Charge Recovery Measurements with TLP

High Power Pulse Instruments (HPPI)

http://www.hppi.de/

February 11, 2018

Outline

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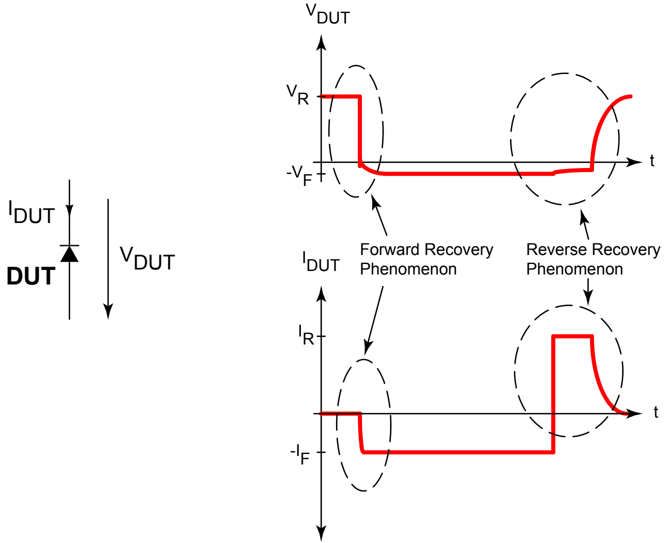
Definitions

TLP Setup

Various Generic Setups

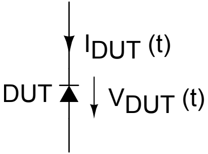
Measurement Setup With Discrete Current Sensor

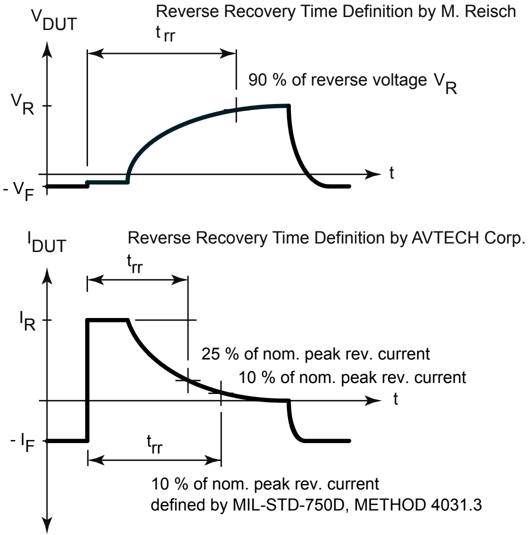
Charge Recovery Phenomenon of Diodes



Reverse Recovery Time of Diodes

Various Definitions





Reverse Recovery Time of Diodes

Various Definitions

Reverse Recovery Setup:

50 Ω and 100 Ω

Reverse Recovery Definition - I:

25 % of nominal peak reverse current [1]

Reverse Recovery Definition - II:

10 % of nominal peak reverse current [2]
MIL-STD-750D, method 4031.3

Reverse Recovery Definition - III:

90 % of reverse voltage [3]

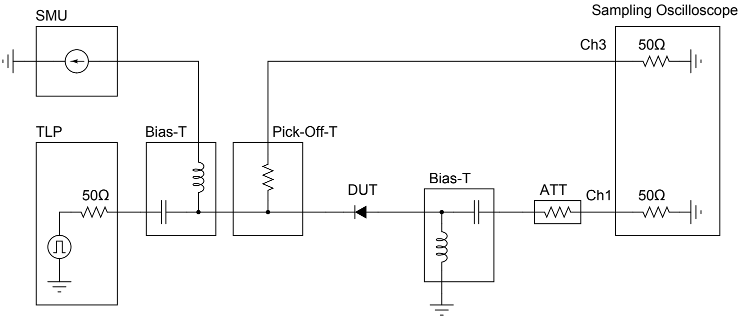
Reverse Recovery Definition - IV:

Reverse recovered charge [4]

