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ECE 4813

Semiconductor Device and Material Characterization

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As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

Electrical Techniques

- **On Wafer**
  - **Sometimes used for device trimming (adjustment of a parameter such as resistance by laser trimming or some other electrical method such as calibrated memory techniques).**
  - **Subject to limitations in dense integrated circuits**
  - **Often a test device is dedicated to allow process control**

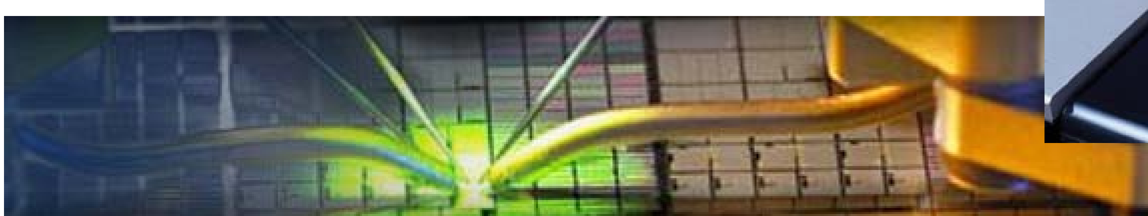
- **Packaged Devices**
  - **Finished devices are accessed through package leads**
  - **Stray resistance, inductance and capacitance complicate direct device parameter extraction but do account for real world operation.**

On Wafer DC to RF Electrical Techniques

- Low (zero) frequency measurements can be made using "simple" probes
- Special Cases of ultra-low (< ~100pA) and very high currents (>~100mA) need special probe considerations
- Probe stations can be manual (research) or fully automated

Automated systems may have:

- Motorized (magnetic and/or piezo) positioners
- Microscopes and computer imaging
- Thermal and mechanical isolation
- Various probes, probe cards



Figures from Cascade Microtech Inc.

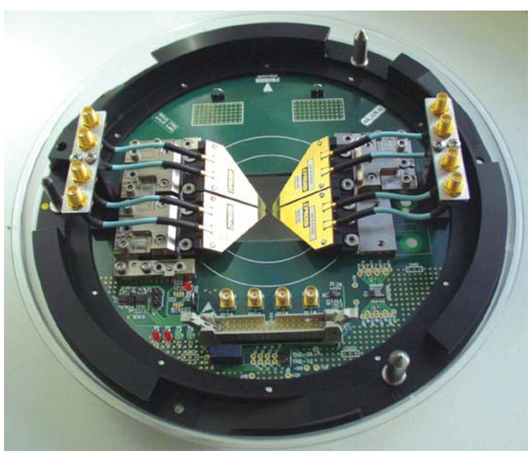
On Wafer DC to RF Electrical Techniques

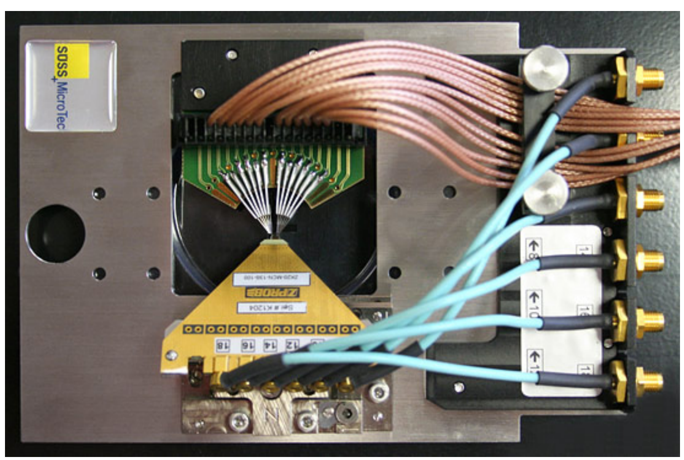
Probe Types:

- DC "Nominal Current"
  - Nothing Fancy. Just a Tungsten (for robustness and "spring factor") sharpened wire. Can be gold or BeCu coated for better electrical contact

- Coplanar RF
  - Used for high frequency single or double signal line measurements where control over the characteristic impedance (reflections/transmission issues) is important. Ground – signal (GS) and ground –signal – ground (GSM) configurations are most common but others (GSSG and GSGSG) do exist. Different probe contact spacing's determine (in part) the impedance of the probe.

- RF Integrated Circuits and Probe Cards for DC, RF and even Optical mixed use





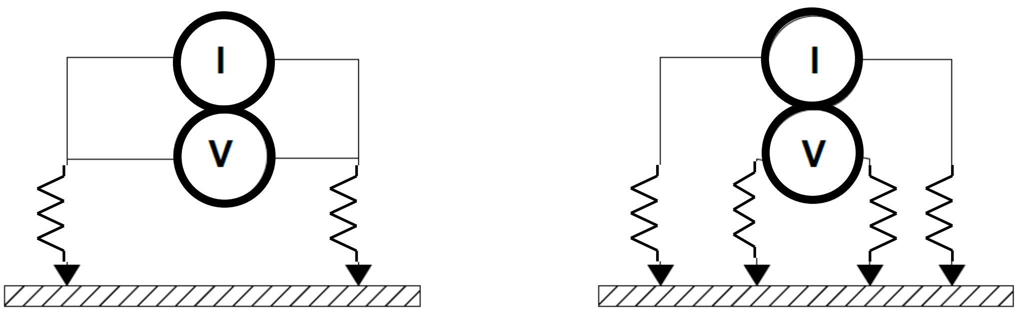
Figures from Cascade Microtech Inc.

