Diode Reverse Recovery and its Effect on Switching Losses

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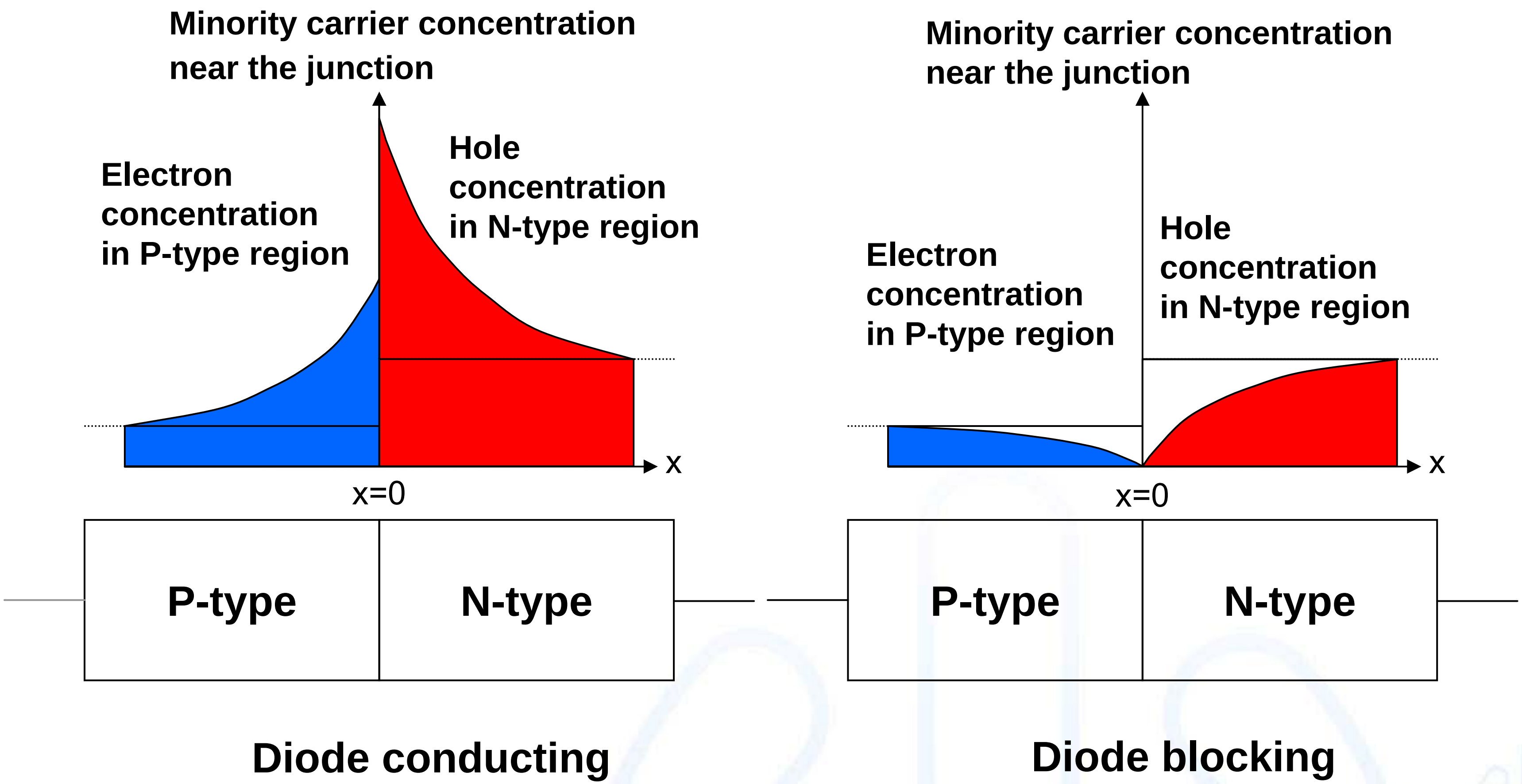
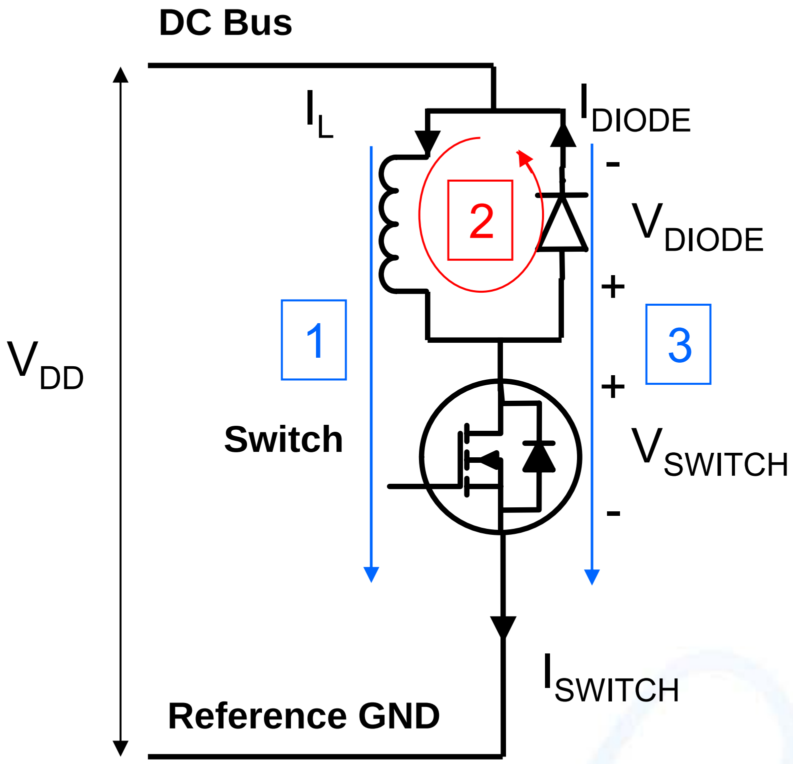
Agenda

1. Basics
2. Mathematical Estimations
3. Comparison of the Estimations with real measurements
4. Switching Losses vs. Voltage
5. Switching Losses vs. Current
6. E_{ON} Losses during Hard Switching with different Diode Technologies
7. Effect of parallel Caps on Switching Losses
8. Switching Losses vs. rise and fall time
9. Summary

Diode charge distribution in conducting and non-conducting states



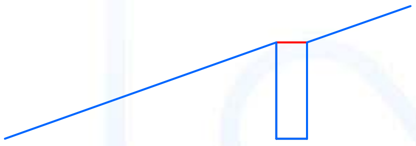
Diode Forced Commutation Behavior



Step 1: Switch is turned on
Current rises

Step 2: Switch is turned off
Current is circulating

Step 3: Switch is turned on again, Diode is recovering and current continues rising



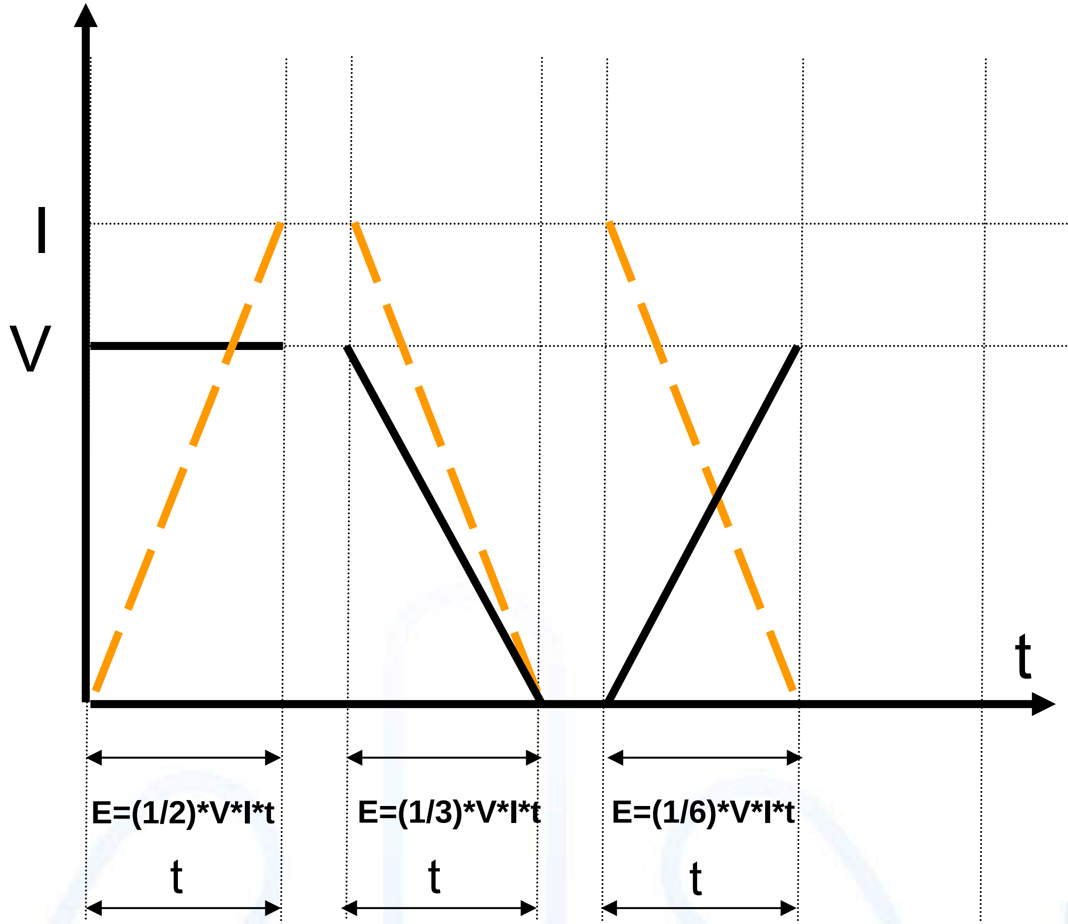
Switching loss calculations

- Definition of Power Losses

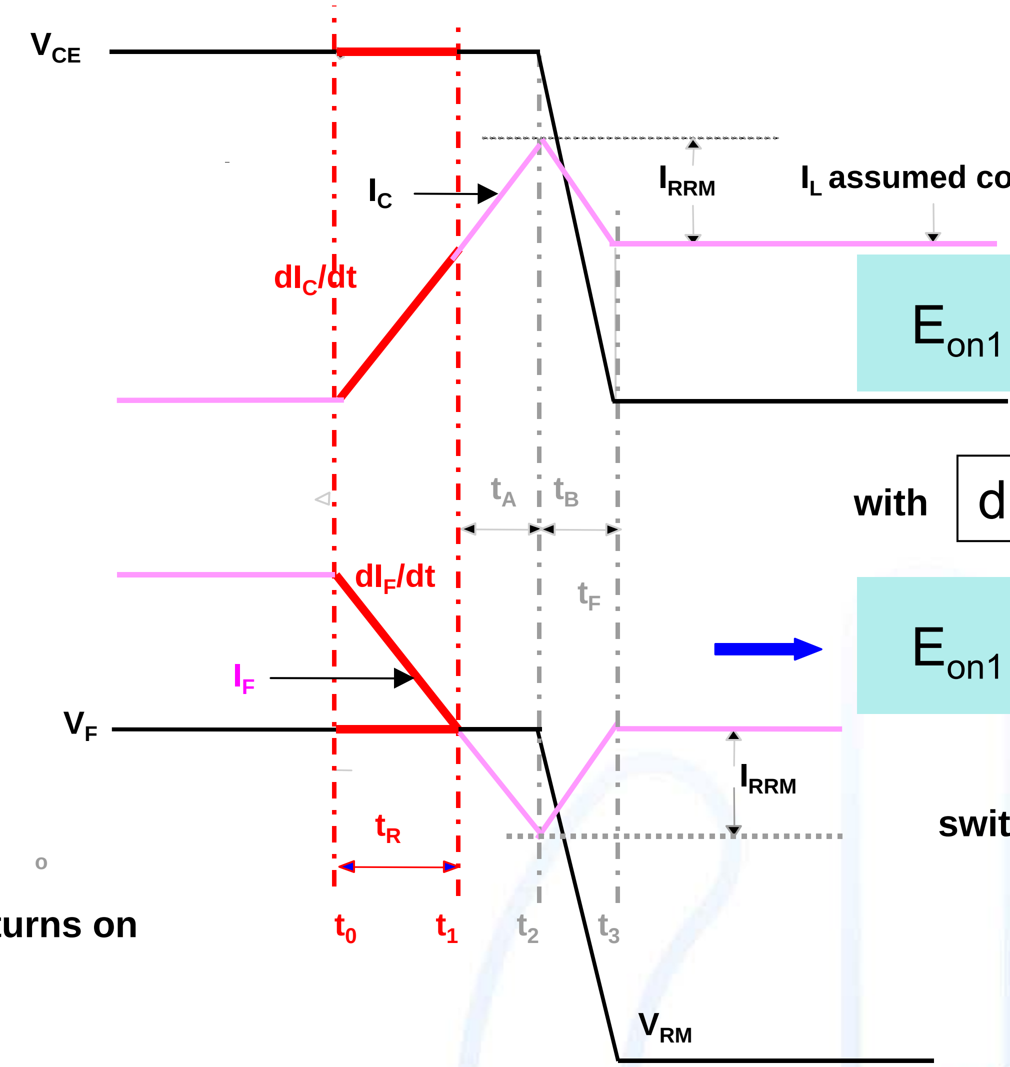
$P = 1/T \cdot \int V(t) \cdot I(t)\,dt$
$= \text{mean}(V(t) \cdot I(t))$

$E = P \cdot t$
$= \int V(t) \cdot I(t)\,dt$
$= \text{area}(V(t) \cdot I(t))$

$Pon = E_{ON} \cdot f$;
$Poff = E_{OFF} \cdot f$



Turn On Loss Due to Diode Recovery (Phase t_R)



