MEASUREMENT OF CURRENTS AND HIGH VOLTAGES

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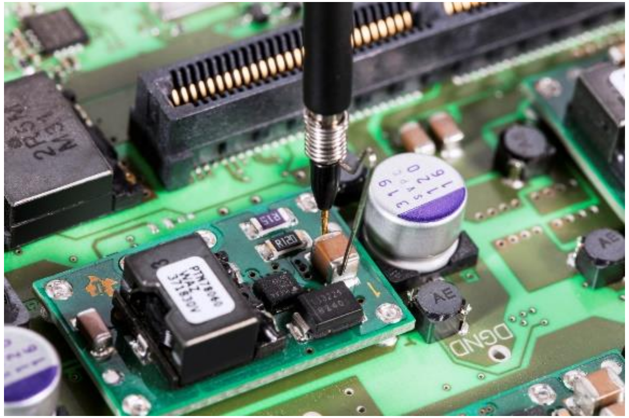
Make ideas real

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



HOW TO ESTIMATE THE NEEDED BANDWIDTH?

- Required scope bandwidth depends on test signals frequency components
- Bandwidth relates to rise time $\mathbf{t_r}$
- If only a max. slew rate is given the rise time is calculated accordingly: $t_r = \frac{\Delta Voltage}{Slew\ Rate}$

- Estimating the Bandwidth needed

  Investigating the units:

  Rise time t_r is expressed in [s]
  Frequency is expressed in [Hz]

  $$f_{max} = 1/t_r$$

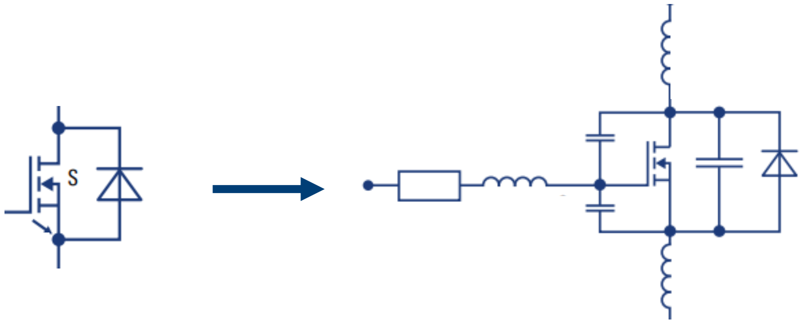
  - **As a rule of thumb $\boldsymbol{f_{max}}$ can be estimated by using the equation $\boldsymbol{f_{max} = 0.5/t_r}$**

PARASITICS – WHY CONSIDER THEM?

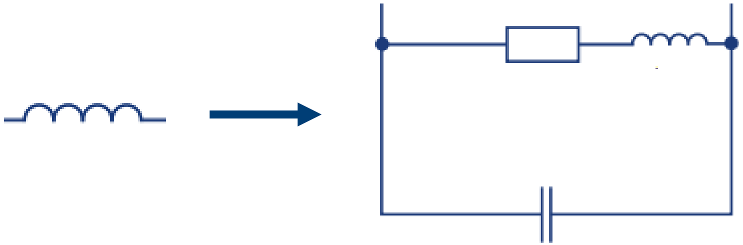
WHAT IS MEANT BY PARASITICS?

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

Transistor



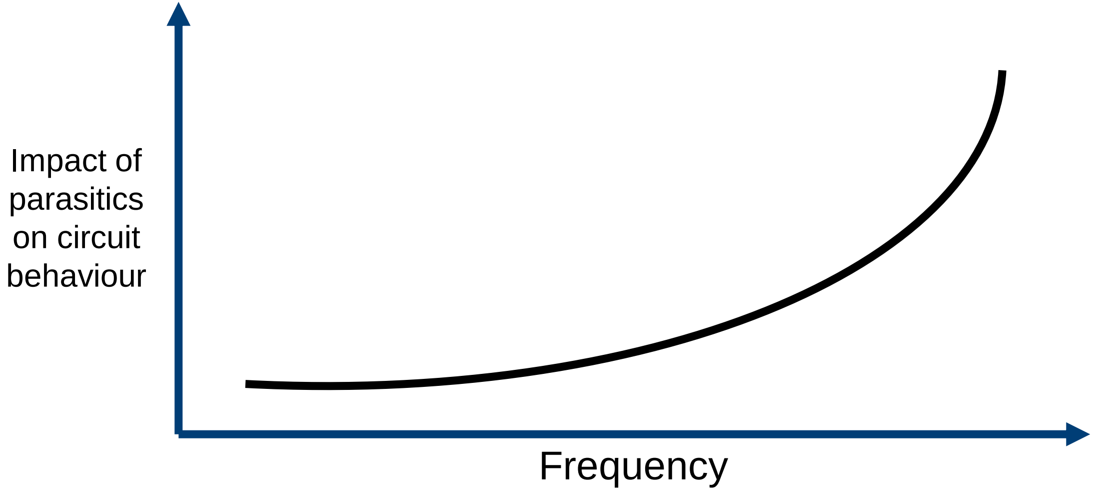
Inductor



Capacitor

IS IT ALWAYS AT HIGH FREQUENCIES?

