Driving SiC MOSFETs with unipolar gate voltage

Theory and experimental data on 650 & 1200 V Gen3

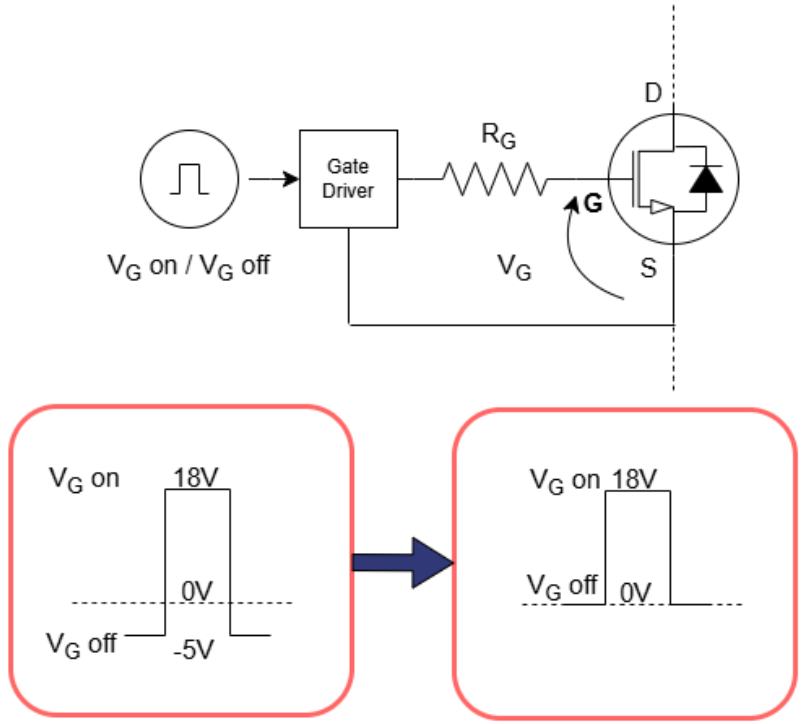
Advancements in SiC MOSFET turn-off driving: From negative bias to 0 V

We test the differences between unipolar (Vgs-on, Vgs-off: 18V, 0V) and bipolar (18V, -5 V) gate driving strategies on a SiC MOSFET

SiC MOSFETs are finding increasing application in high power converters due to better electrical, mechanical, and thermal performances than traditional Si MOSFETs and IGBT.

The most common automotive and industrial power converters are based on simple legs that are combined to form more complex topologies. Historically, a negative bias for driving turn-off of SiC MOSFETs was a standard recommendation for hard-switched half-bridge based topologies.

This is manly to avoid the very famous Miller turn-on effect (known also as parasitic turn-on) and any undesired spurious turn-on events.

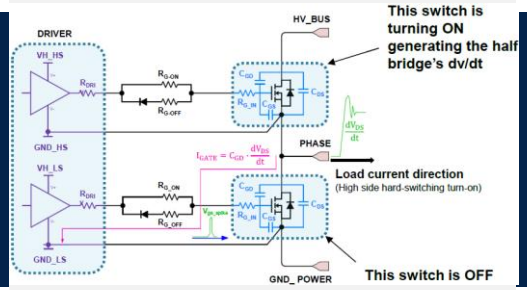


0V turn-off offers design advantages in terms of simplifying the transition from silicon to SiC and allowing easier driving circuits that can save space in highly space-constrained applications.

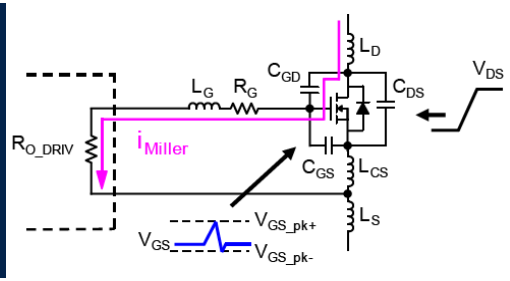
Miller turn-on effect during transitions

In power converters, minimizing the undesired Miller turn-on effect is crucial for enhancing efficiency and reducing power losses

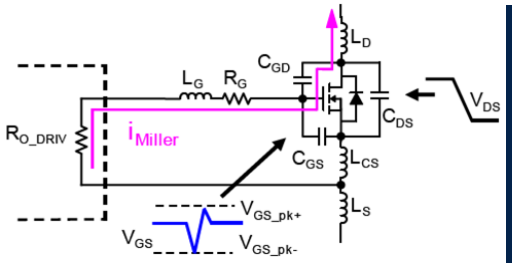
Miller turn-on due to high dv/dt transient in HB topology



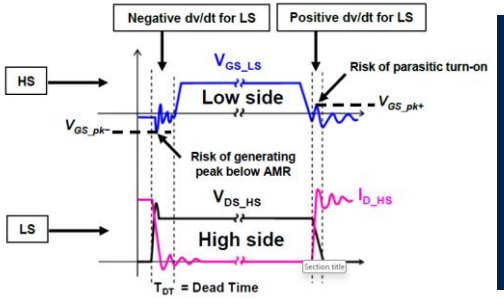
Miller current generation with positive dv/dt



Miller current generation with negative dv/dt



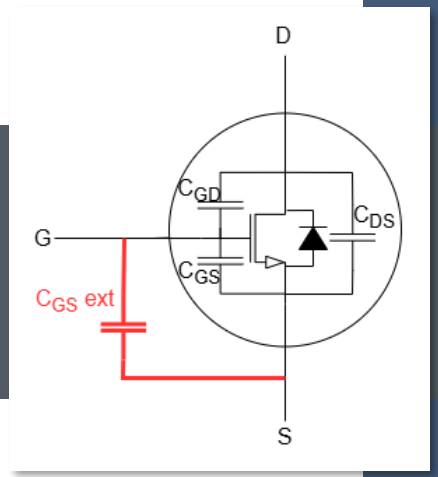
Duality of glitch phenomena



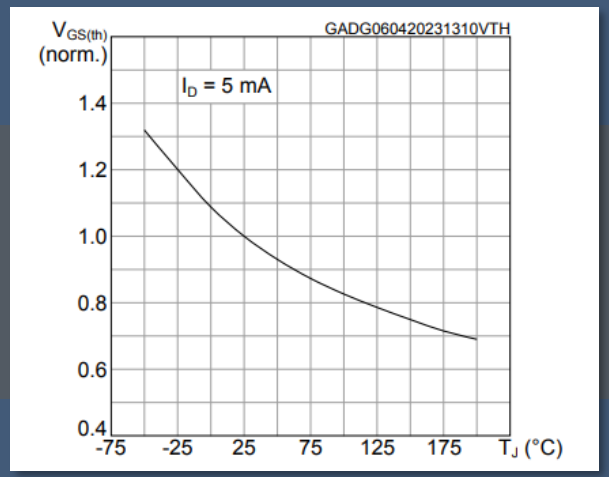
One effective strategy is to use a negative gate-source voltage Vgs-off during turn-off. This approach helps to mitigate the effects of ringing and overshoot, which can otherwise lead to unintended turn-on due to the Miller effect.

K elements in Miller turn on phenomenon

Vgs(th) threshold voltage is the minimum gate-to-source voltage to create a conducting path between MOSFET source & drain terminals



Normalized gate threshold voltage vs. temperature



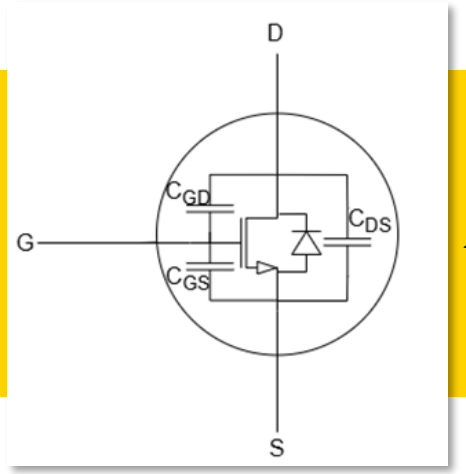
Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
$V_{(BR)DSS}$	Drain-source breakdown voltage	V_{GS} = 0 V, I_D = 1 mA	1200			V
I_{DSS}	Zero gate voltage drain current	V_{GS} = 0 V, V_{DS} = 1200 V			10	µA
I_{GSS}	Gate-body leakage current	V_{DS} = 0 V, V_{GS} = -10 to 22 V			±100	nA
$V_{GS(th)}$	Gate threshold voltage	V_{DS} = V_{GS}, I_D = 5 mA	1.8	3.0	4.2	V

Room temperature testing:
The threshold voltage is tested at room temperature during production to ensure that the devices meet the specified minimum threshold voltage.

Temperature effects:
Vgs(th) tends to decrease at higher temperatures, although this parameter is not typically measured during production. This behavior must be considered in applications where devices operate at elevated temperatures.

Why the capacitance ratio is important

Parasitic capacitance can lead to undesired energy storage and release during switching, causing delays or unwanted oscillations



$$Ratio = \frac{C_{GD}}{C_{GS}} = \frac{Crss}{Ciss - Crss} << 1$$

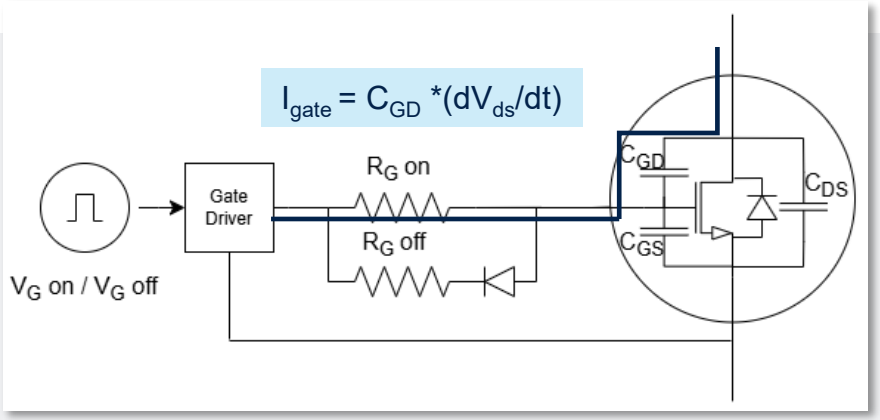
Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
C_{iss}	Input capacitance	V_{DS} = 800 V, f = 1 MHz, V_{GS} = 0 V	-	1990	-	pF
C_{oss}	Output capacitance		-	102	-	pF
C_{rss}	Reverse transfer capacitance		-	12	-	pF

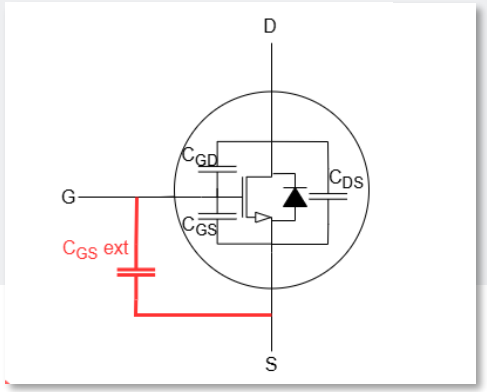
A lower capacitance ratio in a device can reduce susceptibility to the false turn-on phenomenon. This means that the device is less likely to experience unintended turn-on events during switching, which can lead to additional power losses.

To improve device performance and reliability, it is crucial to manage parasitic capacitance carefully. This might involve optimizing the device design, selecting appropriate materials, and using external components to dampen unwanted effects.

Miller turn-on mitigation in MOSFETs

The designer can find a list of the most important key elements which allows optimizing performance



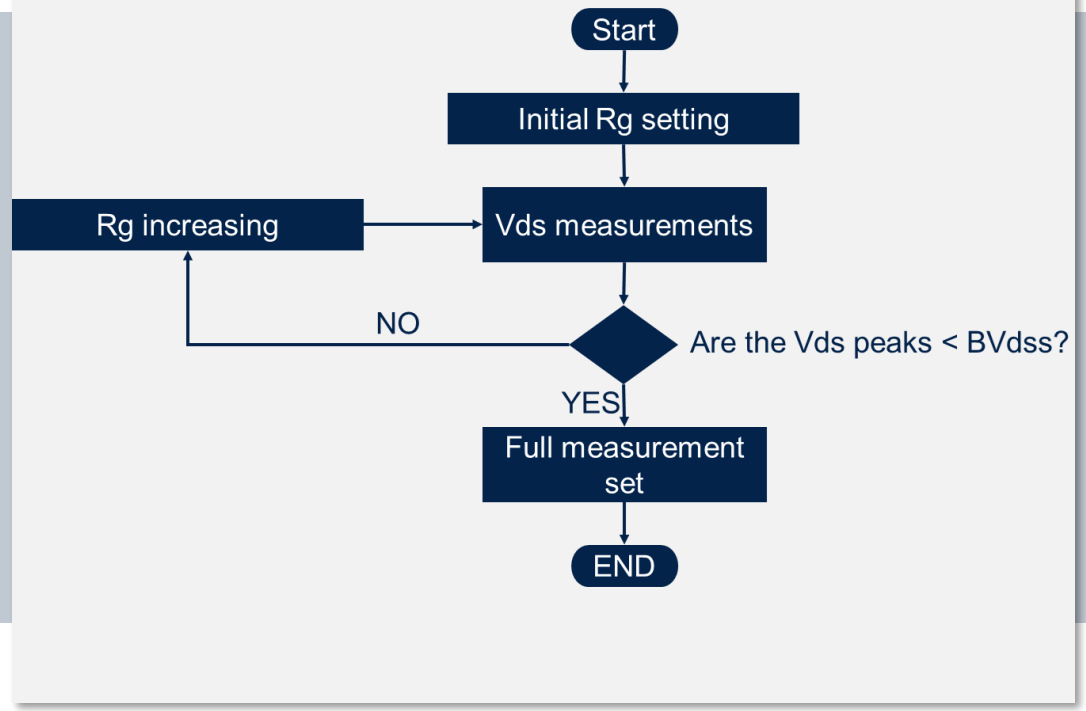


- **Gate resistance**: select a gate resistance such that the ratio is Rgon/Rgoff ≥ 1.5. This ensures faster turn-off compared to turn-on, reducing the risk of Miller turn-on.
- **External capacitance (C_{GS}-ext)**: add an external capacitance between the gate and source. A few nF can be enough to improve performance and reduce Vgs spikes.
- **Active Miller clamp**: use a gate driver with an active Miller clamp to prevent the gate voltage from rising due to the Miller effect during switching.
- **PCB layout**: optimize the PCB layout to minimize stray inductances, which can exacerbate the Miller effect.
- **Miller capacitance ratio**: choose MOSFETs with a gate-drain to gate-source capacitance ratio (C_{GD}/C_{GS}) as low as possible (much less than 1). This helps reduce the Miller effect.
- **Threshold voltage** (V_{GS}(th)): threshold voltage is key and the worst-case condition must be considered for appropriate design robustness.
- **Driving network**: optimize the network according to the design boundary conditions.

Measurement results V_{gsoff} = 0 V

Driving Rg choice

Choosing the right gate resistance involves a tradeoff between switching speed and safe operation (VDS spike < Vdss)

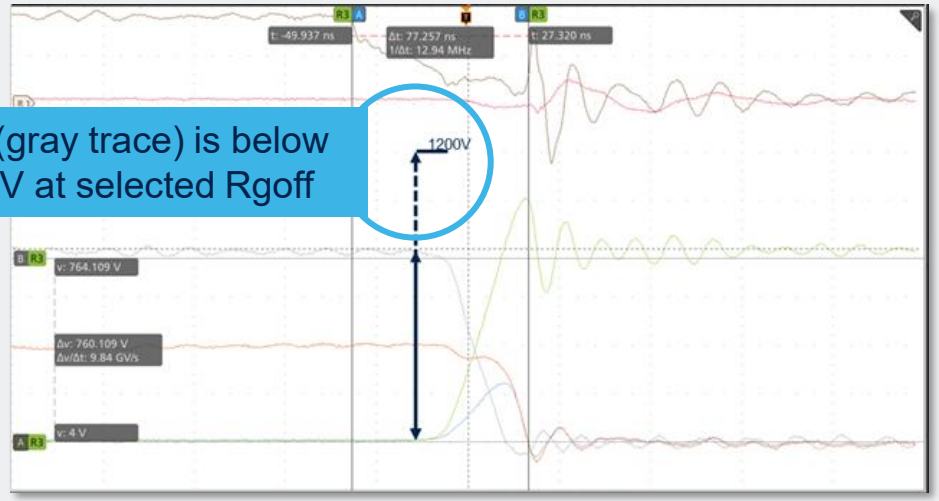


- **For Rgoff**, use the lowest value to ensure the Absolute Maximum Rating is not exceeded (with appropriate margin) at Vgs-off = -5 V. Then reduce it for 0V OFF to match the speed that would be obtained with a negative driving voltage.
- The same sequence on the left can then be used to choose the **proper Rgon** to mitigate the Vds spike across the complementary switch in the half bridge. In this case, you don't need to tune the Rgon value when moving to unipolar driving.
- Once the optimal Rgon and Rgoff values have been identified, measurements are performed at room and high temperatures to assess the behavior.
- Configurations with and without the Active Miller clamp are considered.

