POWER ELECTRONICS MEASUREMENT CHALLENGES

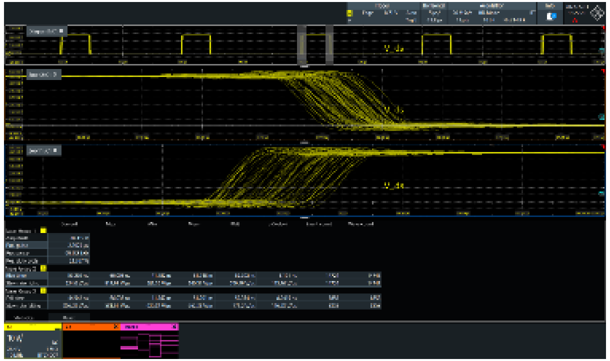
Alexander Kuellmer

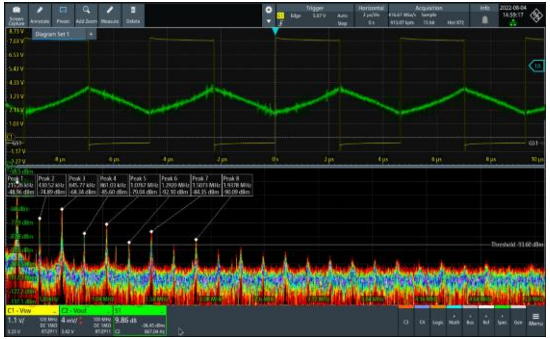
ROHDE&SCHWARZ

Make ideas real

TESTING THE DESIGN

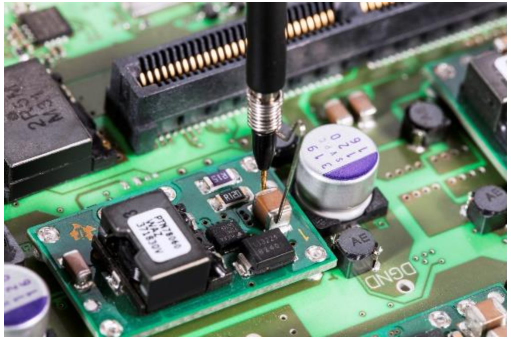
- Verify sub-circuits and switching times of the transistors
- Switching losses
- Characterization of passive components
- Stability
- Efficiency
- Transient response, start-up, shut down
- Voltage ripple
- Electromagnetic compatibility





MAIN CHALLENGES

- High frequencies: Wide bandgap materials
- Dynamic range: Operation in wide ranges of current and voltages
- Alignment of current and voltage signals
- Noise: DC-DC converters can produce noise that can interfere with measurements
- Dynamic performance: Rapid changes in output voltage and current
- Accessibility to the DUT

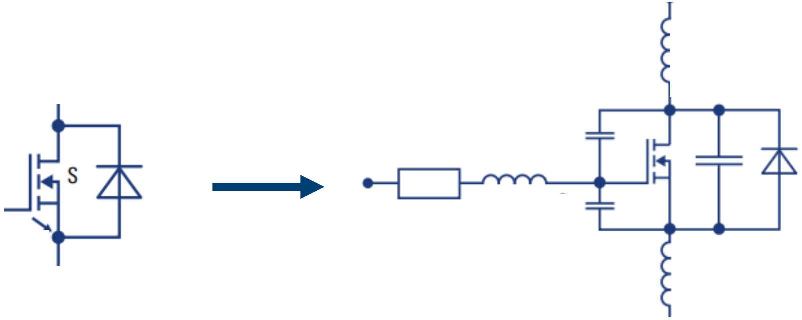


CONNECTIONS / PARASITICS

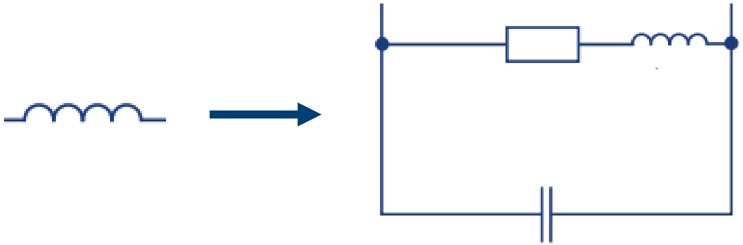
WHAT IS MEANT BY PARASITICS?

- This term refers to undesirable components or effects that accompany the intended electrical behavior of a circuit.

Transistor



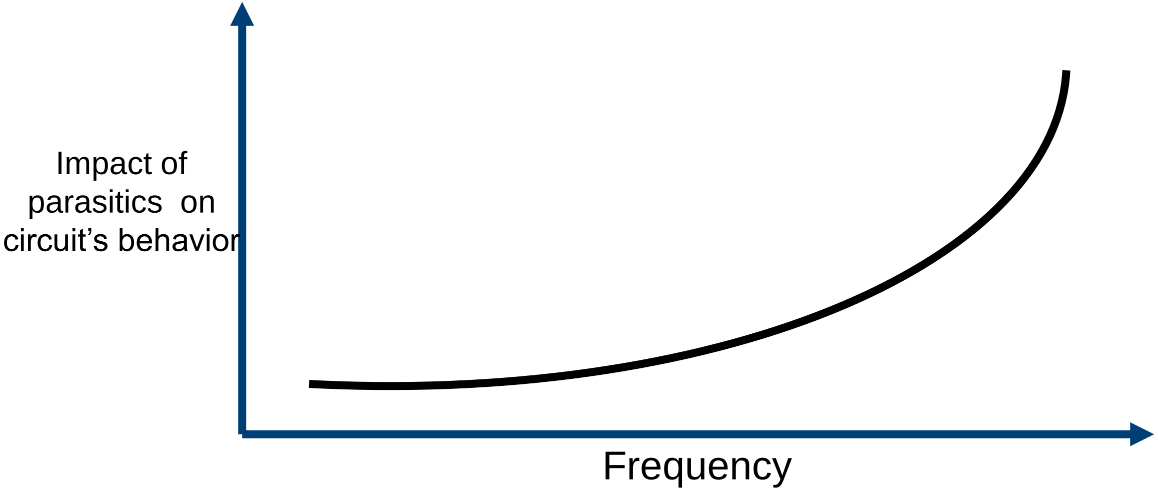
Inductor



Capacitor

IS IT ALWAYS AT HIGH FREQUENCIES?

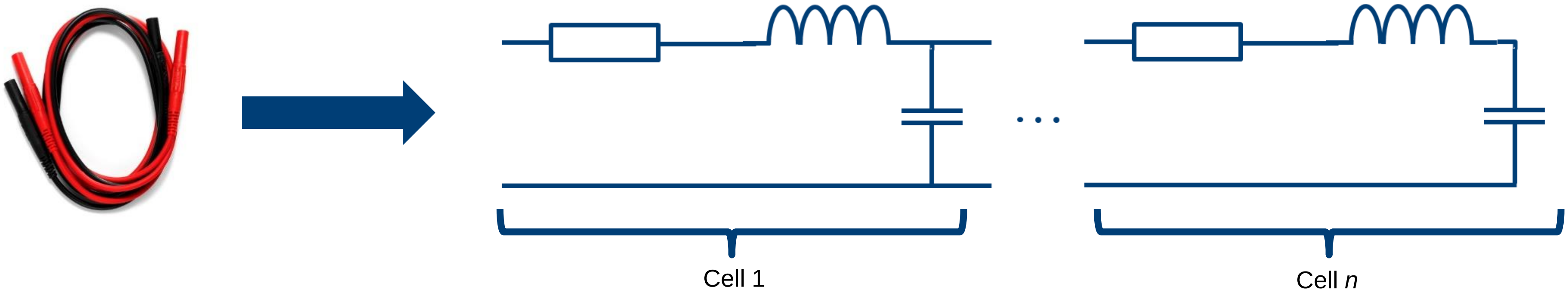
- Parasitic elements can exist at low frequencies.
- However, their impact may be less noticeable at lower frequencies compared to higher frequencies, as the parasitic elements may not have a significant effect on the behavior of the circuit.