Outline

General 100 Ω Measurement Setup

Reverse and Forward Recovery

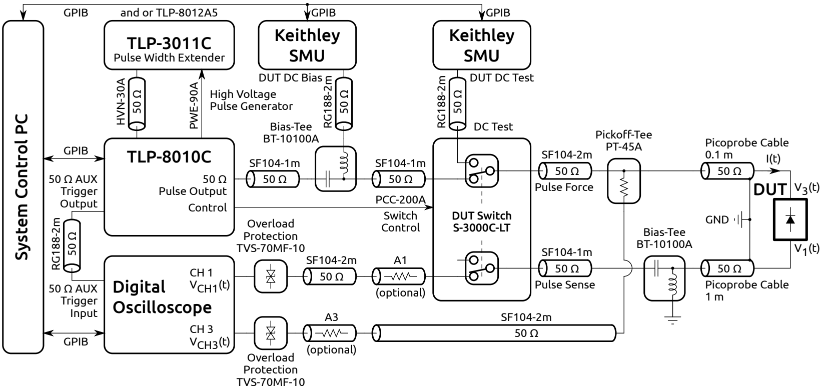


$$V_{DUT} = V_{Ch3} \cdot k_{PT} - V_{Ch1} \cdot k_{ATT}$$

$$I_{DUT} = \frac{V_{Ch1} \cdot k_{ATT}}{50\,\Omega}$$

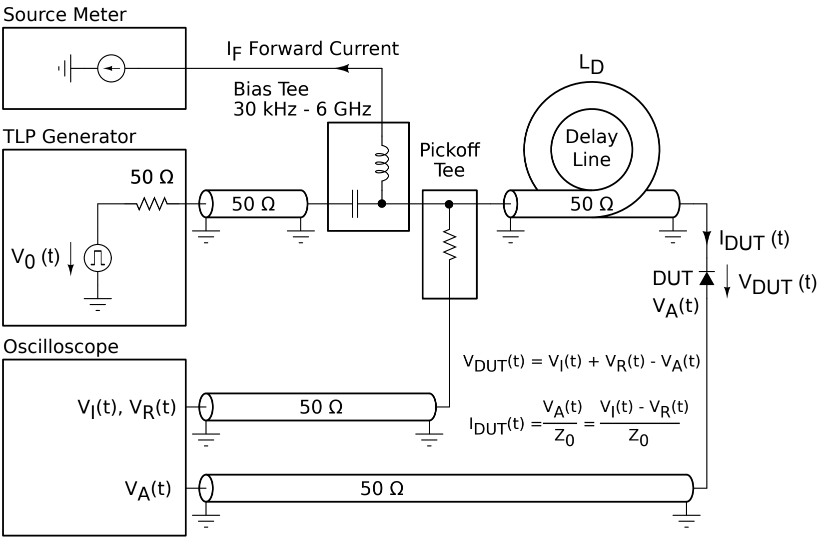
Detailed 100 Ω Measurement Setup

Reverse and Forward Recovery



General 100 Ω TDR Measurement Setup

Sub-ns Recovery Time Measurement



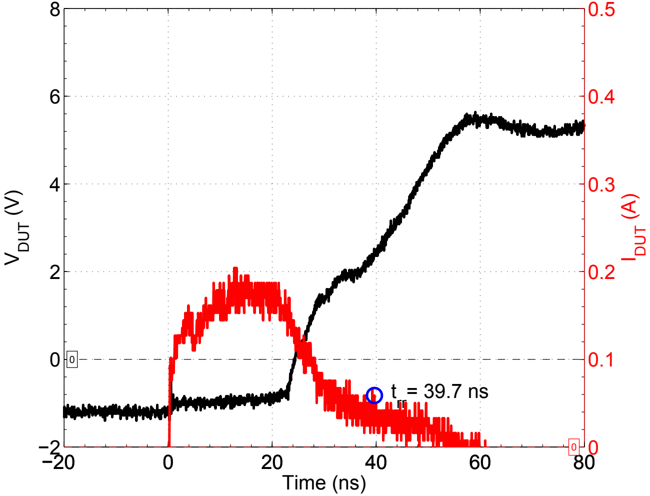
Reverse Recovery Time of Diodes

t_{rr} Extraction Procedure

- Set the pulse parameters to minimum available rise time of 100 ps and a pulse width which is approximately two to three times the expected reverse recovery time.
- Operate diode in forward mode with a defined forward bias current I_F.
- Apply a reverse mode TLP pulse with a defined reverse voltage $V_R = V_{TLP} - |V_F|$. The pulse width of the TLP has to be increased until the voltage V_R remains steady state.
- Measurement of the nominal peak reverse current.
- Extract 25 % (or 10 % according MIL-STD) of the nominal peak reverse current.
- The time where the current I_{DUT} decreases down to 25 % (or 10 % according MIL-STD) of the nominal peak reverse current, is the reverse recovery time.