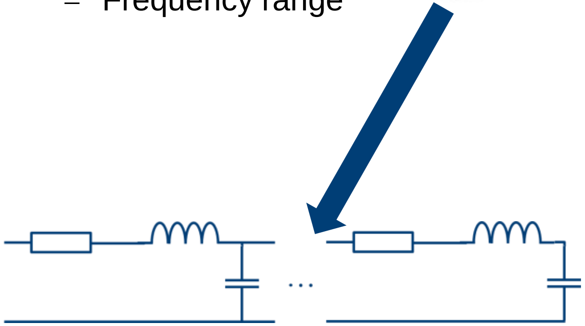
- Parasitic elements can exist at low frequencies.
- However, their impact may be less noticeable at lower frequencies compared to higher frequencies, as the parasitic elements may not have a significant effect on the behavior of the circuit.



WHERE DO PARASITICS OCCUR?

Cables

- ► Parasitics dominated by
  - – Length
  - – Geometry
  - – Overall Quality
  - – Frequency range



Connectors

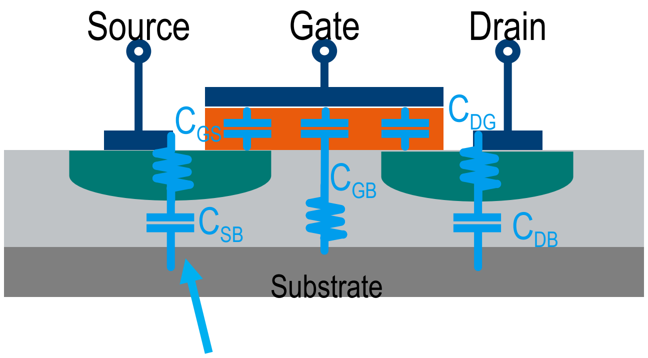
- ► The model is similar to the one used for cables.
  - \- Resistance and inductance are mainly dominated by the length and chosen material.
  - \- Capacitance: depends on the geometry of the pin

Clips

- ► Same like for Cable and Connector:
  - – Length and geometry dominate the effective R, L and C of the clip.
  - – So each clip will cause different variations to the measurement.

WHERE DO PARASITICS OCCUR?

Packaging



Inner parasitics

PCB / Testpoint

- With new package technologies test points in the PCB have to be utilized.
- Depending on frequency these could be pinheaders or have to be coaxial style.
- But in dependency of the frequency range investigated they will influence the resonant behavior of the system.

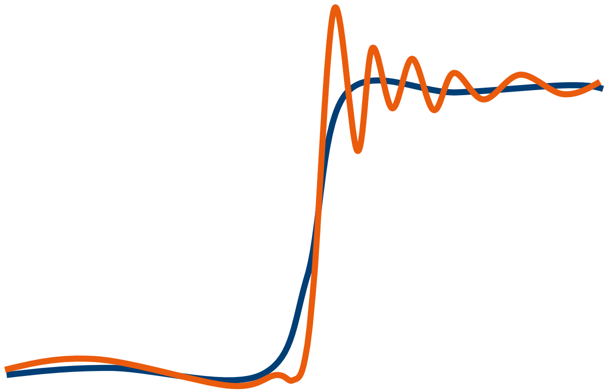
Current measurement

- All methods have one thing in common:
  - In dependency of the frequency they have significant influence on the displayed signal!

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

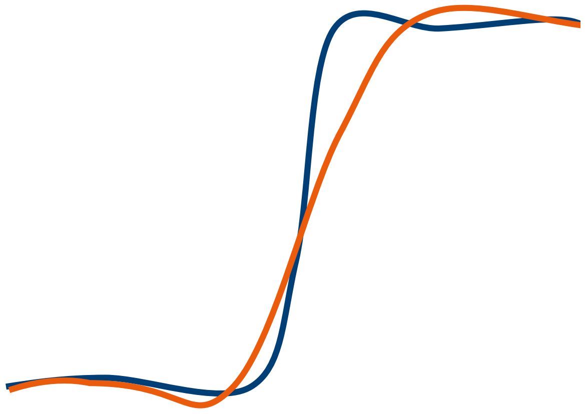


Overestimation of the overshoot → Design a filter to compensate overshoot → Oversize of filter components → **Increased costs and reduced efficiency**