PARASITICS IN CABLES

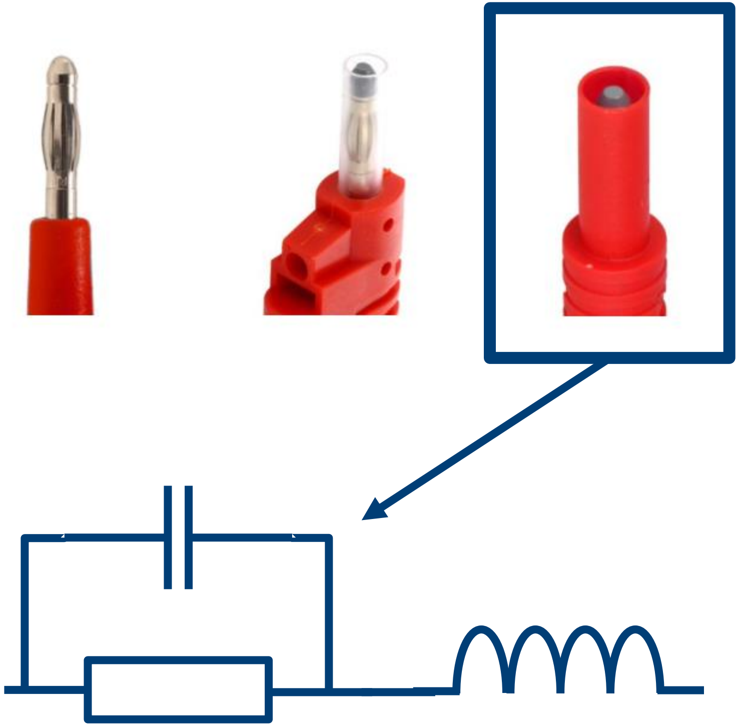
- The parasitics depend on the cable length, geometry and the materials used in its construction.
- The cable is modeled as a transmission line.
- The parasitic capacitance and inductance may lead to high-frequency distortions and a reduction in the accuracy of the measurements.

- The values of these components are frequency dependent.



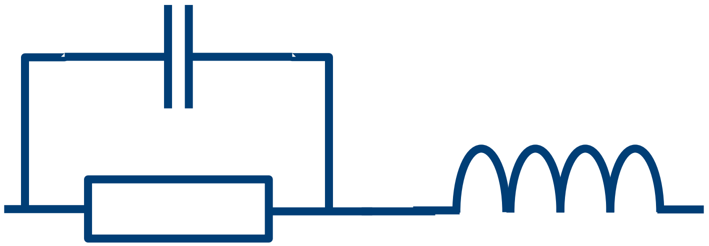
PARASITICS IN CONNECTORS

- The cable connectors also have parasitic elements that may affect the measurements.
- The model is similar to the one used for cables.
  - Resistance: Due to conductive wire in the plug
  - Parasitic inductance: Represents the inductance of the plug
  - Parasitic capacitance: Formed in the shrouded test plugs (HV applications) between the center pin and the conductive sleeve.
- Parasitics depend on the type and quality of the plug.

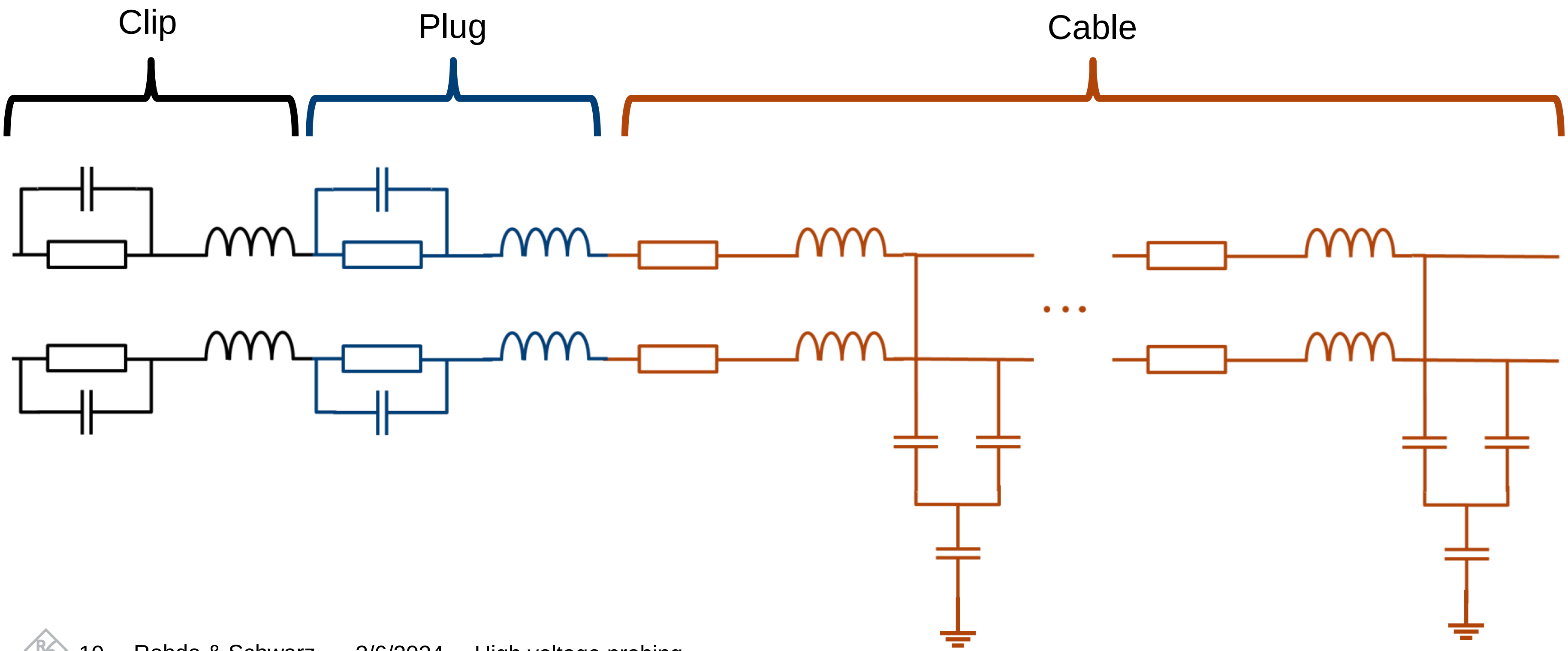


PARASITICS IN CLIPS

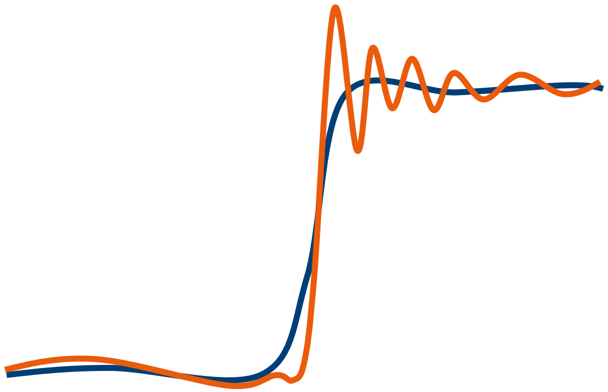
- Similar to cables and connectors, clips also influence the measurement and should be modeled.
- It consist of the resistance and the inductance of the conductive element and the capacitance of the clip and the insulating material.
- Longer clips will lead to a