On Wafer DC to RF Electrical Techniques

- Probe Types:

- DC "Special Cases"
- Four Point or two point measurements?

Difference between 2P and 4P :



2 point probing **4 point probing**

- In a two point measurement, the contact and wiring resistance driven by a current creates an erroneous voltage source
- In a 4 point measurement, the current drawn by a voltmeter is miniscule so no erroneous voltage drop occurs.
  - Even a small contact resistance of (for this example 0.1 ohms total – noting that contact resistance is actually measured in ohm-mm^2) can create significant erroneous voltage drops (V=1volt if I = 10 amps).

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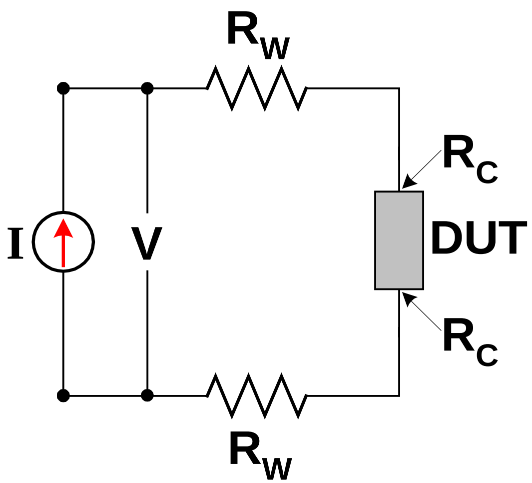
On Wafer DC to RF Electrical Techniques

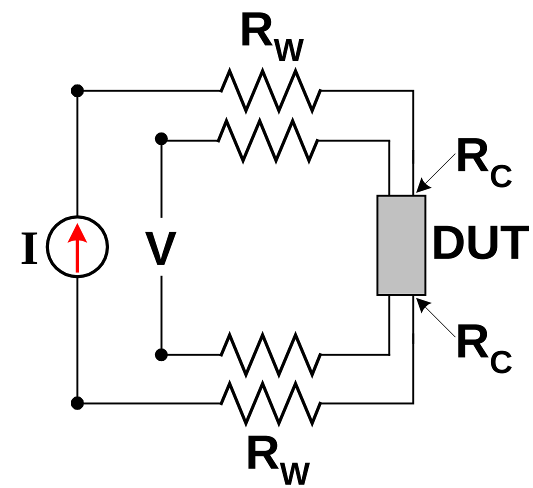
- Probe Types:

- DC "Special Cases": Four Point or two point measurements?