An example of how to select Rg

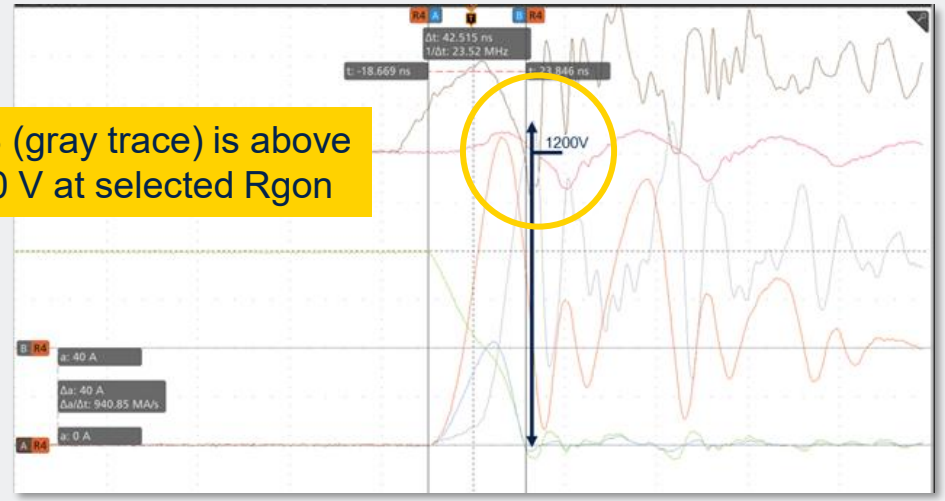
In these comparisons, a typical and safe switching speed is applied, and the same speed is imposed in all the configurations tested

Turn off



Selected Rgoff is OK

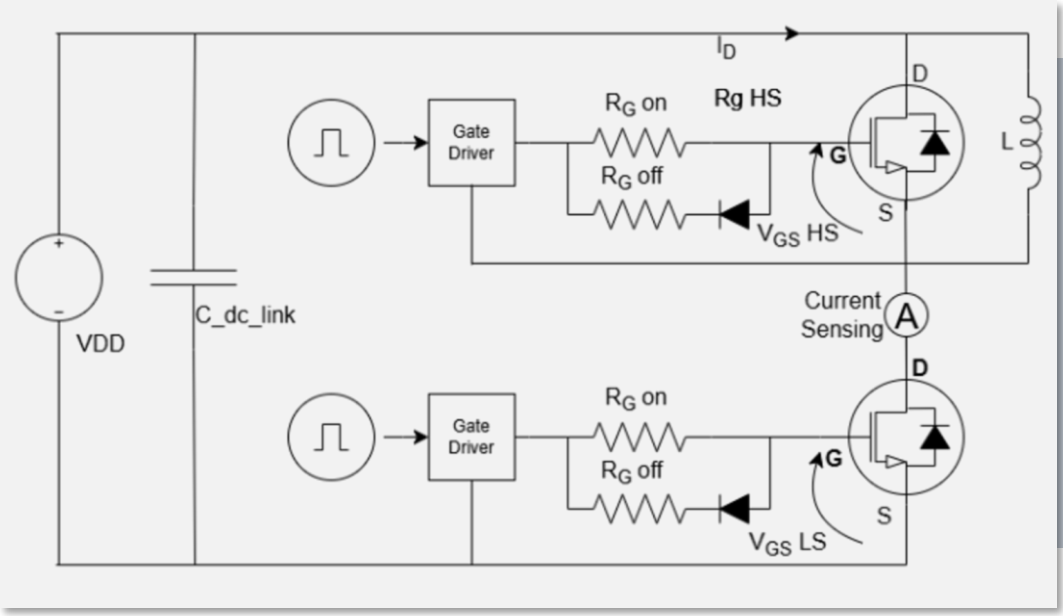
Turn on



Need to increase Rgon and test again

Double pulse test schematic and test conditions using a 1200 V device

The comparison represents the E_{sw} vs I_D using a 1200 V device with 27 mΩ typ Gen3 SiC MOSFET as test vehicle

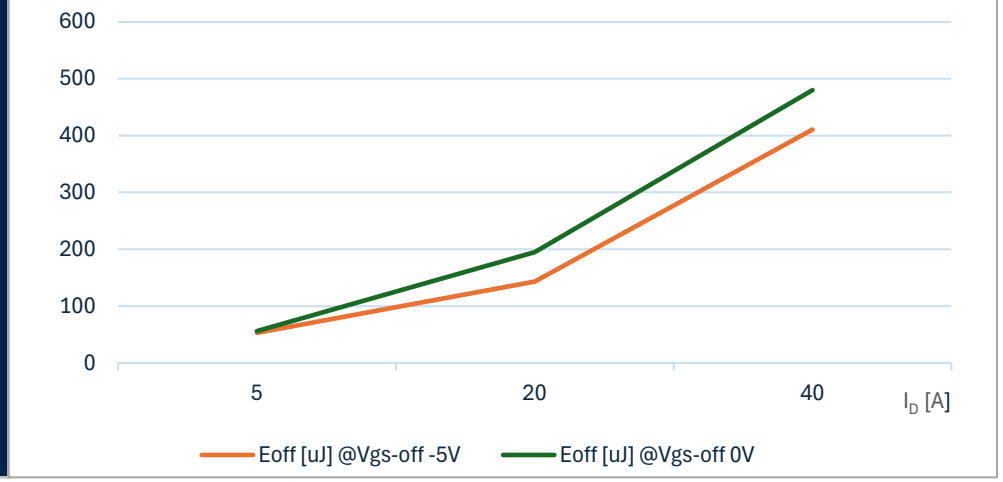


Test conditions:

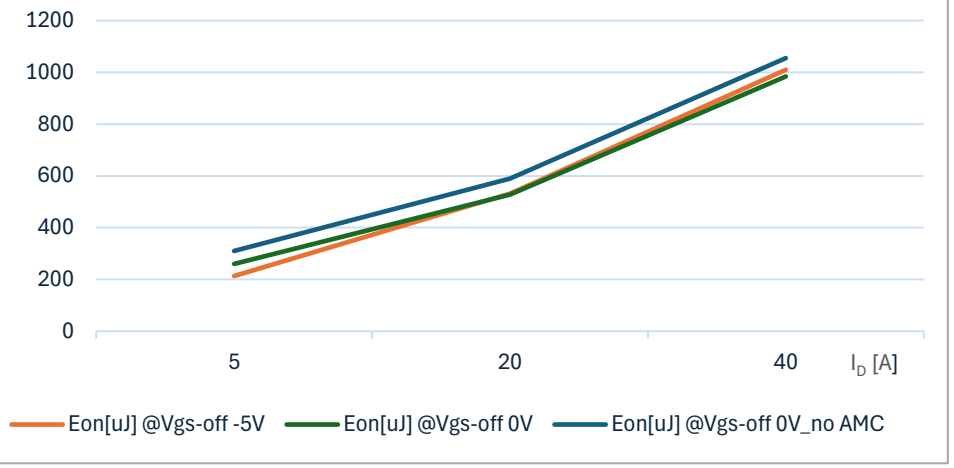
- T_J = 150°C
- Turn-on speed: di/dt_{ON} ≈ 2 A/ns
- Turn-off speed: dv/dt_{OFF} ≈ 35 V/ns
- V_{DD} ≈ 800 V
- 0 Vgs-off with and without Active Miller clamp vs negative driving voltage as PoR
- $V_{GS}(th)$ = 2.8 V

Energy comparison bipolar vs unipolar driving using a 1200 V device

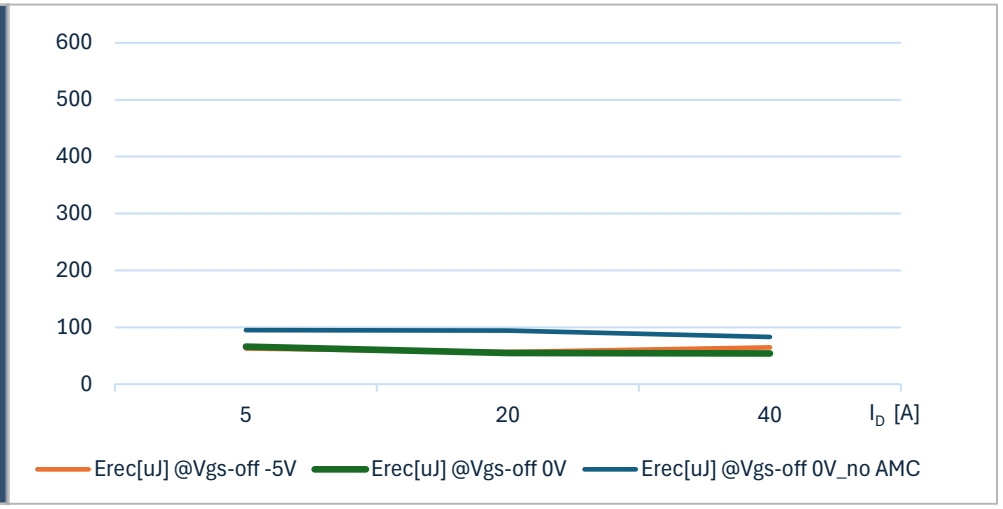
E^*_{OFF} [µJ] @150°C



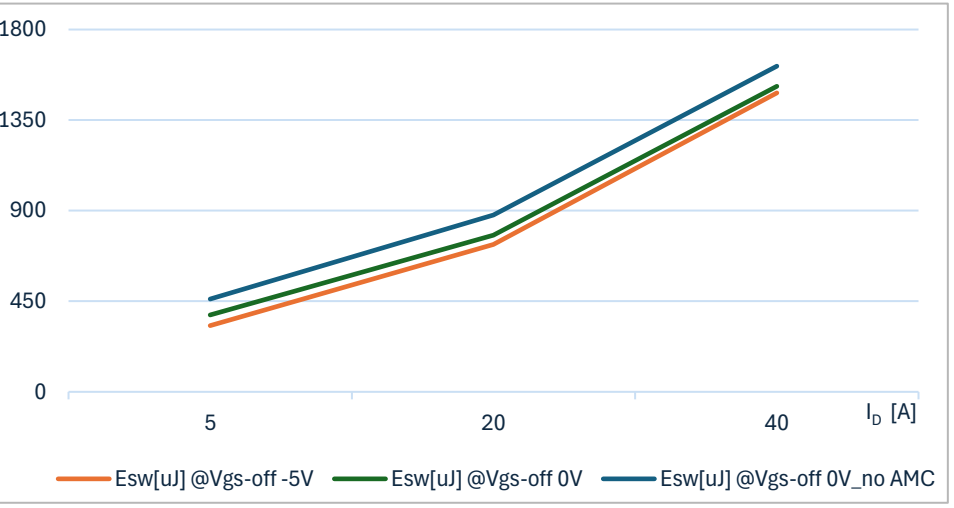
E_{ON} [µJ] @150°C



E_{REC} [µJ] @150°C



E_{SW} [µJ] @150°C



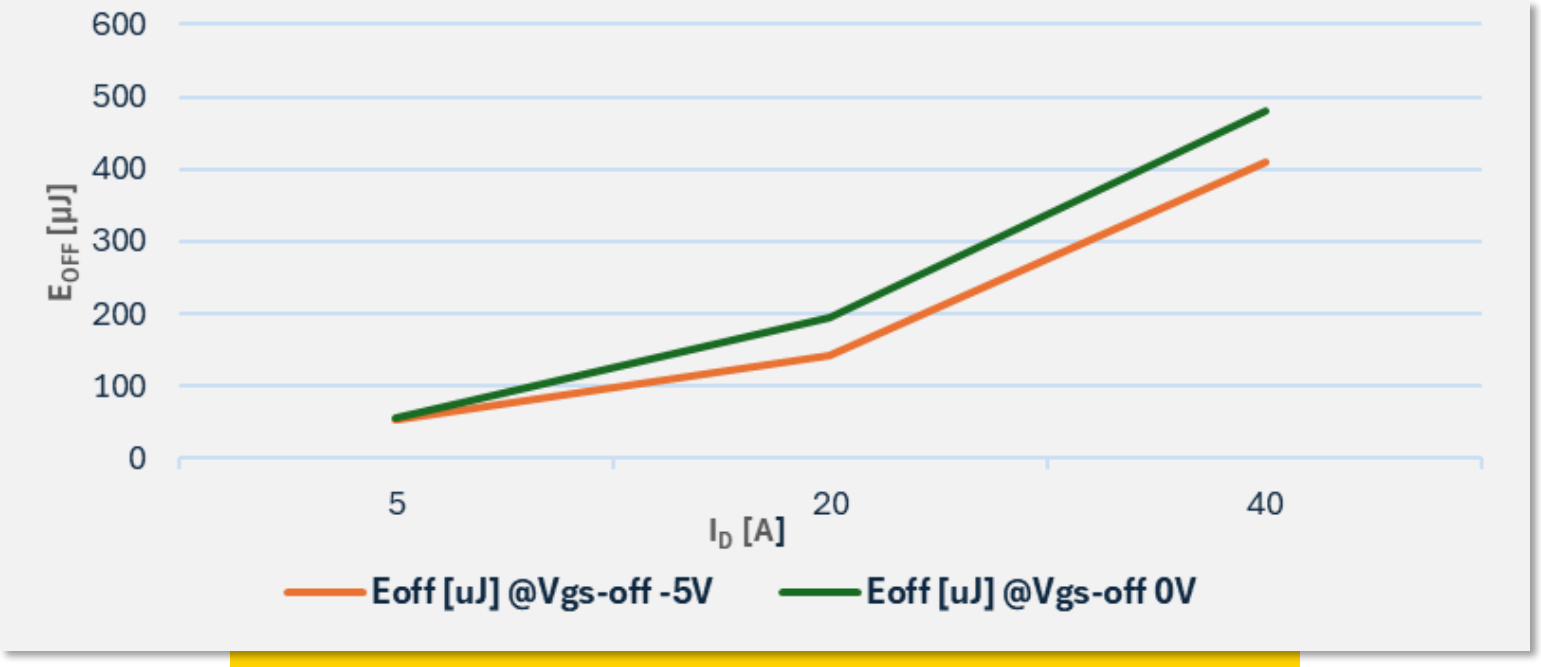
**Eoff is not influenced by Active Miller clamp*

Conditions: Turn-on speed: $di/dt_{ON} \approx 2A/ns$ - Turn-off speed: $dv/dt_{OFF} \approx 35V/ns$

Energy comparison bipolar vs unipolar driving using a 1200 V device

Eoff (turn-off speed: $dv/dt_{OFF} \approx 35$ V/ns)

From 0 to 20% higher loss with 0 V turn off

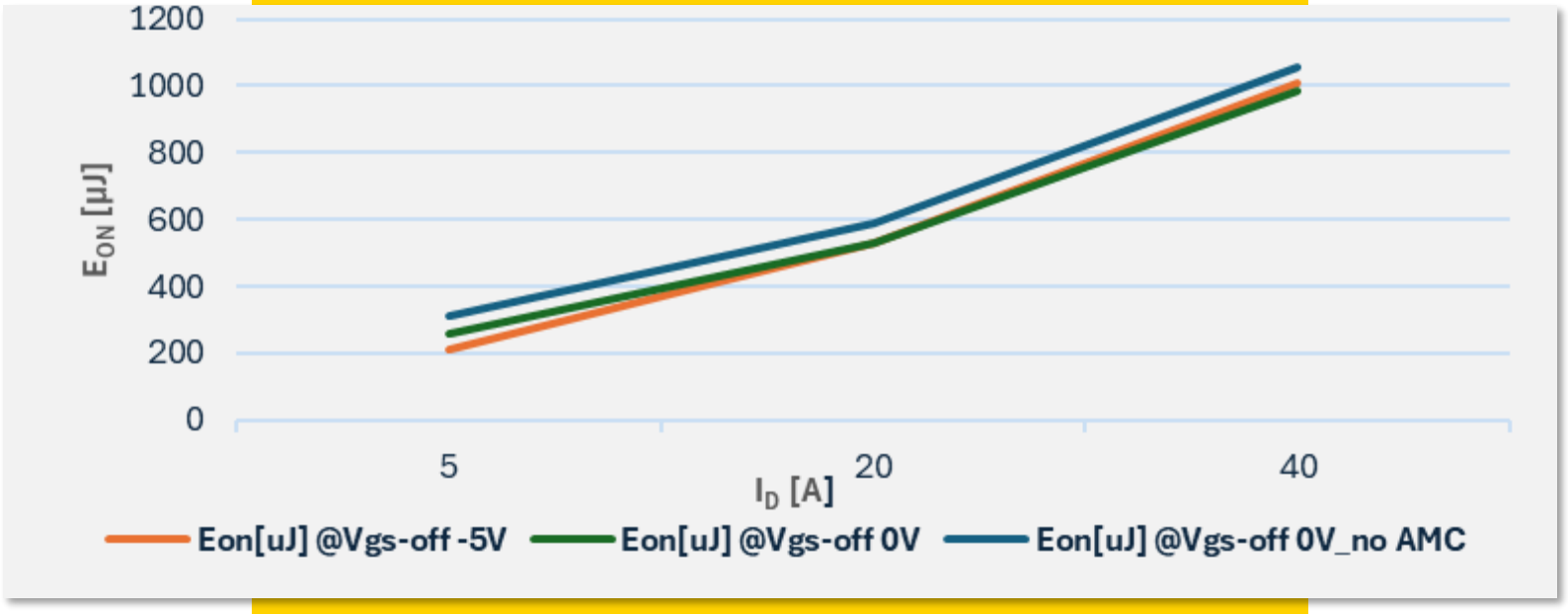


Eoff is not influenced by Active Miller clamp

Energy comparison bipolar vs unipolar driving using a 1200 V device

Eon (turn-on speed: $di/dt_{ON} \approx 2A/ns$)