COMPLETE MODEL OF THE INTERCONNECTIONS



INFLUENCE IN MEASUREMENTS
OVERSHOOT



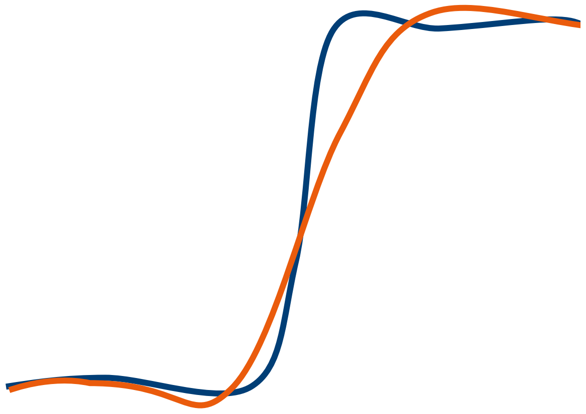
- It is important to differentiate the overshoot of the DUT and the one influenced by the probing.
- Parasitics of the interconnections create an impedance mismatch with the signal source.
- This leads to reflections and ringing → Increase in overshoot

Overestimation of the overshoot → Design a filter to compensate overshoot → Oversize of filter components → **Increased costs and reduced efficiency**

INFLUENCE IN MEASUREMENTS
RISE TIME / SLEW RATE

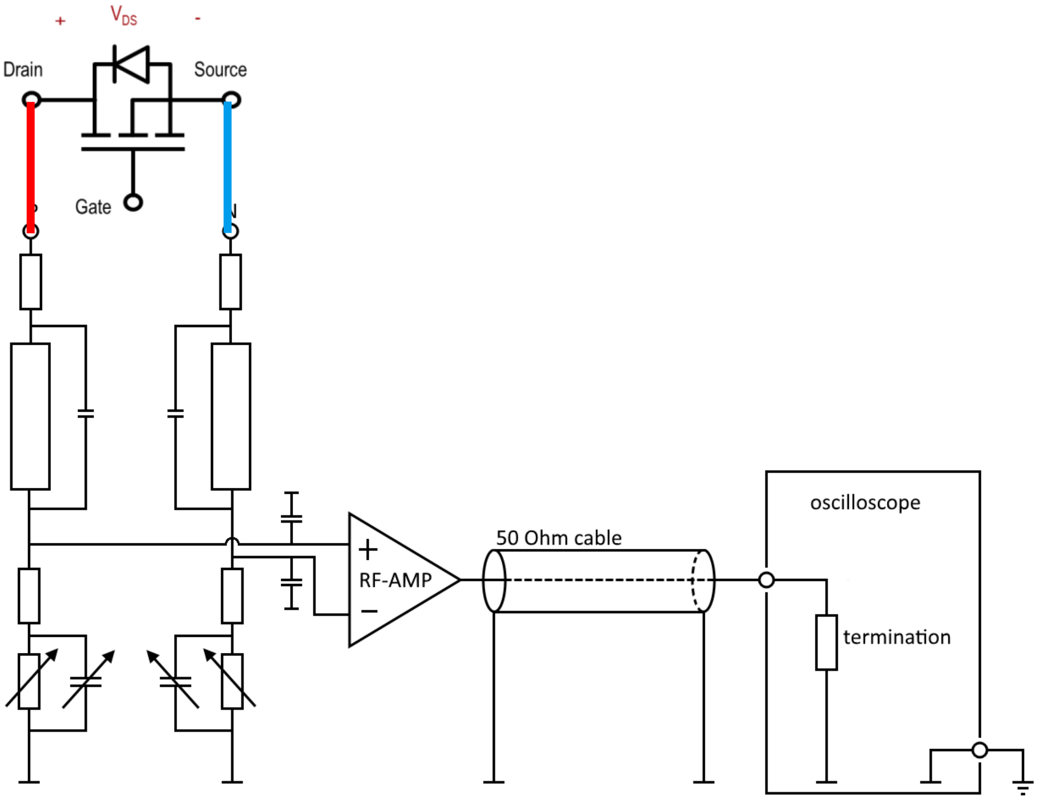
- Parasitics of interconnections have a significant impact on the rise time of a high frequency signal.
- The sharp edges of GaN and SiC devices make them more sensitive to parasitic effects.

- In general, each parasitic element affects the slew rate that is measured:
  - Parasitic capacitance: Acts as a low-pass filter, leading to an underestimation of the rise time.
  - Parasitic inductance: Causes ringing and oscillations which affect the rise time / slew rate.
  - Parasitic resistance: Voltage drop, especially in high-current applications.