INFLUENCE IN MEASUREMENTS
RISE TIME / SLEW RATE

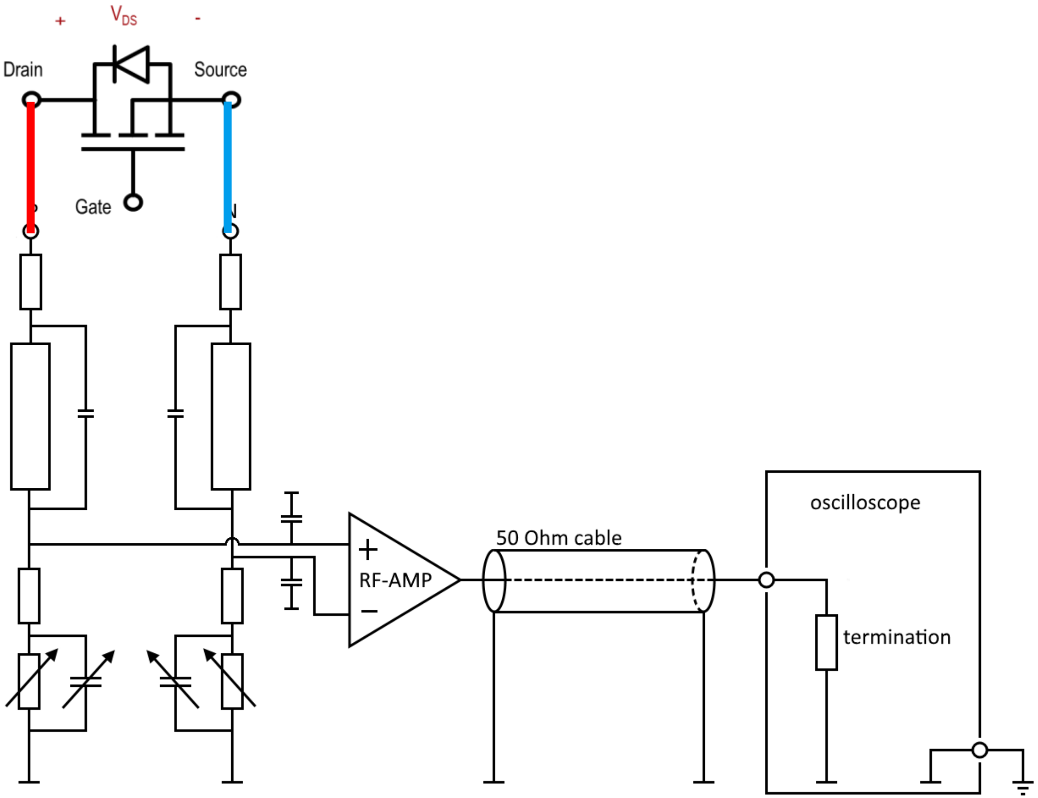
- Parasitics of interconnections have a significant impact on the rise time of a high frequency signal.
- The sharp edges of GaN and SiC devices make them more sensitive to parasitic effects.