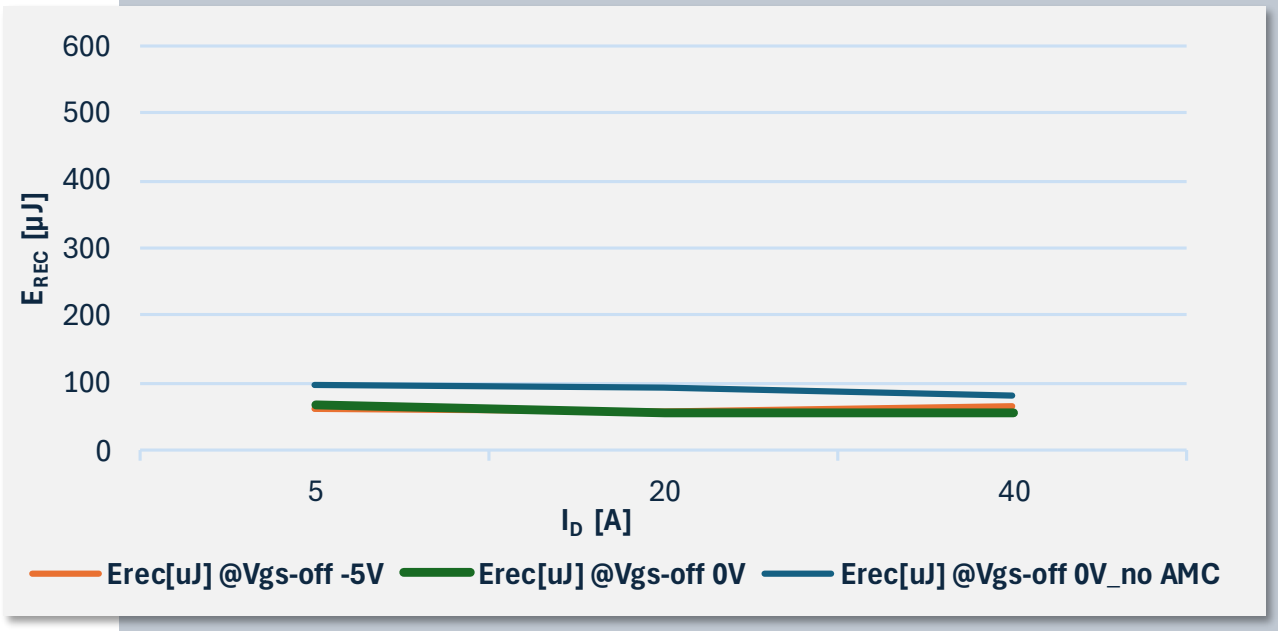
Almost no differences between negative and 0 Vgs-off with Active Miller clamp

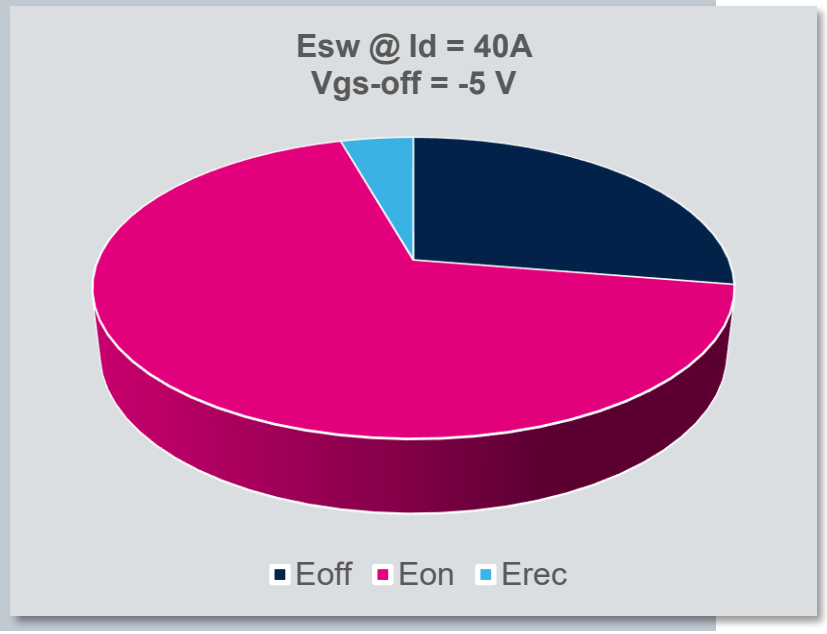


Energy comparison bipolar vs unipolar driving using a 1200 V device

Erec (turn-on speed: $di/dt_{ON} \approx 2A/ns$)

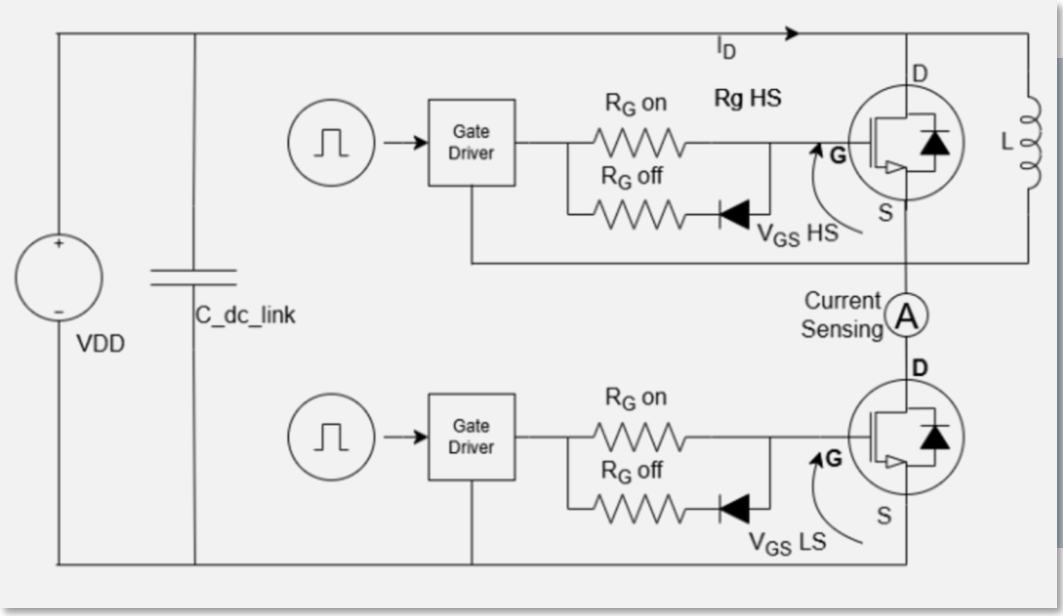
In all the analyzed cases, the contribution of Erec is very small in comparison with Eon and Eoff. Even if there are small differences between negative and 0 Vgs-off, their contribution to the overall power losses is negligible





Double pulse test schematic and test conditions using a 650 V device

The comparison represents the E_{sw} vs I_D using a 650 V device with 29 mΩ_{typ} Gen3 SiC MOSFET as test vehicle

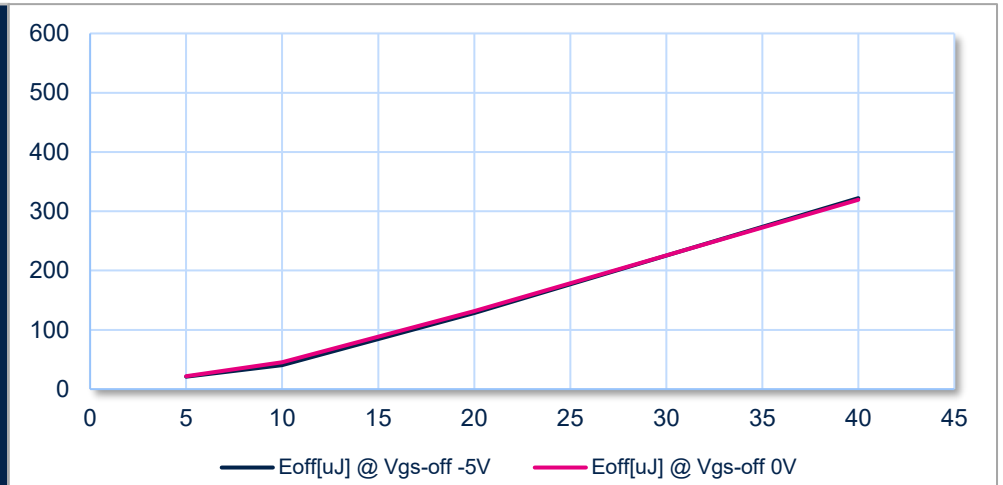


Test conditions:

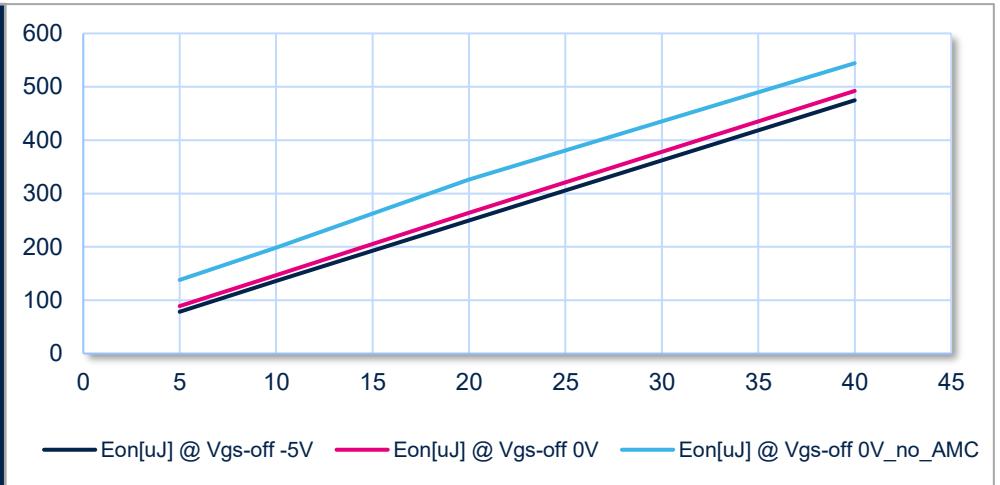
- T_J = 150°C
- Turn-on speed: di/dt_{ON} ≈ 1.5 A/ns
- Turn-off speed: dv/dt_{OFF} ≈ 18 V/ns
- V_{DD} ≈ 400 V
- 0 Vgs-off with and without Active Miller clamp vs negative driving voltage as PoR
- $V_{GS}(th)$ = 2.8 V

Energy comparison bipolar vs unipolar driving using a 650 V device

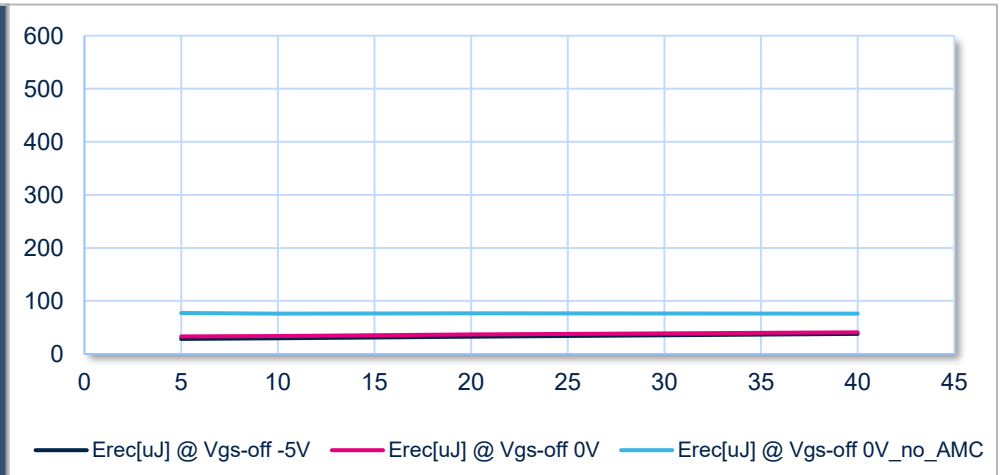
E^*_{OFF} [µJ] @150°C



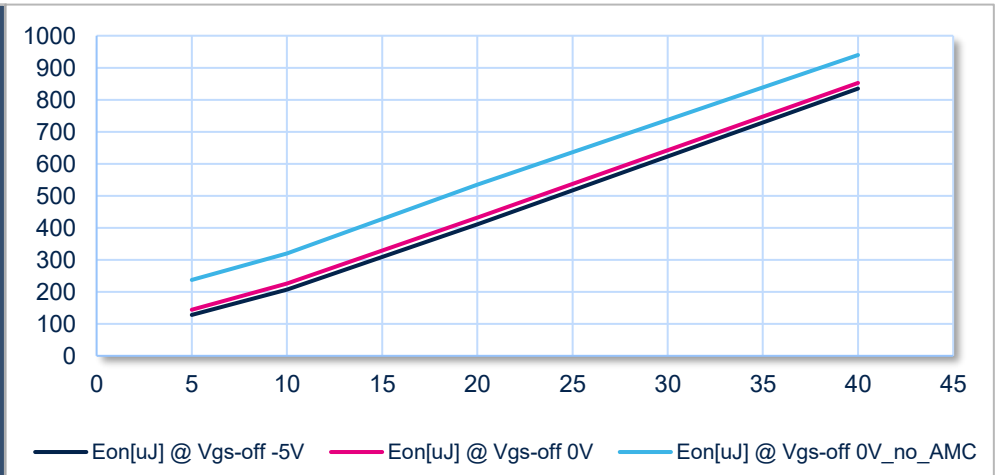
E_{ON} [µJ] @150°C



E_{REC} [µJ] @150°C



E_{SW} [µJ] @150°C

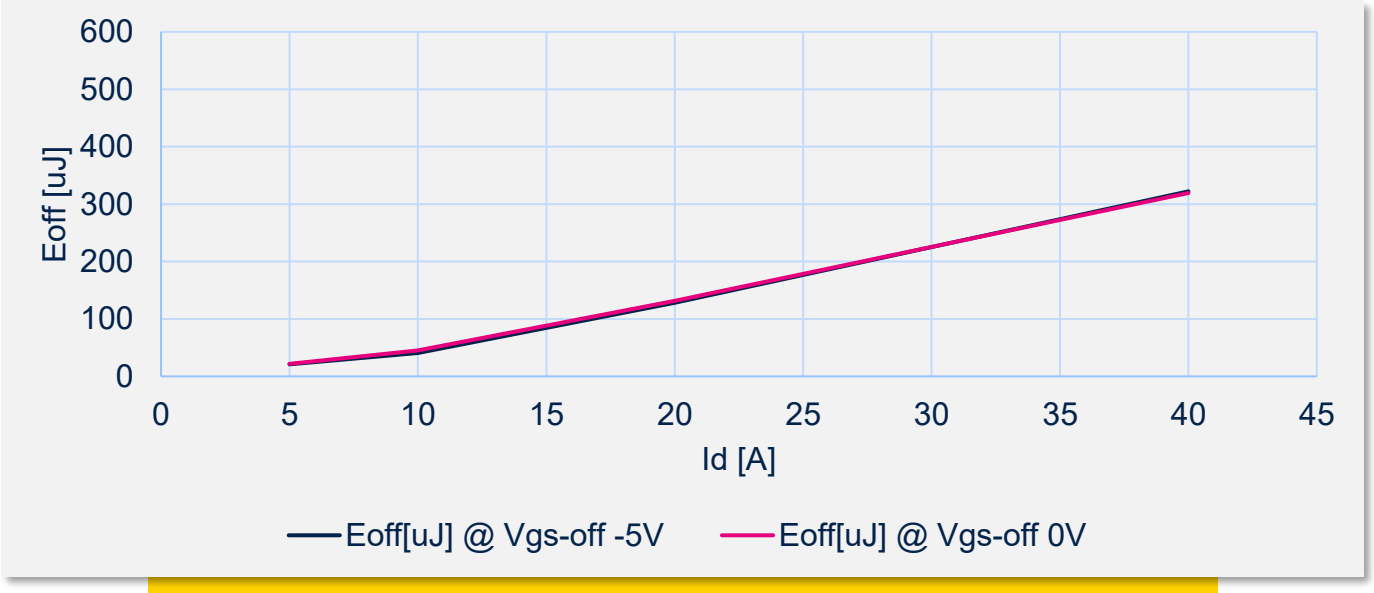


**Eoff is not influenced by Active Miller clamp*

Energy comparison bipolar vs unipolar driving using a 650 V device

Eoff (turn-off speed: dv/dt_{OFF} ≈ 18 V/ns)