MODEL

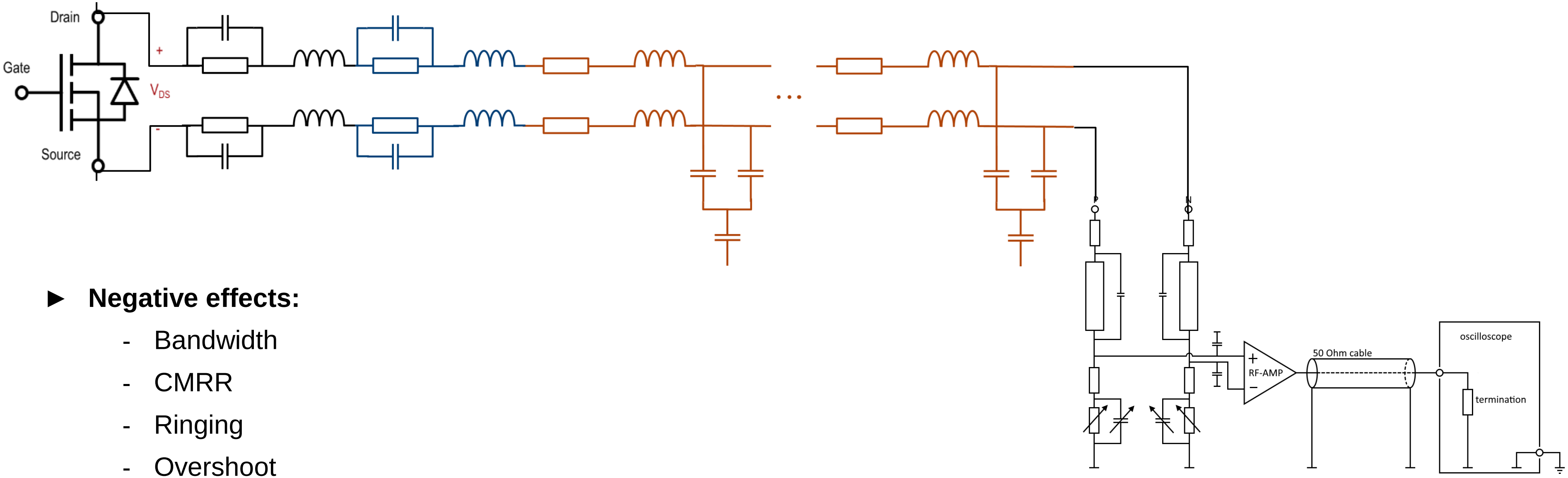
Ideal



+
V_{DS}
-
Drain
Source
Gate
P
N
RF-AMP
50 Ohm cable
oscilloscope
termination

MODEL

Real



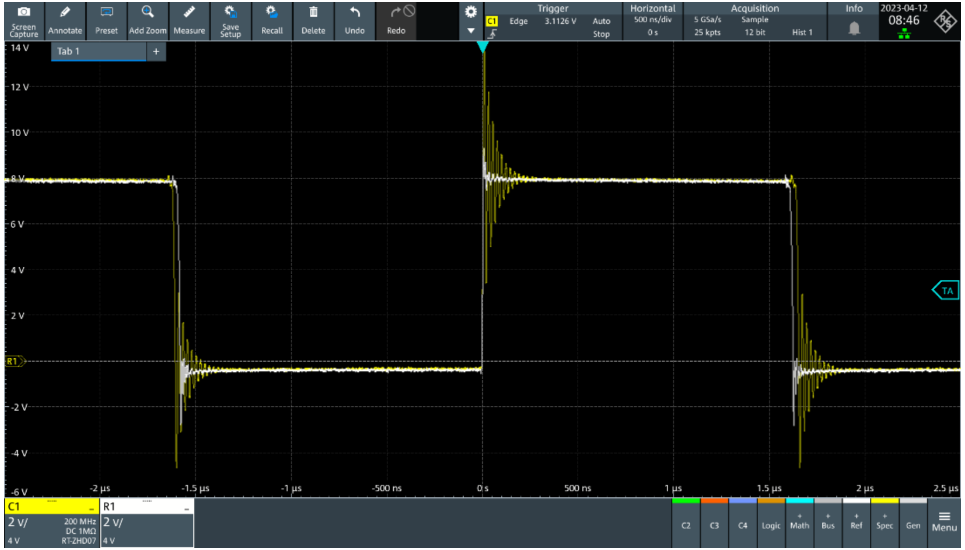
- **Negative effects:**
  - Bandwidth
  - CMRR
  - Ringing
  - Overshoot