2-Terminal



4-Terminal

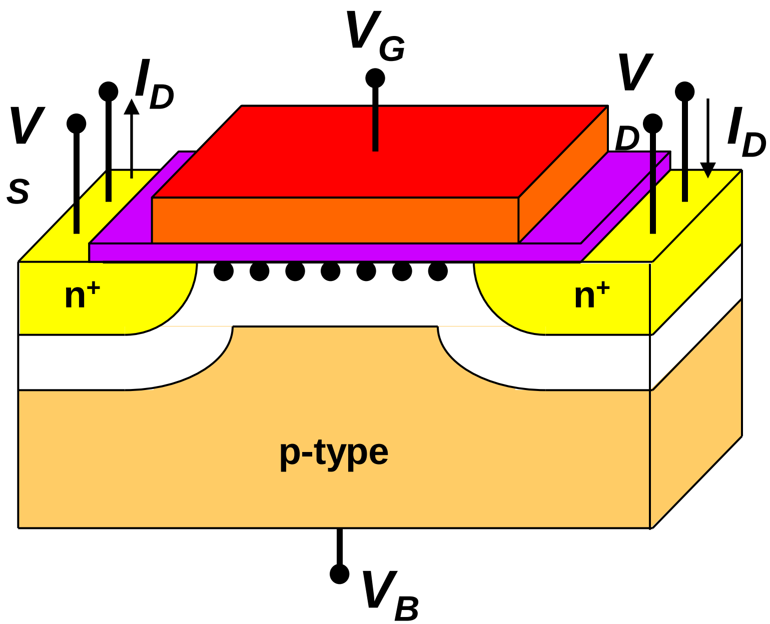


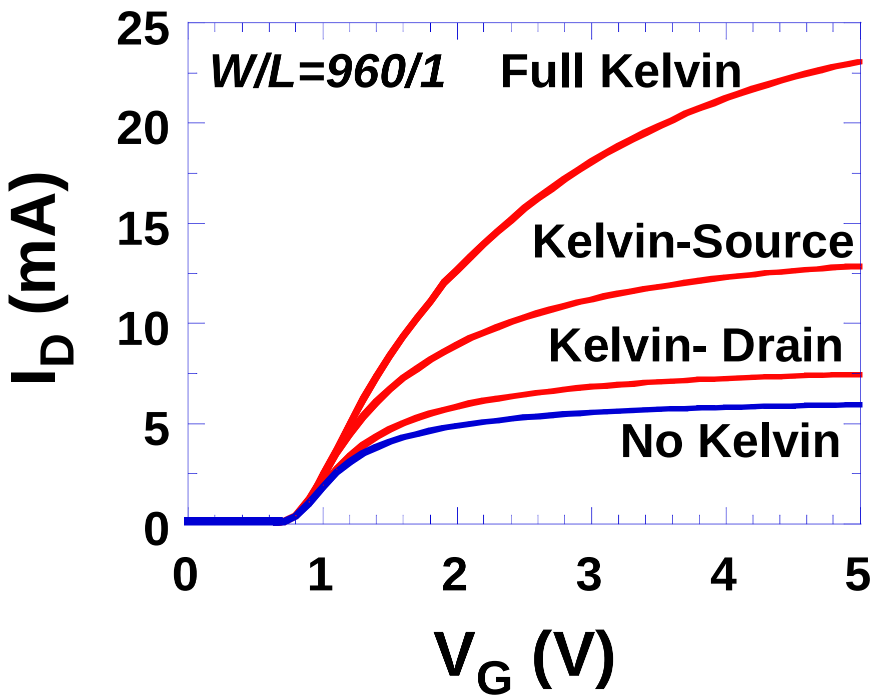
$$V = (2R_W + 2R_C + R_{DUT})I \Rightarrow R_{equ} = 2R_W + 2R_C + R_{DUT}$$

$$V = R_{DUT}I \Rightarrow R_{equ} = R_{DUT}$$

- In a two point measurement, the contact and wiring resistance driven by a current creates an erroneous voltage source
- In a 4 point measurement, the current drawn by a voltmeter is miniscule so no erroneous voltage drop occurs.
  - Even a small contact resistance of (for this example 0.1 ohms total – noting that contact resistance is actually measured in ohm-mm^2) can create significant erroneous voltage drops (V=1volt if I = 10 amps).

Four-Terminal/Kelvin Measurements



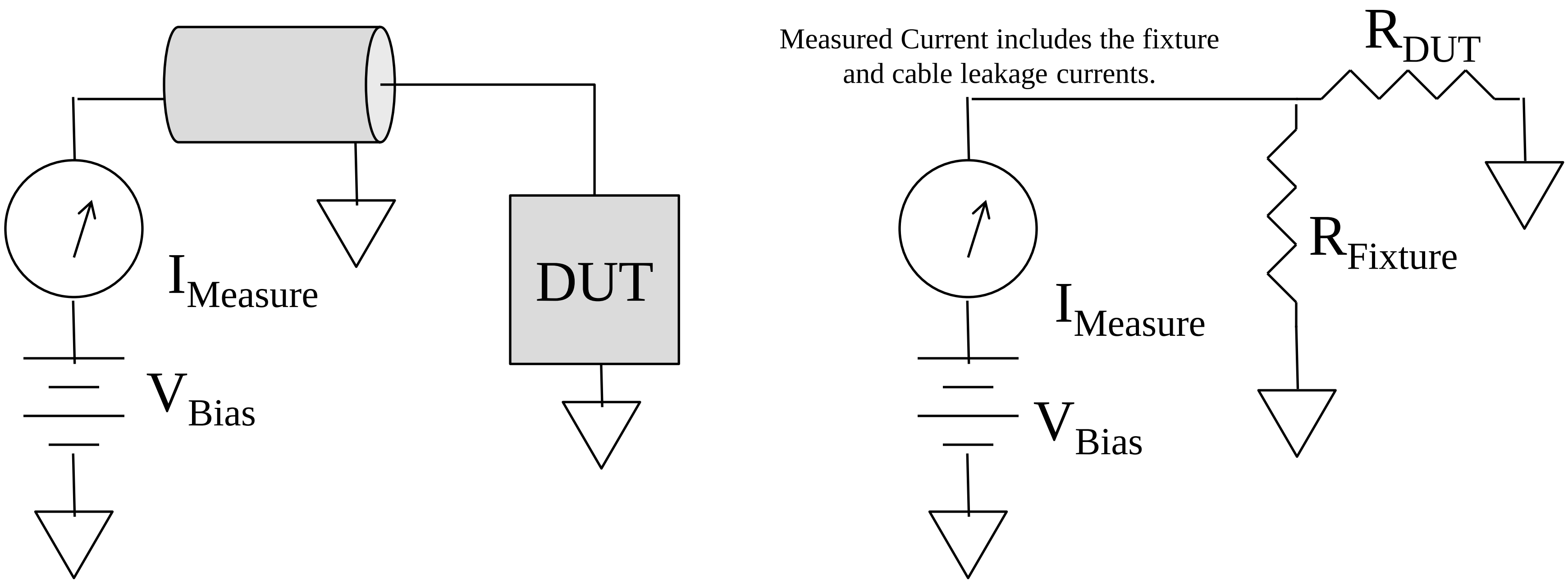


Courtesy of J. Wang, ASU

On Wafer DC to RF Electrical Techniques

- Probe Types:

- DC "Special Cases": Guarded Measurements
- Low Current and/or High Voltage
  - Consider the following: A typical 3 meter RG-58 teflon coaxial cable has a signal to ground resistance of ~10-100 Meg-ohms. How can such a cable be used to measure a 1pA current at ~ 1volt? The cable leakage alone is ~10-100 nA.
  - Circuit boards and on wafer leakage have similar "surface leakage resistances".



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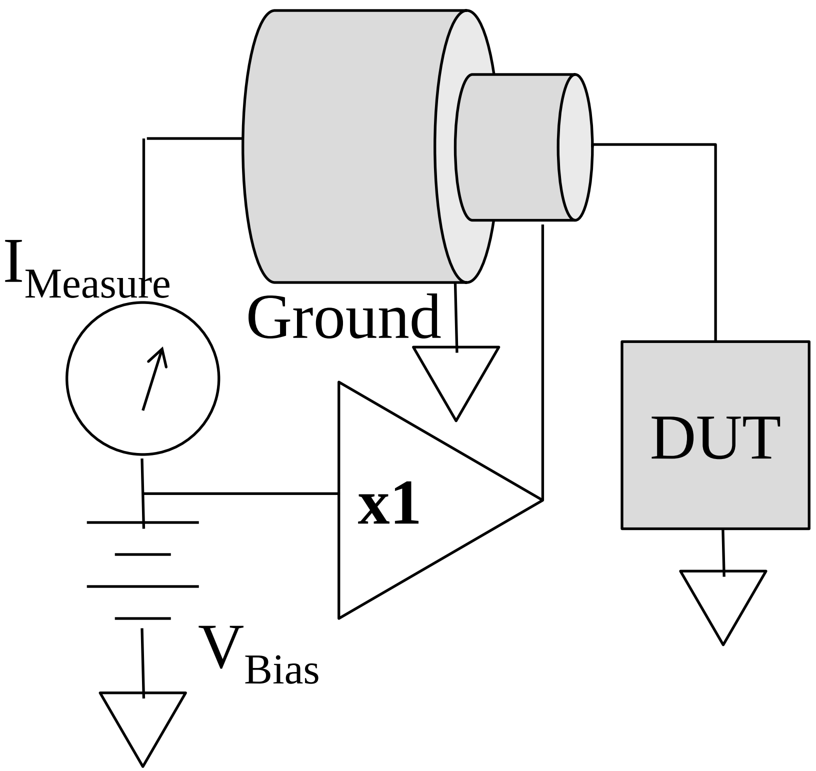
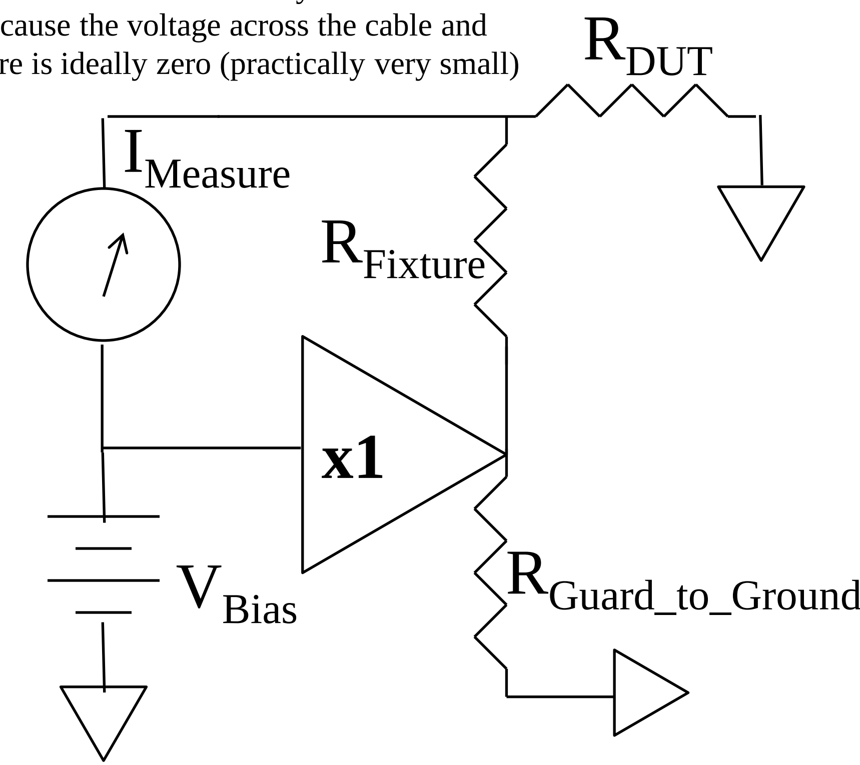
On Wafer DC to RF Electrical Techniques