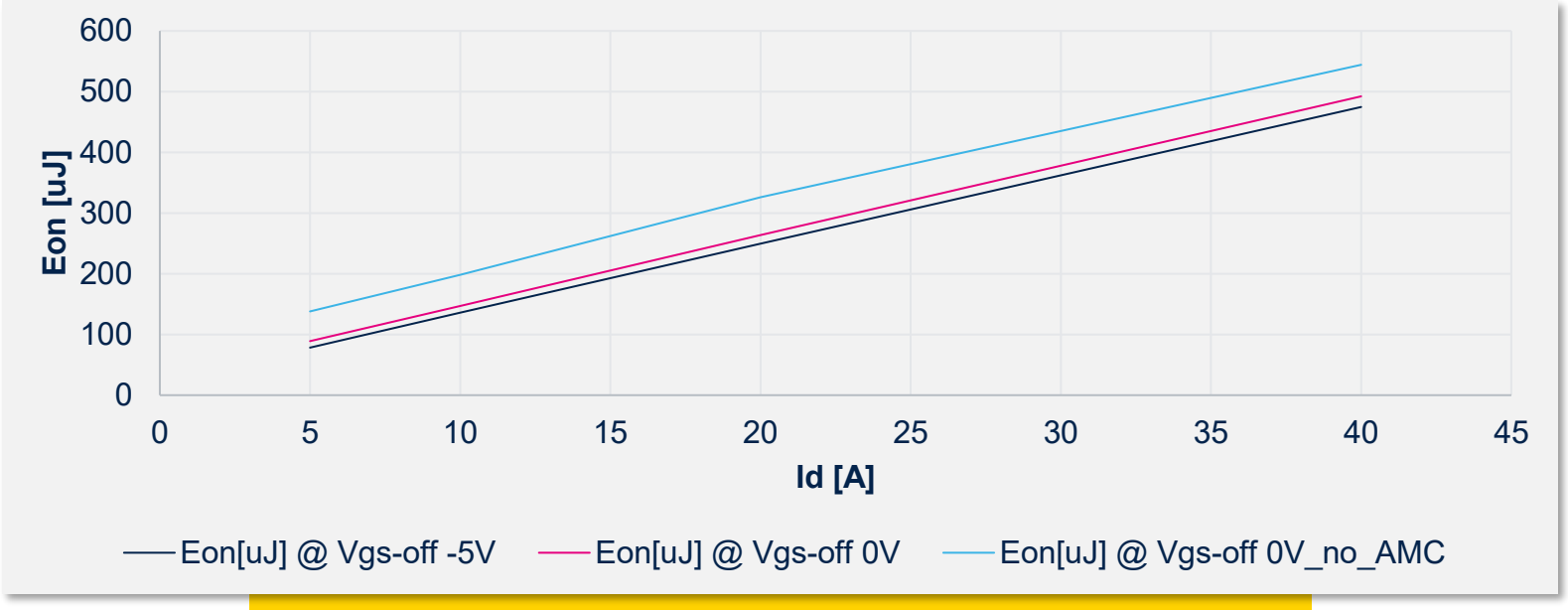
Almost no differences in Eoff with 0 V turn off



Energy comparison bipolar vs unipolar driving using a 650 V device

Eon (turn-on speed: $di/dt_{ON} \approx 1.5$ A/ns)

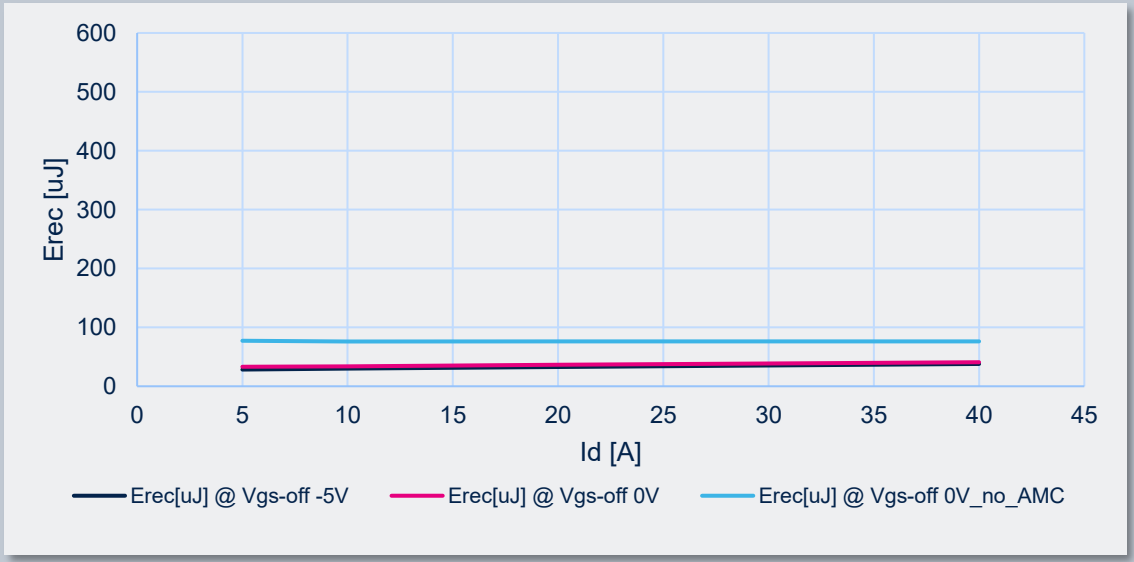
Almost no differences between negative and 0 Vgs-off with Active Miller clamp

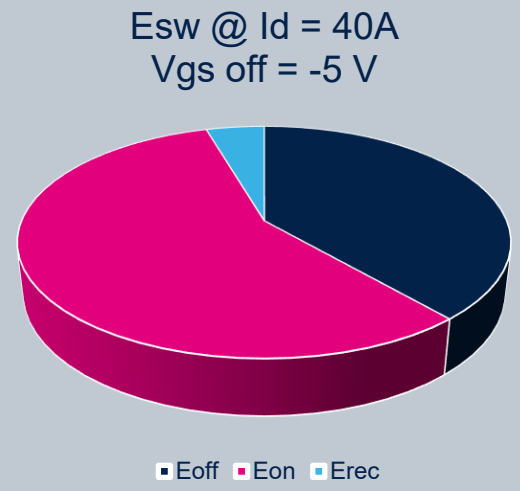


Energy comparison bipolar vs unipolar driving using a 650 V device

Erec (turn-on speed: $di/dt_{ON} \approx 1.5$ A/ns)

In all the analyzed cases, the contribution of Erec is very small in comparison with Eon and Eoff. Even if there are small differences between negative and 0 Vgs-off, their contribution to the overall power losses is negligible.



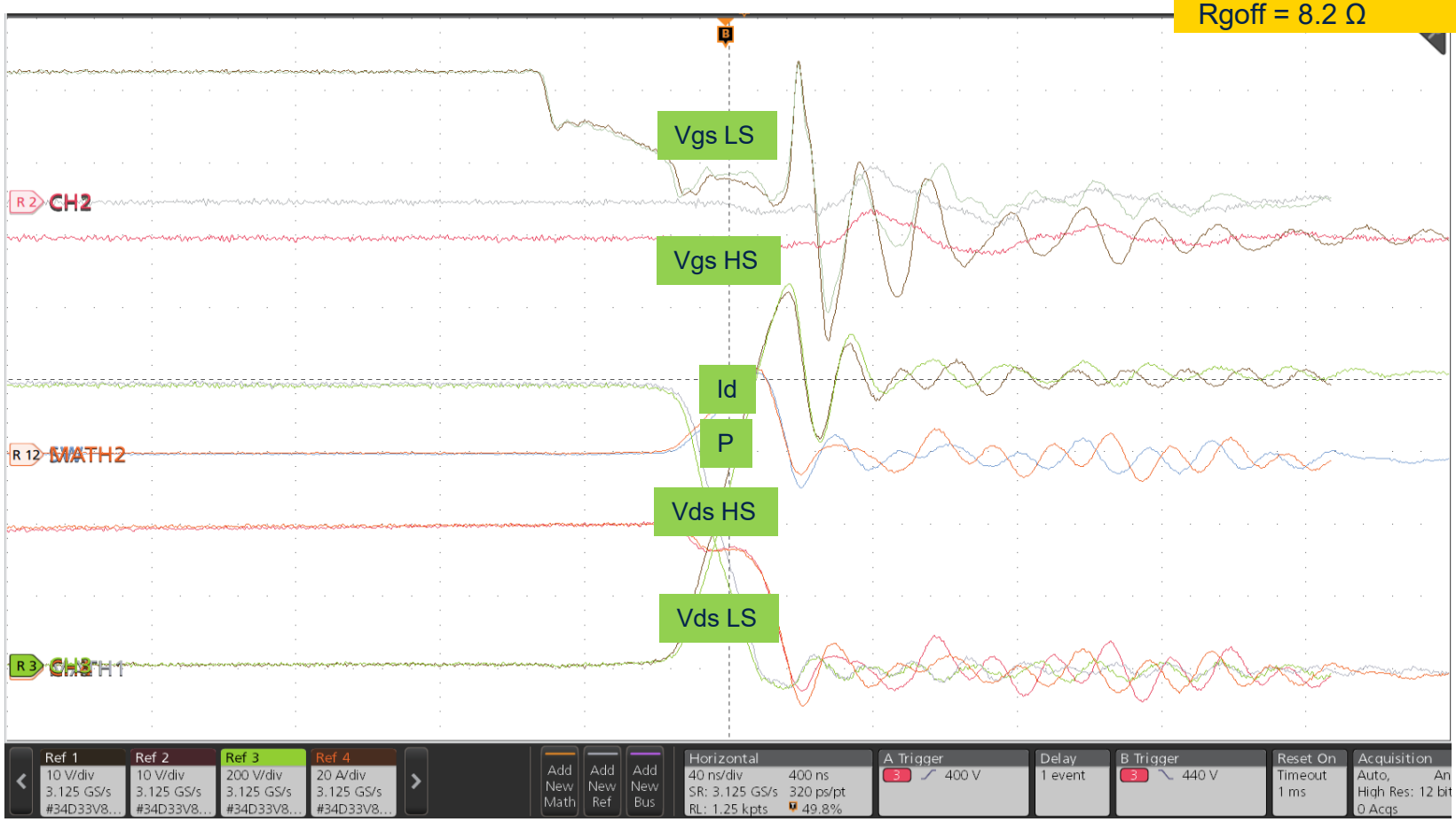


Experimental results: waveforms

Turn off waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 25°C
Vgs-off = -5 V, Rgon = 27 Ω,
Rgoff = 8.2 Ω

Vgs-on = 0 V (AMC/no AMC),
Rgon = 27 Ω, Rgoff = 4.7Ω



	Eoff [uJ]
-5 V	407
0V AMC / 0V no AMC	460

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn off waveform comparisons using a 1200 V device

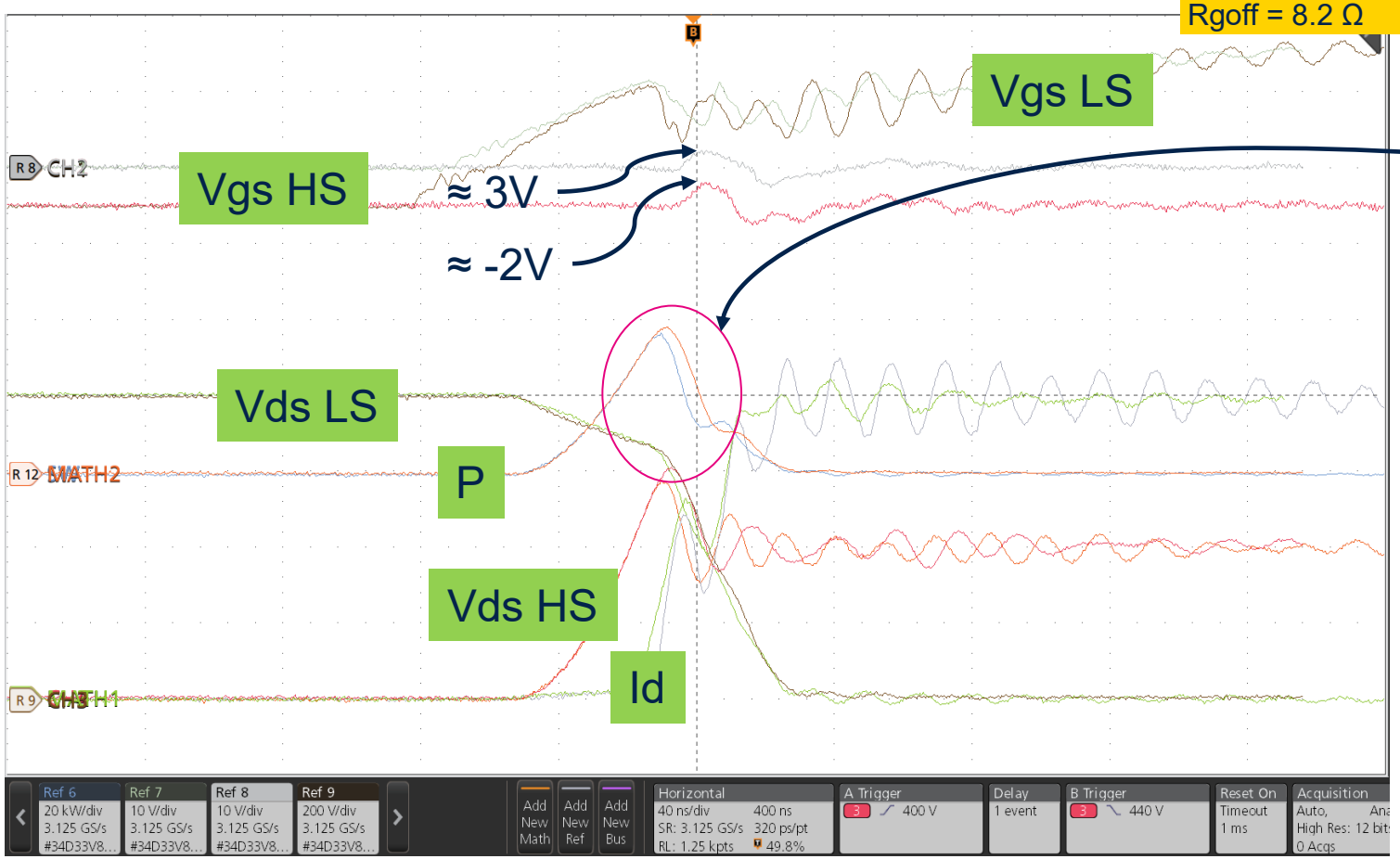
VDD = 800 V, ID = 40 A, T = 150°C Vgs-on = 0 V AMC Rgon = 27 Ω, Vgs-off = -5 V, Rgon = 27 Ω, Rgoff = 4.7 Ω
Rgoff = 8.2 Ω

	Eoff [uJ]
-5 V	410
0V AMC / 0V no AMC	480

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn on waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 25°C Vgs-off = 0 V AMC, Rgon = 27 Ω, Vgs-off = -5 V, Rgon = 27 Ω, Rgoff = 4.7 Ω Rgoff = 8.2 Ω

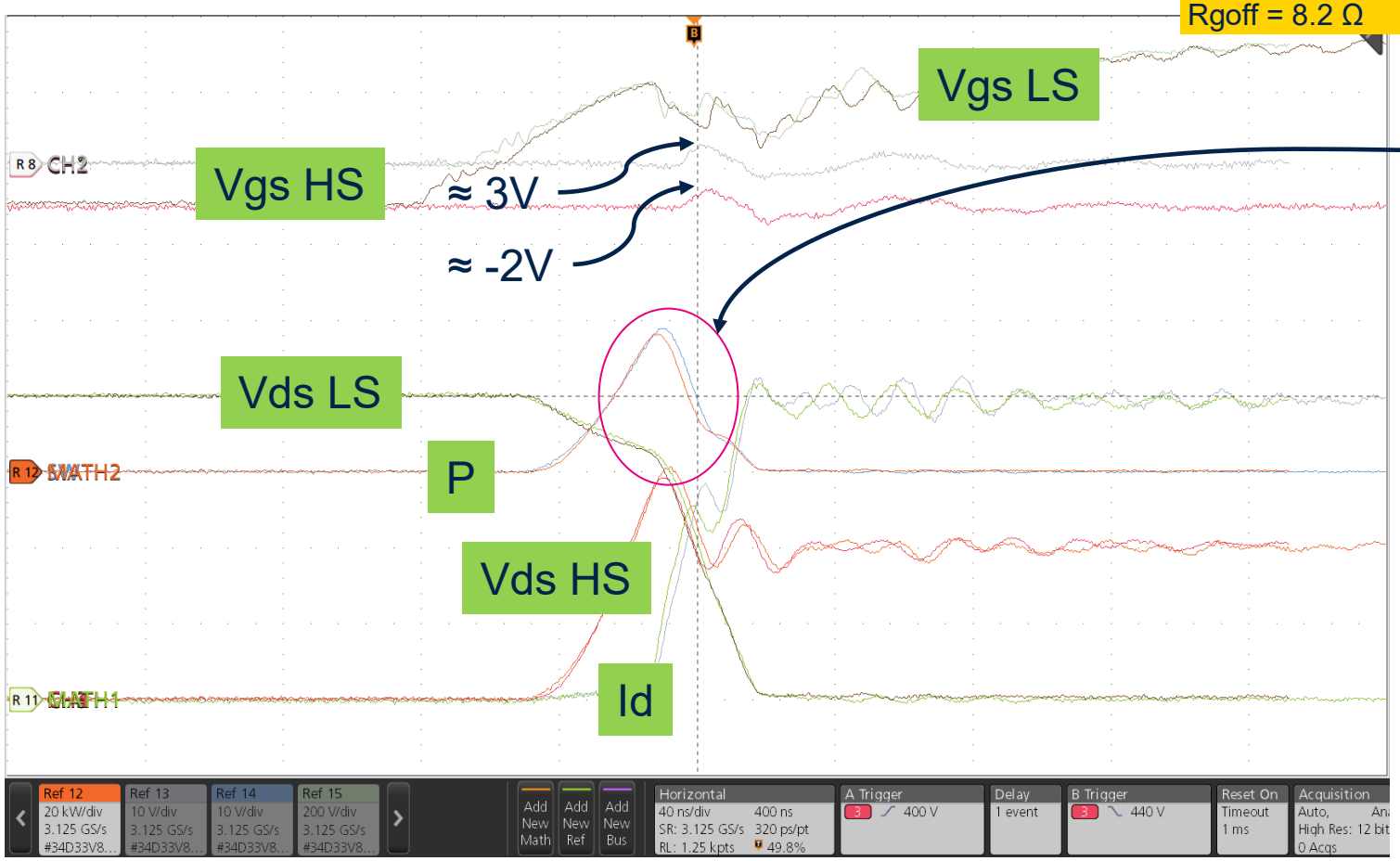


	Eon [uJ]
-5 V	1100
0V AMC	1220

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn on waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 150°C Vgs-off = 0 V AMC, Rgon = 27 Ω, Vgs-off = -5 V, Rgon = 27 Ω, Rgoff = 4.7Ω
Rgoff = 8.2 Ω