I_L assumed constant during switching time

$$E_{on1} = \frac{V_{out} * I_L * t_R}{2}$$

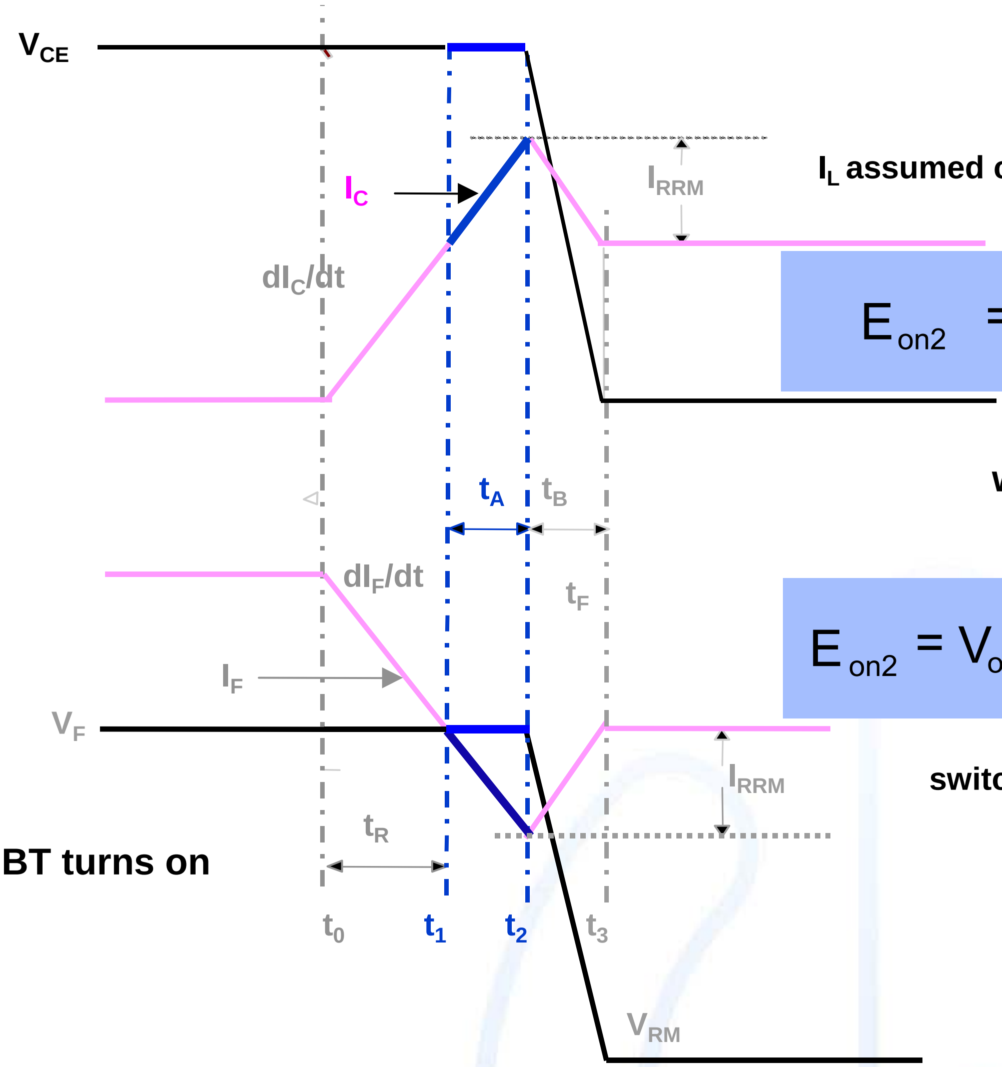
with $dI/dt = I_L / t_R$

$$E_{on1} = \frac{V_{out} * I_L^2}{2 * dI/dt}$$

switching time: $t_R+t_A+t_B$

$t = t_0$ IGBT turns on

Turn On Loss Due to Diode Recovery (Phase t_A)



t = t_0 IGBT turns on

I_L assumed constant during switching time

$$E_{on2} = V_{out} * \left(I_L + \frac{I_{RRM}}{2} \right) * t_A$$

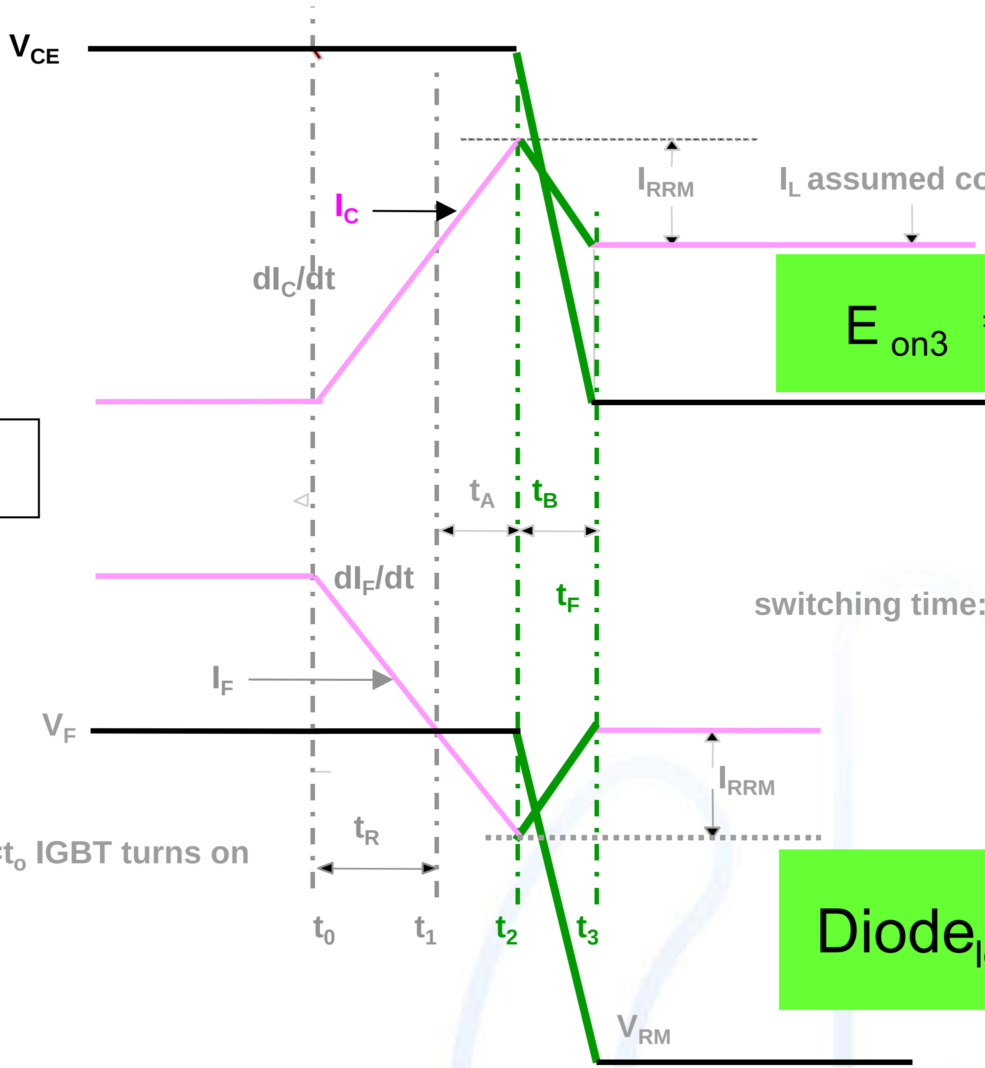
with $$dI/dt = \frac{I_{RRM}}{t_A}$$

$$E_{on2} = V_{out} * \left(I_L * \frac{I_{RRM}}{2} + I_{RRM}^2 \right) * \frac{dt}{2 * dI}$$

switching time: $t_R + t_A + t_B$

Turn On Loss Due to Diode Recovery (Phase t_B)

$t_F = t_B$



I_L assumed constant during switching time

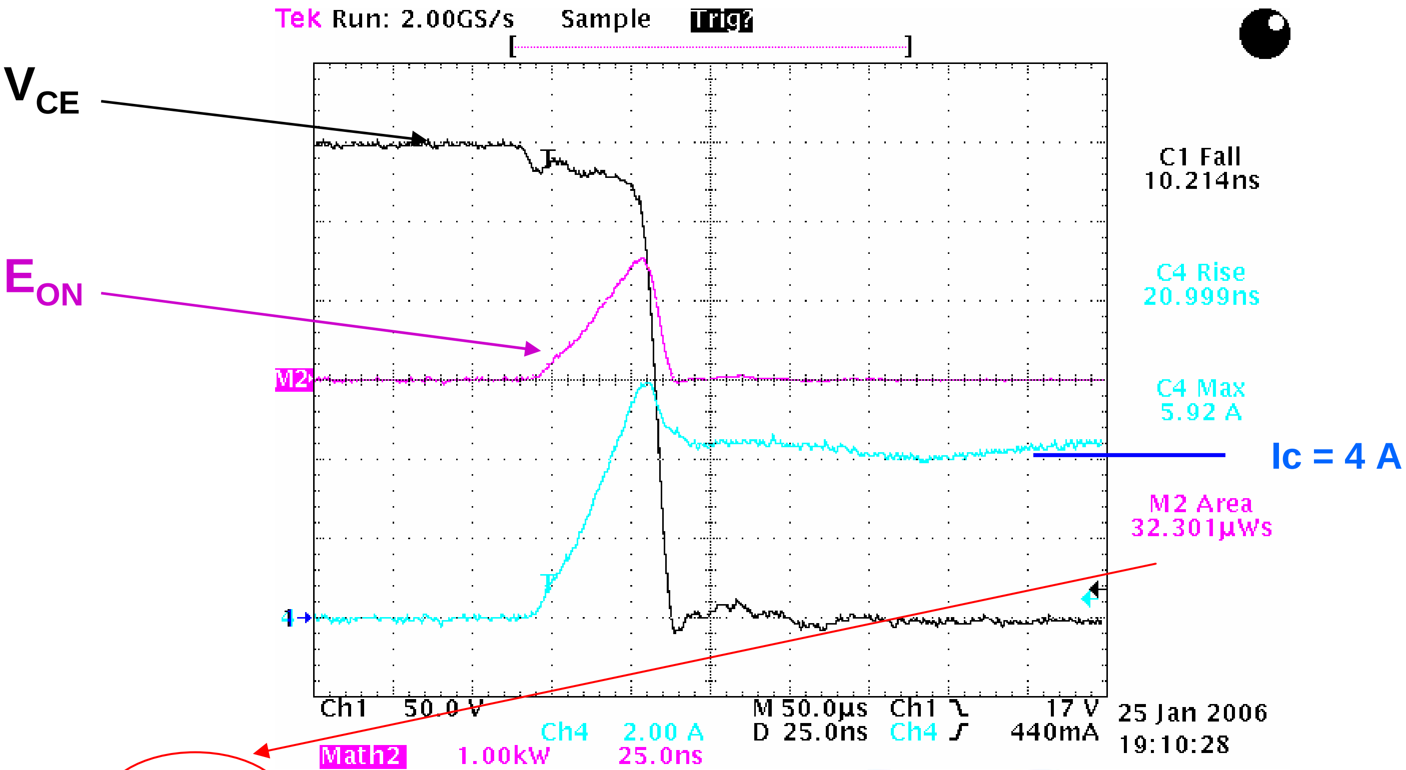
$$E_{on3} = V_{out} * \left(\frac{I_L}{2} + \frac{I_{RRM}}{3} \right) * t_B$$

switching time: $t_R + t_A + t_B$

At $t=t_o$ IGBT turns on

$$Diode_{loss} = \frac{V_{out} * I_{RRM} * t_B}{6}$$

Double check of the formulas:
Eon calculation vs. measurement



Eon =	32.67	uJ	Pon =	1.63	W	50	(kHz) Frequency
Eon1 =	11.20	uJ	Pon =	0.56	W	4	(A) Current
Eon2 =	14.00	uJ	Pon =	0.70	W	280.00	(V) Udc
Eon3 =	7.47	uJ	Pon =	0.37	W		
						2.00E+08	(A/s) dI/dt
Diode:						2	(A) Irr; Diode
Eoff =	9.33E-01	uJ	Poff =	0.05	W	1.00E-08	(s) tf fall time

8A Stealth II versus Stealth™ comparison

Loss calculation 25 °C and 125 °C

Specification	FFP08S60S		ISL9R860P2	
	T_C=25ºC	T_C=125ºC	T_C=25ºC	T_C=125ºC
t_A / ns (typ)	11.9	25.2	16.4	15.1
t_B / ns (typ)	7.1	32.8	60.6	37.9
I_{RRM} / A (typ)	2.2	4.3	3.4	6.5
Q_{RR} / nC (typ)	21	125	150	190
Switch losses example calculation / µJ	118	232	246	220
V_F / V (typical)	2.1	1.6	2.0	1.6

Measured with di/dt=200A/us, see datasheets for full details
Example: Loss in switch for 8A, di/dt=200A/us, V_{DD}=390V
Equations in Power Seminar 2007 documentation

8A Stealth II versus Stealth™ comparison

Loss calculation 75 °C and 100 °C

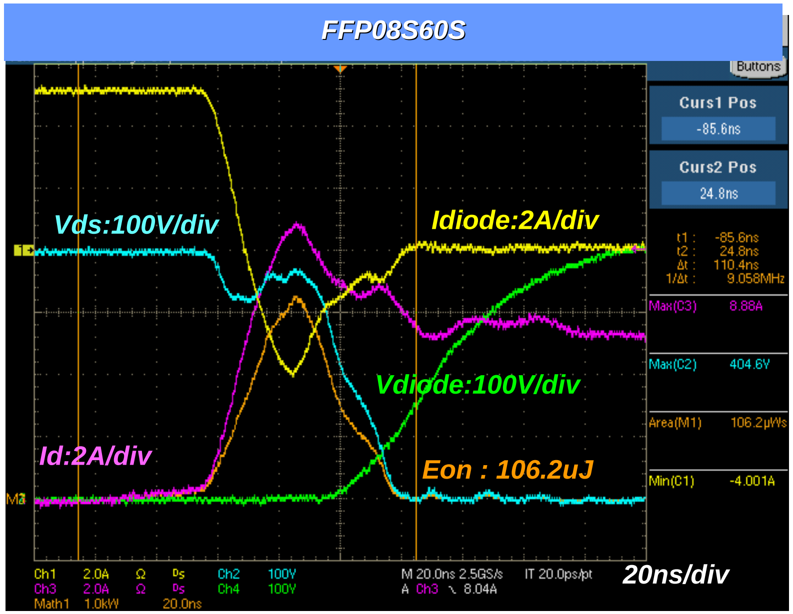
Specification	FFP08S60S		ISL9R860P2	
	T_C=75ºC	T_C=100ºC	T_C=75ºC	T_C=100ºC
t_A / ns (typ)	18.5	21.9	15.8	15.5
t_B / ns (typ)	20	26.4	49.2	43,5
I_{RRM} / A (typ)	3.3	3.8	5.0	5.7
Switch losses example calculation / µJ	172	201	235	228
V_F / V (typical)	1.85	1.725	1.8	1.7
Switching loss @ 100 kHz / W	17.2	20.1	23.5	22.8

