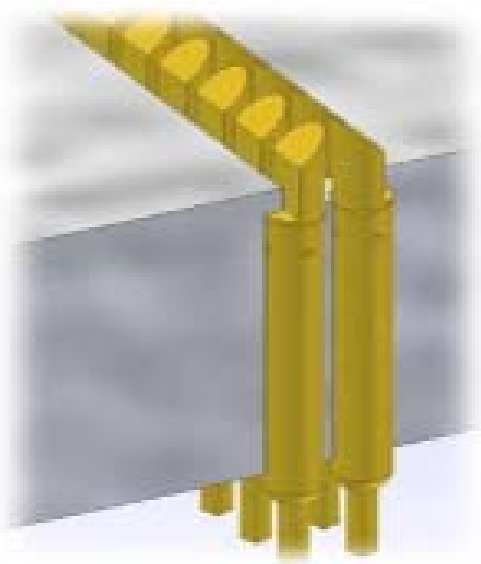
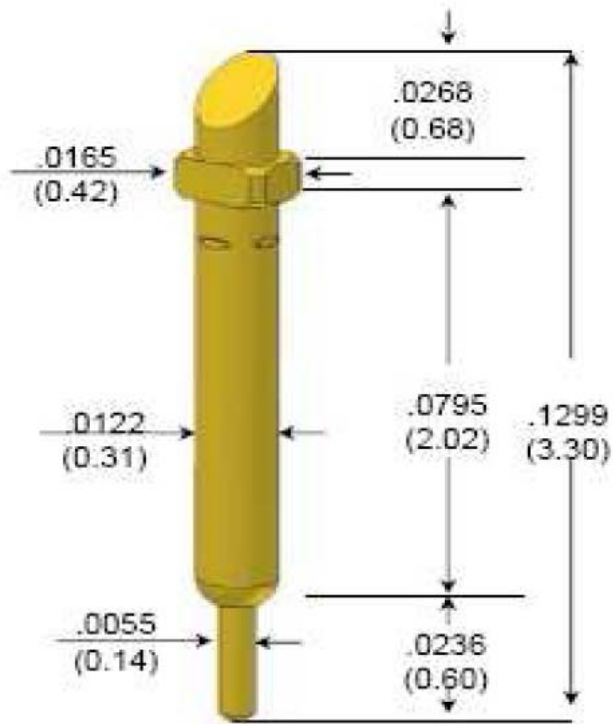


Kelvin Contact Examples (from internet)



Spring Probes

Kelvin Contact Examples (from internet)



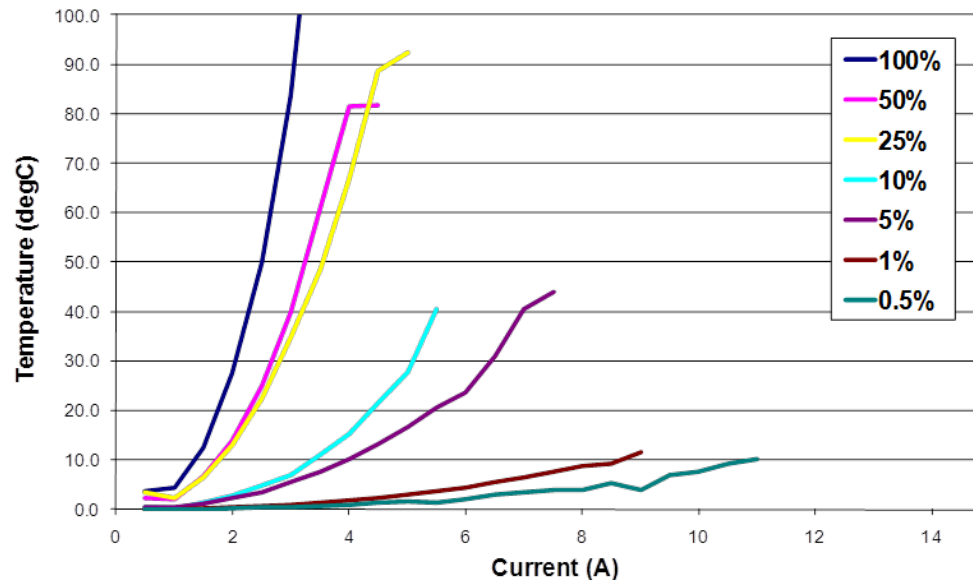
More Spring Probes

Gemini Kelvin Probe Specifications



Probe Pitch	0.4 mm and up (inline) 0.65 and up full array; 0.4, 0.5 partial array
Kelvin Tip Spacing	0.10 mm minimum
Board-Side Spacing	0.4 mm (@ 0.1 mm DUT-side spacing)
Test Height	3.22 mm
Probe Compliance	0.44 mm total (0.26 mm DUT-side)
Force at Test Height	25 – 30 g
Loop Inductance	1.05 nH (single probe) 0.65 nH (dual probe)
Bandwidth	-1dB @ 20 GHz (single probe) -1dB @ 12 GHz (dual probe)
Contact Resistance	75m Ω (typical, new probe)
Tip Styles	Single-Edge (DUT), 0.16 mm Radius (board)
Probe Finish	Hard Gold
Current Carrying Capacity	1.8 A Continuous (20° C rise) 8.6 A maximum @ 1% duty cycle

Current Carrying Capacity



The temperature rise of the spring pin due to Joule heating is measured at ½ Amp increments for both steady-state current and current at smaller duty cycles. The steady-state current that results in 20° C, 40° C, and 60° C temperature rises are shown below, as well as the maximum current at 1% duty cycle.