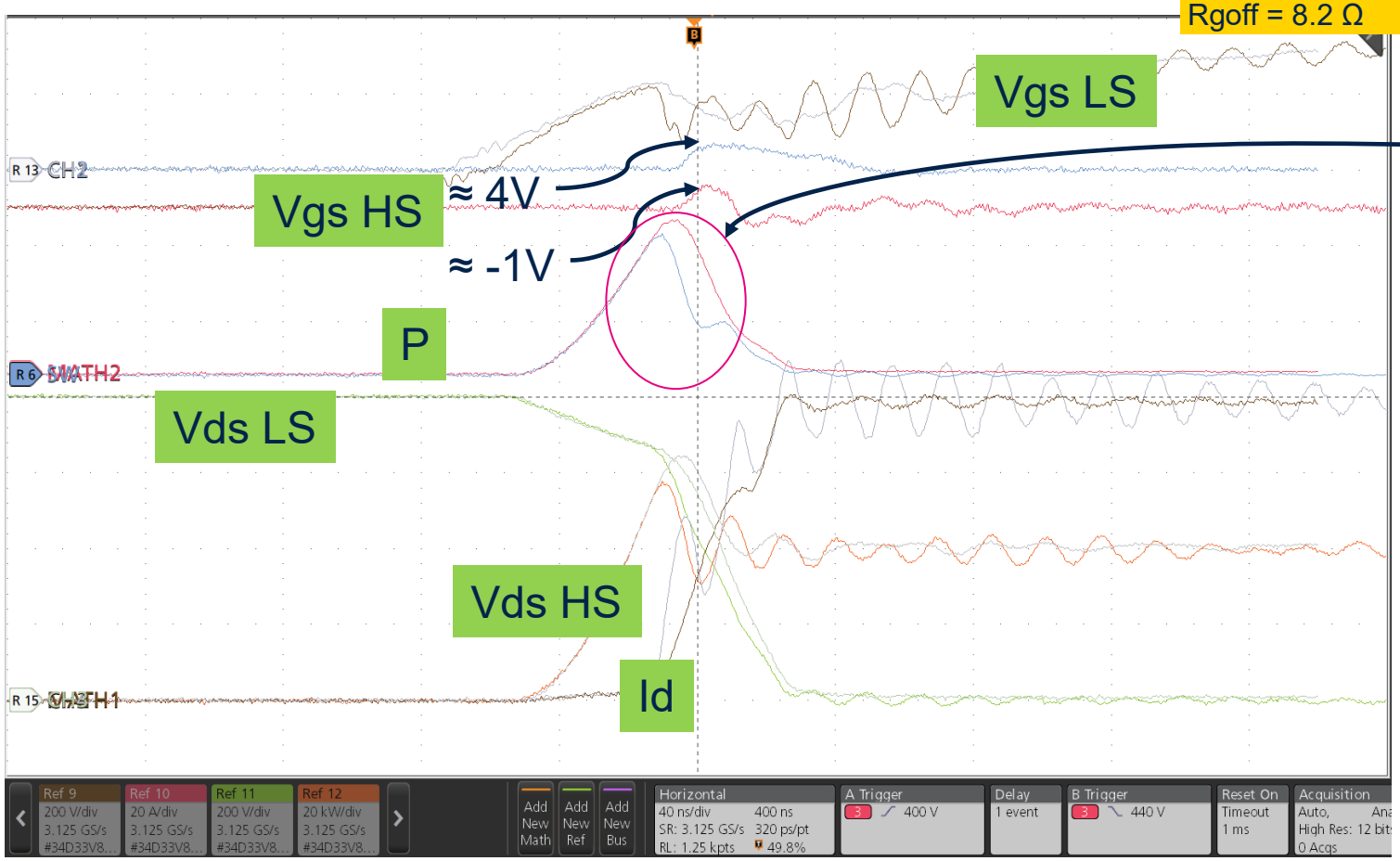


	Eon [uJ]
-5 V	1055
0V AMC	984

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn on waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 25°C Vgs-off = 0 V no AMC, Rgon = 27 Ω, Vgs-off = -5 V, Rgon = 27 Ω, Rgoff = 4.7 Ω Rgoff = 8.2 Ω

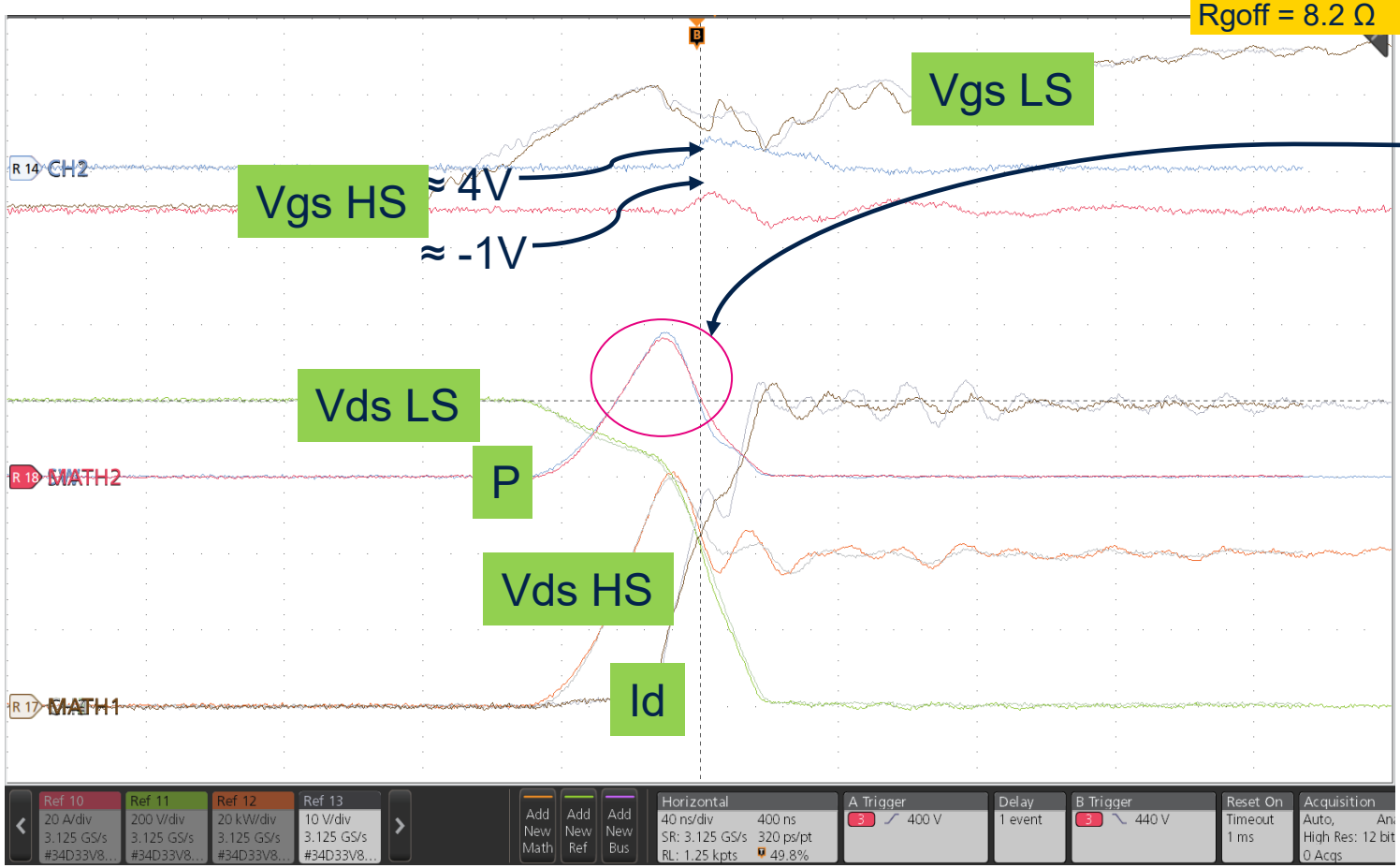


	Eon [uJ]
-5 V	1100
0V NO AMC	1370

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V NAMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn on waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 150°C Vgs-off = 0 V no AMC, Rgon = 27 Ω, Vgs-off = -5 V, Rgon = 27 Ω, Rgoff = 4.7 Ω Rgoff = 8.2 Ω



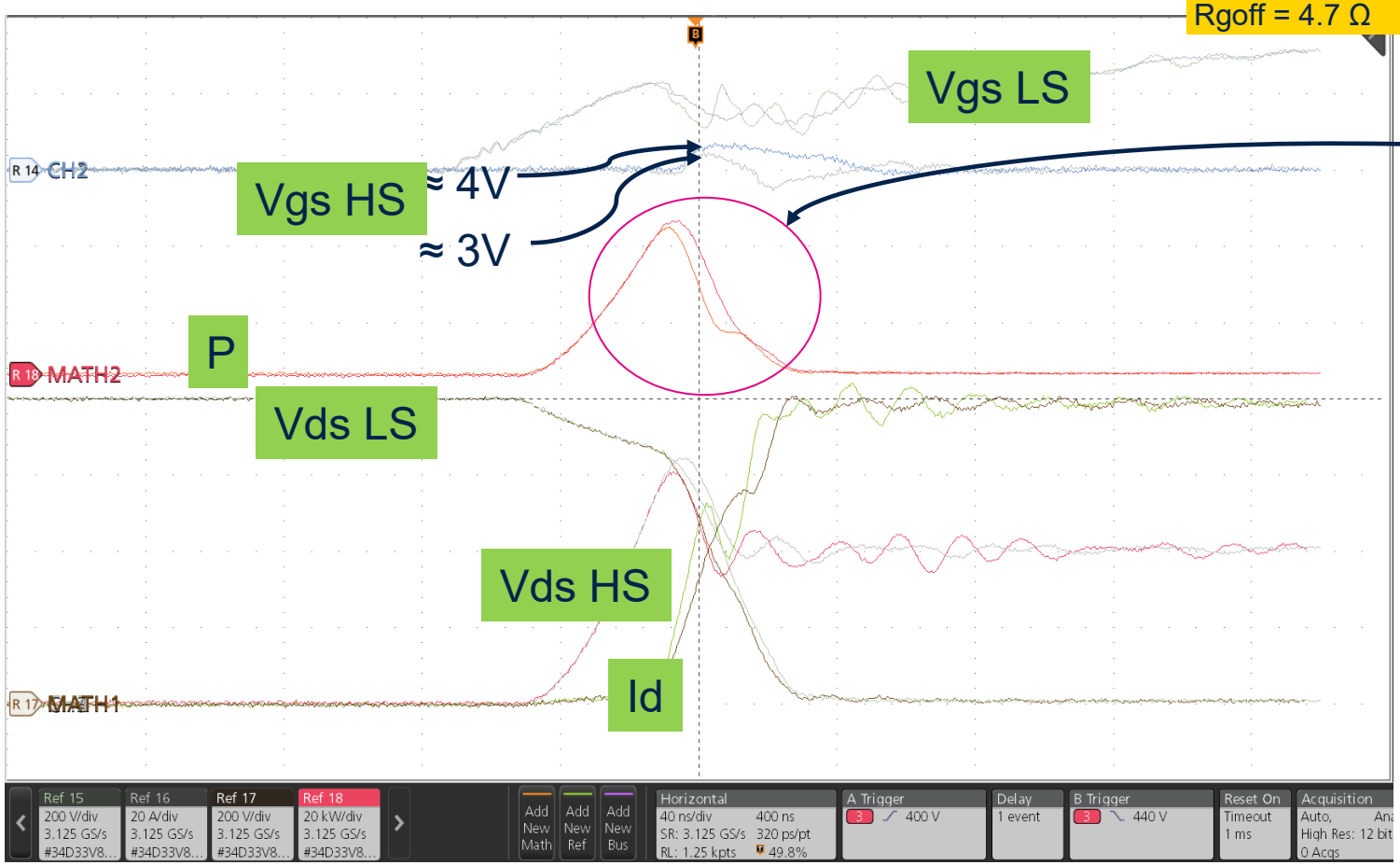
	Eon [uJ]
-5 V	1055
0V NO AMC	1055

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V NAMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn on waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 25°C Vgs-off = 0 V AMC, Rgon = 27 Ω, Rgoff = 4.7 Ω

Vgs-off = 0 V no AMC, Rgon = 27 Ω, Rgoff = 4.7 Ω

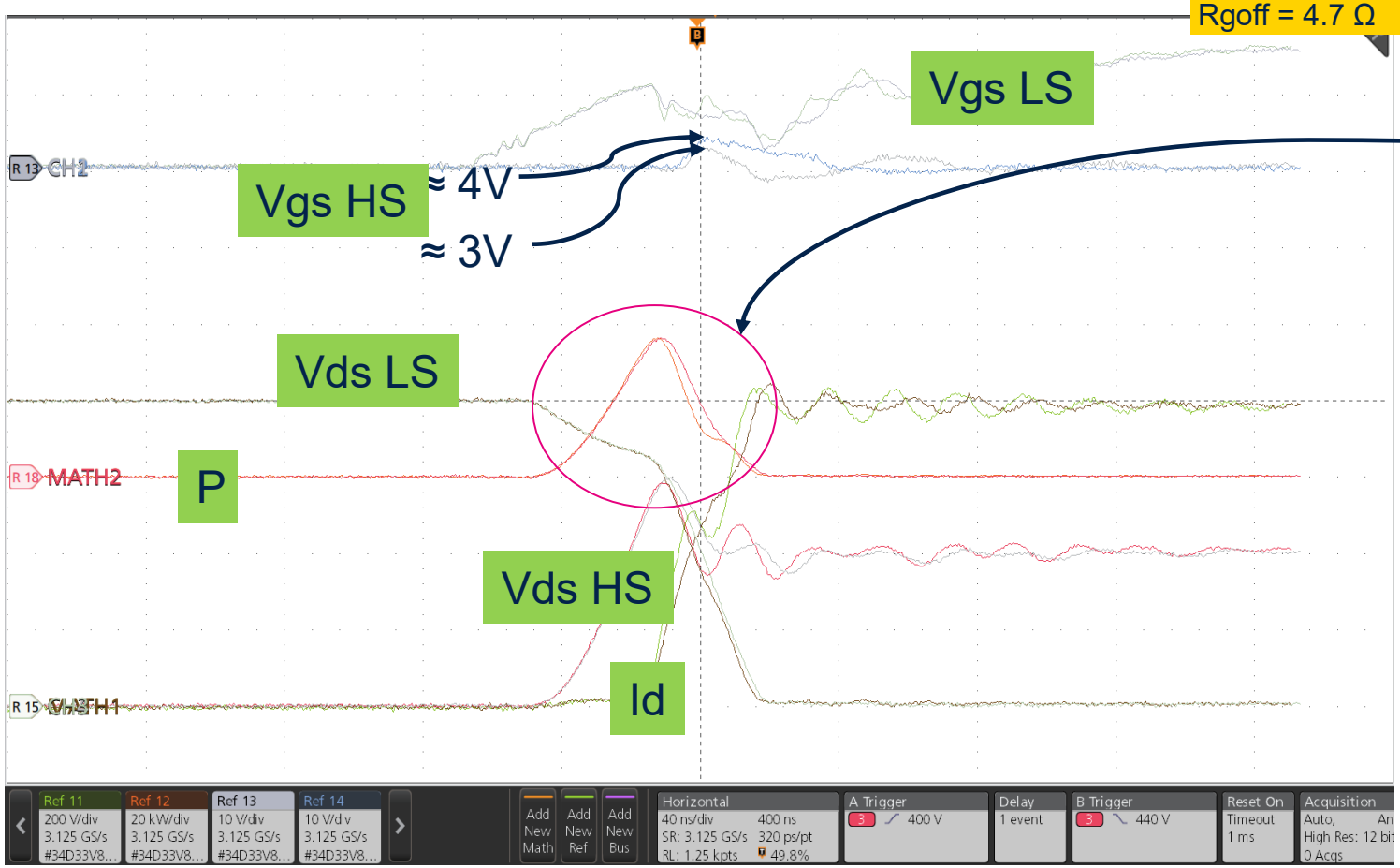


	Eon [uJ]
0V AMC	1220
0V NO AMC	1370

Legend	CASE Vgs OFF = 0V AMC	CASE Vgs OFF = 0V NAMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn on waveform comparisons using a 1200 V device

VDD = 800 V, ID = 40 A, T = 150°C Vgs-off = 0 V no AMC, Rgon = 27 Ω, Vgs-off = 0 V AMC, Rgon = 27 Ω, Rgoff = 4.7 Ω Rgoff = 4.7 Ω