- Probe Types:

- DC "Special Cases": Guarded Measurements
- Low Current and/or High Voltage
    - Solution: Tri-axial cables and "Guarding" provide a solution.
    - Guarded cables (tri-axial) and sample probes and fixtures nullify leakage





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On Wafer DC to RF Electrical Techniques

- Probe Types:

- DC "Special Cases"
- High Current – requires larger thermal mass for stability. Contact areas on wafer are typically bigger (to avoid trace vaporization), typically ~ 1x1 mm <u>or larger</u>.

- Thermal Concerns:
  - Often, thermal issues dominate power on-wafer probing as heat sinks are not available for the device. Solutions include:
    - Reduced power testing and statistical correlation to packaged device performance
    - Pulsed testing to lower average power while providing high instantaneous power
    - Destructive sampling testing

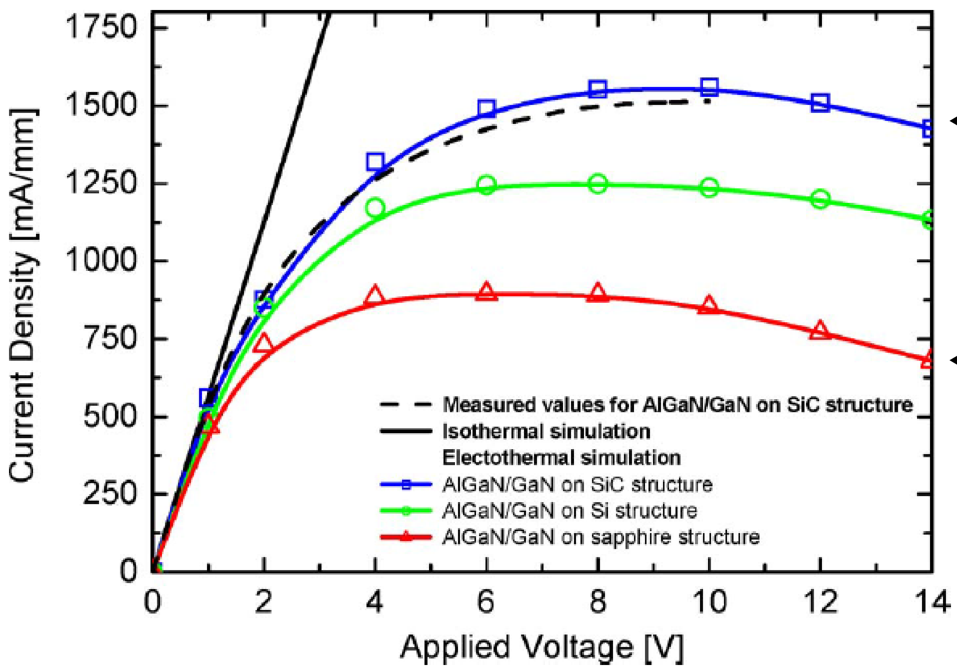
- Contact resistance Concerns:
  - The contact resistance of the probe itself is often enough to modify the device results.
  - Four point (sometimes erroneously referred to as Kelvin) probing are used to avoid contact resistance losses.

Figures from Cascade Microtech Inc.

On Wafer DC to RF Electrical Techniques

- Probe Types:

- DC “Special Cases”: Power Dissipation Limitations
- Compare two GaN HEMT RF power transistors on a good thermal conductor (SiC) vs a poor thermal conductor (Sapphire)



← Good thermal conductor

← Poor thermal conductor

2178 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 56, NO. 10, OCTOBER 2009

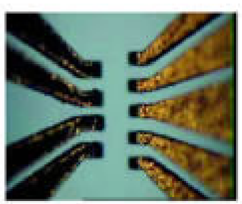
Effects of Self-Heating on Performance Degradation in AlGaN/GaN-Based Devices

Brahim Benbakhti, Ali Soltani, Karol Kalna, *Member, IEEE*, Michel Rousseau, and Jean-Claude De Jaeger

On Wafer DC to RF Electrical Techniques

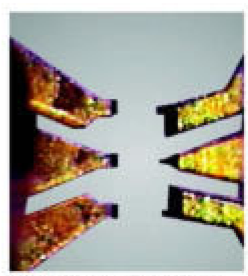
- Probe Types:

- RF "Special Cases": Impedance controlled probes
- Co-planar probes are used where characteristic impedance must be controlled (high frequency).
  - Probe spacing (in part) controls the impedance.
  - Most of the time, there is an input and an output probe.
  - An impedance calibration source is most often used (a short, an open and a known calibrated impedance network).