COMPARISON

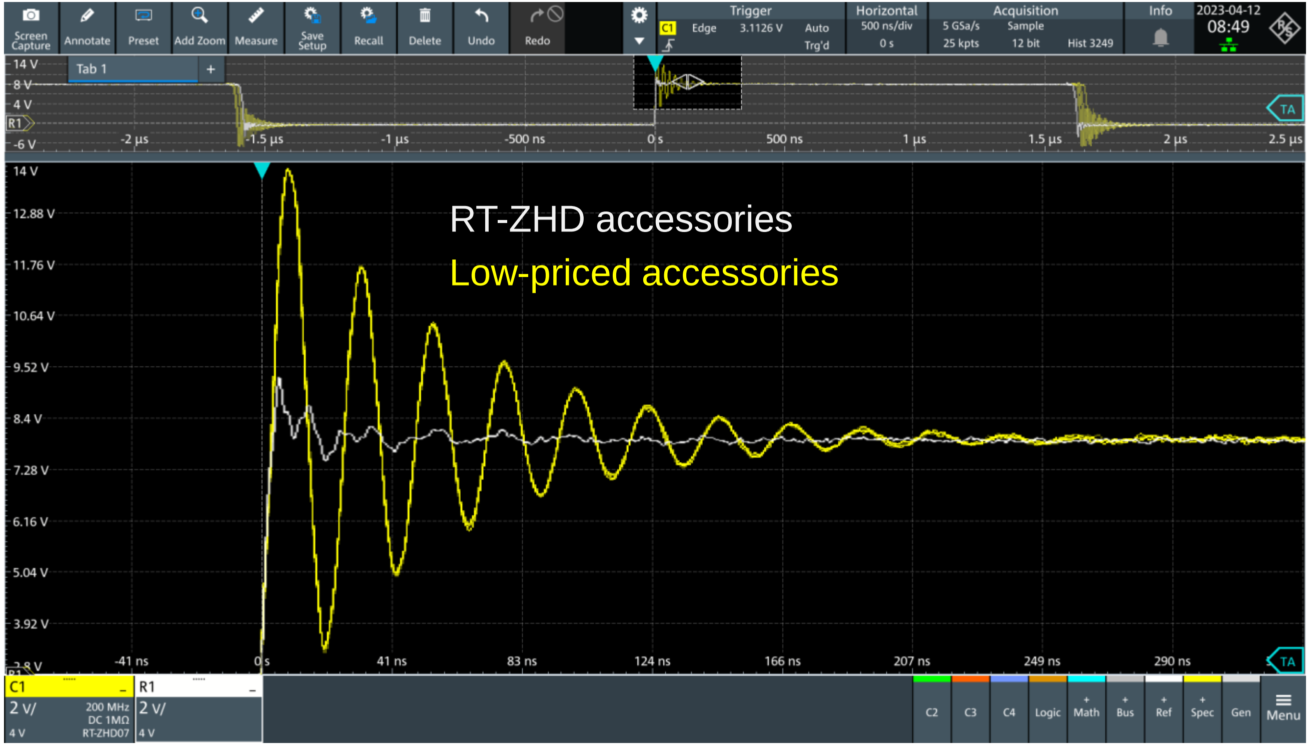
RT-ZHD probe

RT-ZHD Accessories

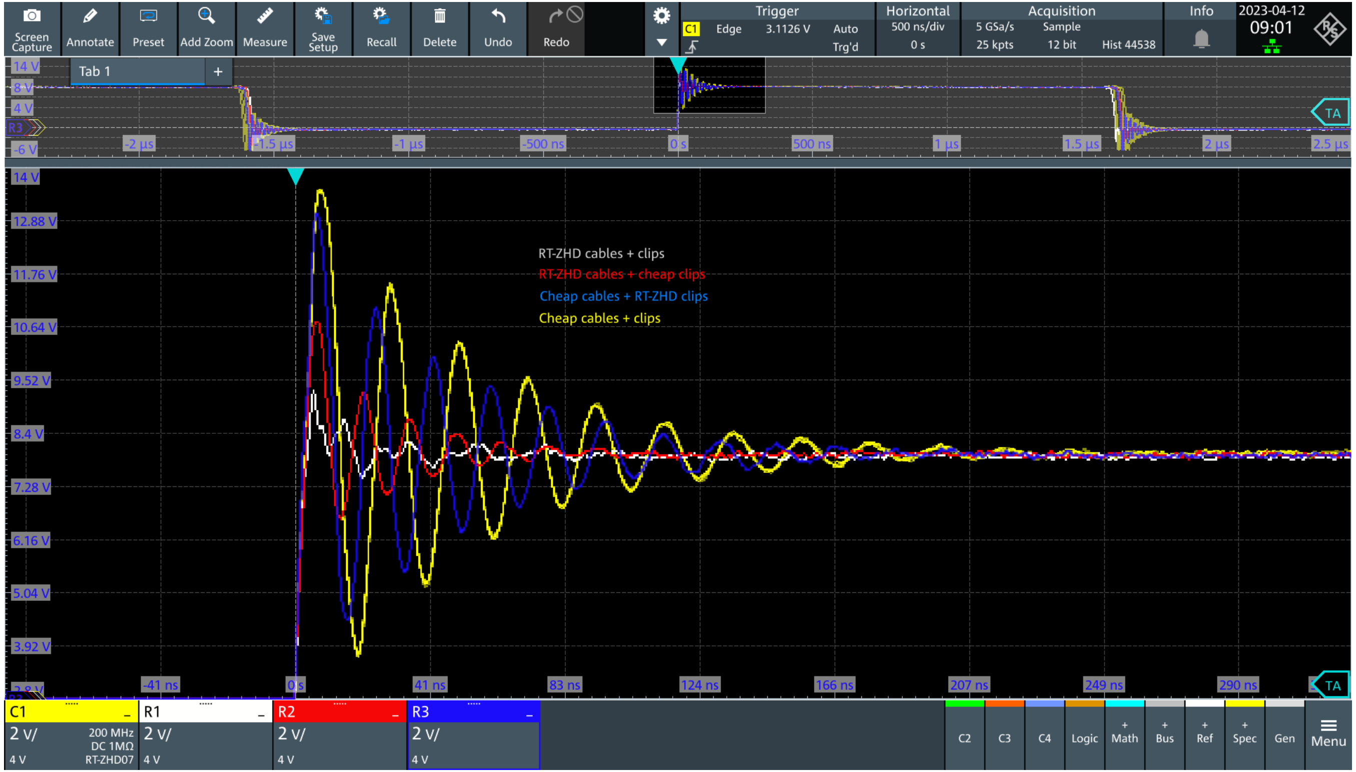
Low-priced Accessories



COMPARISON

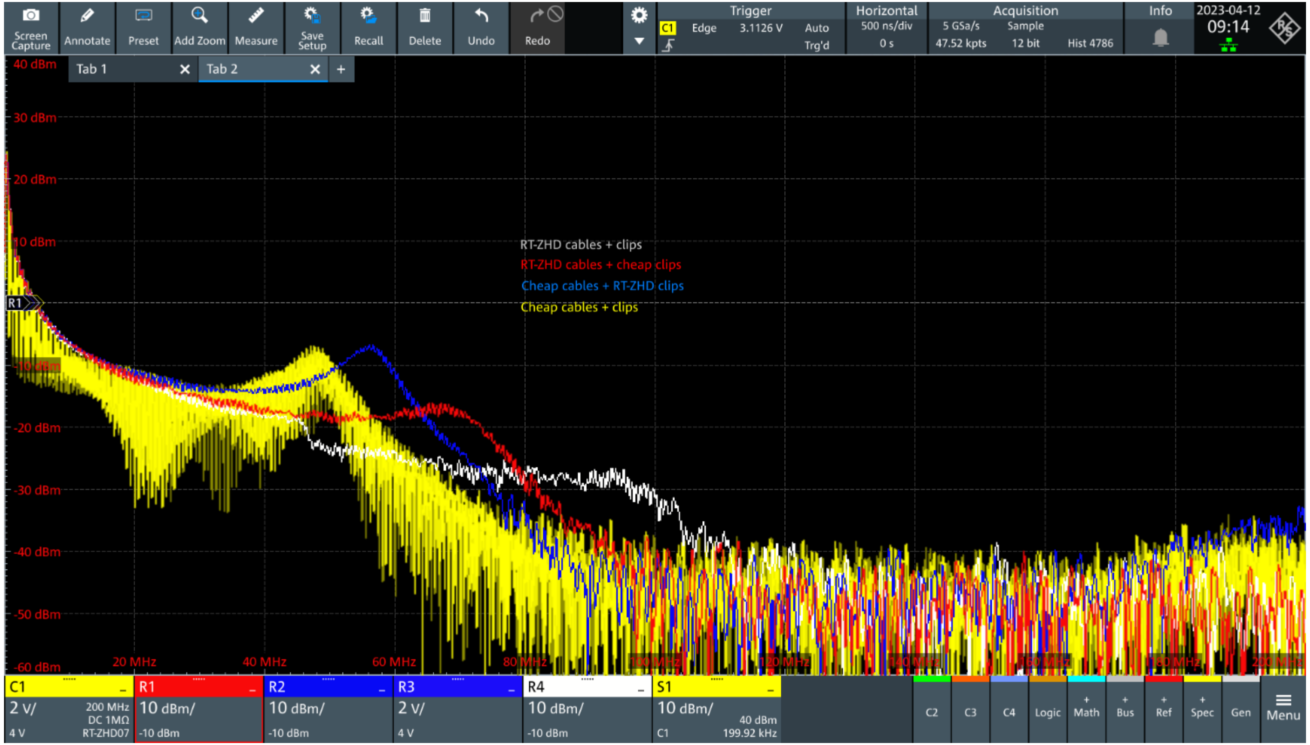

RT-ZHD accessories
Low-priced accessories
Screen Capture
Annotate
Preset
Add Zoom
Measure
Save Setup
Recall
Delete
Undo
Redo
Trigger
Edge
3.1126 V
Auto
Trg'd
Horizontal
500 ns/div
0 s
Acquisition
5 GSa/s
25 kpts
Sample
12 bit
Hist 3249
Info
2023-04-12
08:49
Tab 1
14 V
12.88 V
11.76 V
10.64 V
9.52 V
8.4 V
7.28 V
6.16 V
5.04 V
3.92 V
-41 ns
0 s
41 ns
83 ns
124 ns
166 ns
207 ns
249 ns
290 ns
C1
2 V/
200 MHz
DC 1MΩ
RT-ZHD07
4 V
R1
2 V/
4 V
Menu

COMPARISON



- **Best case**
  - 1 V overshoot
  - 12,5 %
- **Worst case**
  - 5 V overshoot
  - 62,5 % !!