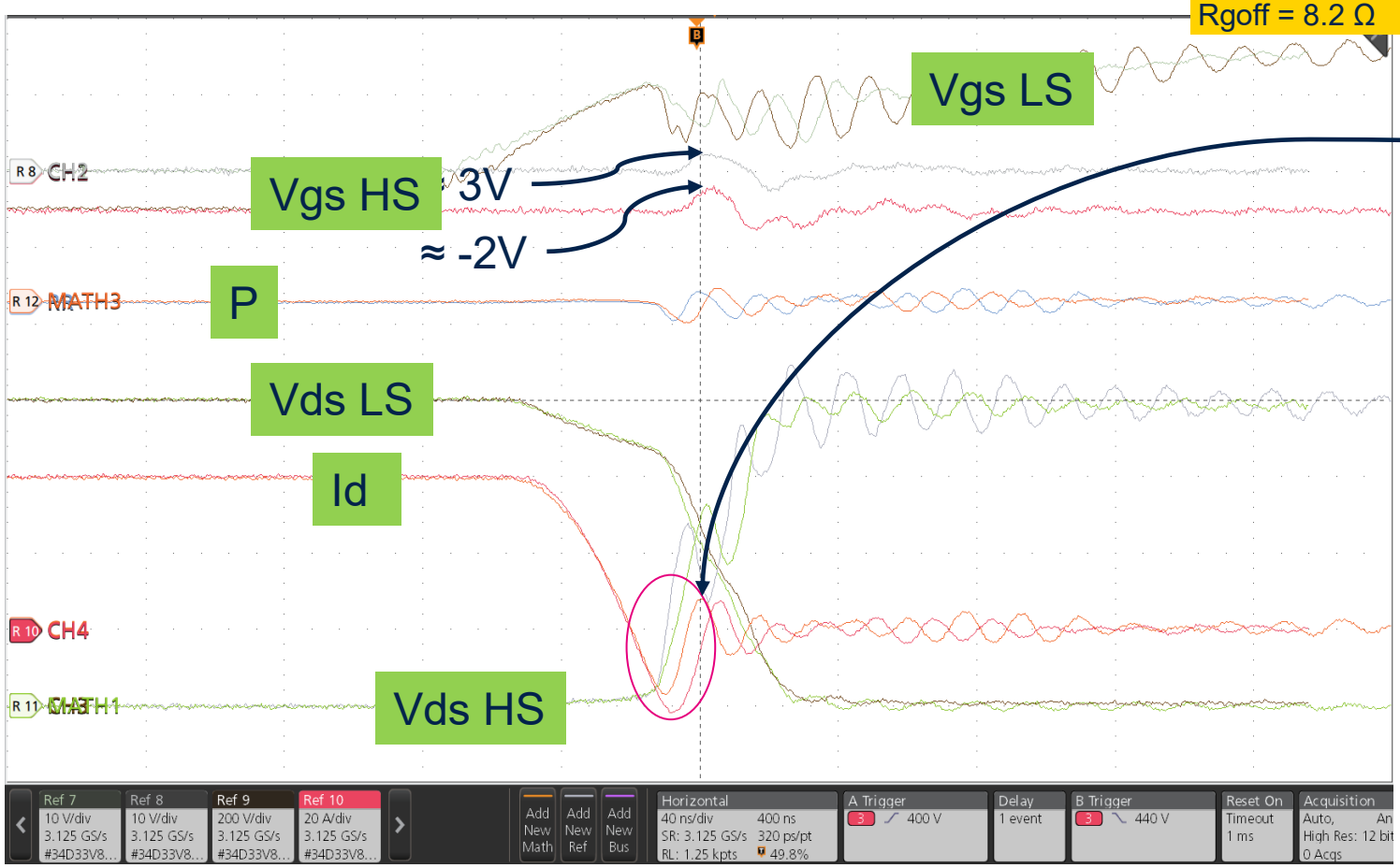


	Eon [uJ]
0V AMC	984
0V NO AMC	1055

Legend	CASE Vgs OFF = 0V AMC	CASE Vgs OFF = 0V NAMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Reverse recovery waveforms comparison using a 1200 V device

VDD = 800 V, ID = 40 A, T = 25°C Vgs-off = 0 V AMC, Rgon = 27 Ω, Vgs-off = -5 V, Rgon = 27 Ω, Rgoff = 4.7 Ω Rgoff = 8.2 Ω

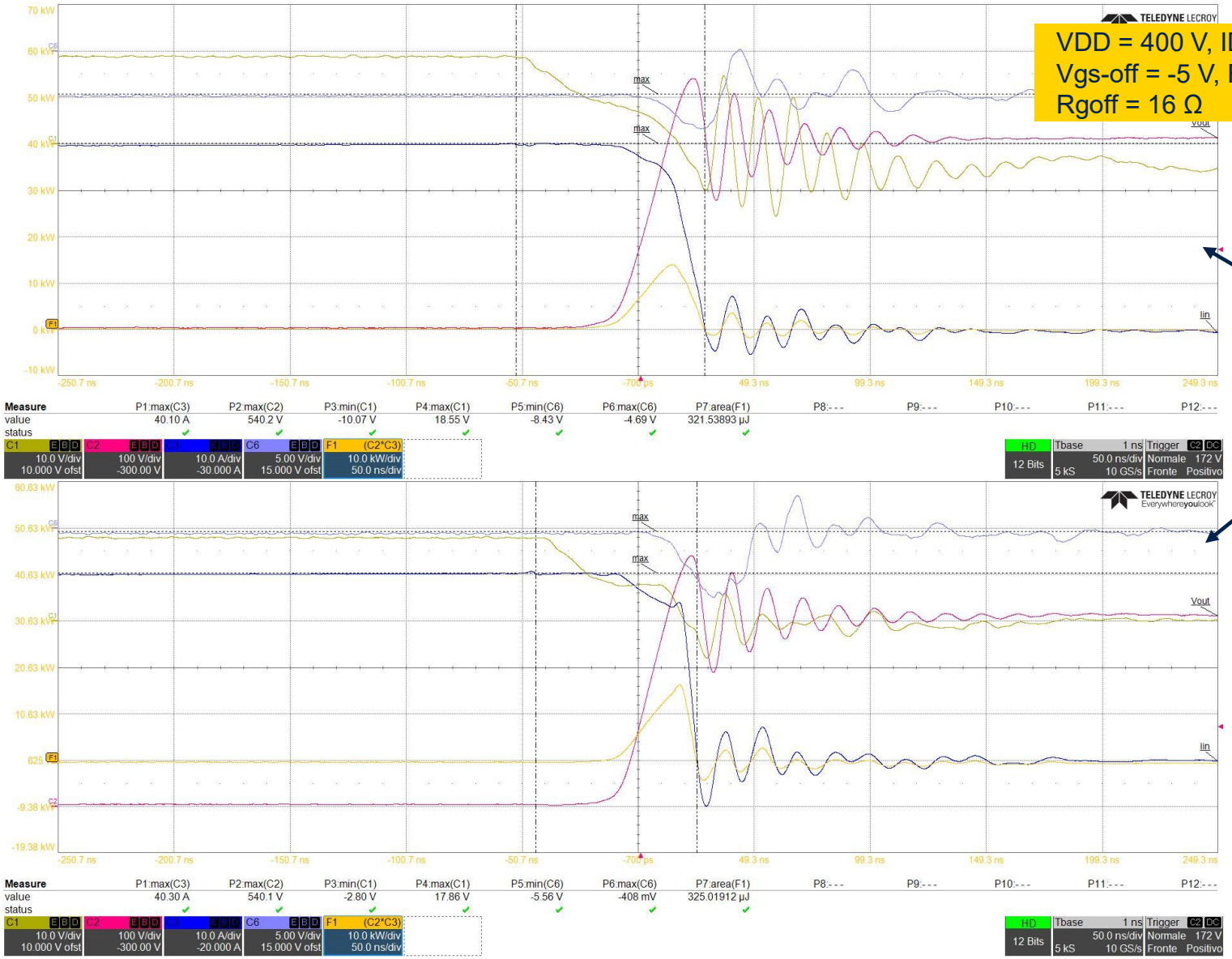


	Erec [uJ]	Irm [A]
-5 V	45	17
0V AMC	57	21

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Vds HS		
Id		
P		

Turn off waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 25°C Vgs-on = 0V (AMC/no AMC),
Vgs-off = -5 V, Rgon = 47 Ω, Rgon = 47 Ω, Rgoff = 10 Ω
Rgoff = 16 Ω

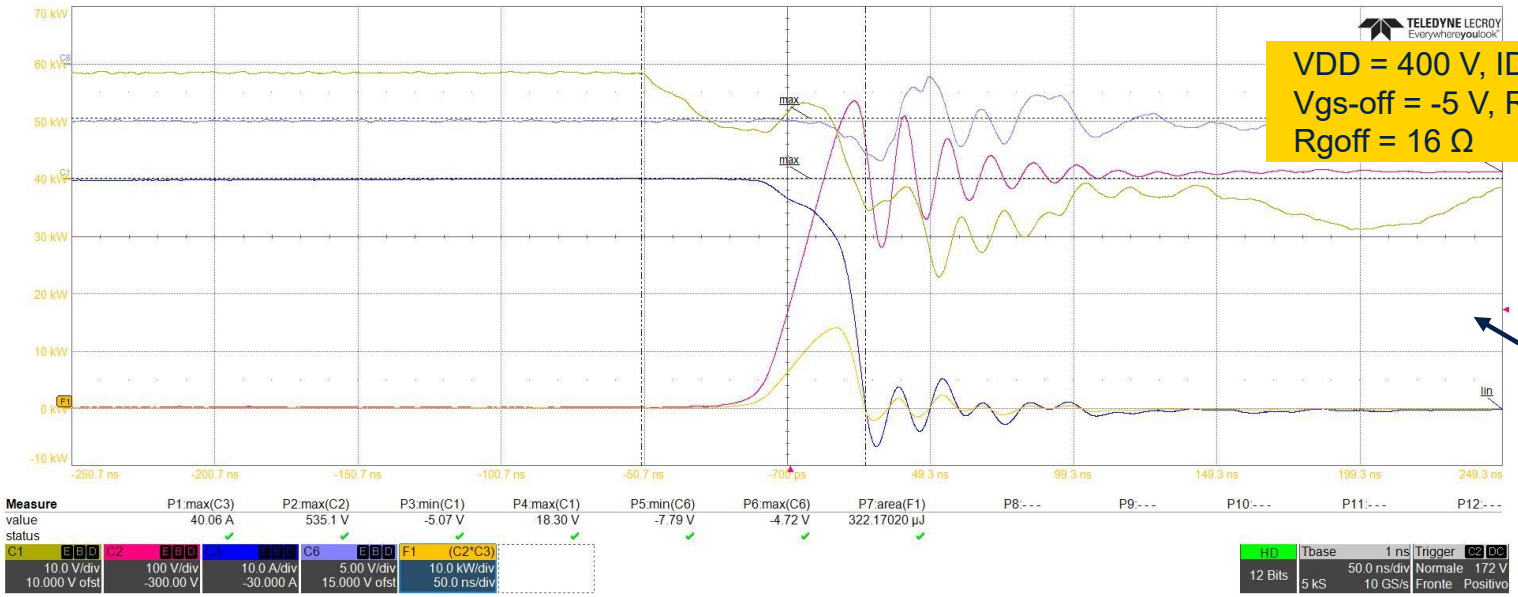


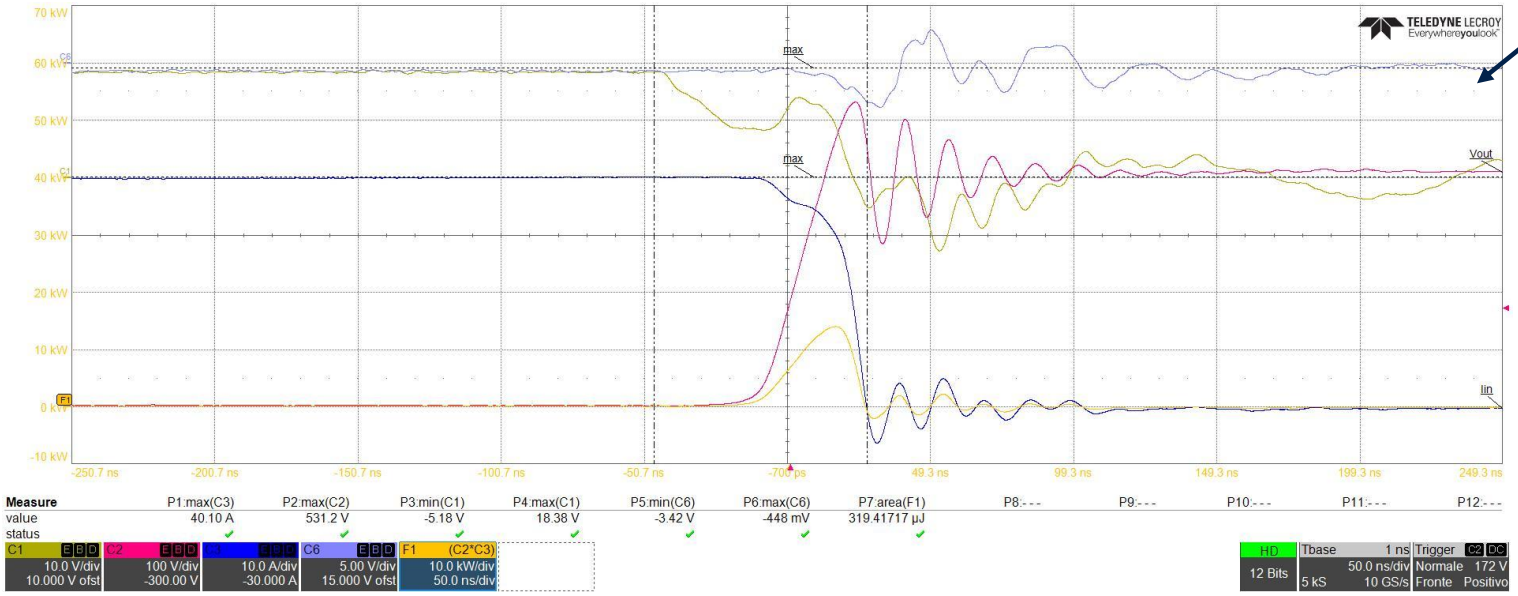
	Eoff [uJ]
-5 V	322
0V AMC / 0V no AMC	325

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn off waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 150°C Vgs-on = 0 V AMC Rgon = 47 Ω, Vgs-off = -5 V, Rgon = 47 Ω, Rgoff = 10 Ω



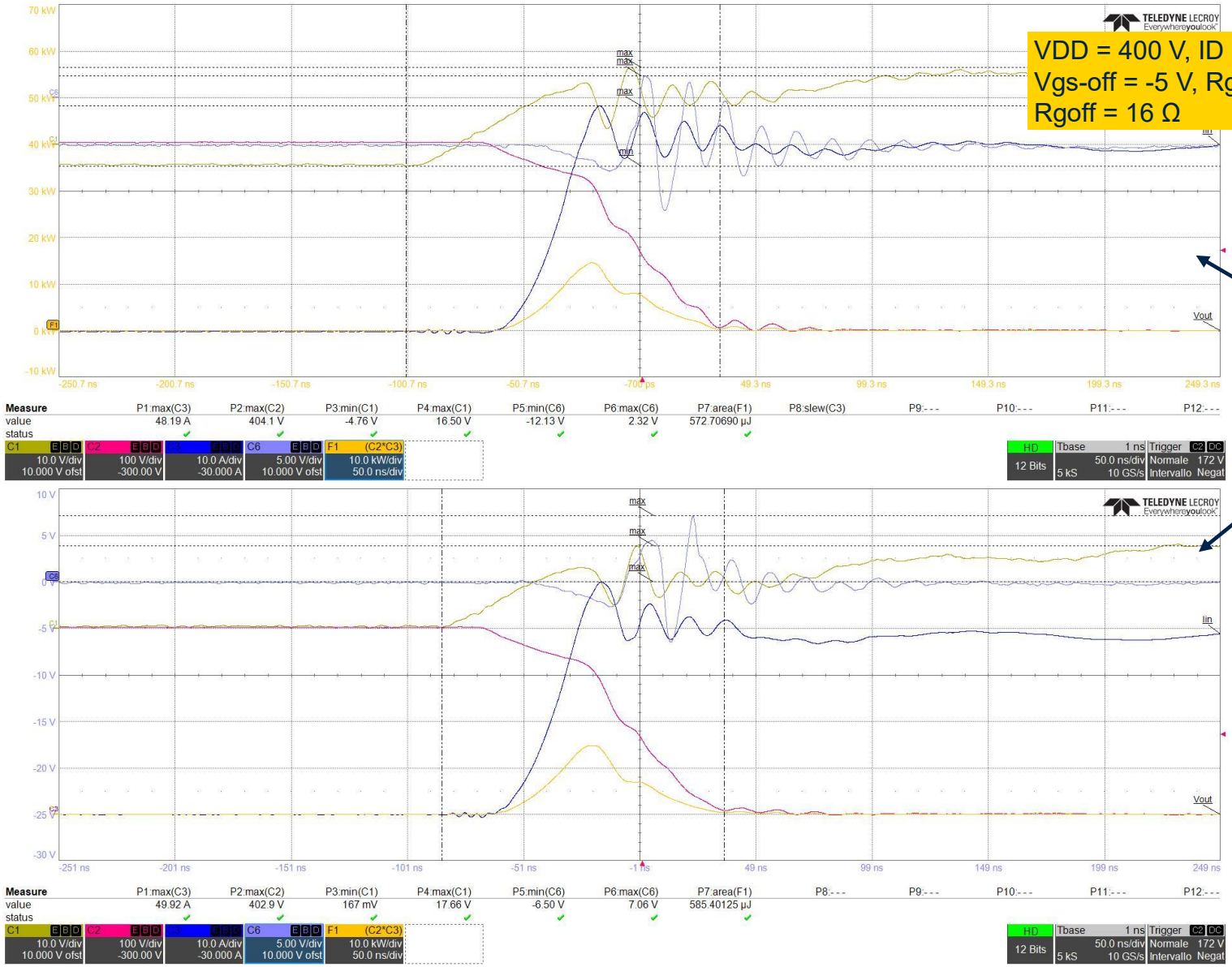


	Eoff [uJ]
-5 V	322
0V AMC / 0V no AMC	319

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn on waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 25°C Vgs-off = 0 V AMC, Rgon = 47 Ω, Vgs-off = -5 V, Rgon = 47 Ω, Rgoff = 10 Ω Rgoff = 16 Ω