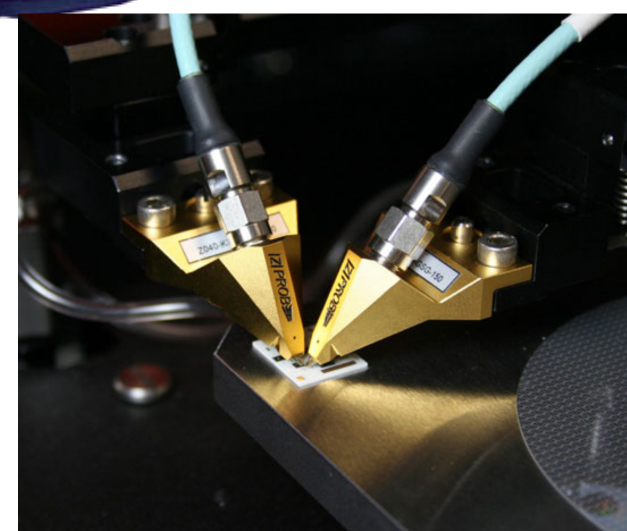
ACP-GSSG (left) vs. ACP-GSGSG (right)

G-S-S-G differential probes (left) and G-S-G-S-G probes (right).



Standard ACP tip (left) vs. ACP-RC tip (right)

Two probe tip configurations for G-S-G probes.



Figures from Cascade Microtech Inc.

Instrumentation: Simple Source Measure Units

- Most Basic of Modern Equipment

- Can source current / measure voltage
- Can source voltage / measure current
- Used to determine current/voltage characteristics and resistance parameters.
- Sometimes it is best to source current and measure.
- Generally useful for DC up to ~KHz frequencies only.

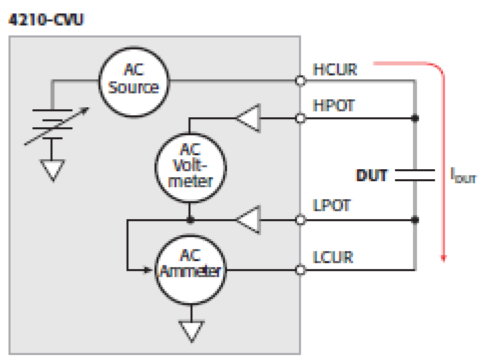
DC to audio range source-measure units. Can be combined in racks or in reduced footprint OEM stacks to provide 100’s of measurement channels.

SM units can be combined in racks or in reduced footprint OEM stacks to provide 100’s of measurement channels.

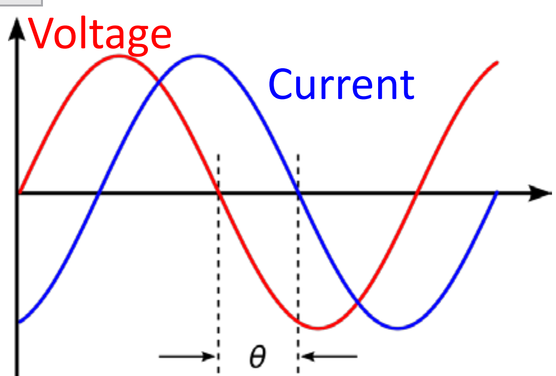
Figures from Keithley Electronics Inc.

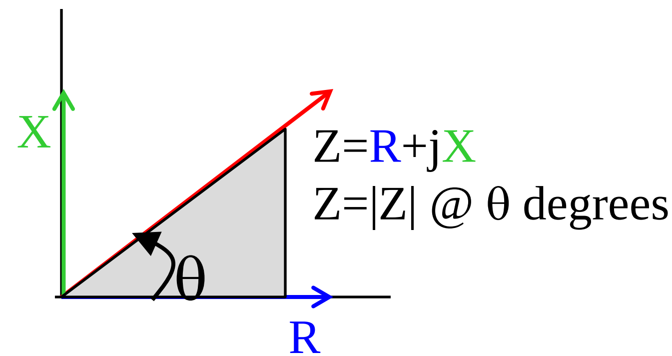
Instrumentation: AC Impedance Analyzers

- Useful for determining resistance, capacitance and inductance.
- An AC current is sourced (and measured for accuracy) and compared in magnitude and phase to a measured voltage. In some capacitance meter configurations, an ac voltage is sourced and the ac complex current is measured.
- Phase angles are determined as is the magnitude of the current to determine a complex impedance Z.
- Further interpretation requires an assumption regarding the type of network present.
- Phase sensitive detectors (Phase locked loops) are used for phase measurements.