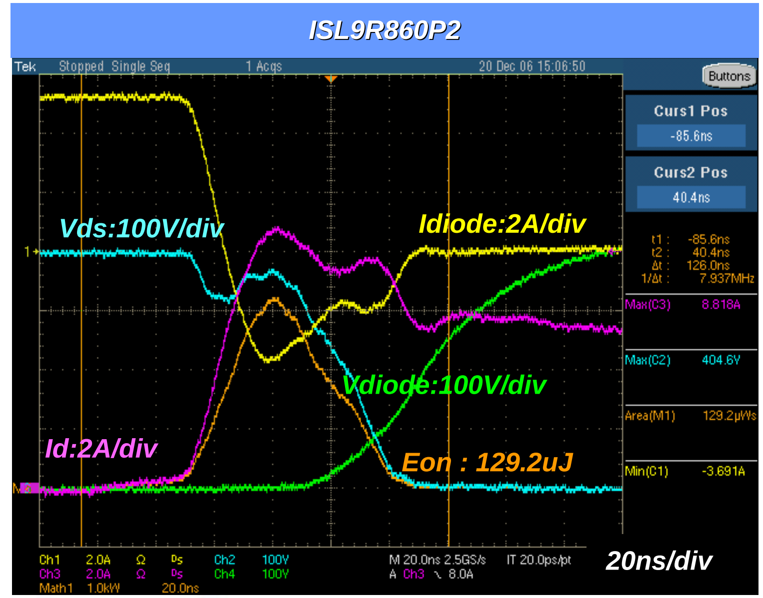
Calculated with di/dt=200A/us, see datasheets for full details
Example: Loss in switch for 8A, di/dt=200A/us, V_{DD}=390V
Equations in Power Seminar 2007 documentation
Linear approximation: of ta, tb, Irrm and Vf

6.3 W difference on switching losses

8A Stealth II versus Stealth™ comparison

Loss measurements



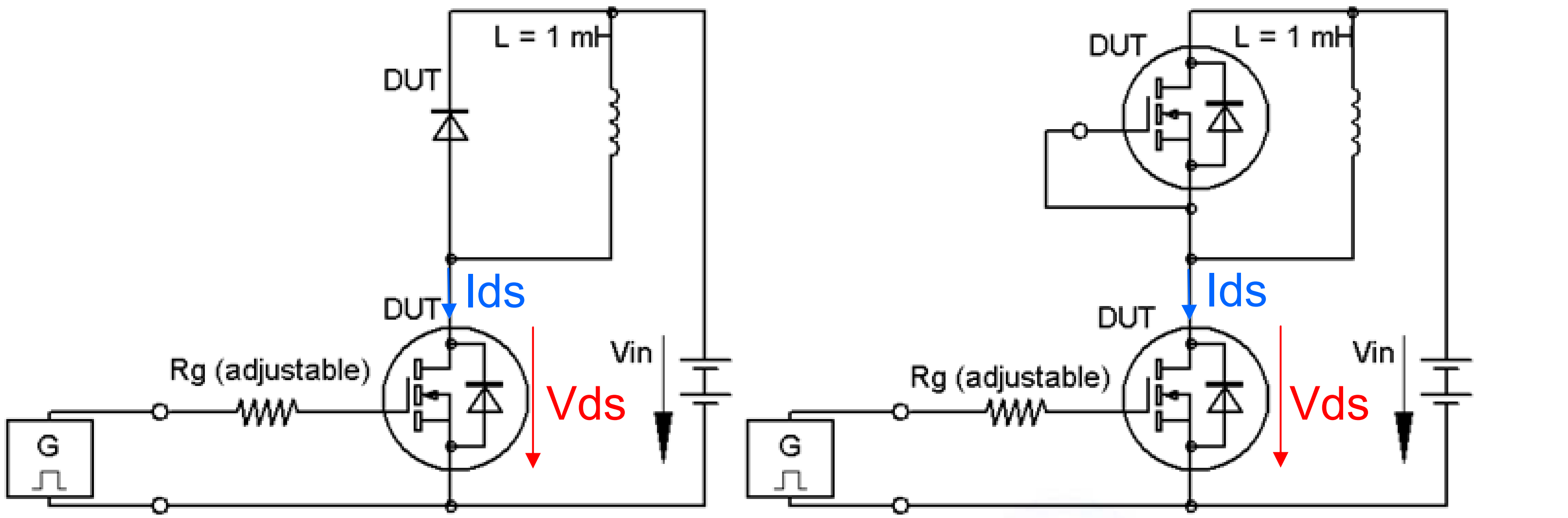


DUTs	Ta	TMOSFET	Tdiode	dTMOSFET	dTdiode	Pin	Vout	Iout	Pout	Efficienccy	PF
ISL9R860P2	26.2	120.2	76.7	94.0	50.5	431.2	401.240	0.984	394.70	91.54	0.999
FFP08S60S	**26.2**	**113.3**	**70.1**	87.1	43.9	**426.0**	**401.240**	**0.984**	**394.70**	**92.65**	**0.999**