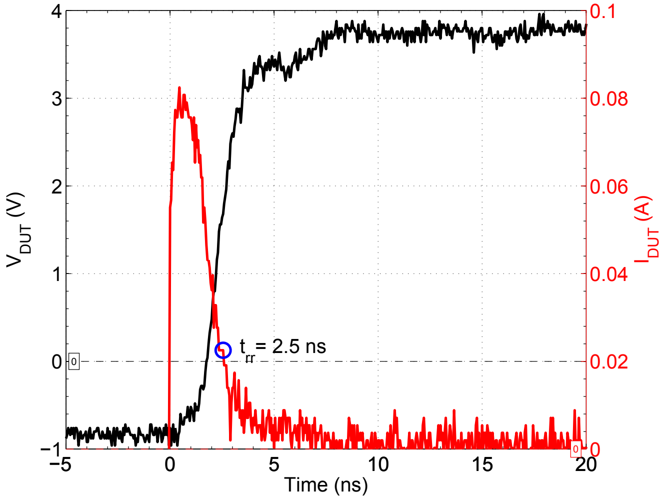
Reverse Recovery Transient Waveforms

Example: 39.7 ns



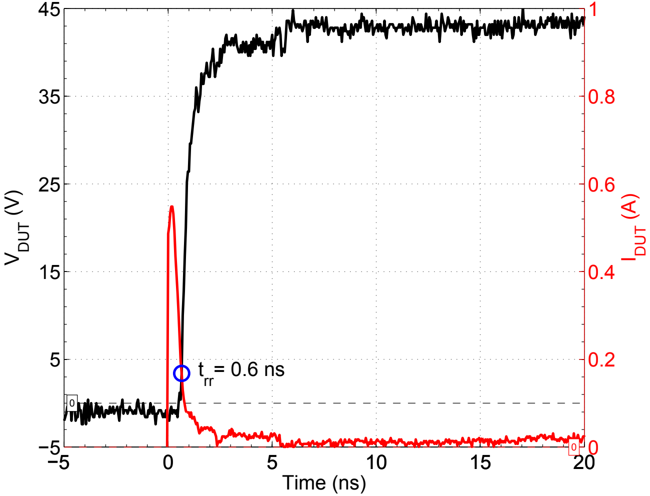
Reverse Recovery Transient Waveforms

Example: 2.5 ns



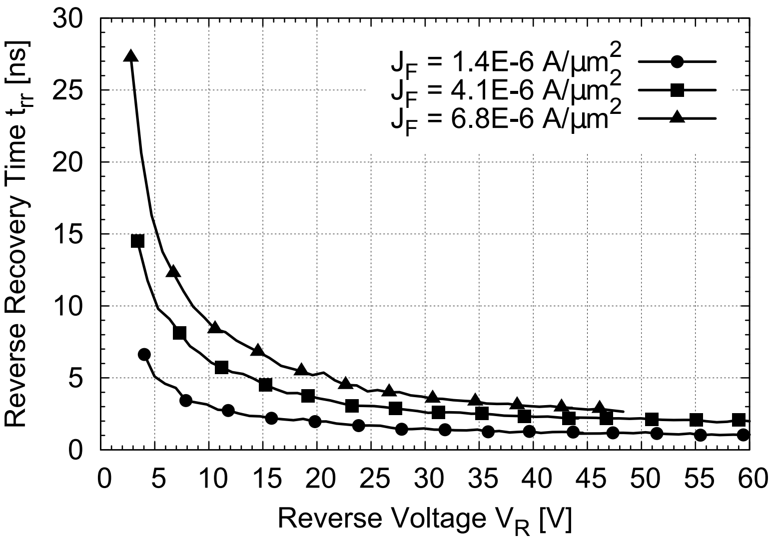
Reverse Recovery Transient Waveforms

Example: 0.6 ns



50 Ω Reverse Recovery Measurement Setup

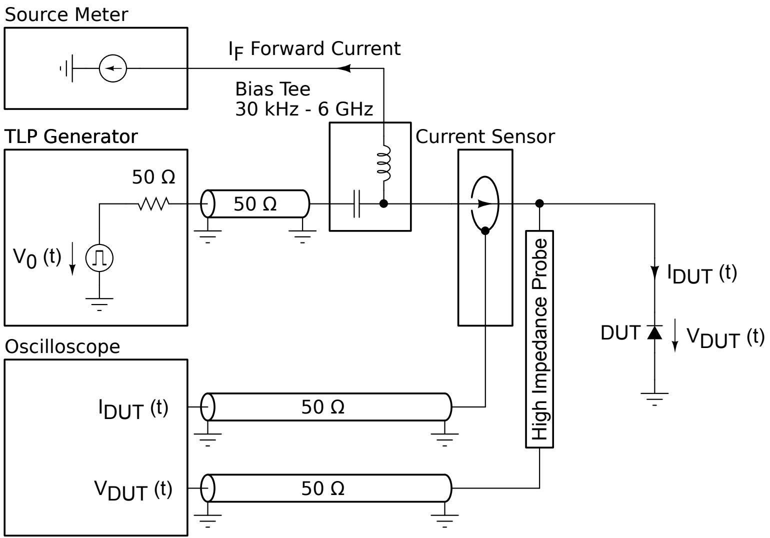
Example: Reverse Recovery Measurement Result of a Silicon Diode