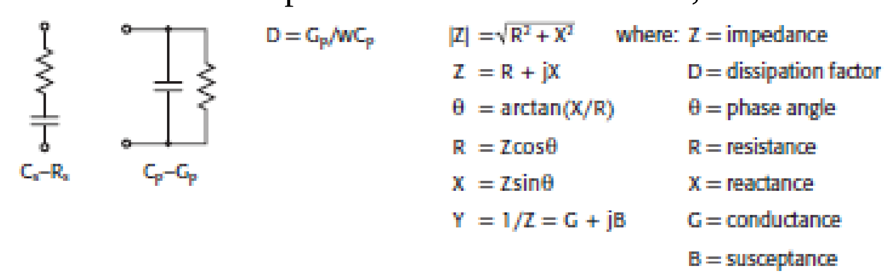


AC impedance meter





The desired property is derived from the assumed network. Example: in a series RC network, C=-X/ω



Basic AC impedance parameters

Some figures from Keithley Electronics Inc.

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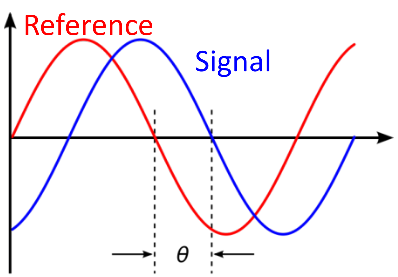
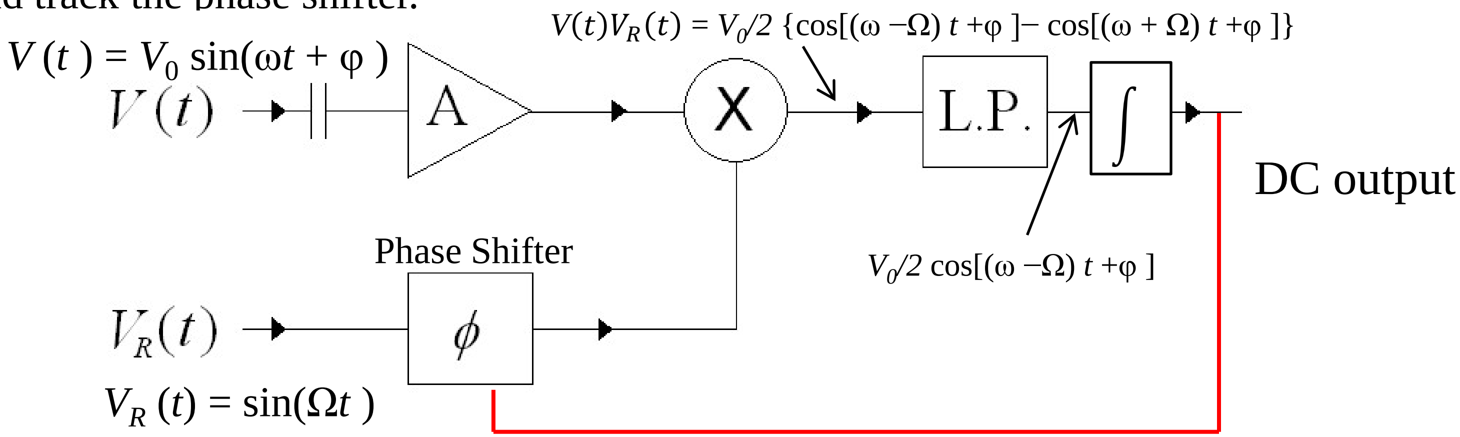
Instrumentation: Phase locked loops and Lock-in Amplifiers

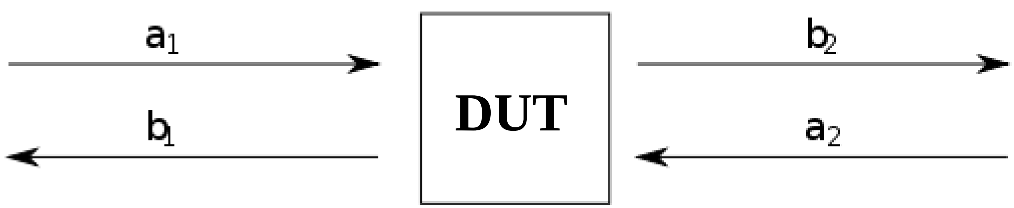
- Phase sensitive detectors (Phase locked loops) are used for phase measurements.
- A Lock-in amplifier essentially rejects all signals that are not at a specific frequency acting like a very narrow band filter with very high noise rejection (sometimes as high as 100 dB signal to noise ratio).
- A lock-in amplifier multiplies the input signal by a phase shifted "reference signal" and integrates it over a time longer than the signals period. The resulting integrated signal is a DC signal (or very slowly varying AC signal).
  - The contribution from any signal that is not at the same frequency as the reference signal is attenuated to (near) zero.
  - The out-of-phase component of any signal that has the same frequency as the reference signal is also attenuated to (near) zero. This is also why a lock-in is a phase sensitive detector.
  - By adding a phase shifter in front of the multiplier (demodulator), the phase shift can be adjusted to maximize the signal from the PSD allowing the phase of the signal to be measured and tracked in time. In this way, the output of the Lock-in amplifier can be used in a control loop to adjust and track the phase shifter.