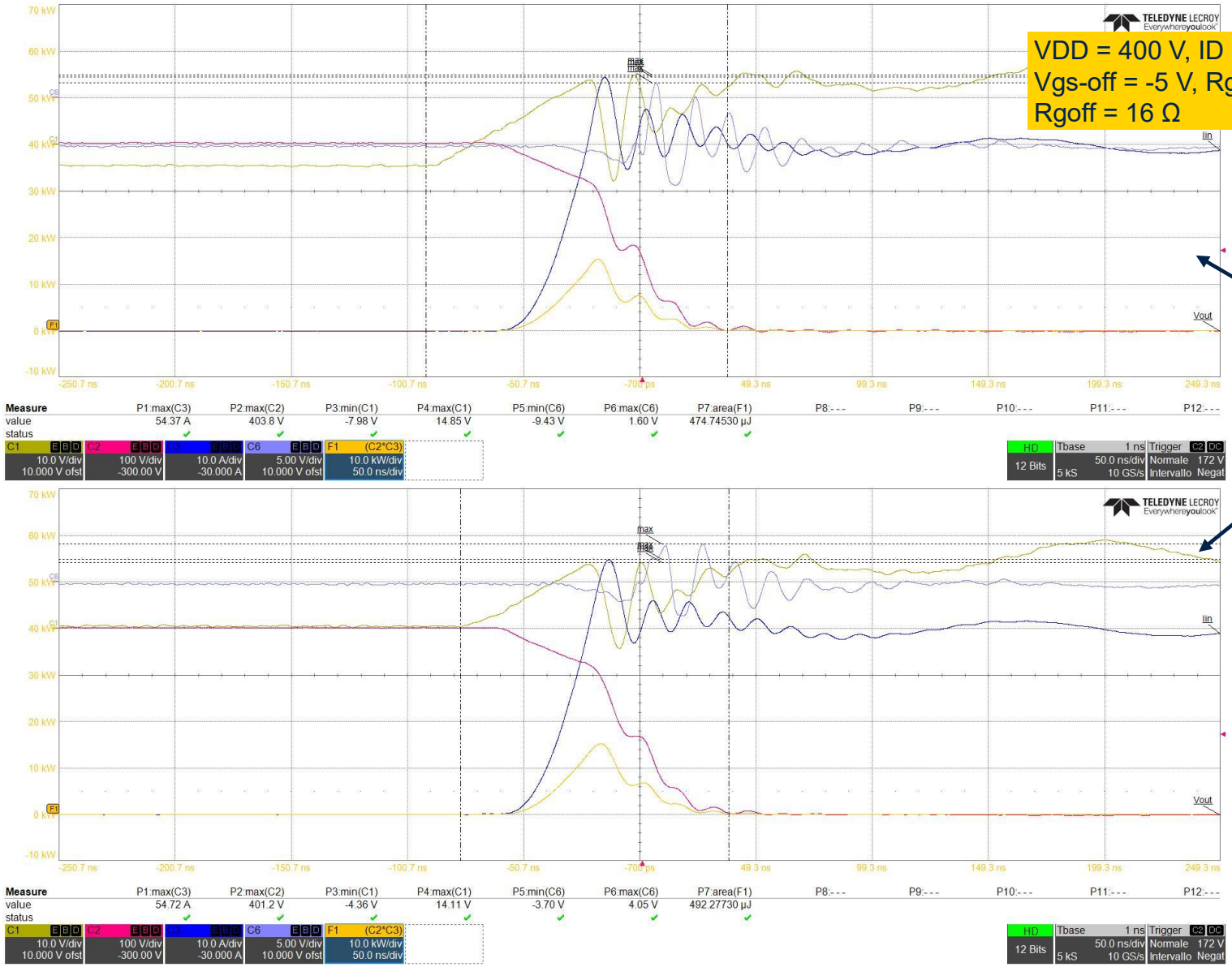


	Eon [uJ]
-5 V	572
0V AMC	585

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn on waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 150°C Vgs-off = 0 V AMC, Rgon = 47 Ω, Vgs-off = -5 V, Rgon = 47 Ω, Rgoff = 10 Ω Rgoff = 16 Ω



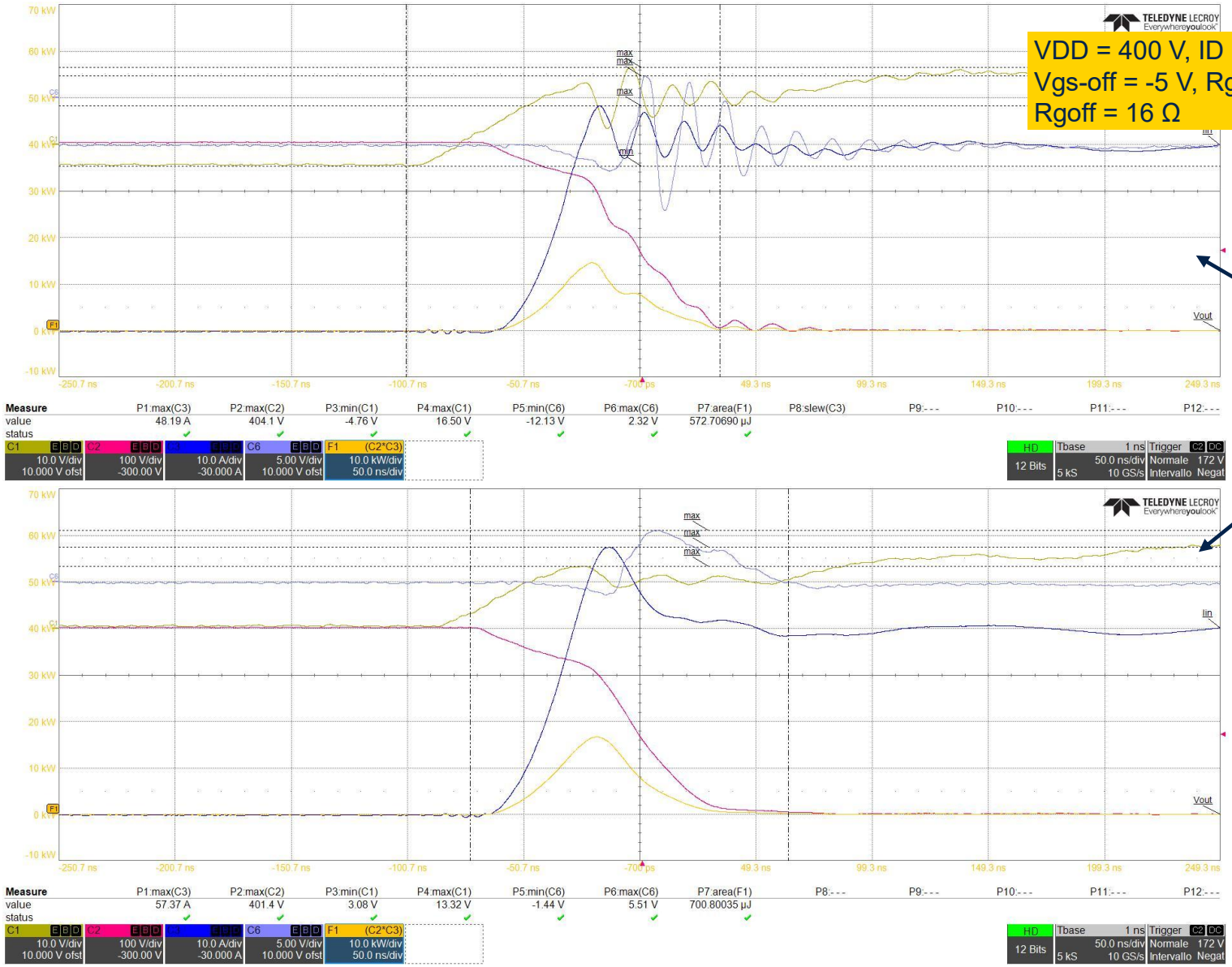
	Eon [uJ]
-5 V	474
0V AMC	492

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn on waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 25°C
Vgs-off = -5 V, Rgon = 47 Ω,
Rgoff = 16 Ω

Vgs-off = 0 V no AMC, Rgon = 47 Ω,
Rgoff = 10 Ω



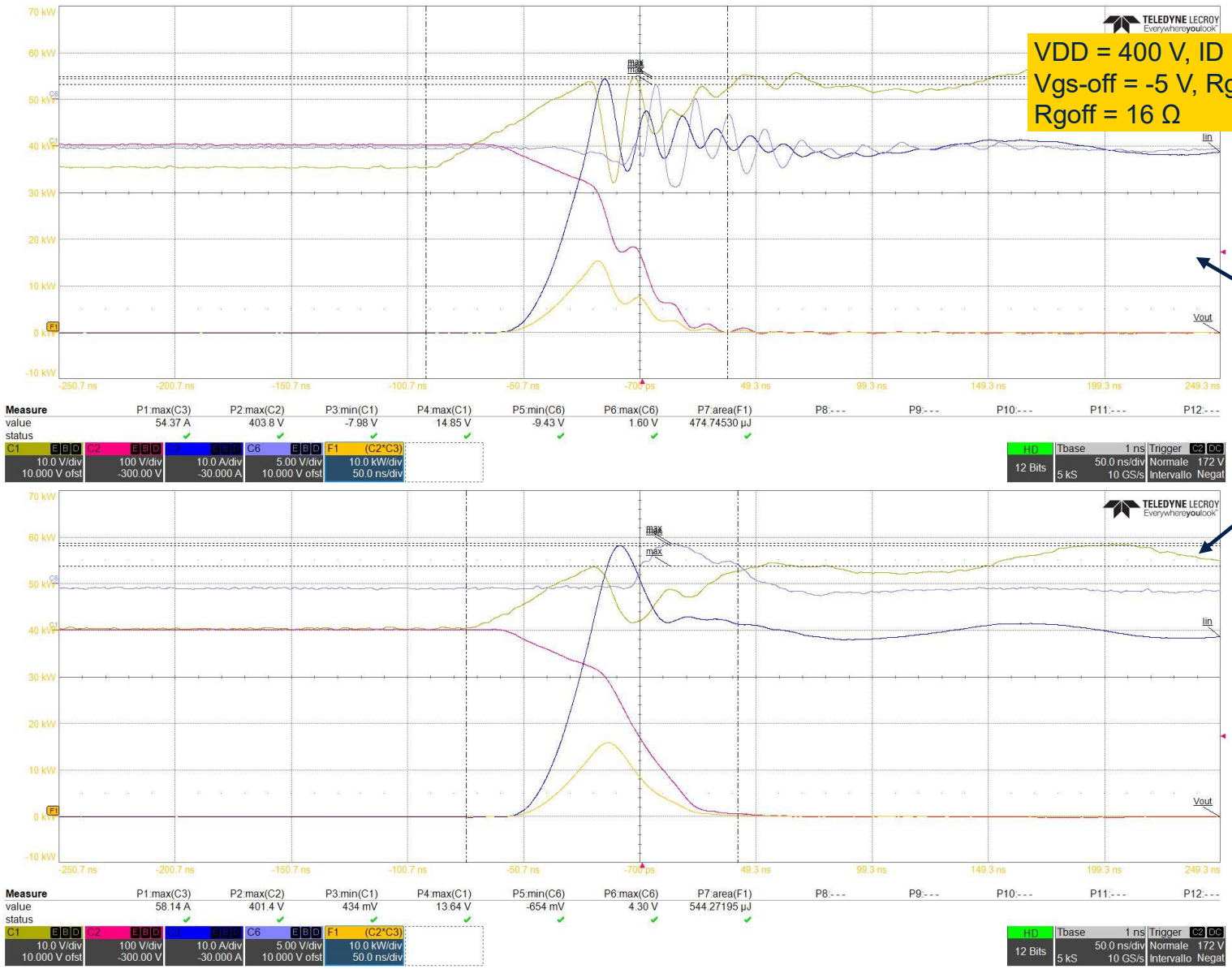
	Eon [uJ]
-5 V	573
0V NO AMC	701

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn on waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 150°C
Vgs-off = -5 V, Rgon = 47 Ω,
Rgoff = 16 Ω

Vgs-off = 0 V no AMC, Rgon = 47 Ω,
Rgoff = 10 Ω

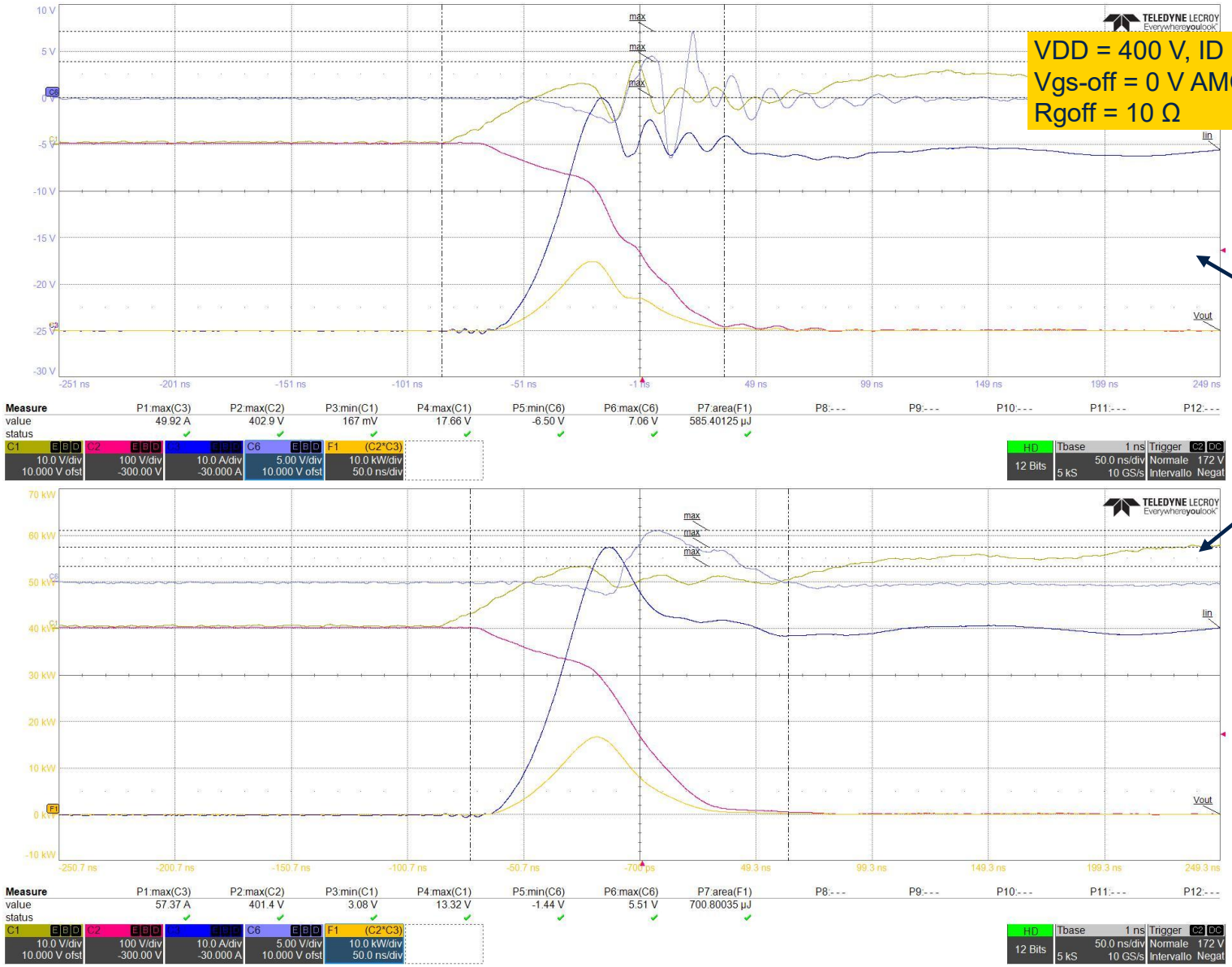


	Eon [uJ]
-5 V	475
0V NO AMC	544

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn on waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 25°C Vgs-off = 0 V no AMC, Rgon = 47 Ω, Vgs-off = 0 V AMC, Rgon = 47 Ω, Rgoff = 10 Ω Rgoff = 10 Ω