Outline

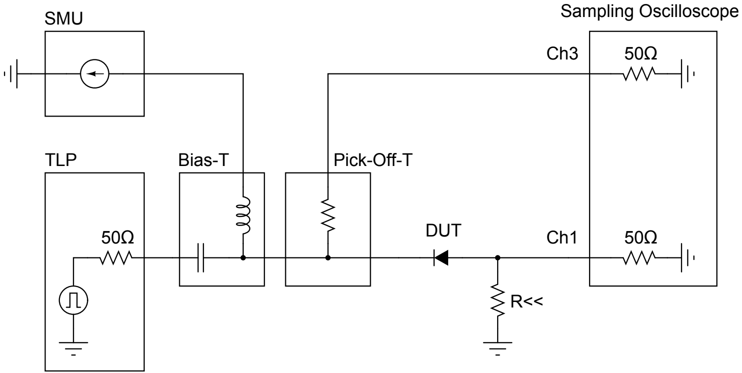
Reverse Recovery Time of Diodes

50 Ω Reverse Recovery Measurement Setup



Reverse Recovery

50 Ω Setup with Shunt Current Sense Resistor

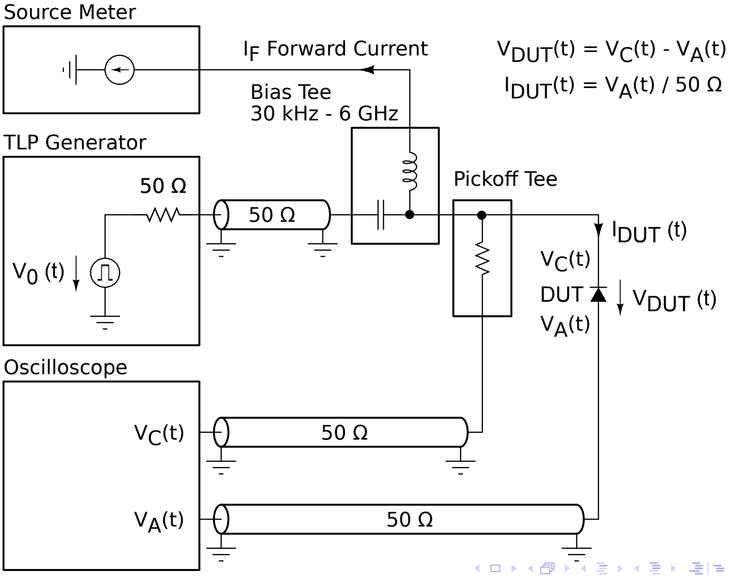


$$V_{DUT} = V_{Ch3} \cdot k_{PT} - V_{Ch1}$$

$$I_{DUT} = \frac{V_{Ch1}}{R}$$

Reverse Recovery Time of Diodes

100 Ω Reverse Recovery Measurement Setup

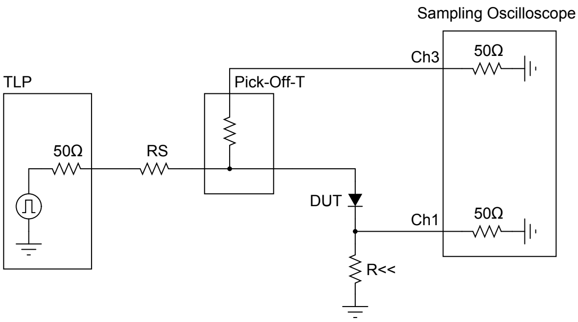


$V_{DUT}(t) = V_C(t) - V_A(t)$

$I_{DUT}(t) = V_A(t) / 50\ \Omega$

Forward Recovery

50 Ω+RS Setup

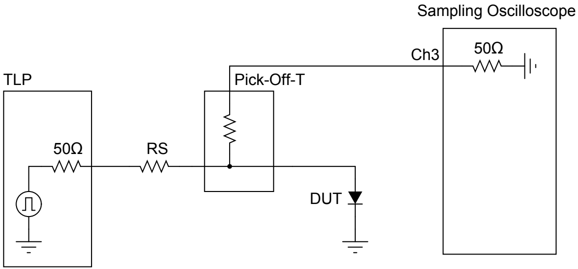


$$V_{DUT} = V_{Ch3} \cdot k_{PT} - V_{Ch1}$$