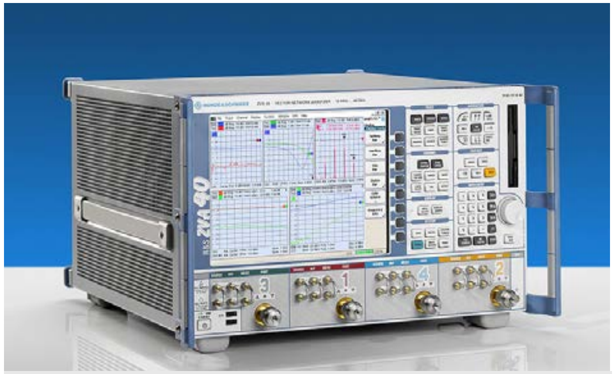


Instrumentation: Vectored Network Analyzers

- Typically used from ~10KHz to ~200 GHz.
- Reflection and Transmission properties of a DUT are measured in a two port configuration.
- RF wave is injected to the DUT and a reflection, and transmission is measured. Reverse direction can be measured as well allowing S_{11}, S_{12}, S_{21} and S_{22} measurements



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$



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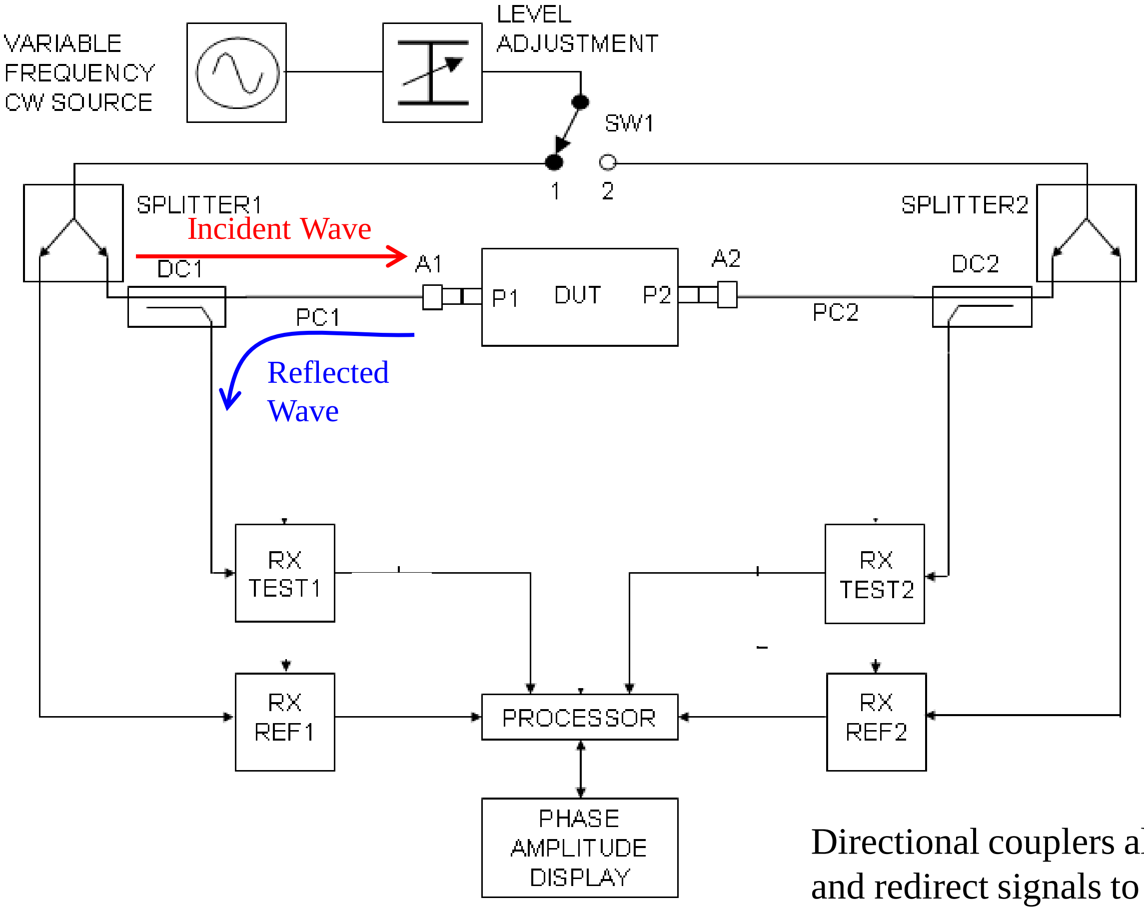
Instrumentation: Vectored Network Analyzers

- RF wave is injected to the DUT and a reflection, and transmission is measured. Reverse direction can be measured as well allowing S_{11}, S_{12}, S_{21} and S_{22} measurements.
- Measurements are often made by "down converting" (using modulation to allow lower frequency measurements) the received signals. Low frequencies allow digital magnitude and phase determination.



Directional couplers allow signals to pass in one direction and redirect signals to a different port for the reverse direction.

Some figures from Agilent Inc.