Test condition : Vin=220Vac, Pout=400V/ 1A(400W), Fs=100kHz

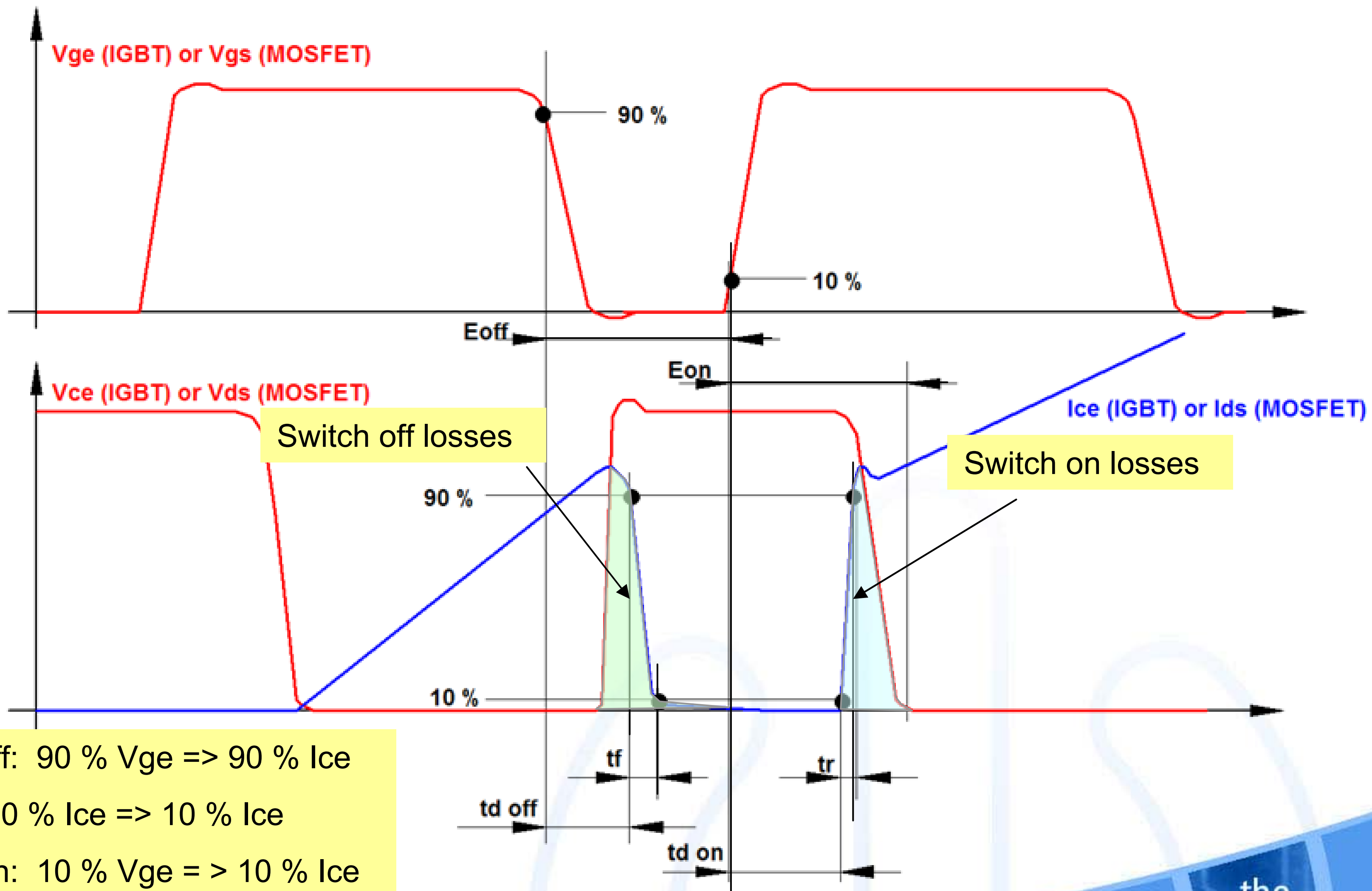
5.2 W difference in input power

Test circuits



Test Circuits which are used for the following measurements

Waveforms and loss definition



td off: 90 % Vge => 90 % Ice

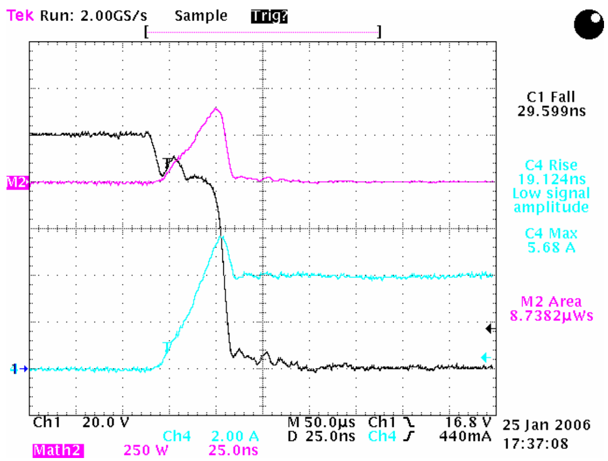
tf: 90 % Ice => 10 % Ice

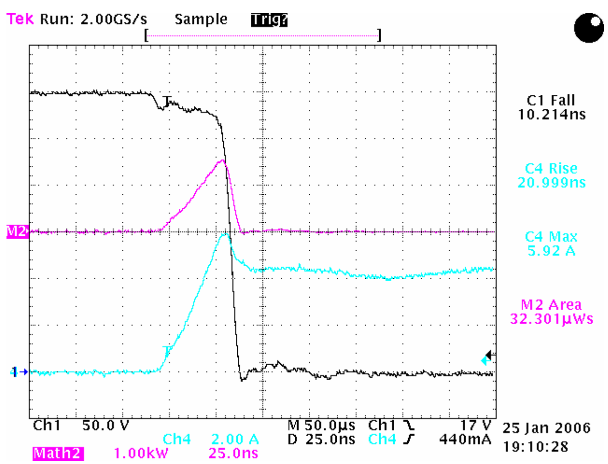
td on: 10 % Vge = > 10 % Ice

tr: 10 % Ice => 90 % Ice

Switching Losses vs. Voltage
FQP9N50C + ISL9R460

E_{ON}





E_{ON} / E_{OFF} losses

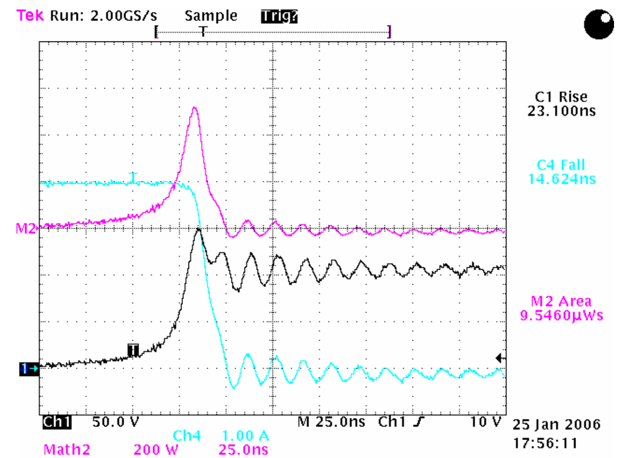
V_{IN} = 100V

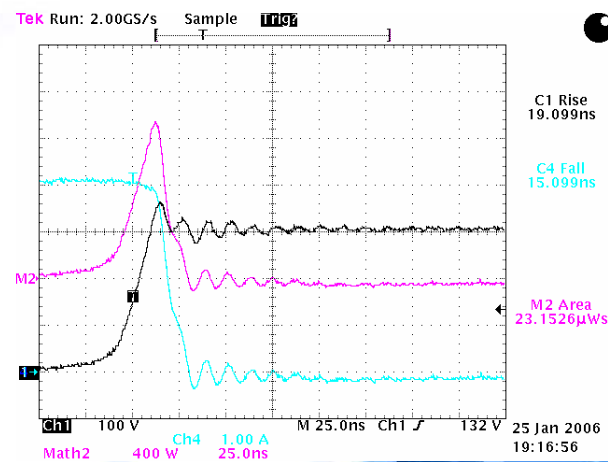
E_{ON} = 8.7uJ
E_{OFF} = 9.5uJ

V_{IN} = 300V

E_{ON} = 32.3uJ
E_{OFF} = 23.1uJ

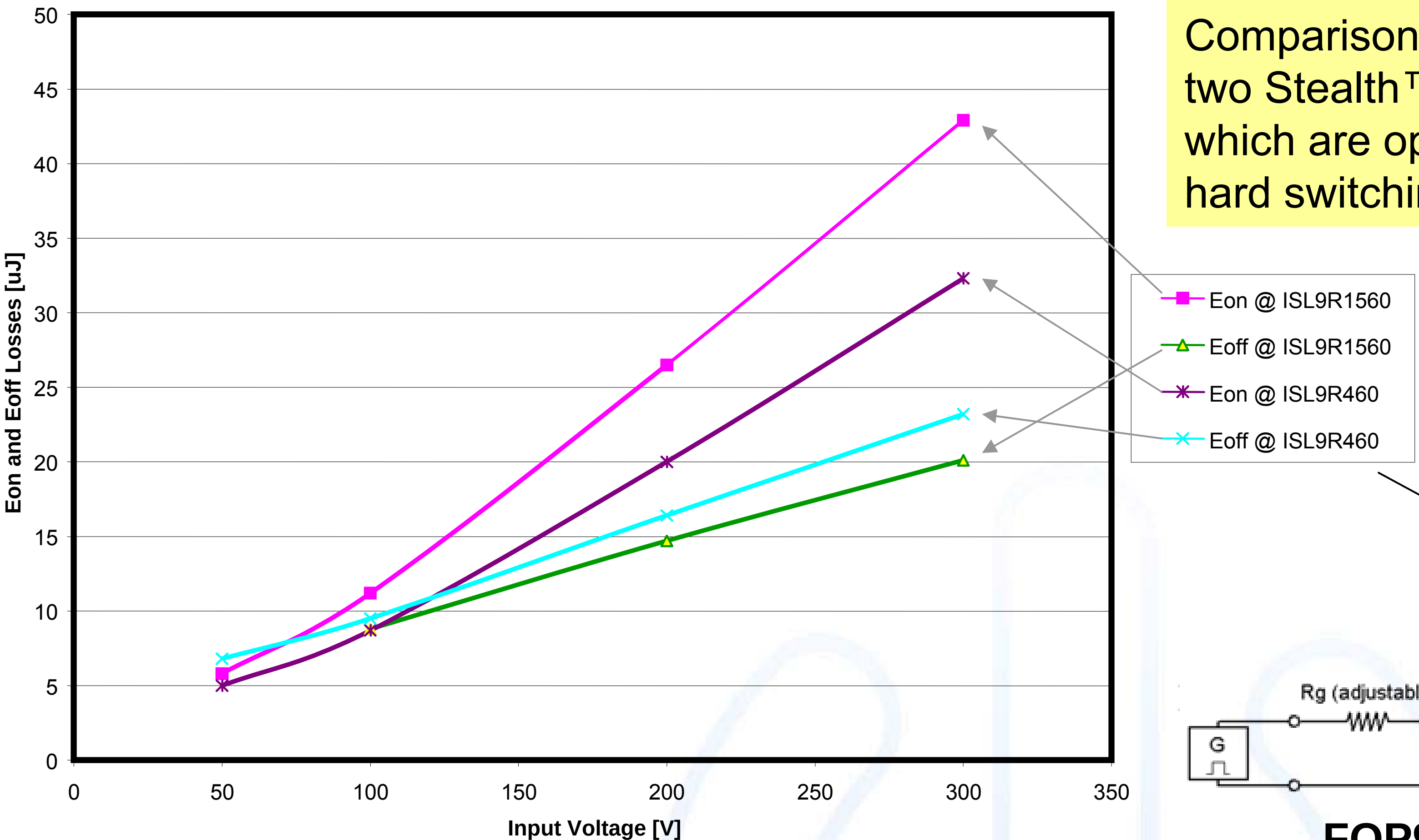
E_{OFF}



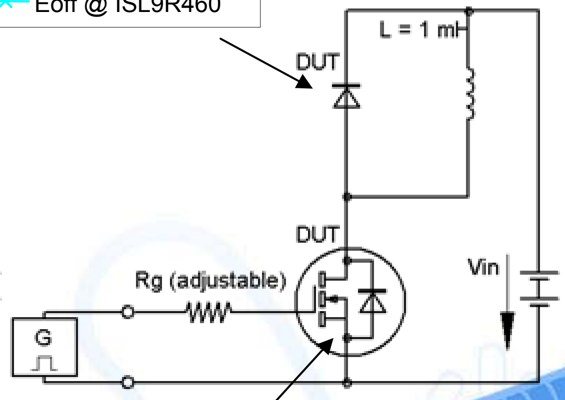


Switching Losses vs. Voltage: E_{ON} and E_{OFF} losses

Eon and Eoff losses of the FET - FQP9N50C vs. Input Voltage



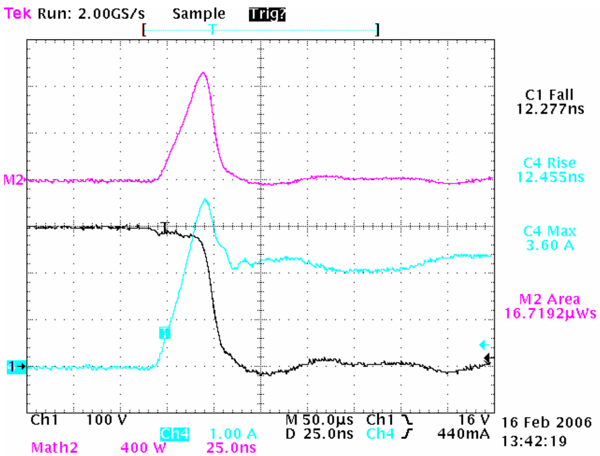
Comparison of two Stealth™ diodes, which are optimized for hard switching



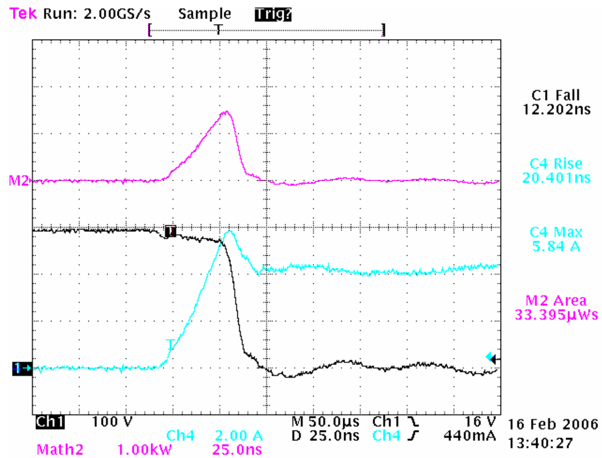
FQP9N50C

Higher Current rating of the Diode will increase Eon, but decrease Eoff (Diode capacitance acts as a snubber). Eon is dominating!

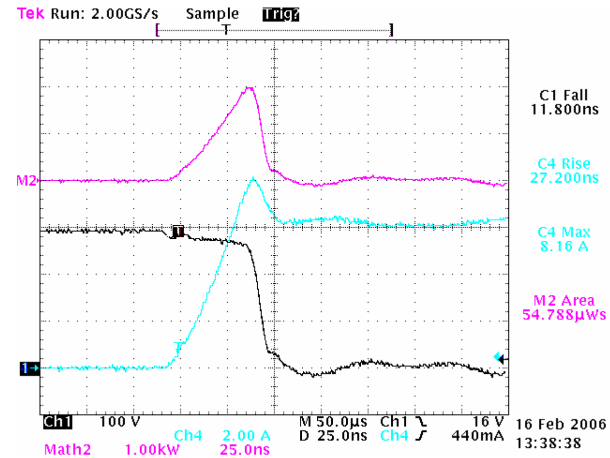
Switching Losses vs. Current
FQP9N50C + ISL9R460 @ V_{IN} = 300V



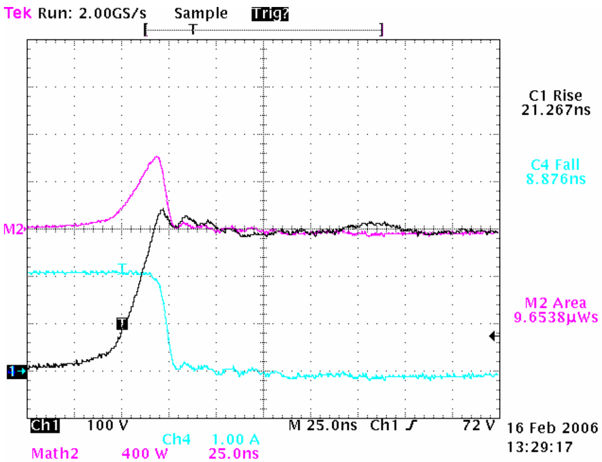
I = 2A, E_{ON} = 16.7uJ



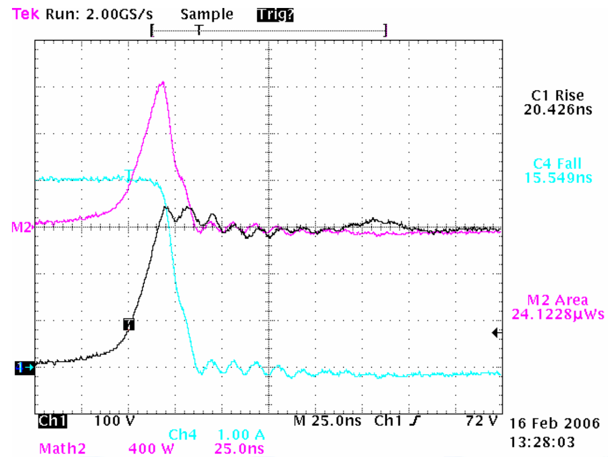
I = 4A, E_{ON} = 33.4uJ



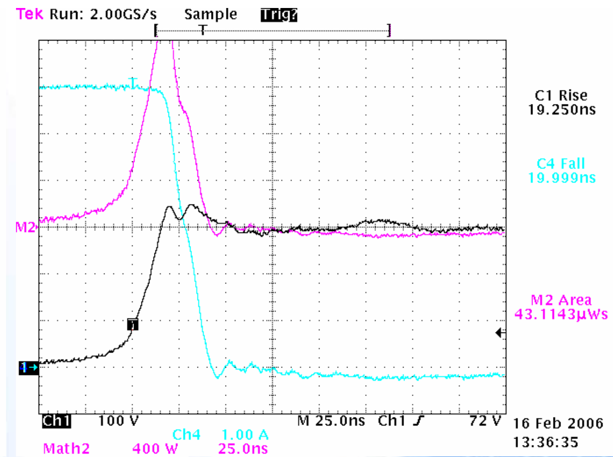
I =6A, E_{ON} = 54.8uJ



I = 2A, E_{OFF} = 9.7uJ



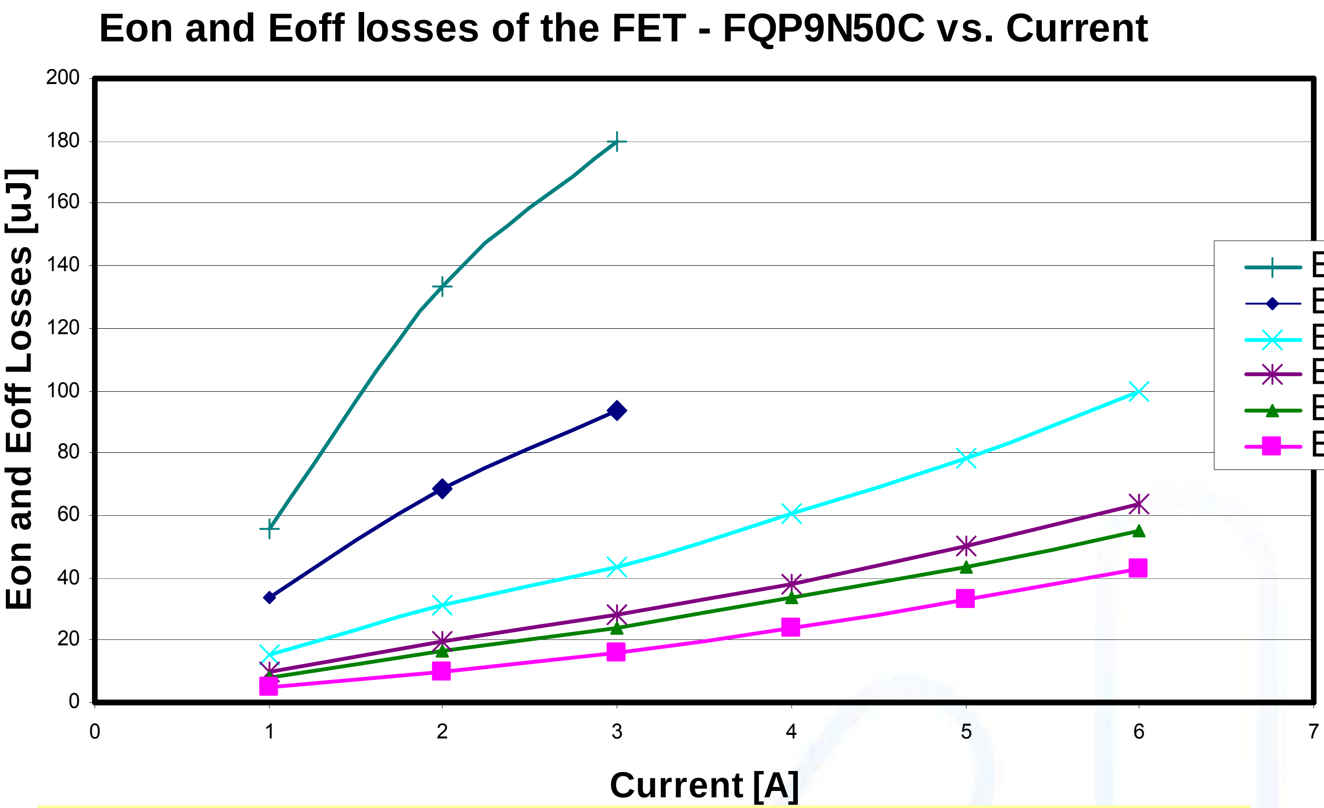
I = 4A, E_{OFF} = 24.1uJ

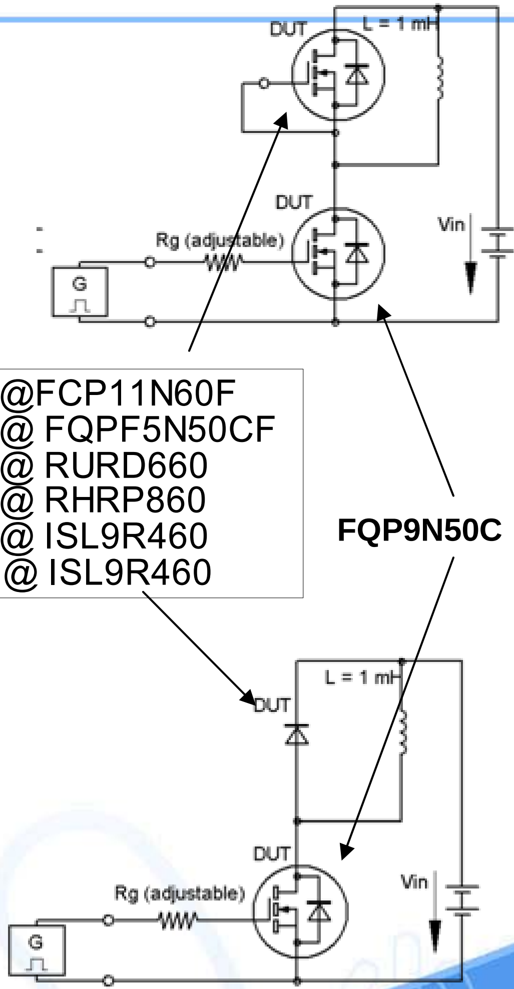


I =6A, E_{OFF} = 43.1uJ

(nearly) Linear relation between current and losses.