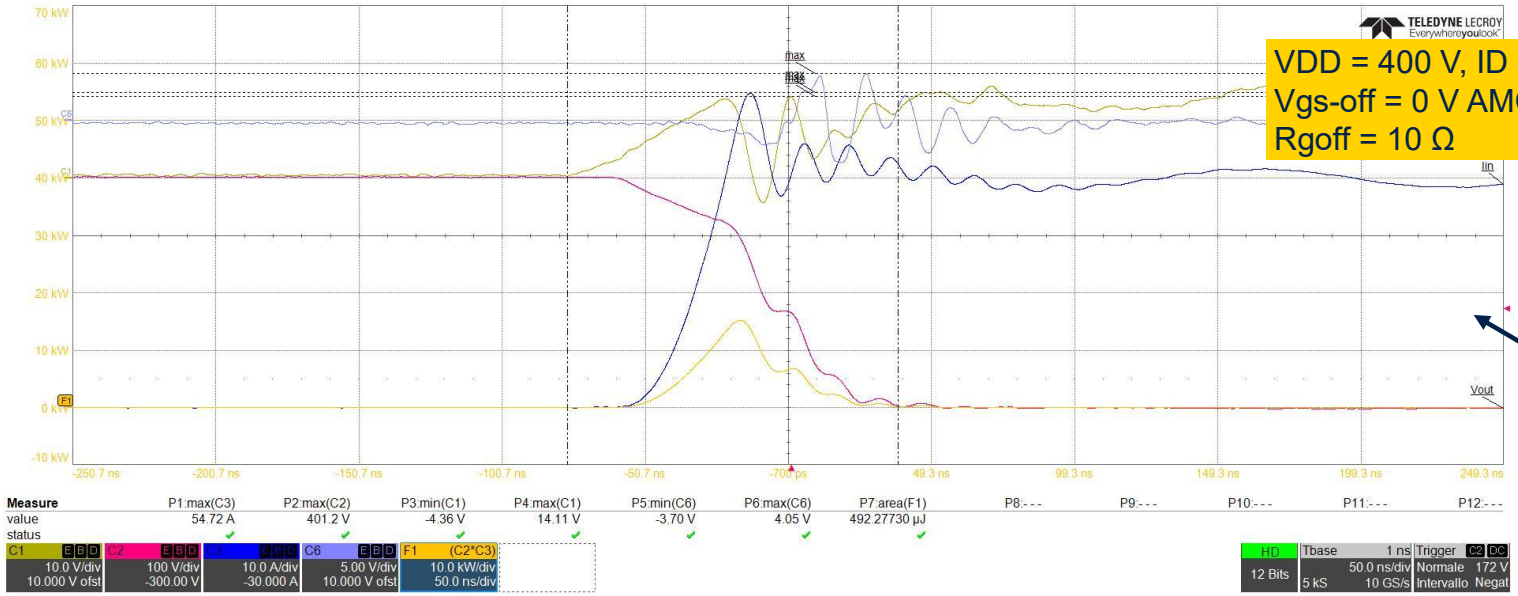


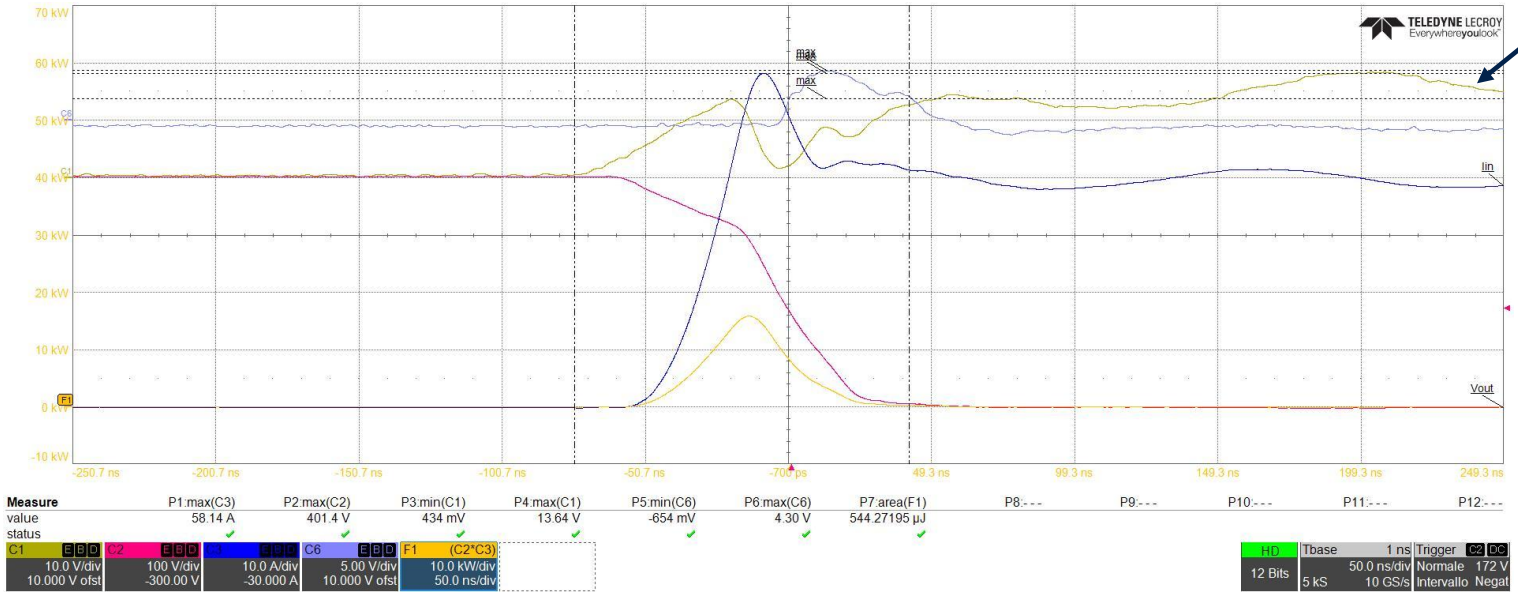
	Eon [uJ]
0V AMC	585
0V NO AMC	700

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Turn on waveform comparisons using a 650 V device

VDD = 400 V, ID = 40 A, T = 150°C Vgs-off = 0 V no AMC, Rgon = 47 Ω, Vgs-off = 0 V AMC, Rgon = 47 Ω, Rgoff = 10 Ω Rgoff = 10 Ω



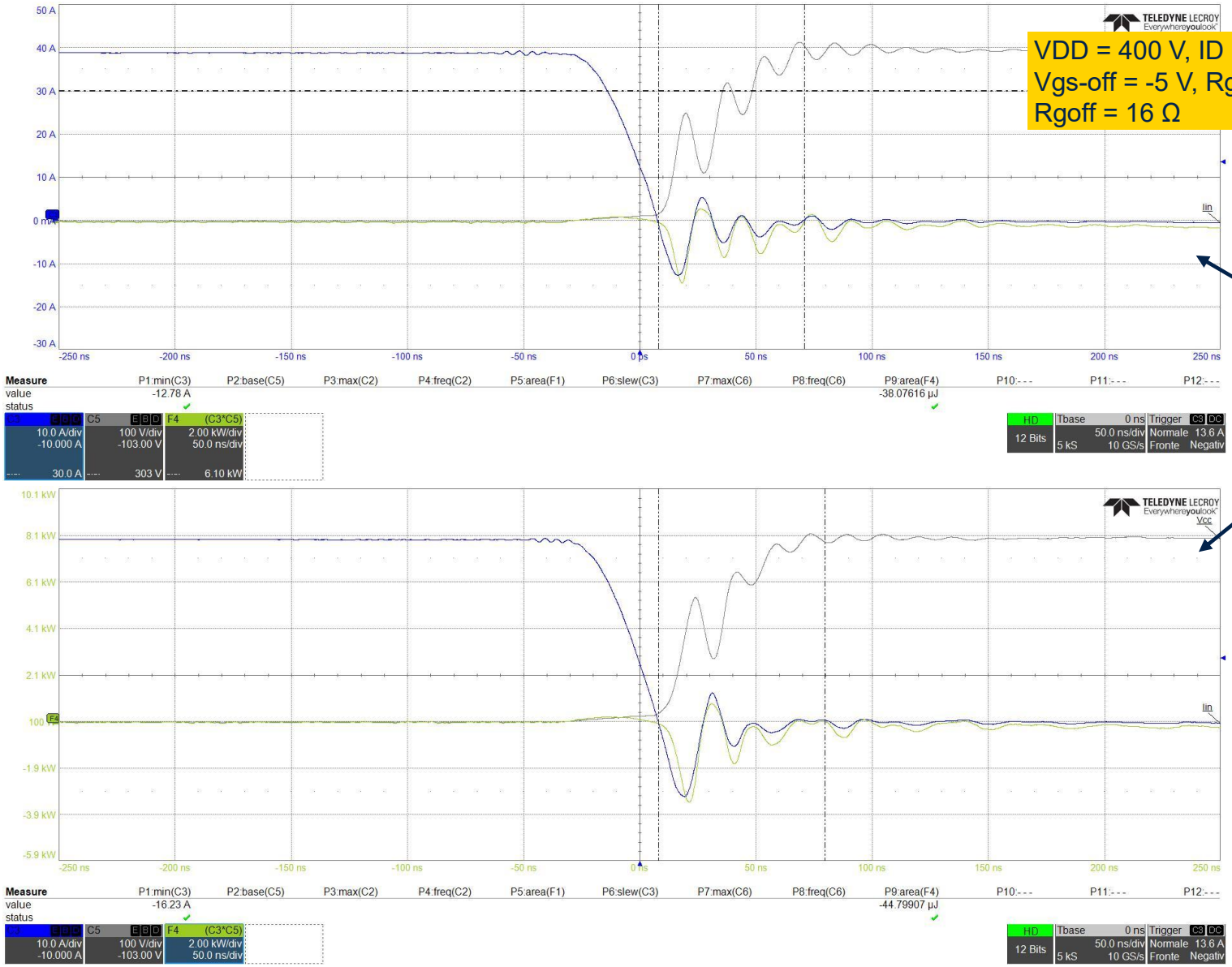


	Eon [uJ]
0V AMC	492
0V NO AMC	544

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vgs LS		
Vgs HS		
Vds LS		
Id		
P		

Reverse recovery waveforms comparison using a 650 V device

VDD = 400 V, ID = 40 A, T = 25°C Vgs-off = 0 V AMC, Rgon = 47 Ω, Vgs-off = -5 V, Rgon = 47 Ω, Rgoff = 10 Ω Rgoff = 16 Ω



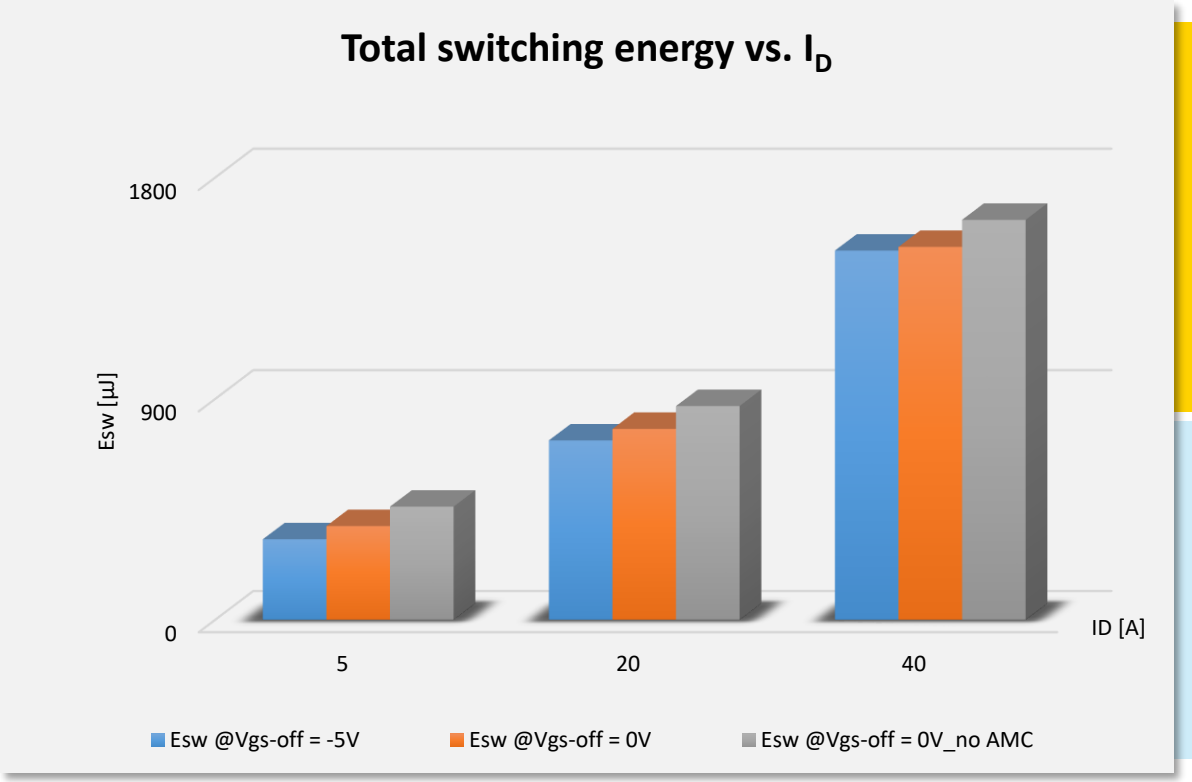
	Erec [uJ]	Irm [A]
-5 V	38	13
0V AMC	45	16

Legend	CASE Vgs OFF = -5V	CASE Vgs OFF = 0V AMC
Vds hS	—	—
Id	—	—
P	—	—

Summary and conclusions

Energy comparison bipolar vs unipolar driving
Summary of test results using a 1200 V device

Experimental data on 1200V; SiC MOSFET Gen3; 27mΩ typ



Test condition:

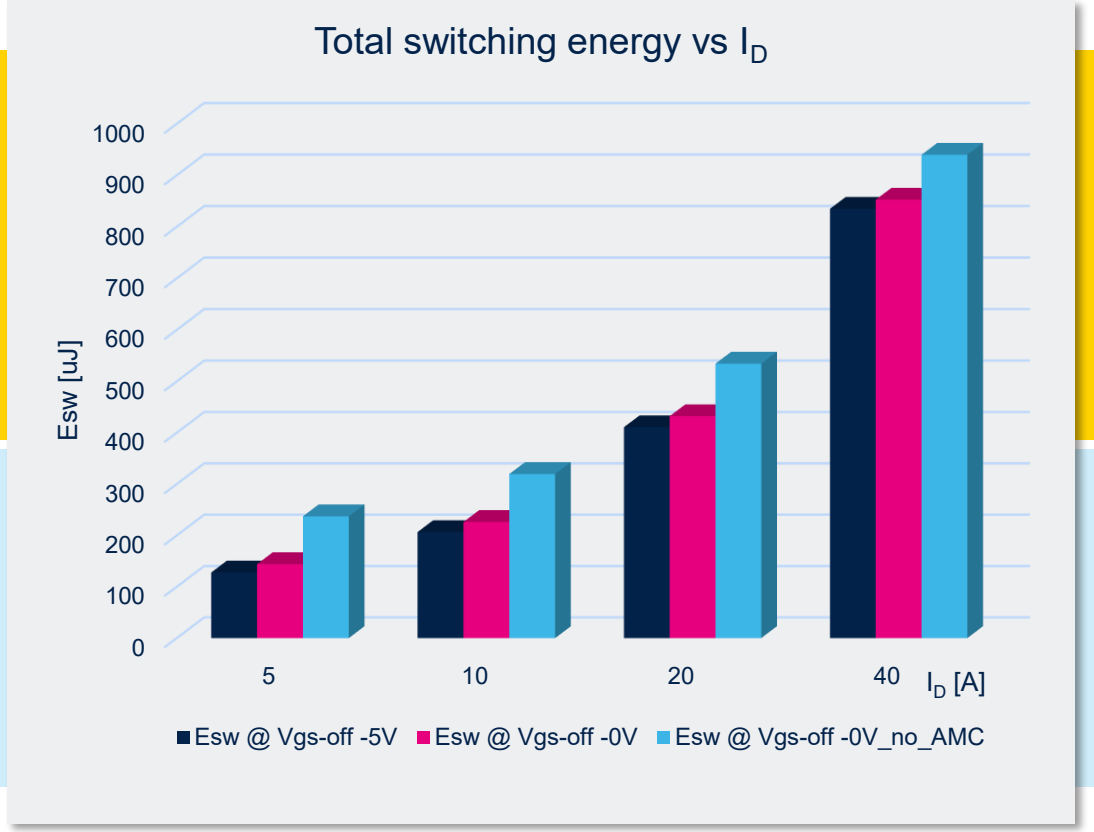
- T_J = 150°C,
- Turn-on speed: di/dt_{ON} ≈ 2 A/ns
- Turn-off speed: dv/dt_{OFF} ≈ 35 V/ns
- VDD ≈ 800V
- 0 Vgs-off with and without Active Miller clamp vs negative driving voltage as PoR

Results:

- In the case investigated (0 V Vgs-off and AMC) the gap between unipolar and bipolar driving is negligible especially at high load
- Removing the Active Miller clamp introduces additional switching losses in the range of 5-10%.

Energy comparison bipolar vs unipolar driving
Summary of test results using a 650 V device

Experimental data on 650V; SiC MOSFET Gen3; 29mΩ typ



Test condition:

- T_J = 150°C,
- Turn-on speed: di/dt_{ON} ≈ 1.5 A/ns
- Turn-off speed: dv/dt_{OFF} ≈ 18 V/ns
- VDD ≈ 400 V
- 0 Vgs-off with and without Active Miller clamp vs negative driving voltage as PoR

Results:

- In the case investigated (0V Vgs-off and AMC) the gap between unipolar and bipolar driving is negligible especially at high load
- Removing the Active Miller clamp introduces additional switching losses in the range of 5-10%.

Conclusions

Active miller clamp is recommended when applying 0V OFF Vgs

- **R_{gon} and R_{goff}** (and the driving circuit in general) **can be tuned to optimize performance, minimizing spikes** and switching losses with negative and with zero-volt $V_{gs\text{-}off}$.
- The comparison between -5 V and 0V shows negligible differences in case of typical threshold voltage (V_{GS}(th) typ).
- For design robustness, system and driving circuit design should consider **worst case V_{GS}(th) and temperature**, factoring the additional energy loss in comparison with the case at typical V_{GS}(th) .

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