COMPARISON

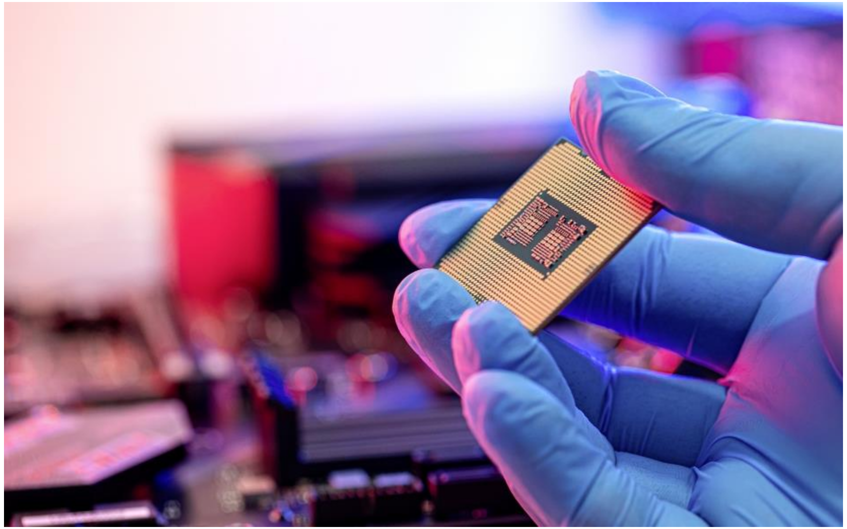


- **Best case**
  - RT-ZHD accessories
- **Worst case**
  - Low-cost accessories

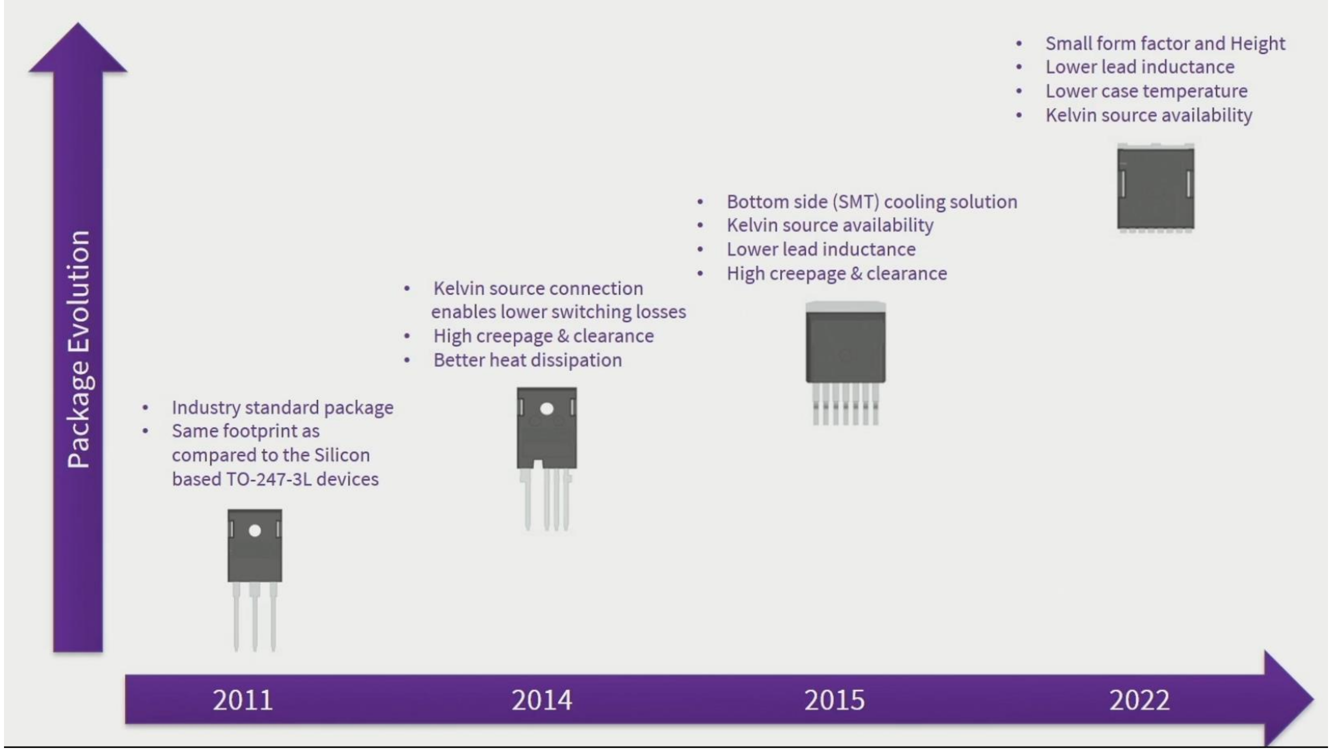
PACKAGING

- Switching speed of WBG semiconductors limit the performance of the conventional packages due to parasitic capacitance and inductance.
- These parasitic components have a direct influence in overvoltage, EMI and in the measurements.

- State-of-the-art integrated circuits (ICs) that use SiC and GaN are capable of integrating half-bridge, full-bridge, push-pull and other architectures into a single package.
- This packaging limit the number of test points in the switching stage. It is not possible to measure the internal signals (Vgs, Id) in such packages.



PACKAGING

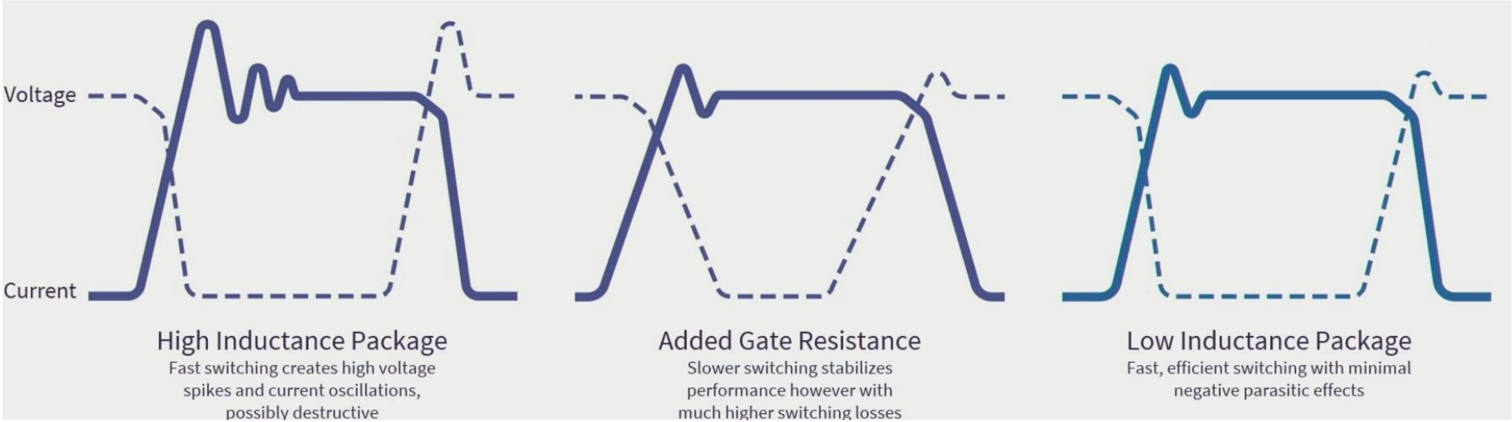


Wolfspeed, 2022

Switching loss is reduced by means of shorter leads

PACKAGING
PARASITICS

- ► New packaging technologies minimize the inductance of the package
- ► Reduction of negative parasitic effects
- ► Better high frequency performance, lower EMI and improved switching performance

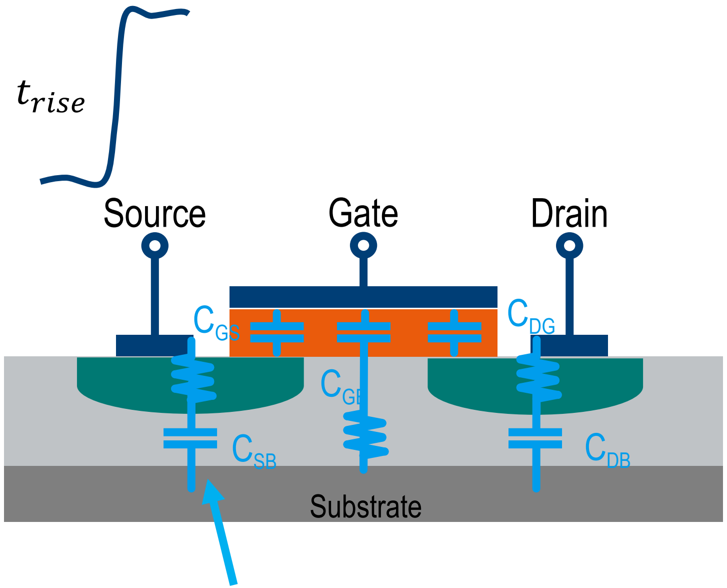


Wolfspeed, 2022

PACKAGING
RISE TIME

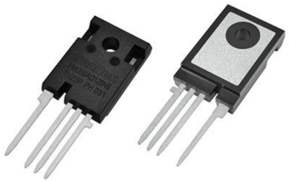
- The rise time at the connector is not the same as the one at the semiconductor.
- The bandwidth of the probe should be estimated accordingly.

t_{rise}



Inner parasitics

+



+

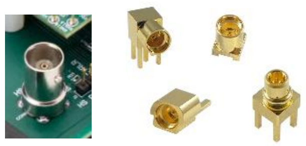
$t_{rise} + dispersion$

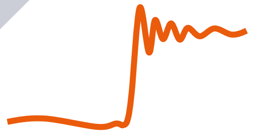
Longer rise time

PACKAGING
ACCESSIBILITY

- Access to the test points is more difficult with new packages.
- Some packages have internal connections that are not easily accessible from the outside.
- The device is prone to damaging and to short circuit.