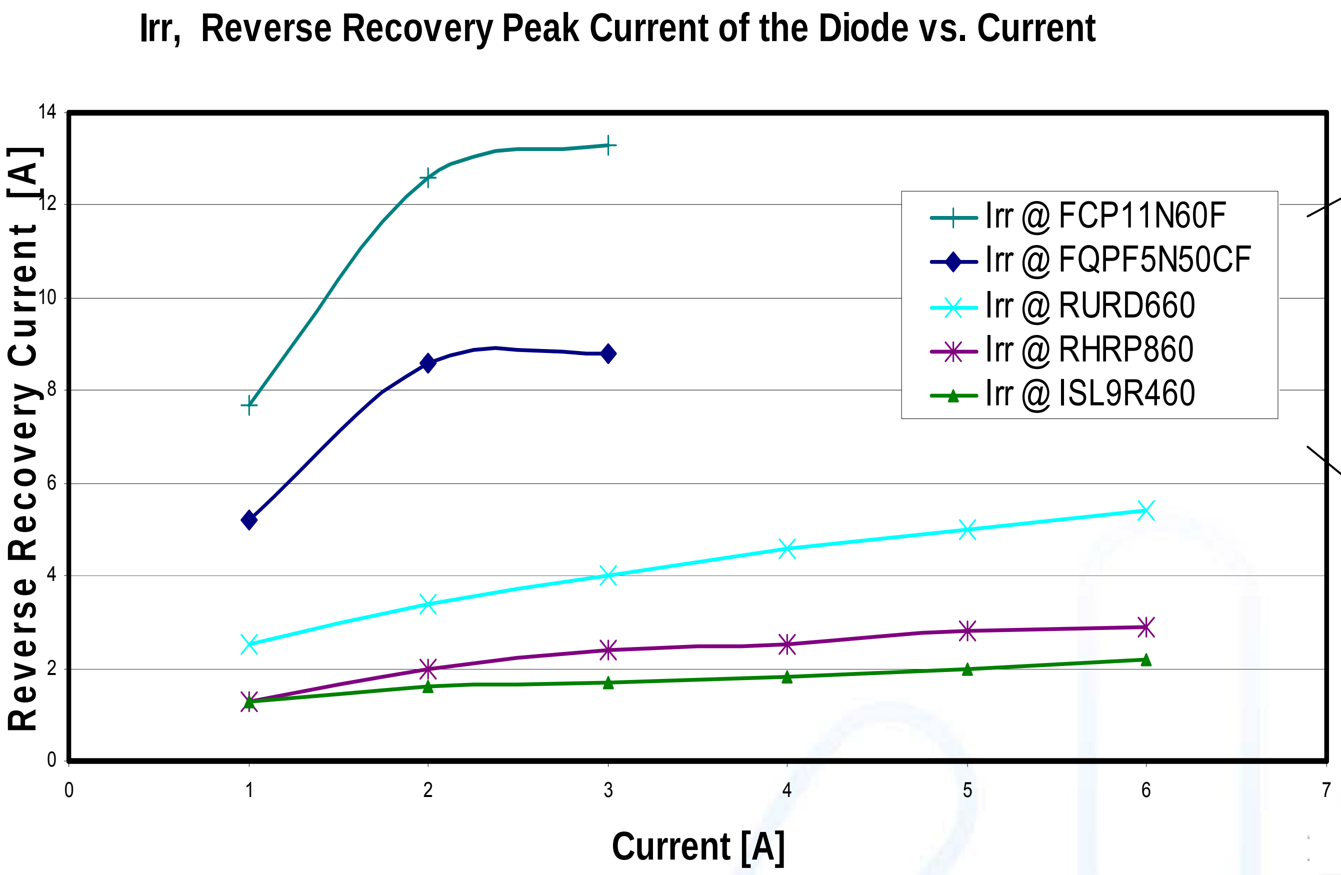
E_{ON} = f (Ice) and E_{OFF} = f (Ice) for different diode technologies and ratings

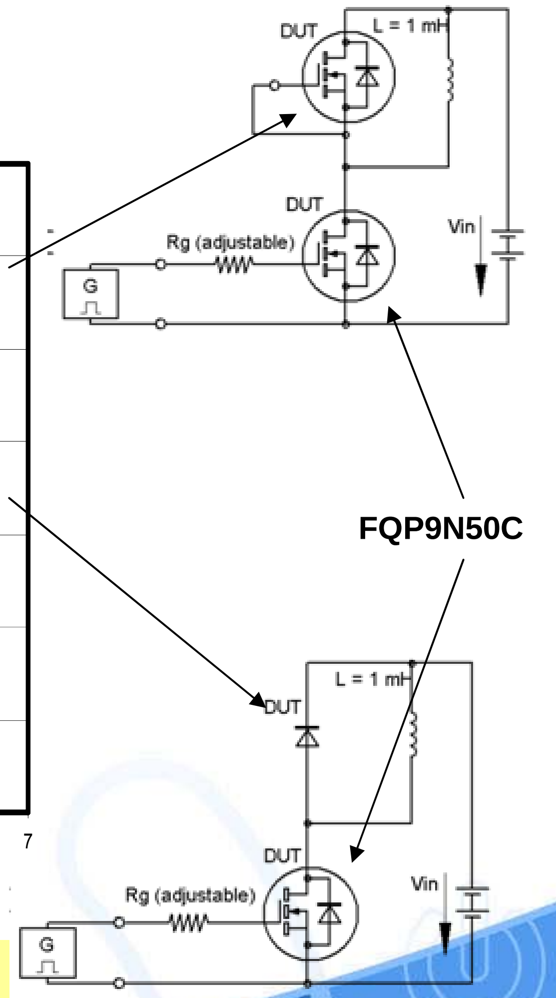




Technologies as well as rating will have a big impact on the Eon losses. Fast recovery FETs will lead to significant higher Eon losses compared to single diode technologies. => Sometimes the reason for external fast recovery diodes.

Variation of I_{RRM} with load current for different diode technologies

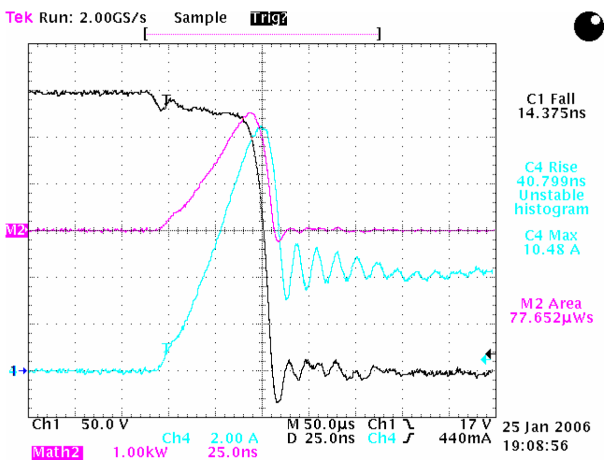




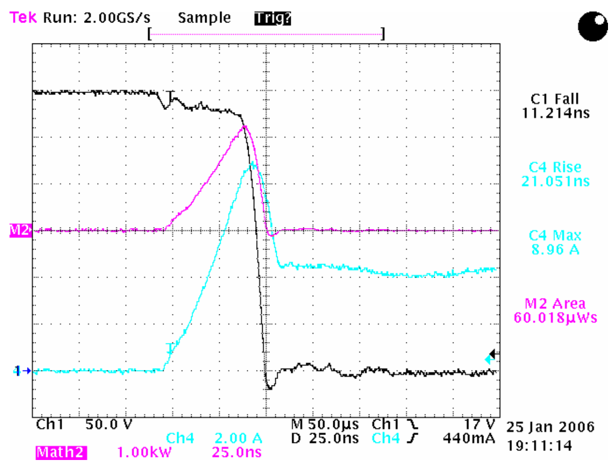
Irr values are a good indicator for a loss comparison of diodes.

Only Irr's measured at the same dI/dt are comparable!

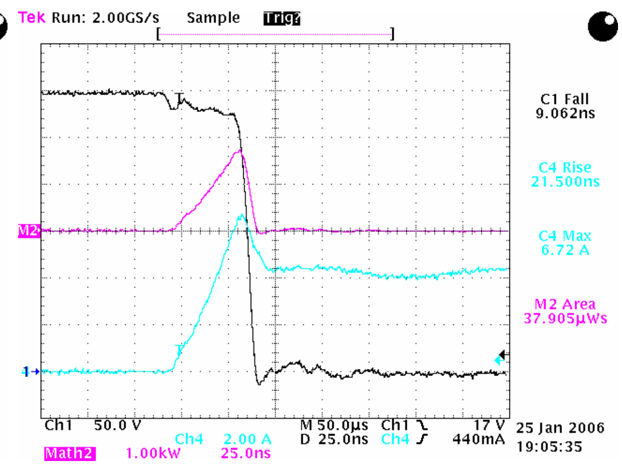
E_{ON} Losses at Hard Switching with different Diode Technology @ V_{IN} = 300V @ I = 4A