$$I_{DUT} = \frac{V_{Ch1}}{R}$$

Forward Recovery

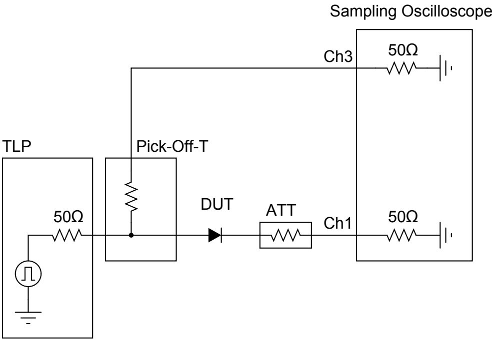
50 Ω+RS Setup



$$V_{DUT} = V_{Ch3} \cdot k_{PT}$$

Forward Recovery

100 Ω Setup

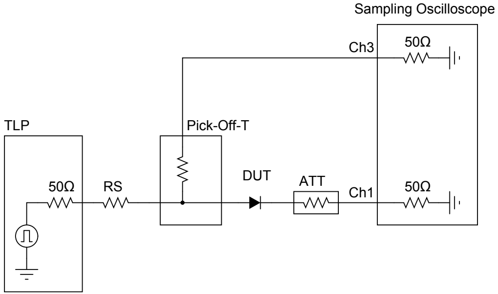


$$V_{DUT} = V_{Ch3} \cdot k_{PT} - V_{Ch1} \cdot k_{ATT}$$

$$I_{DUT} = \frac{V_{Ch1} \cdot k_{ATT}}{50\,\Omega}$$

Forward Recovery

100 Ω+RS Setup



$$V_{DUT} = V_{Ch3} \cdot k_{PT} - V_{Ch1} \cdot k_{ATT}$$

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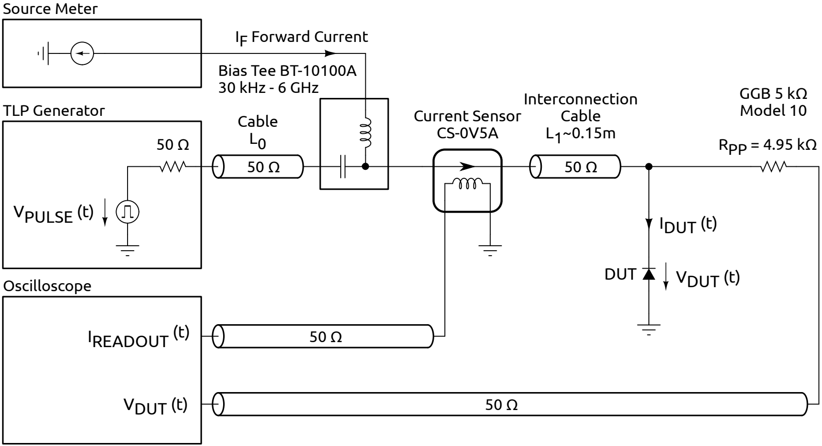
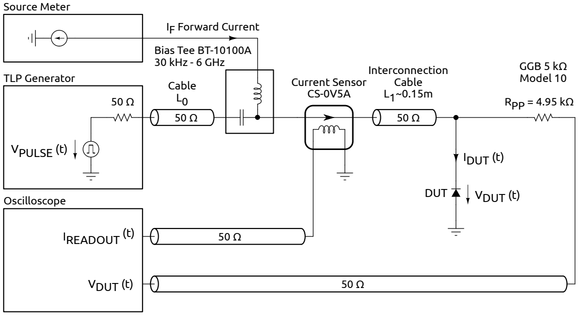
Measurement Setup with Discrete Current Sensor