- 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

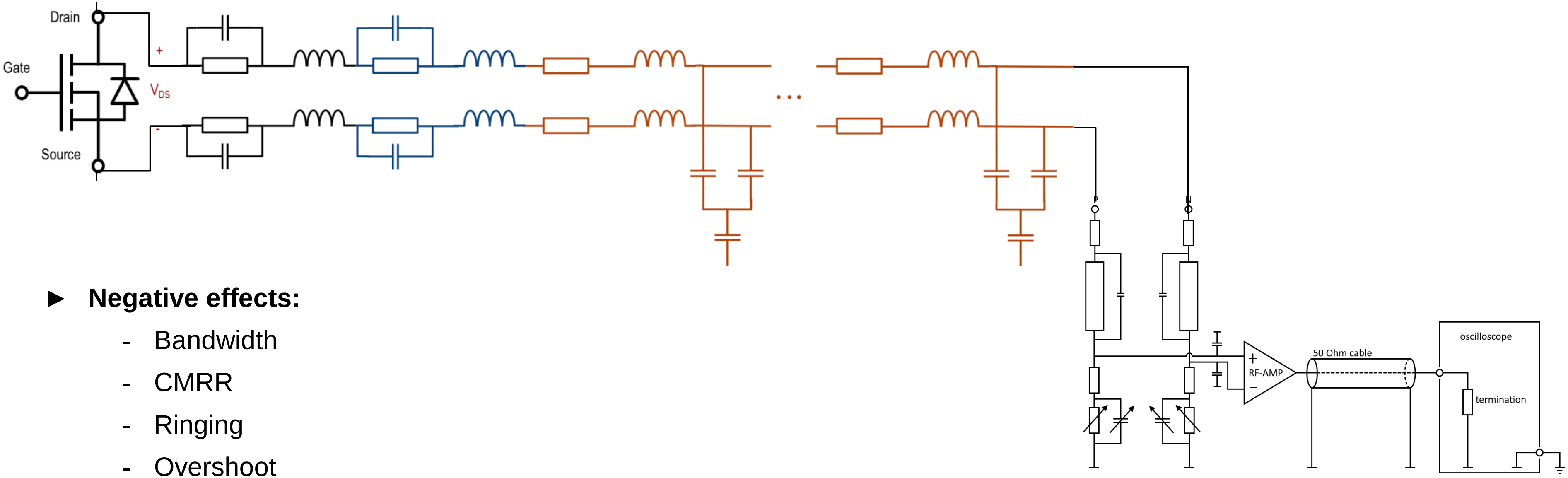
Ideal



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

MODEL

Real



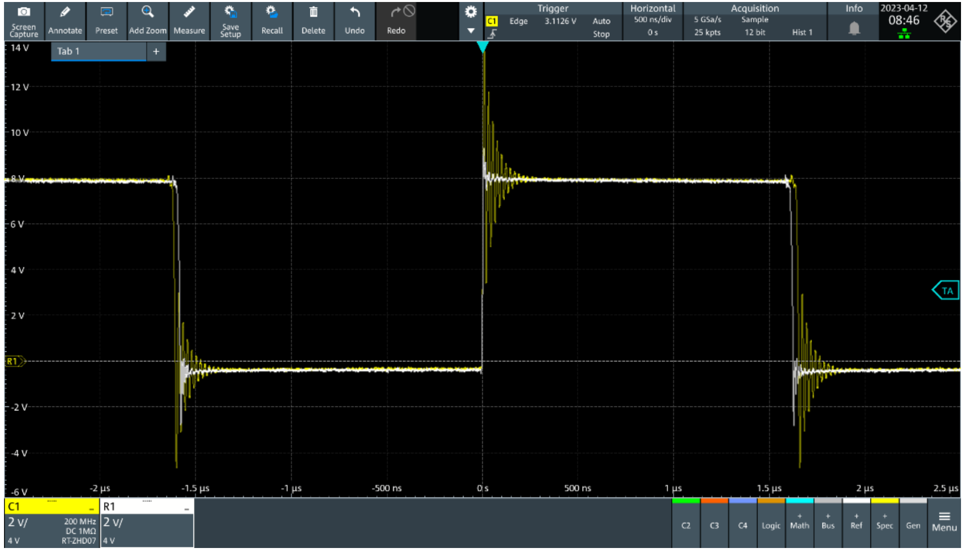
- **Negative effects:**
  - Bandwidth
  - CMRR
  - Ringing
  - Overshoot