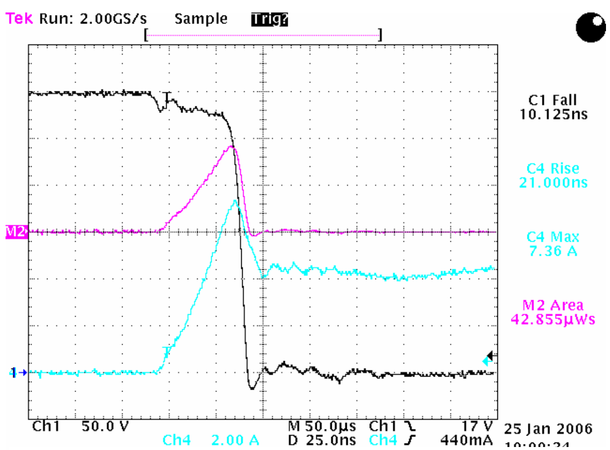
MUR1560; E_{ON} = 77.7uJ



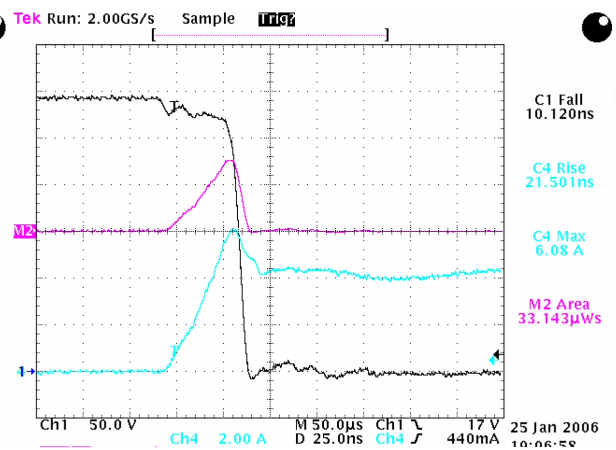
RURD660; E_{ON} = 60.1uJ



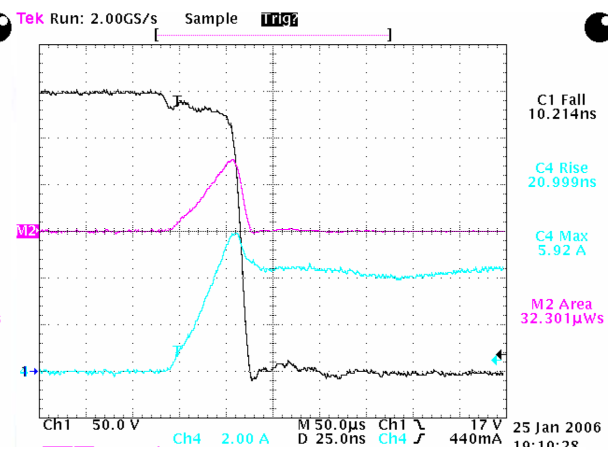
RHRP860; E_{ON} = 37.9uJ



ISL9R1560; E_{ON} = 42.9uJ

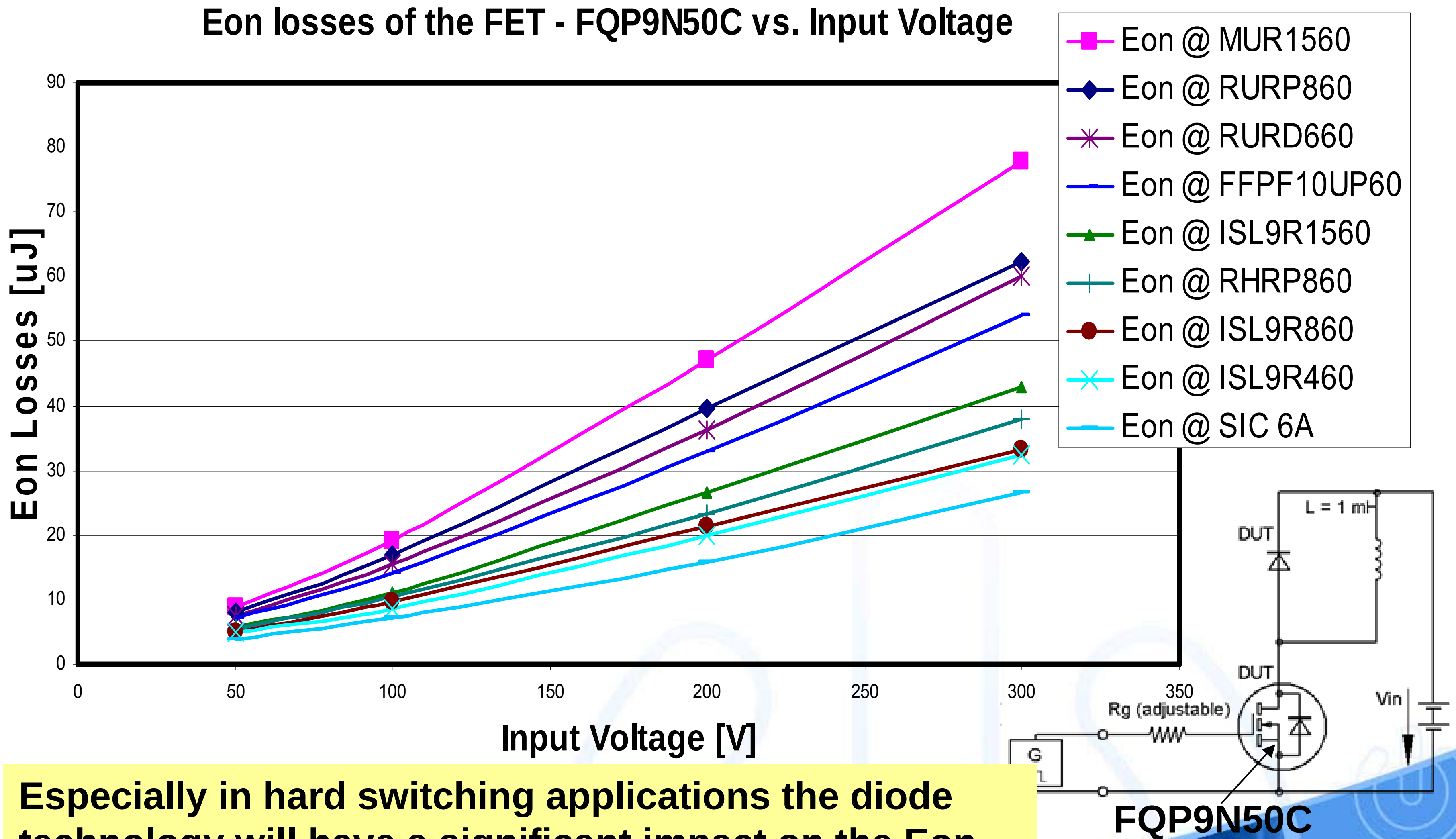


ISL9R860; E_{ON} = 33.1uJ



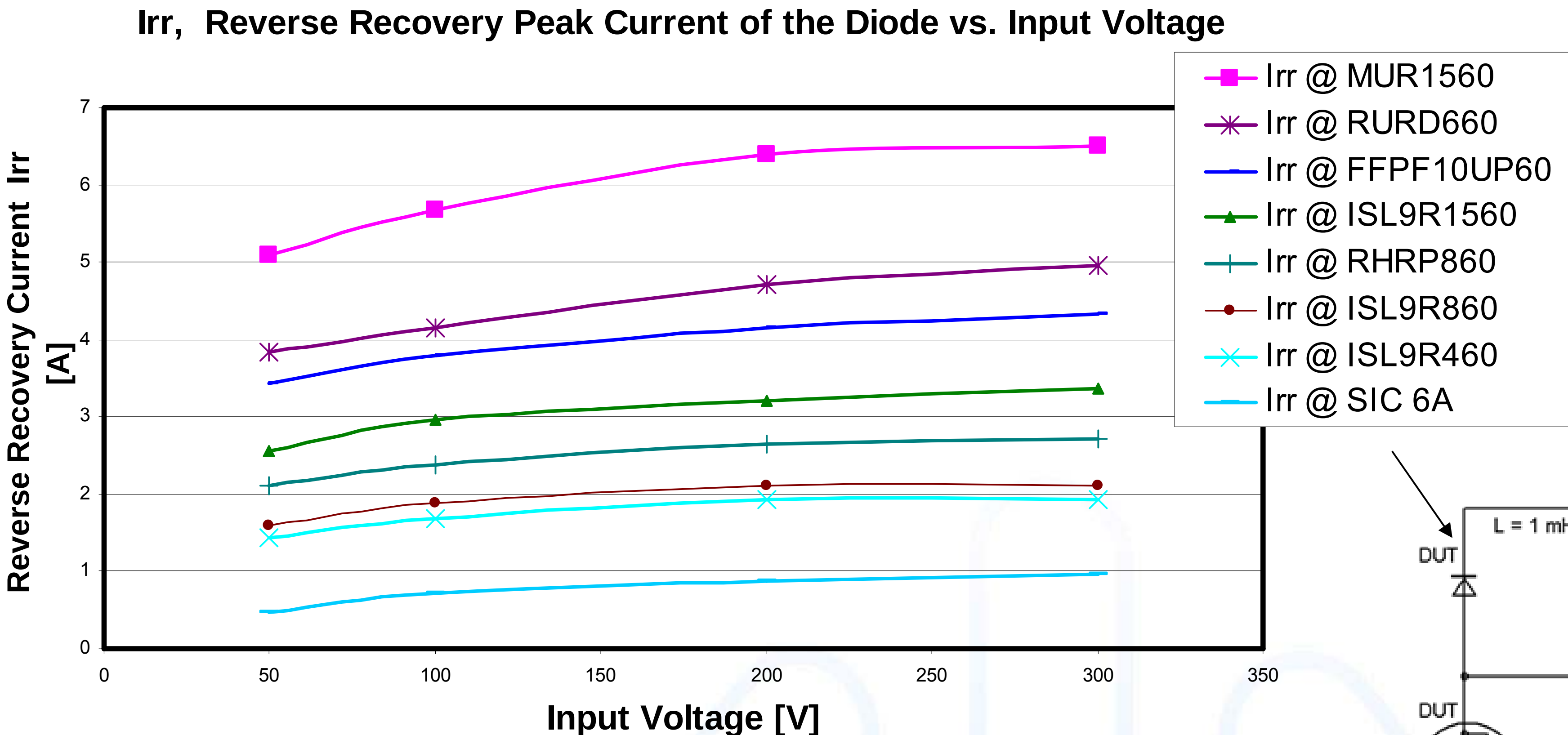
ISL9R460; E_{ON} = 32.3uJ

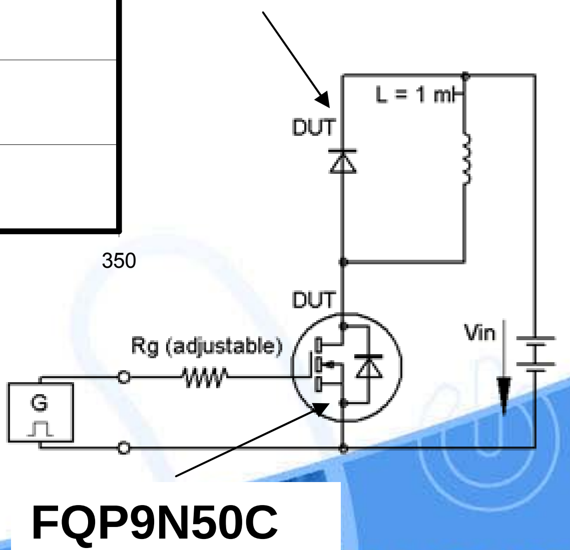
Variation of the E_{ON} Losses with input voltage for different diode technologies and ratings



Especially in hard switching applications the diode technology will have a significant impact on the Eon losses of the switch.

Variation of I_{RRM} with input voltage for different diode technologies





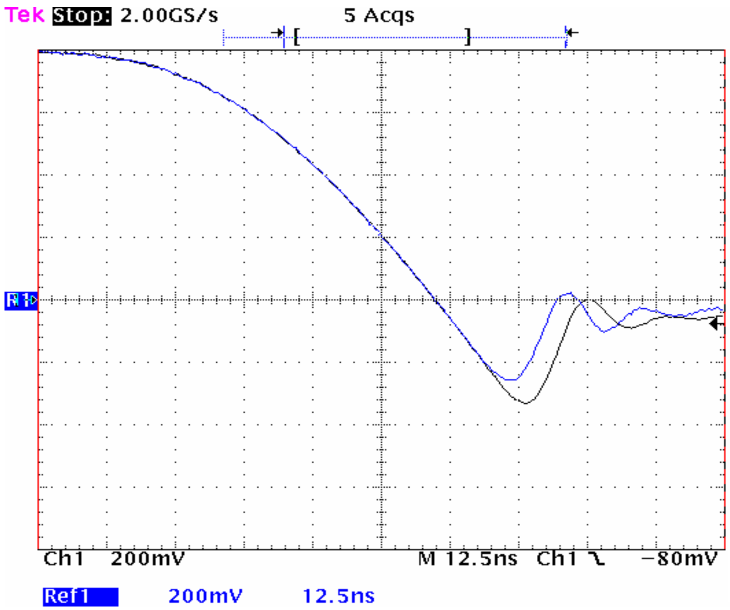
The Irr value is a good parameter to estimate the switching losses of different technologies.

Only Irr's measured at the same dI/dt are comparable!

Effect of temperature on reverse recovery

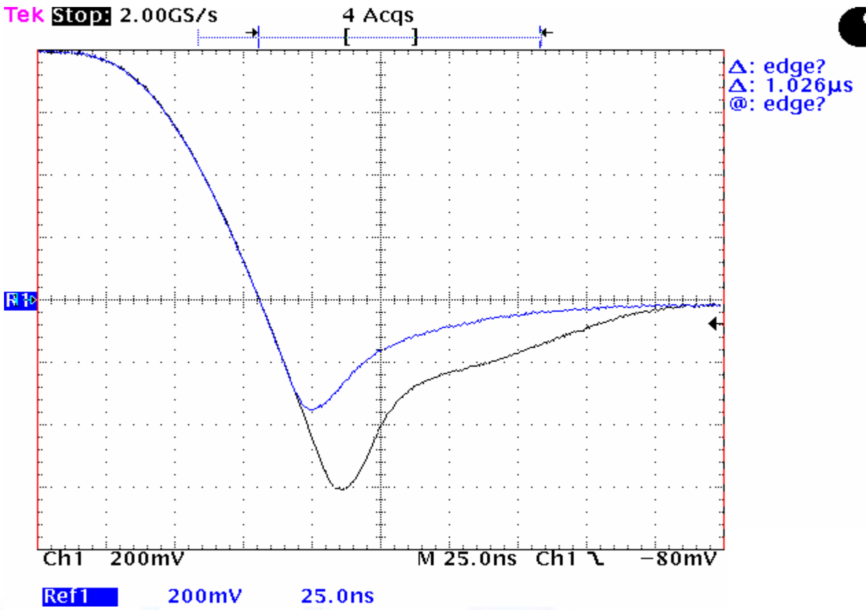
dI/dt = 200A/ms, Vdd = 400V, If = 8A, Tj = 25°C and Tj = 125 °C

Two industry standard diodes



Results for Tj = 25°C

Small difference



Results for Tj = 125°C

Big difference

The difference between low and high temperature reverse recovery behavior is not the same for all technologies. Be careful if you compare only at low temperatures.

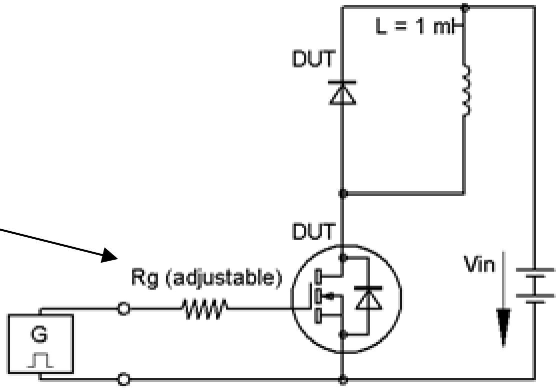
Switching Losses @ increasing switching speed

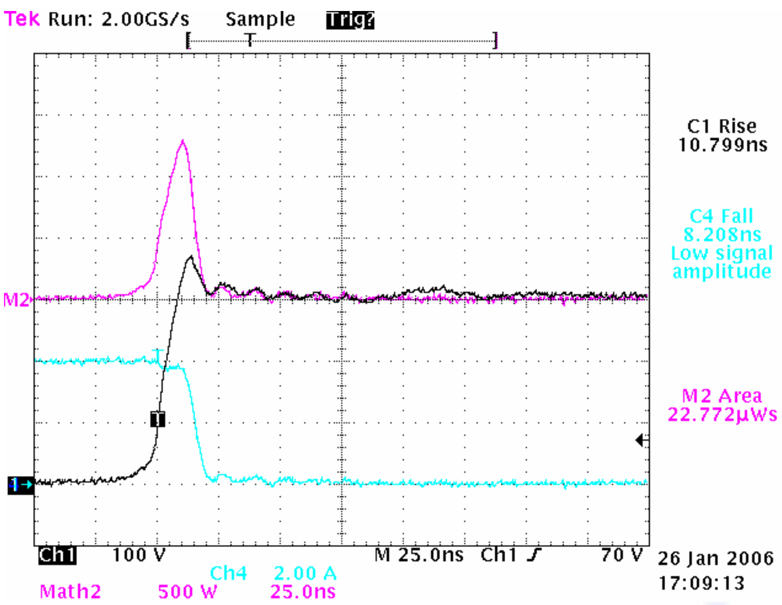
- Switching off:

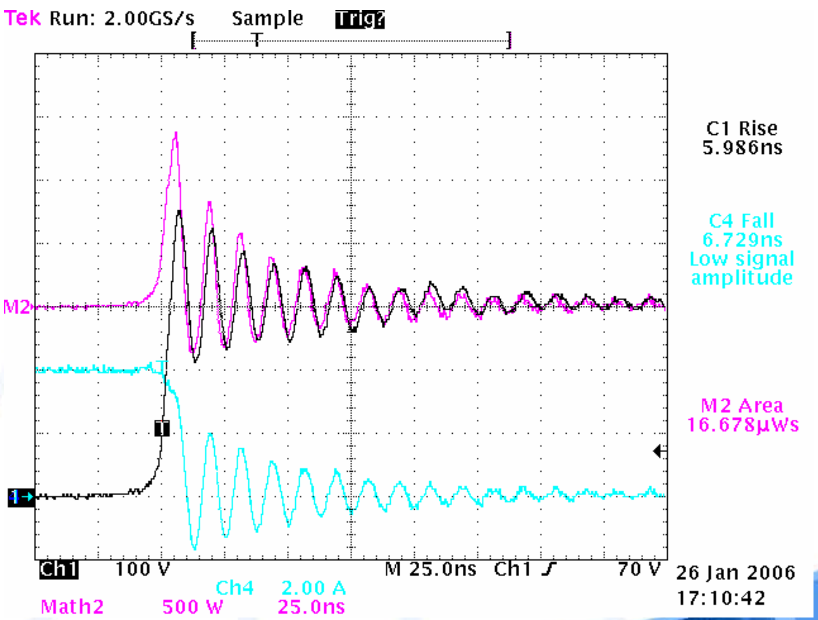
Same FET and Diode, reducing Rg:

E_{OFF} = 22.8uJ ⇔ 16.7uJ
Drawback: ringing due to parasitic Ind. & Caps

All measurements: FDD6N50 + ISL9R460, U = 300V, I = 4A







Recommended Rg

Good switching performance, no ringing

Low Rg

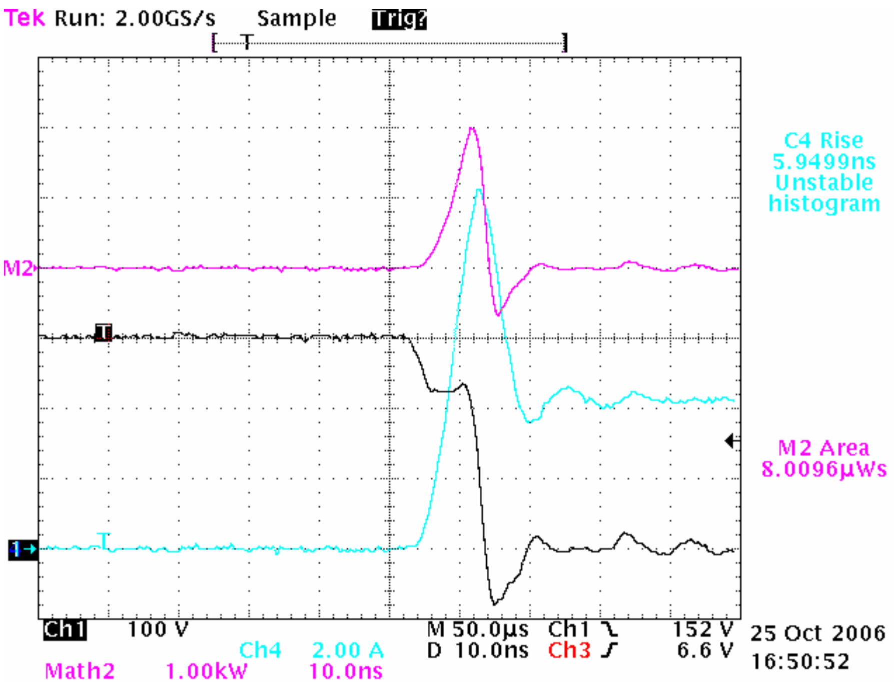
Bad switching performance, ringing, but lower E_{OFF}