Transformer-based Current Sensor



- The transformer-based current sensor does not readout the initial DC current

Setup and Polarity Definition



- Voltage and current polarities are defined as shown in this schematic
- Therefore the diode forward current is considered as a negative value, e.g. $IF = -45\,\text{mA}$
- $I_{DUT,CALC} = I_{READOUT} + I_F$

Measurement Setup with Discrete Current Sensor

Transformer-based Current Sensor

- Because of the transformer, the current sensor will not read out the DC forward bias current IF
- The sensor will read out the difference in the time domain:

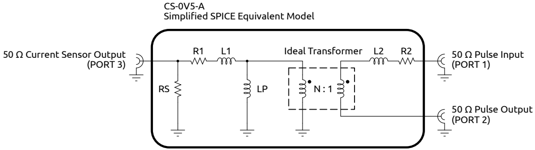
  Read Out Current = IDUT - IF

- This means we need to correct the result by post processing to get the correct IDUT value:

  IDUT = Read Out Current + IF
- In addition the readout signals shows a delay and a plateau due to the cable L_1

100 A, 3 GHz, 50 Ω, 0.5 V/A Current Sensor CS-0V5-A

SPICE Equivalent Model



50 Ω Current Sensor Output
(PORT 3)

50 Ω Pulse Input
(PORT 1)

50 Ω Pulse Output
(PORT 2)

$$N = 18$$

$$k = 0.9999$$

$$RS = 11\,\Omega$$

$$R1 = 0.1\,\Omega$$

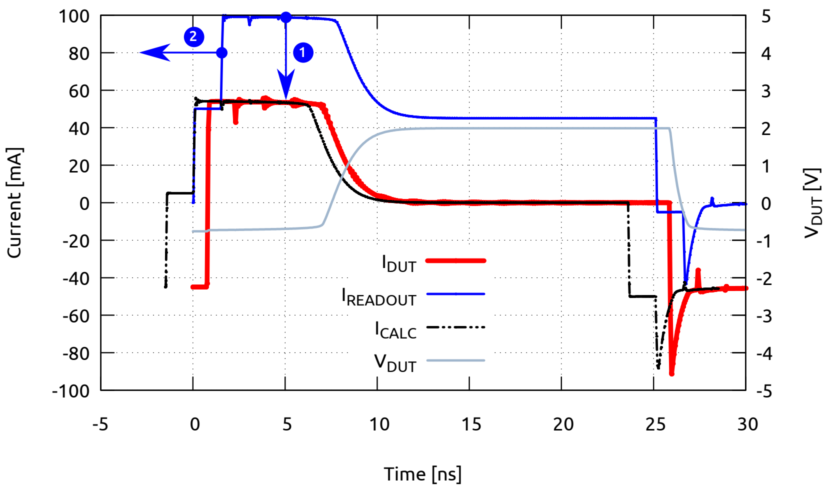
$$LP = 1.324\,\text{mH}$$

$$L1 = LP \cdot \left(\frac{1}{k} - 1\right) = 132.4\,\text{nH}$$

$$L2 = \frac{L1}{N^2} = 0.408\,\text{nH}$$

$$R2 = 0.01\,\Omega$$

How to Correct the Current Sensor Readout Signal?



How to Correct the Current Sensor Readout Signal?