New packaging technologies → Limited accessibility → Test fixtures and adapters are needed → Parasitics due to interconnections





HOW TO MEASURE CURRENTS?

CURRENT MEASUREMENTS

- The selection of a current measurement technique is a challenging task and several aspects must be taken into account:
  - Bandwidth
  - Sensitivity
  - Maximum current
  - Accessibility to the test point
  - Saturation
  - Insertion impedance
  - Positioning

- This selection is a compromise and highly depends on the application

INSERTION IMPEDANCE

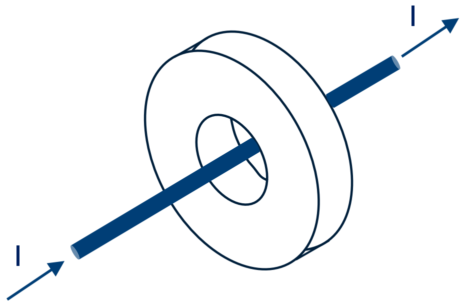
- It refers to the equivalent impedance that appears in series to the circuit (conductor under test) when it is being probed.
- The insertion impedance can be calculated as:

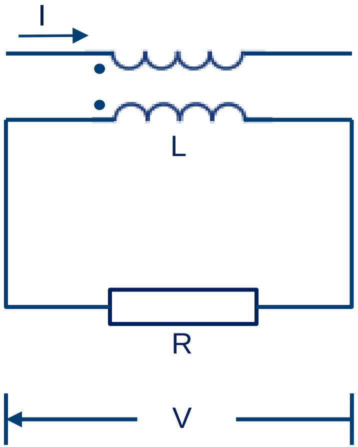
$$Z_{ins} = Z_{refl} + Z_{intr}$$

- Where Z_{refl} is the secondary impedance reflected into the primary by transformer action and Z_{intr} is the intrusion impedance originated by the core material of the current probe.

$$Z_{refl} = \frac{(\omega M)^2}{R + j\omega L}, \quad Z_{intr} = j\omega \frac{L}{N^2} - j\omega \frac{L_0}{N^2}$$

- At lower frequencies, the core losses are negligible.

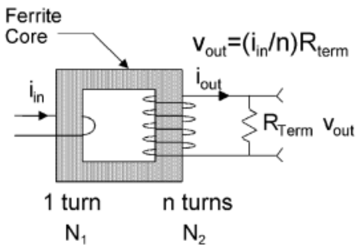




POSITIONING

Orientation of current

- The orientation of the probe matters.
- The current probe is designed to work as a coupled transformer where the primary is the wire and the secondary the probe. Thus, it expects the current to be flowing in a specific direction.

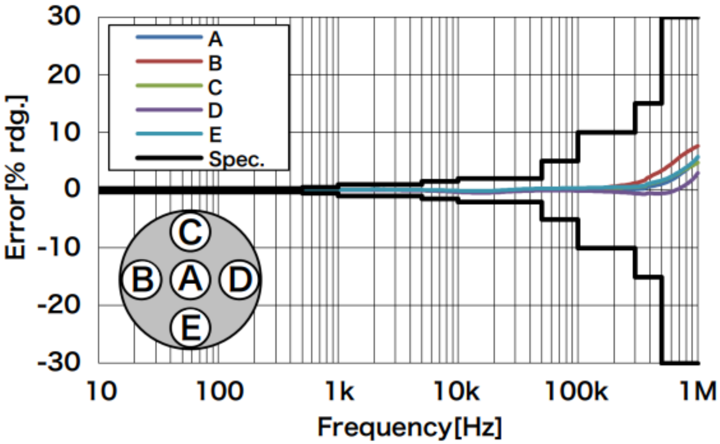


- An incorrect orientation translates into an inverse output voltage of the current probe.
- Probes are calibrated considering a single current direction.

Cable position

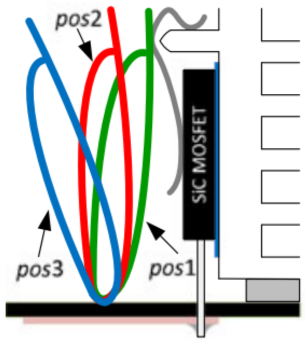
- The clamp-type current probes exhibit dependency on the positioning of the conductor.
- It should be placed in the center of the aperture since the characterization of the probe is done in this position.

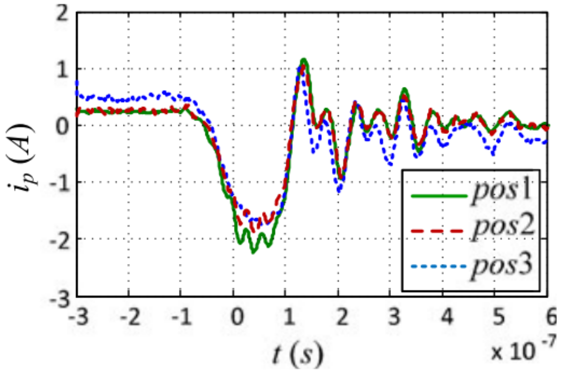
→ achieve best possible accuracy, and reproducibility.

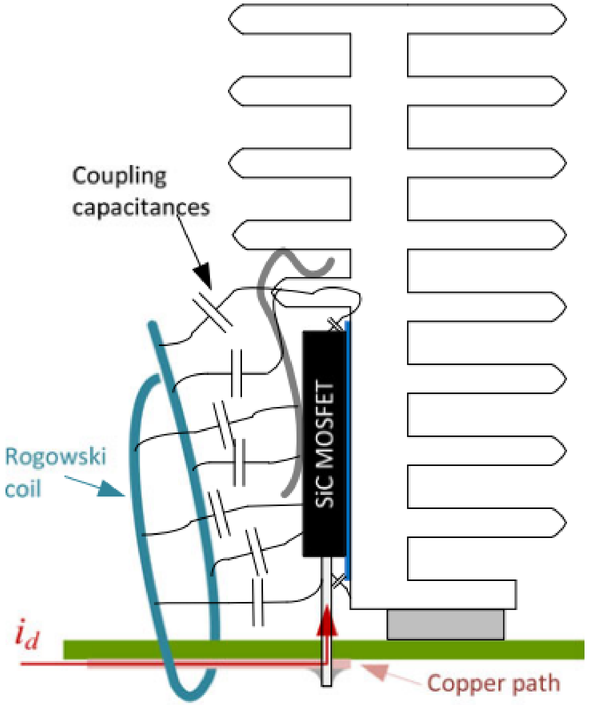


POSITIONING
COUPLING CAPACITANCES

- Besides the conductor position, the relative position of the current probe is also important.
- When the probe is close to a component, it will suffer from electromagnetic interference due to capacitive coupling.
- The distance to nearby components should be kept to a minimum.