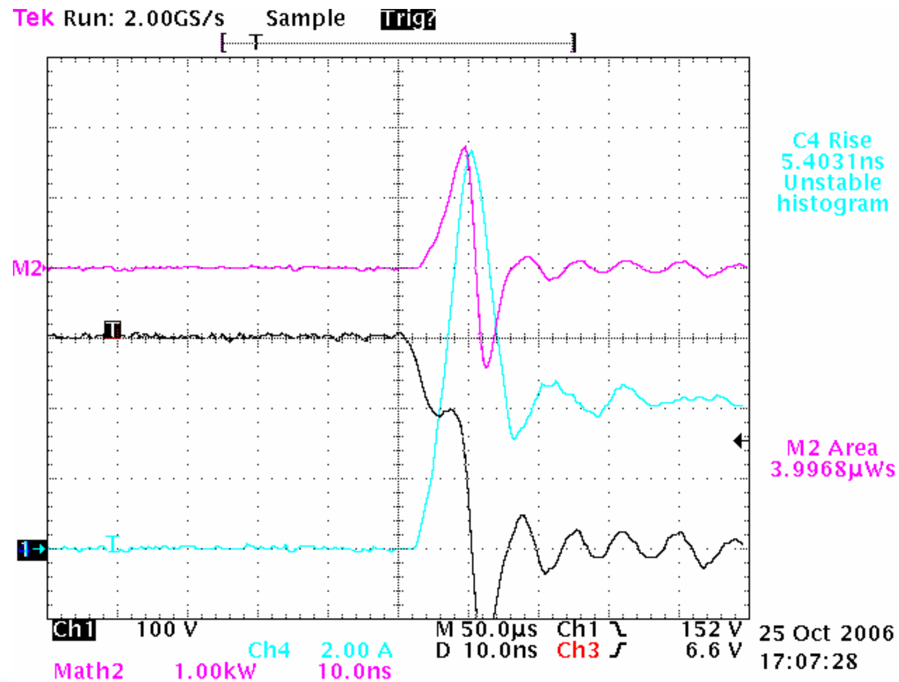
FAIRCHILD SEMICONDUCTOR

Switching Losses @ increasing switching speed - Same MOSFET, different Rg -

FAIRCHILD SEMICONDUCTOR CELEBRATING 50 YEARS

Diode = ISL9R460, U = 300V, I = 4A



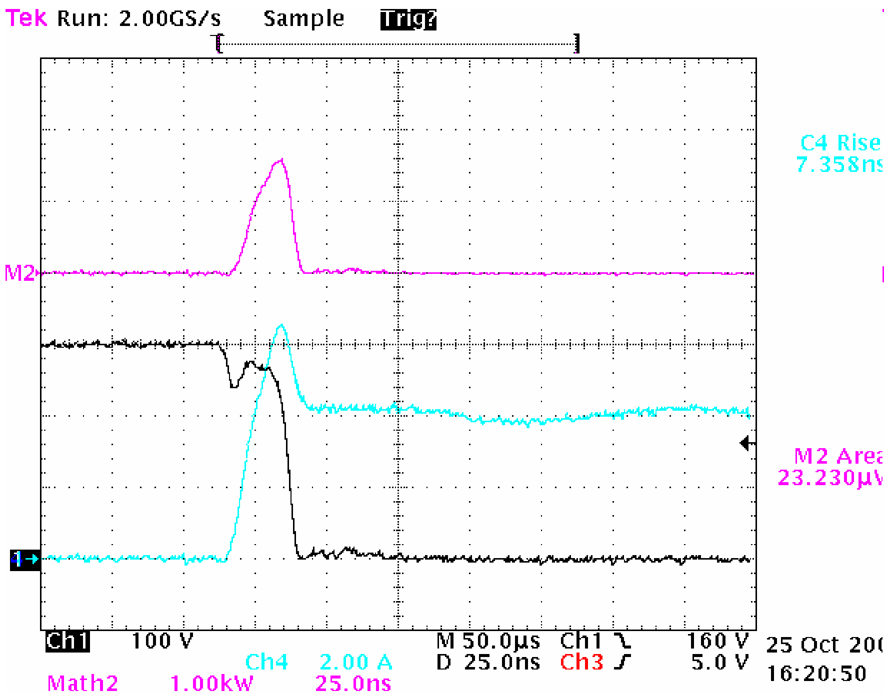


FDD6N50, Rg = 10 Ohm
E_{ON} = 8 uJ
dI/dt = 1400A/us
I_{RRM} = 6.2A

Right : FDD6N50, Rg = 3 Ohm
E_{ON} = 4 uJ
dI/dt = 1600A/us
I_{RRM} = 7.4A

Switching Losses @ increasing switching speed
- Different MOSFET Technologies -

Diode = ISL9R460, U = 300V, I = 4A

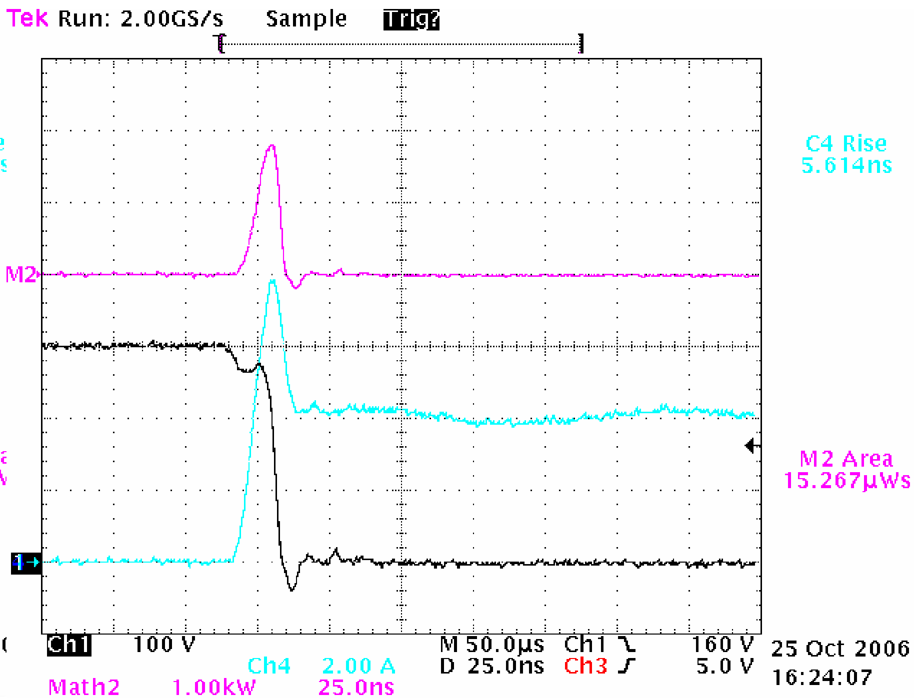


FQP9N50C, Rg = 30 Ohm

E_{ON} = 23.2 uJ

dI/dt = 400 A/us

I_{RRM} = 2.6 A



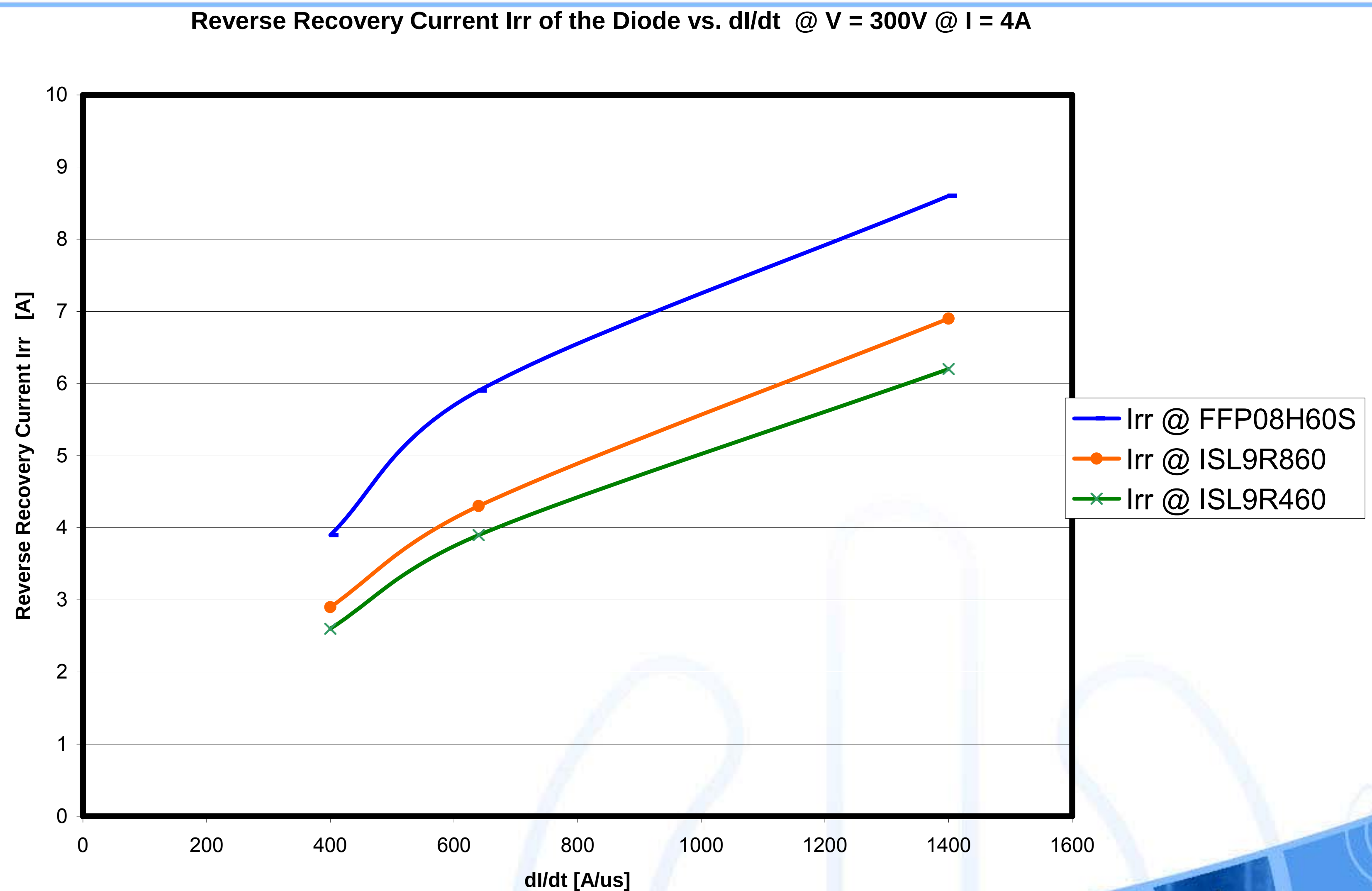
FDD6N50, Rg = 30 Ohm

E_{ON} = 15.3 uJ

dI/dt = 640 A/us

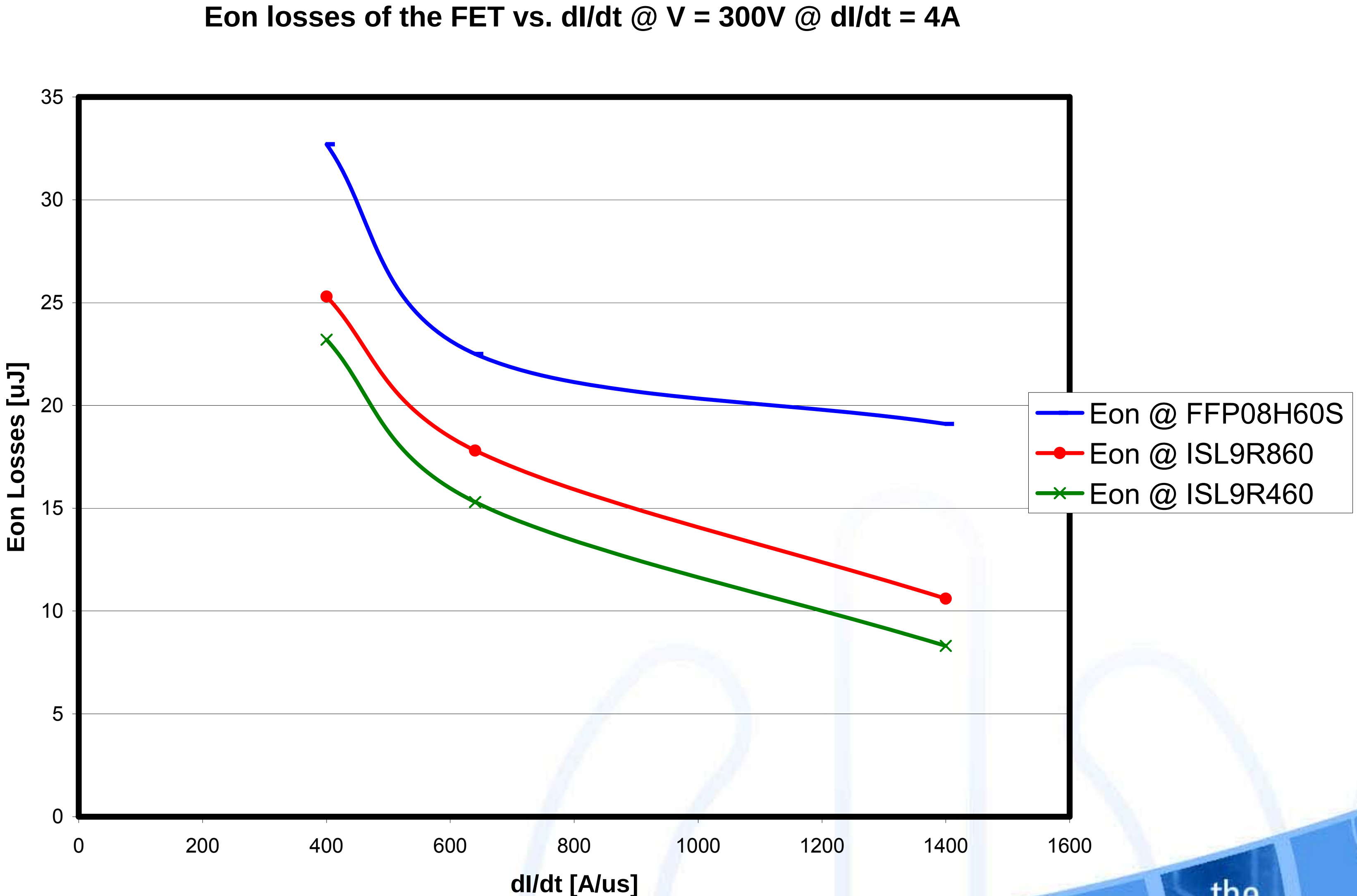
I_{RRM} = 3.9 A

Variation of I_{RRM} with dI/dt for different diode technologies



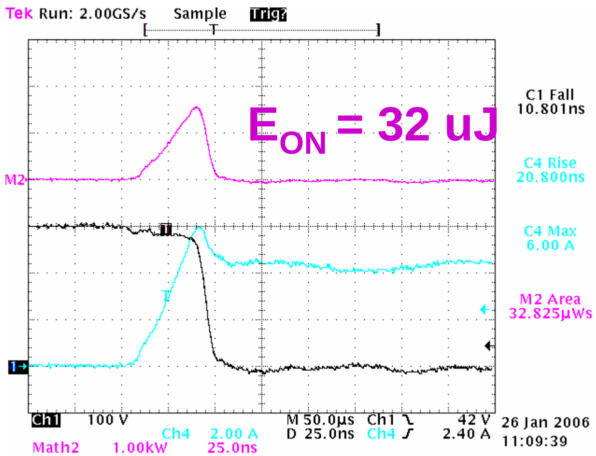
A higher dI/dt will increase the reverse recovery current, but…

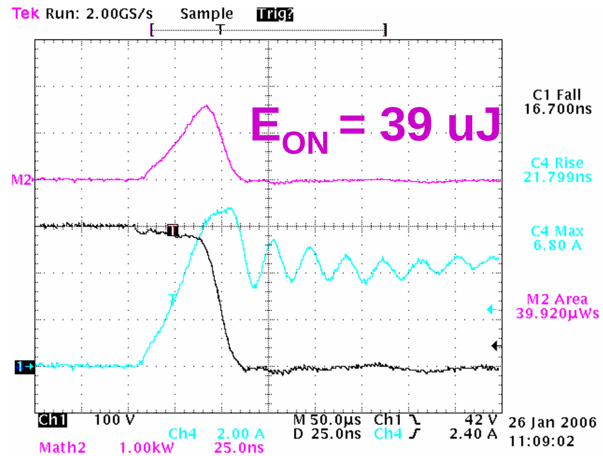
Variation of E_{ON} losses with di/dt for different diode technologies

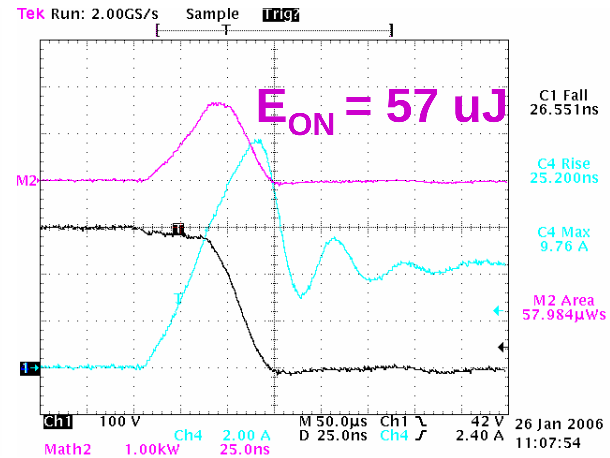


A higher dI/dt will decrease the Eon losses.

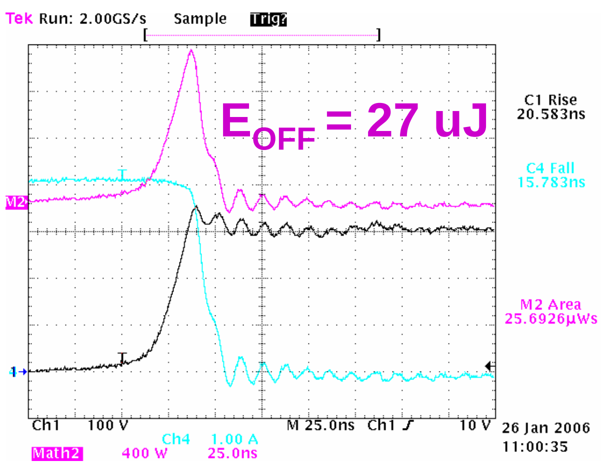
Effect of parallel caps on switching losses
@ V_{IN} = 300V @ I = 4A Diode = ISL9R460

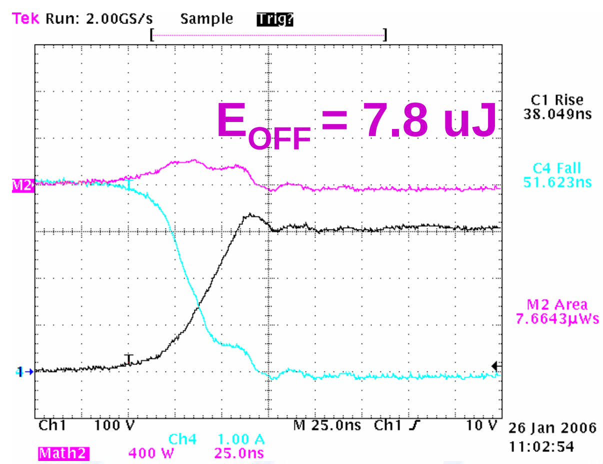


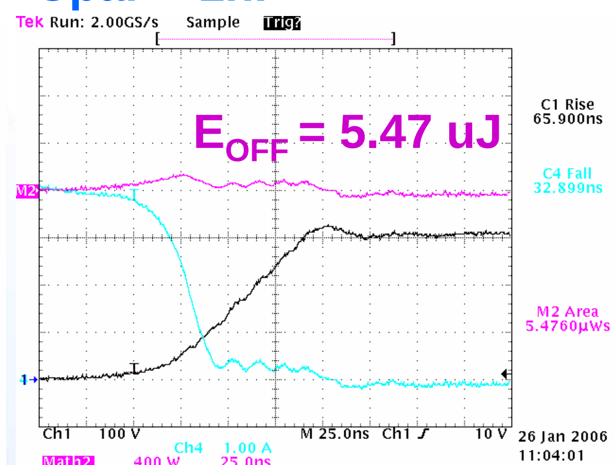




No parallel Capacitance | **Cpar = 470pF** | **Cpar = 1nF**



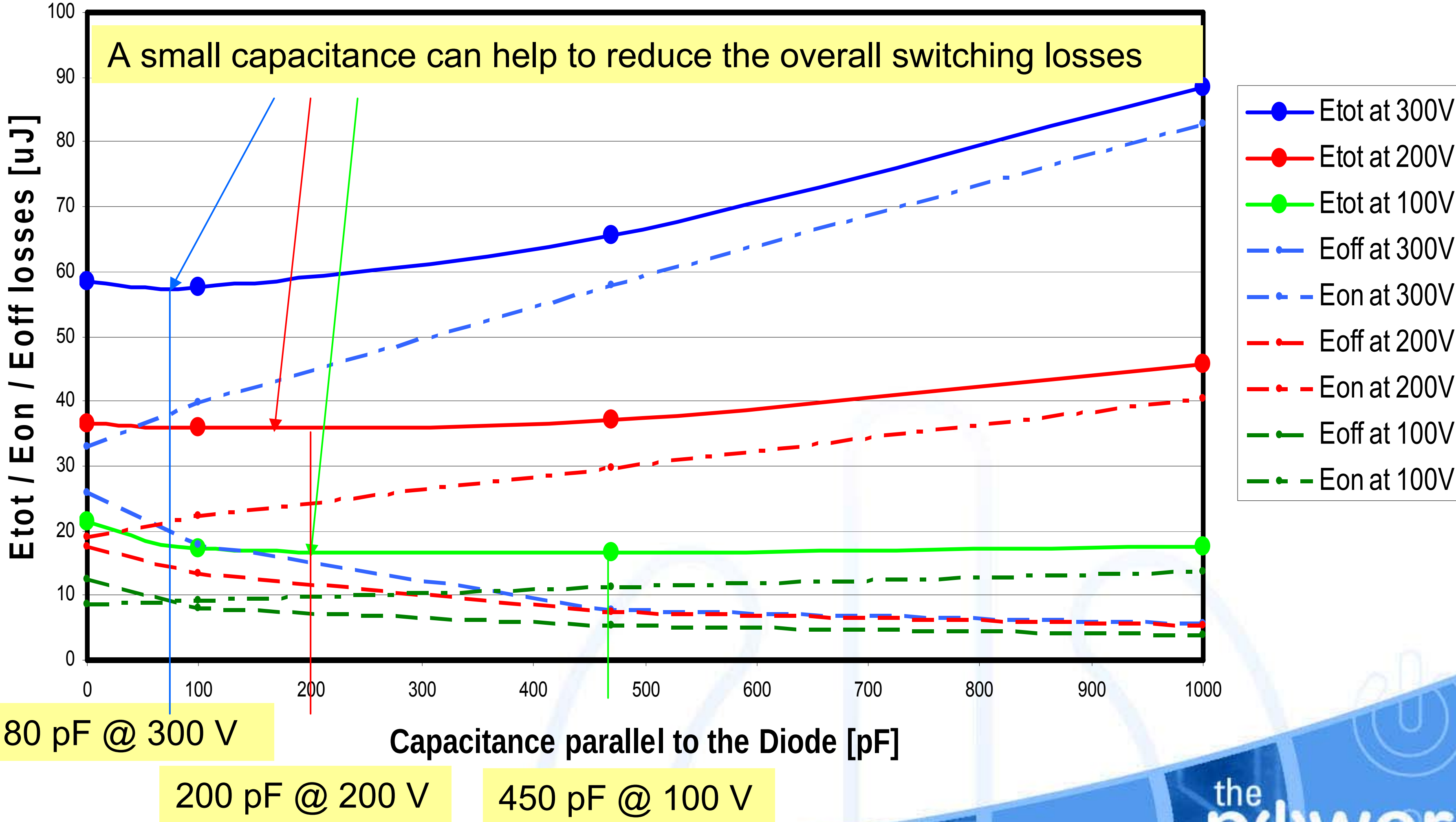




- Increase of the Eon losses due to the parallel Capacitance.
- Advantages in switching off
- Overall losses? …

Effect of parallel caps on switching losses

Eon and Eoff losses with a snubber Capacitance



As higher the voltage, as smaller the cap to decrease the overall losses.

Summary

- Reverse recovery in diodes in half-bridge structures causes
  - small losses in the diodes
  - larger losses in the MOSFET/IGBT

- I_{RRM} and t_{RR} increase with
  - temperature
  - di/dt
  - current (less dominant)

- Larger current rated diodes of the same family
  - have higher I_{RRM} resulting in higher E_{ON} (measured at the same dI/dt for comparison)
  - have larger capacitance, resulting in lower E_{OFF}
  - cause higher total switching losses

- Higher di/dt results in lower E_{ON} losses, but also in a higher I_{RRM}

- Addition of extra capacitance
  - increases E_{ON} losses but decreases E_{OFF} losses
  - addition of extra capacitance could reduce total losses.