Step 1: Shift down the readout signal by IF

Step 2: Shift left the readout signal by the delay time due to $2 \cdot L1$

Probe Parasitics and Cable De-Embedding

Required to avoid wrong readouts

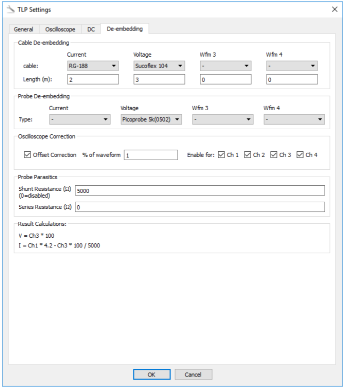
- Voltage attenuation factor of the 5k Picoprobe model 10:

$$\frac{4950\,\Omega + 50\,\Omega}{50\,\Omega} = 100$$

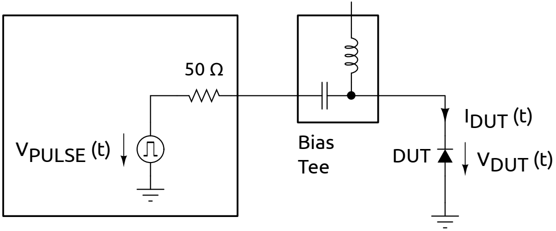
- Probe Parasitic Shunt Resistance:

$$4950\,\Omega + 50\,\Omega = 5000\,\Omega$$

- Activate correct cable de-embedding and offset correction



Maximum Peak Reverse Current



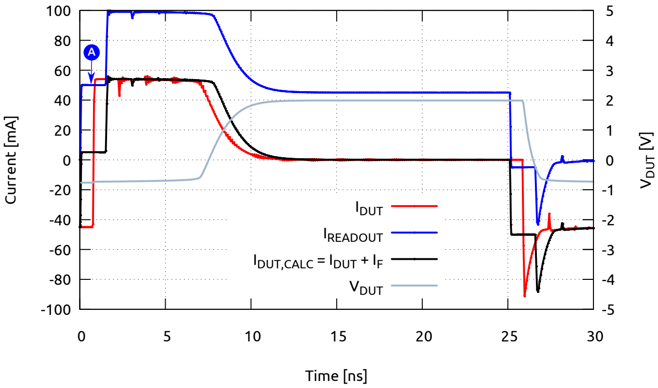
- The maximum peak reverse current is limited by the pulse voltage:

$$I_{DUT,max} = \frac{V_{PULSE}}{50\,\Omega} + I_F$$

- Example:
  $V_{PULSE} = 5\,\mathrm{V}$, $I_F = -45\,\mathrm{mA}$
  Maximum possible peak reverse current: $I_{DUT,max} = 55\,\mathrm{mA}$

Readout Detail A

$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$

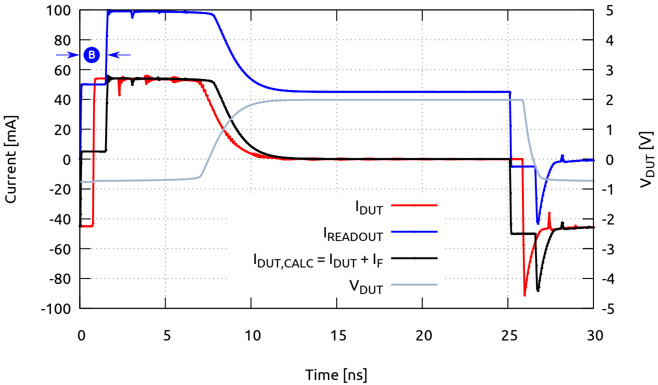


- The amplitude of the plateau **A** results from:

$$I_A = \frac{V_{PULSE}}{2} \cdot \frac{1}{50\,\Omega} = 50\,\text{mA}$$

Readout Detail B

$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$

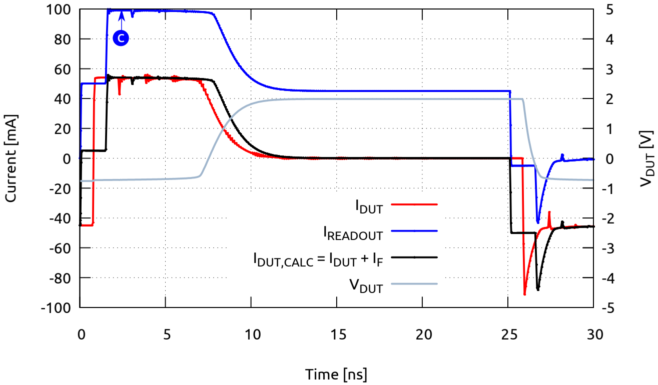


- The pulse width **B** of the plateau results from:

$$t_B = \frac{2 \cdot L_1}{v} \approx \frac{2 \cdot L_1 \cdot \sqrt{\epsilon_r}}{c}$$