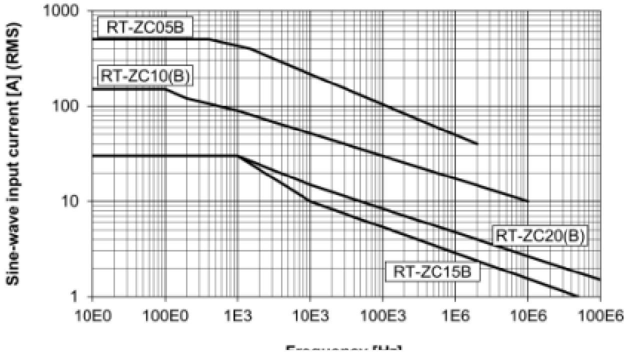


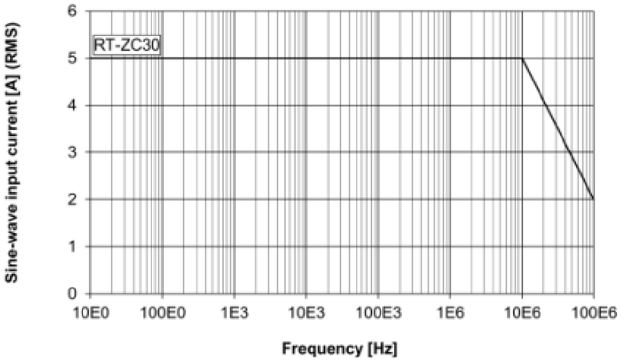


Oyarbide (2017). New Current Measurement Procedure Using a Conventional Rogowski Transducer for the Analysis of Switching Transients in Transistors.

NONLINEARITY OF CURRENT MEASUREMENTS
HIGH CURRENTS AT HIGH FREQUENCIES

- The linear operation of a probe is given by the amp-second product, which is defined as the average current multiplied by the pulse width.
- When the maximum value is reached, the probe goes into saturation and the core is unable to handle the induced flux B.
- The $Z_T I = U$ equation is no longer valid and the peaks of the waveform are not displayed in the oscilloscope.
- The amp-second product evidences the dependence of the core saturation on the frequency. Thus it is important to observe the derating curve in the manufacturers datasheet.





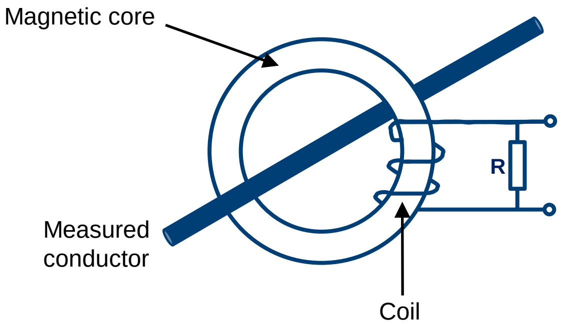
TEMPERATURE

- One of the potential problems when using the clamp-type probes is the damage from self-heating.
- The maximum rated current assumes sine-wave input under standard conditions.
- For frequencies higher than 1 kHz the temperature in the sensor head rises because of the excitation loss that cannot be prevented.
- The temperature also increases when the measured current waveform contains other frequency components

COMMONLY USED PROBES

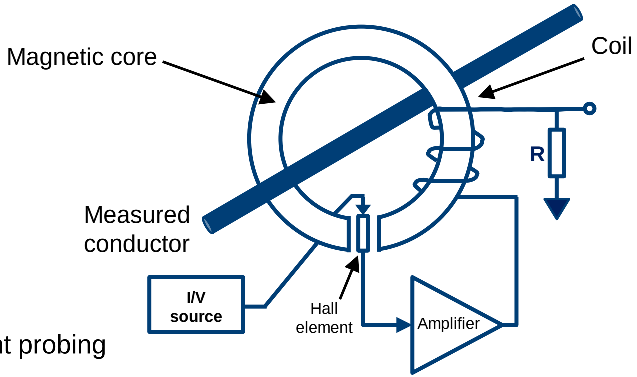
Current transformer

- It produces AC current in the secondary, which is proportional to the current in the primary.
- The number of turns is designed based on the current levels expected to be measured.
- It can only measure AC current.
- CTs reduce currents in a high voltage environment in a way that is safe for measuring equipment.
- Saturation at low frequencies



AC/DC zero flux + Hall element

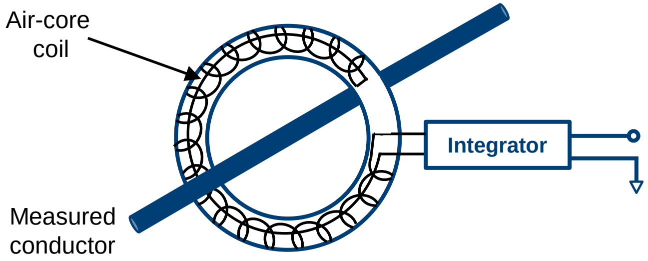
- It combines the CT and hall effect sensors in order to measure AC and DC currents.
- It is characterized by the high sensitivity and low noise.
- Especially designed for oscilloscopes, where small current waveforms must be observed.
- There is an offset drift when the temperature changes.
- High bandwidth: can be greater than 100 MHz.



COMMONLY USED PROBES

Rogowski coil

- This type of sensors do not include a magnetic core, which allows:
  - Low insertion impedance
  - No saturation
  - Lack of heat generation
- Thus, it is suitable for high currents
- It can only measure AC currents
- Bandwidth limited to 50 MHz. The integrator and the length of the cable influence this limit.

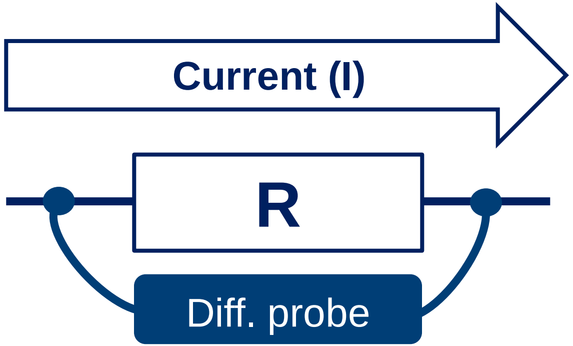


Shunt resistor

- It applies Ohm's law to measure the current.

$$R = \frac{V}{I}$$

- The shunt is a (low-value) resistor that it is connected in series in order to carry the current of interest.
- It can measure AC and DC currents.
- Ideal for SUTs with no clamp accessibility. – but it requires a differential probe



COMMONLY USED PROBES

Sensor	Type	DC?	Bandwidth	Saturation	Position	Intrusive	Current level	Thermal drift?	Precision	Physical principle
Current transformer	Fixed / Clamp	No	< 100 kHz	Yes	Important	Yes	**~ kAmps**	**No**	Average	Faraday's law
Zero flux + Hall	Clamp	Yes	< 120 MHz	Yes	Very important	Yes	< 100 A	Yes	Good	Magnetic field
CT + Fluxgate	Clamp	Yes	< 3 MHz	Yes	Important	Yes	< 1 kA (@ 200 kHz)	**No**	**Excellent**	Magnetic field
Rogowski coil	Clamp	No	< 50 MHz	**No**	Very important	**No**	**< 4 kA**	**No**	Average	Faraday's law
Shunt resistor	Fixed	Yes	**< 1 GHz**	**No**	Does not matter	Yes	< 200 A	Yes	Good	Ohm's law

THANK YOU FOR YOUR ATTENTION

ROHDE & SCHWARZ

Make ideas real