COMPARISON

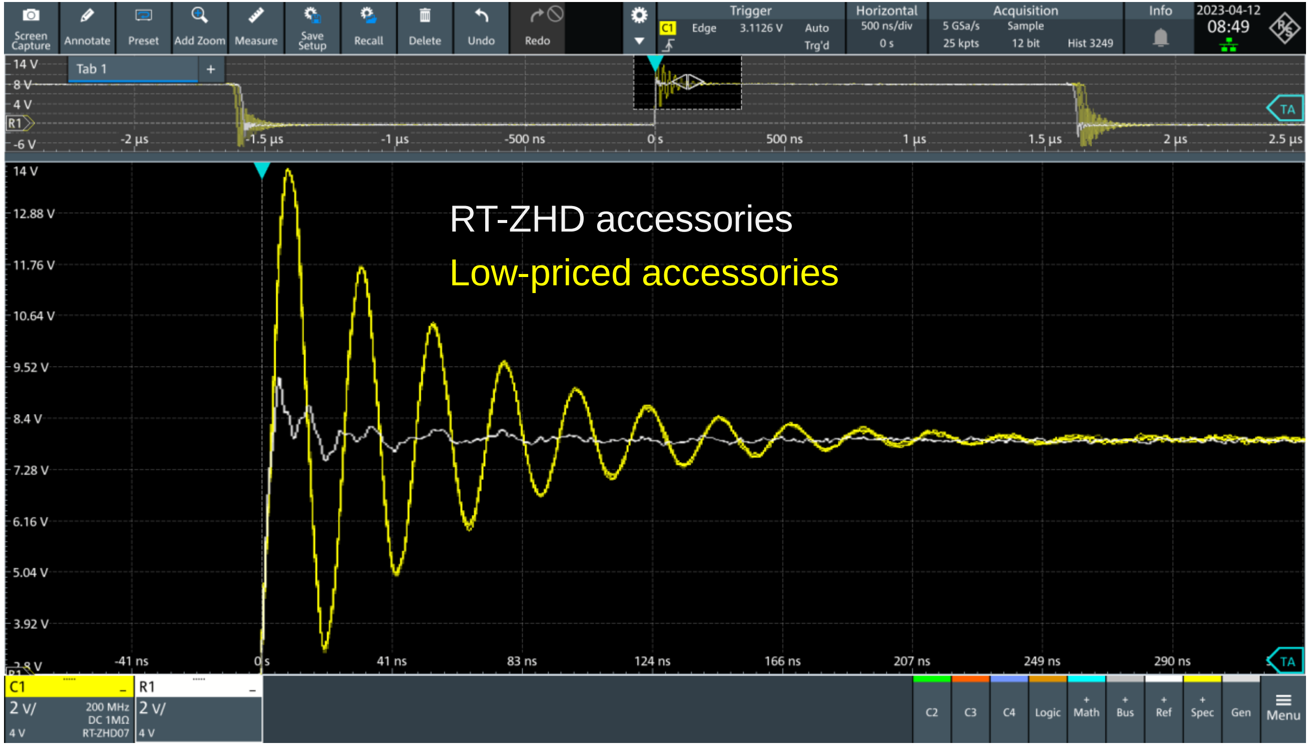
RT-ZHD probe

RT-ZHD Accessories

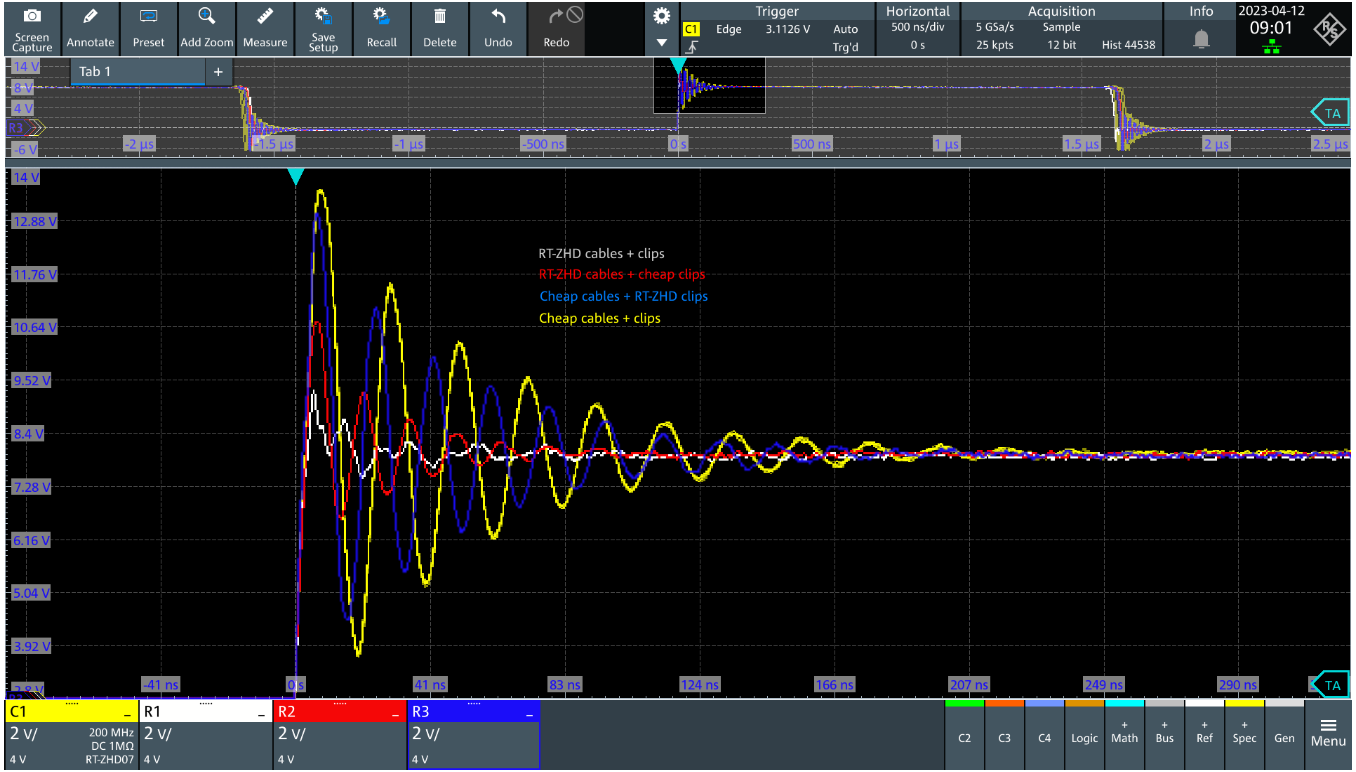
Low-priced Accessories



COMPARISON

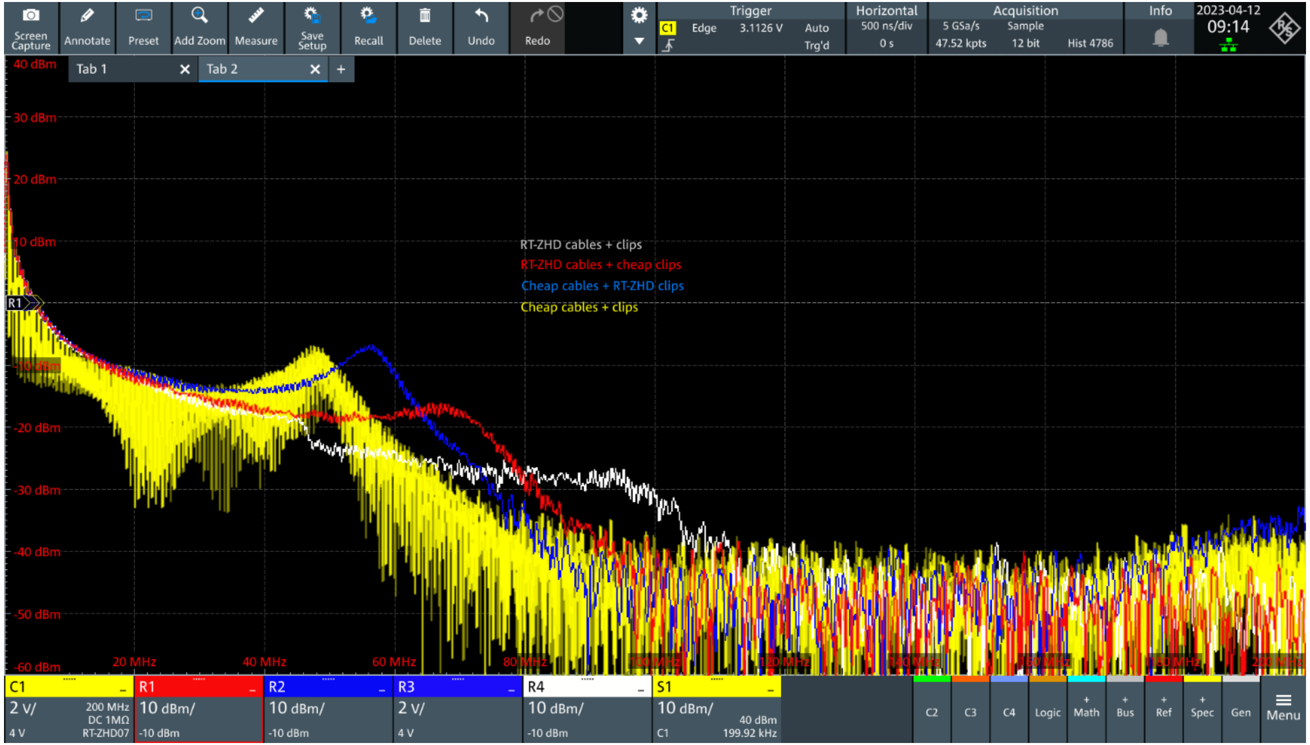

RT-ZHD accessories
Low-priced accessories
Screen Capture
Annotate
Preset
Add Zoom
Measure
Save Setup
Recall
Delete
Undo
Redo
Trigger
Edge
3.1126 V
Auto
Trg'd
Horizontal
500 ns/div
0 s
Acquisition
5 GSa/s
25 kpts
Sample
12 bit
Hist 3249
Info
2023-04-12
08:49
Tab 1
14 V
12.88 V
11.76 V
10.64 V
9.52 V