Readout Detail C

$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$



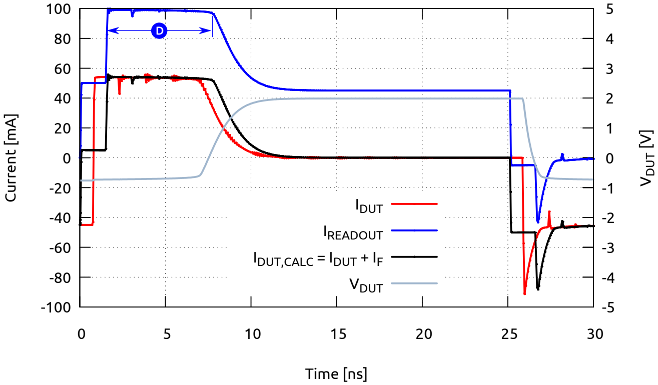
- The amplitude of the plateau **C** results from:

$$I_{C,max} = V_{PULSE} \cdot \frac{1}{50\,\Omega} = 100\,\text{mA}$$

- The value can be lower if Q_{rr} is low, but not higher than $I_{C,max}$

Readout Detail D

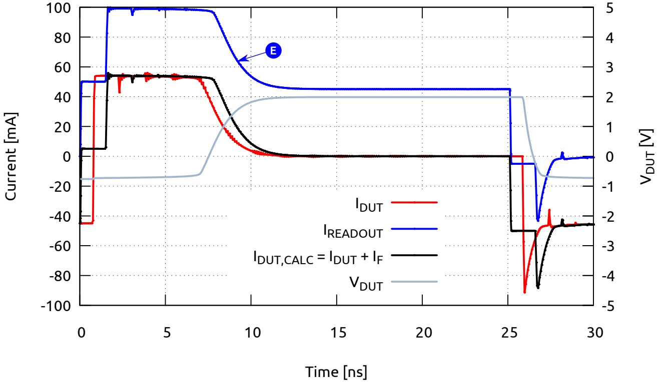
$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$



- The time **D** is depending on Q_{rr}

Readout Detail E

$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$



- The decay **E** is depending on C_{jo}

Calculation of the DUT Current

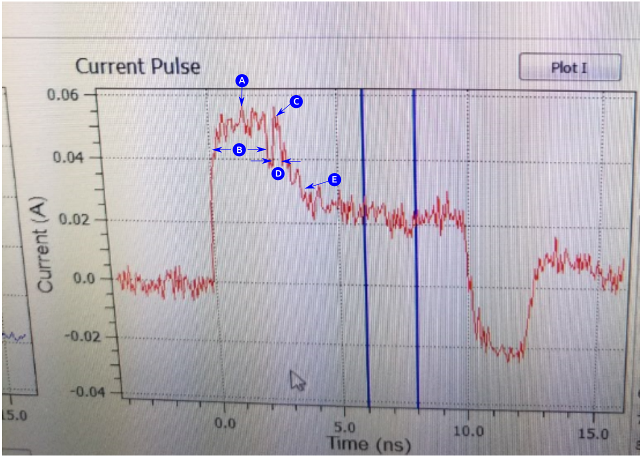
Out of the Readout Current

- Post-processing procedure:

$$I_{DUT,CALC} = I_{READOUT} + I_F$$

- $I_{DUT,CALC}$ is valid after t_B, this means that the time t_B needs to be blanked (set $I_{DUT,CALC} = I_F$) in order to get the right peak reverse current of the diode.
- Precise evaluation of t_B is necessary for this purpose
- In all cases for I_F and V_{PULSE} the calculated peak reverse current and decay give the right result, despite the current sensor delay.

Example With Very Low Q_{rr}



- All details **A-E** as described before

References

[1] AVTECH Electrosystems LTD, “A comparison of reverse recovery measurement systems”, Nov. 2006.

[2] *MIL-STD-750D, method 4031.3, reverse recovery characteristics*,

[3] M. Reisch, *Elektronische Baulemente*, 2nd ed.: Springer, 2007, ISBN: 3-540-34014-9.

[4] N. Shammas, D. Chamund, and P. Taylor, “Forward and reverse recovery behaviour of diodes in power converter applications”, in *Microelectronics, 2004. 24th International Conference on*, vol. 1, May 2004, pp. 3–10.