Gemini Kelvin	
20° C Rise Current	1.8 Amps
40° C Rise Current	2.3 Amps
60° C Rise Current	2.6 Amps
Current at 1% Duty Cycle	8.6 Amps

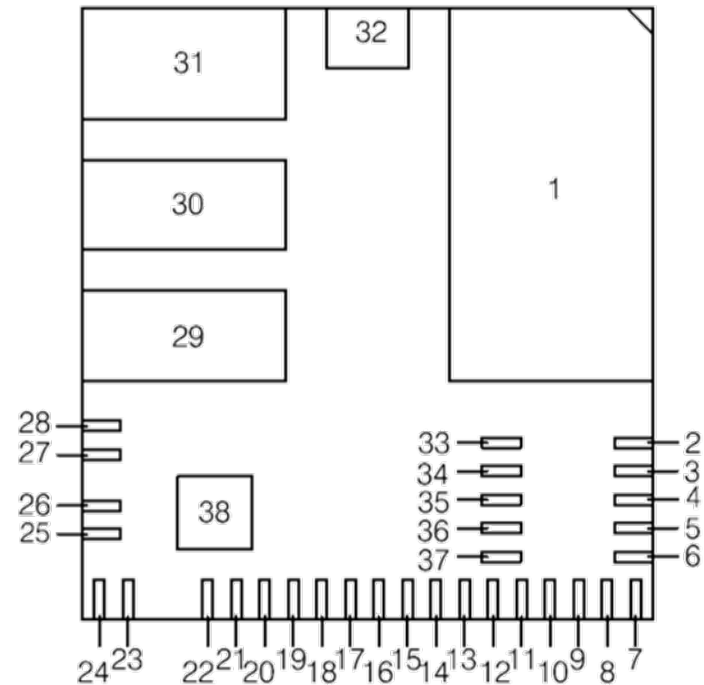
Silicon Valley Test Conference 2011

Understanding Kelvin Further

- Does not eliminate R_c sensitivity as an issue if it results in functional or RF failures
 - Completely eliminates DC Measurement errors caused by contact resistance
 - Both force current / measure voltage and force voltage / measure current
- Sense and correction cannot happen quickly enough to improve at-speed tests

Understanding Kelvin Further

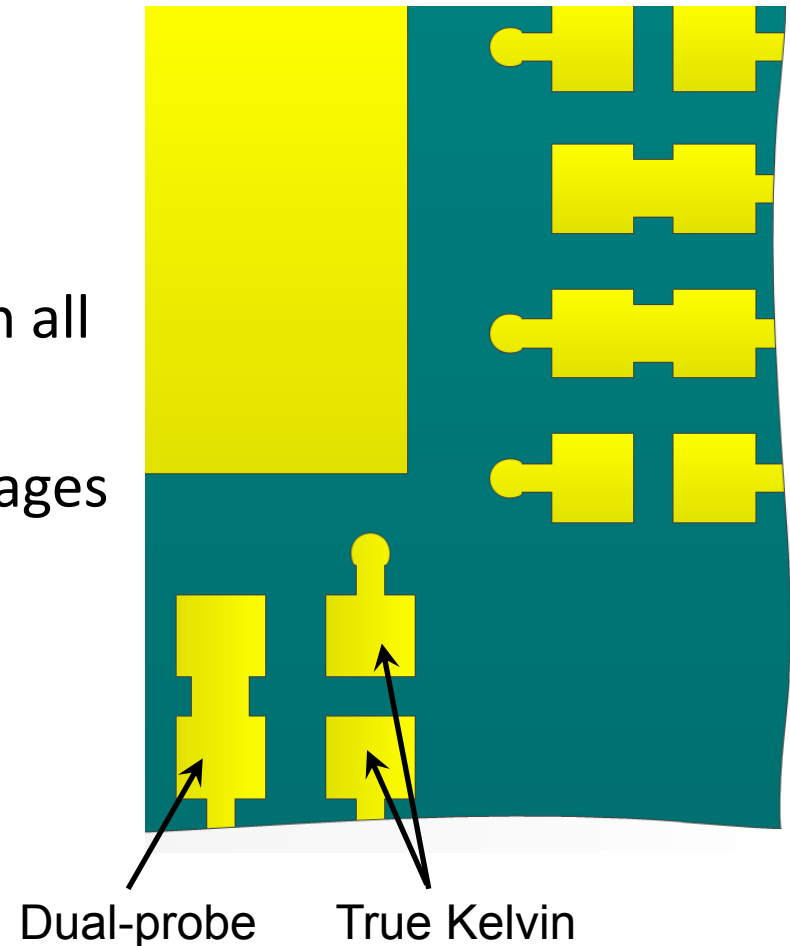
- Devices with internal Kelvin (or large contact pads) do not require special Kelvin contacts
- When many probes can be put on a pad, only one is used for sense, remainder for force



BOTTOM VIEW- ELECTRICAL I/O
(NOT TO SCALE)

Understanding Kelvin Further

- Dual-probe (vs. true Kelvin) is function of board layout, not contactor design
- Kelvin is not usually required on all device contact points
- Dual-probe offers some advantages
 - Lower inductance
 - Lower resistance
 - Higher conductance



Summary

- A Kelvin contact is required for economical testing of devices with measurements sensitive to RC
- Kelvin contacting is more expensive initially but saves cost (and headaches) in the long run
- There are many Kelvin contacts available
- Choose carefully – with many things in life, you get what you pay for.

Thank You

Questions?