8.4 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
C2
C3
C4
Logic
Math
Bus
Ref
Spec
Gen
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

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

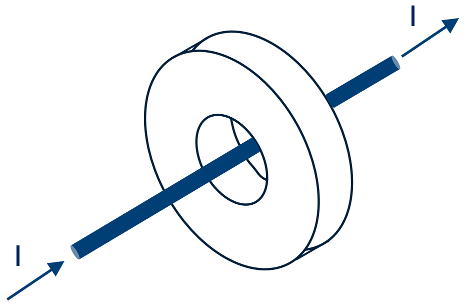
- It refers to the equivalent impedance that appears in series to the circuit (conductor under test) when it is being probed.
- The insertion impedance can be calculated as:

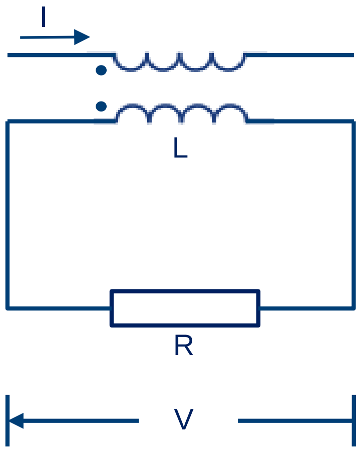
$$Z_{ins} = Z_{refl} + Z_{intr}$$

- 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.

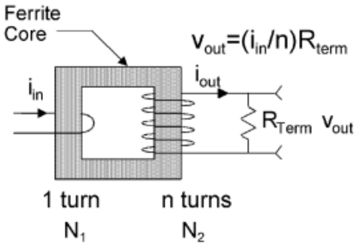




POSITIONING

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.

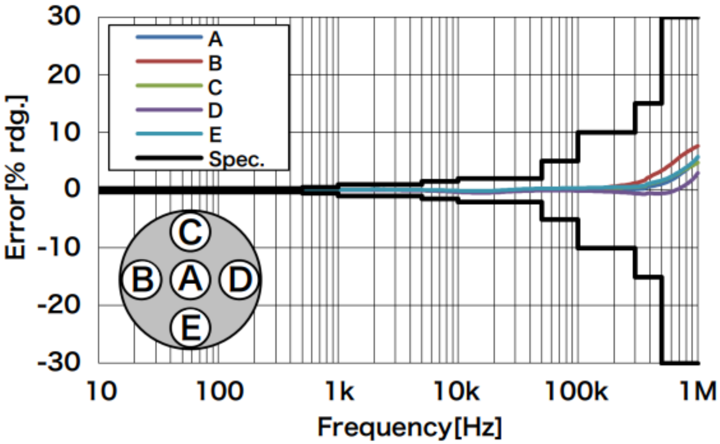


- An incorrect orientation translates into an inverse output voltage of the current probe.
- Probes are calibrated considering a single current direction.

Cable position

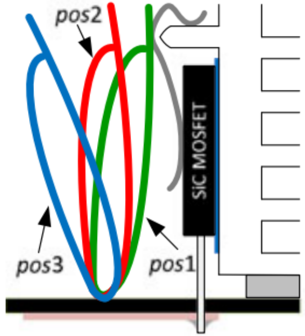
- The clamp-type current probes exhibit dependency on the positioning of the conductor.
- It should be placed in the center of the aperture since the characterization of the probe is done in this position.

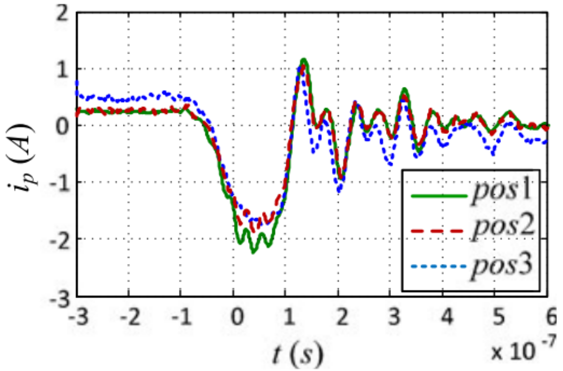
→ achieve best possible accuracy, and reproducibility.

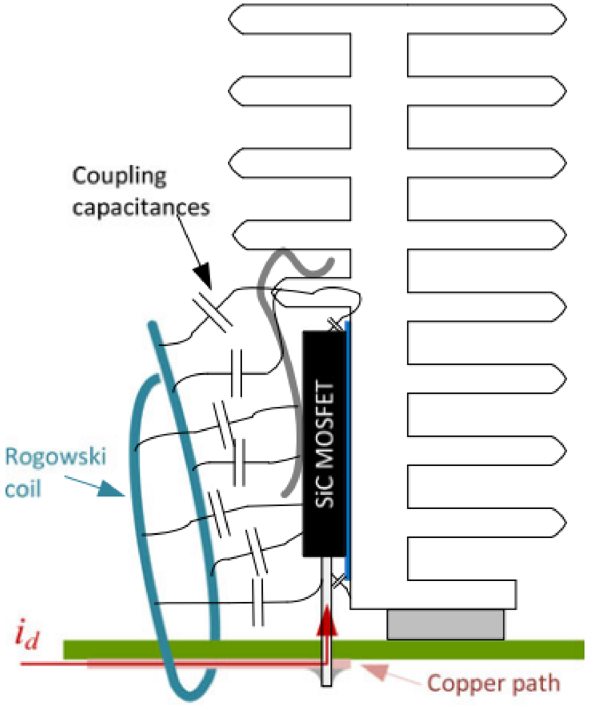


POSITIONING
COUPLING CAPACITANCES

- 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.



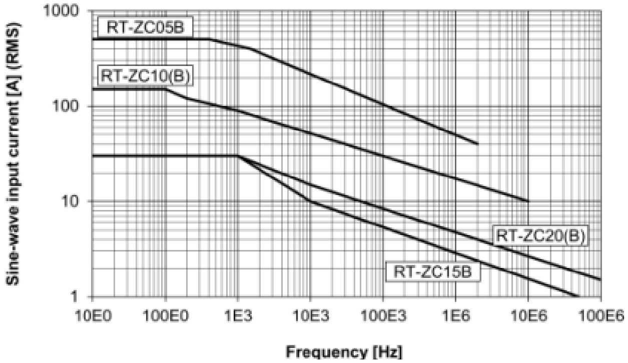


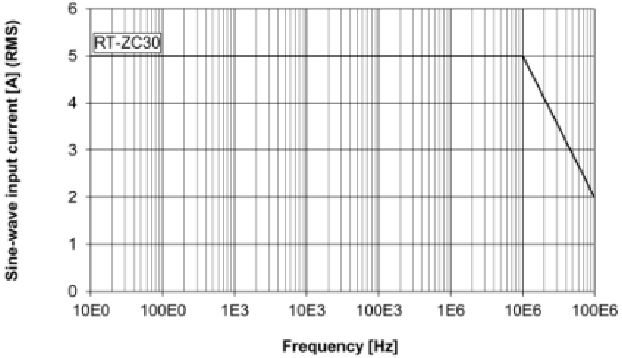


Oyarbide (2017). New Current Measurement Procedure Using a Conventional Rogowski Transducer for the Analysis of Switching Transients in Transistors.

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.





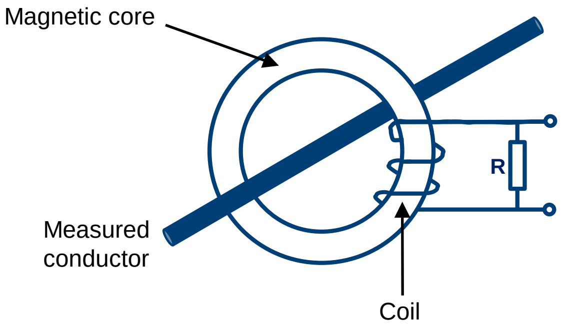
TEMPERATURE

- 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

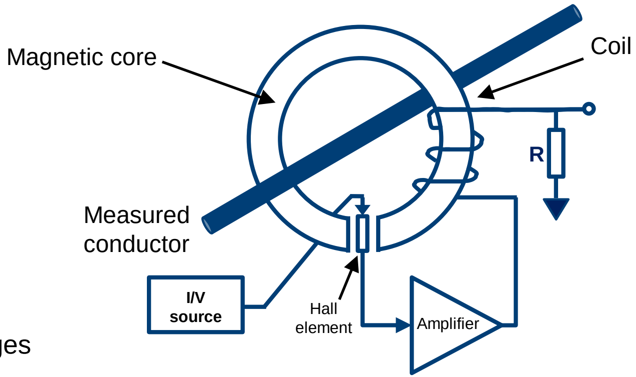
Current transformer (CT)

- 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

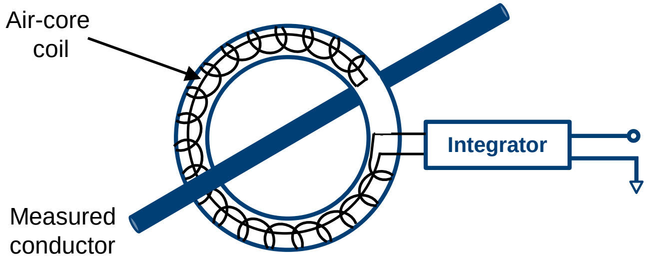
- It combines the CT and hall effect sensors in order to measure AC and DC currents.
- It is characterized by the high sensitivity and low noise.
- Especially designed for oscilloscopes, where small current waveforms must be observed.
- There is an offset drift when the temperature changes.
- High bandwidth: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

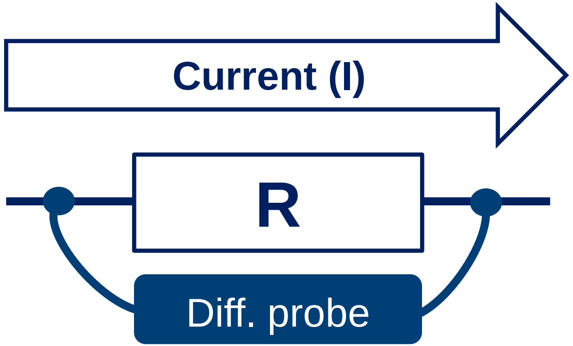


Shunt resistor

- 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