IGBT Double Pulse Test

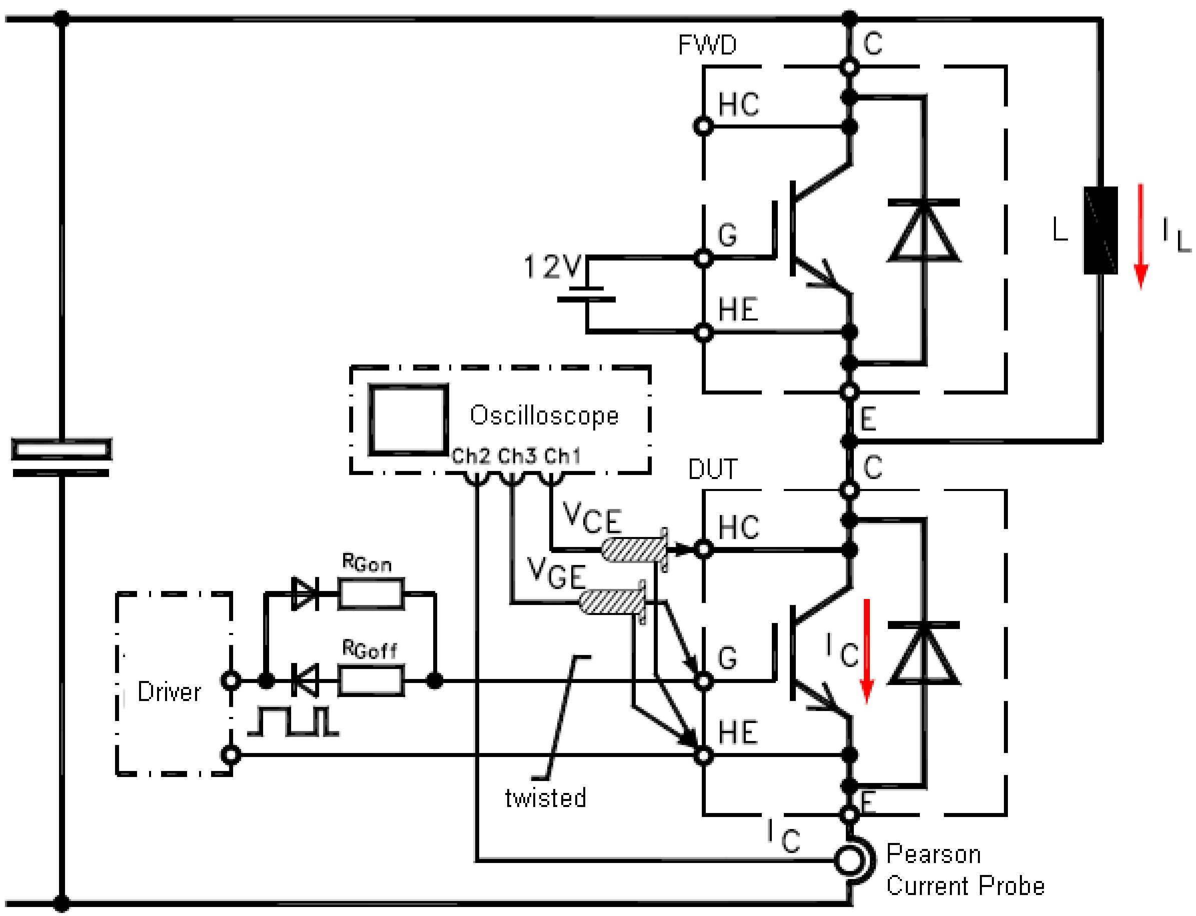
Never stop thinking

IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching

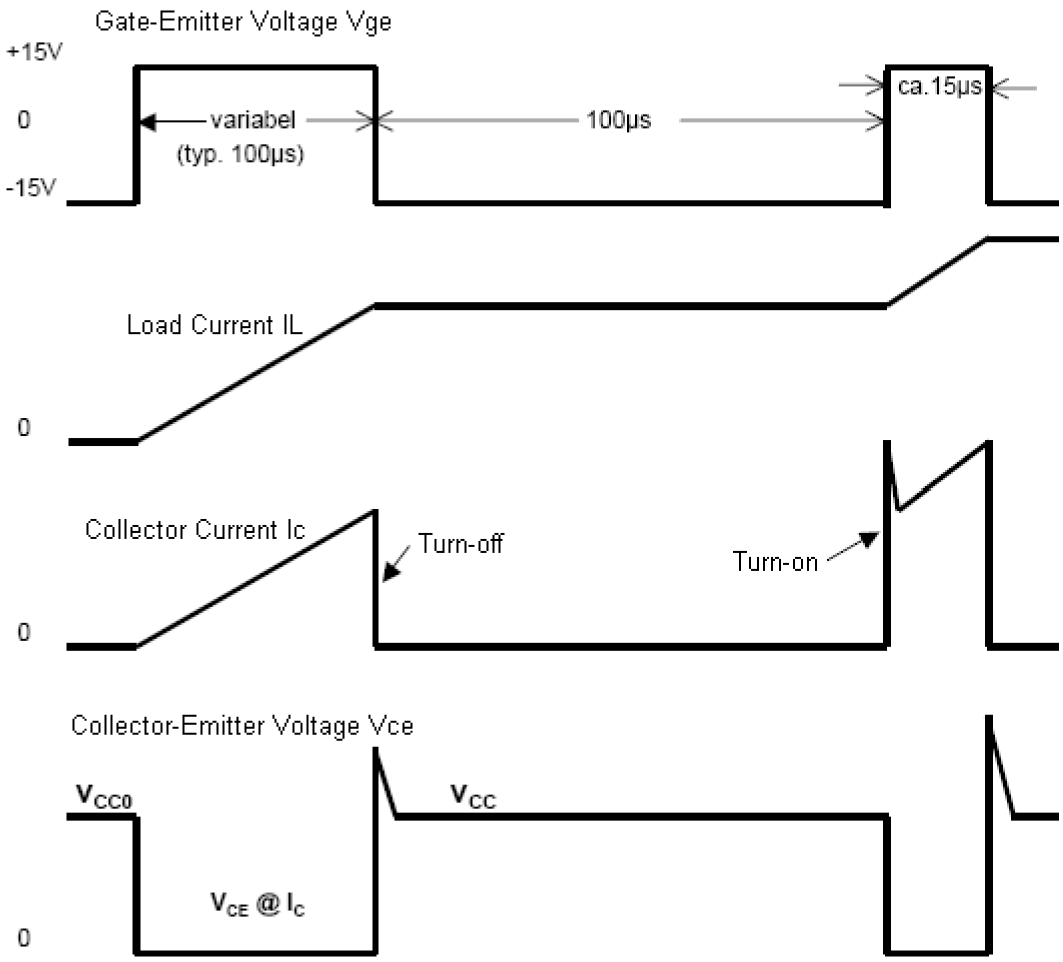
IGBT Measurements
Turn-on & Turn-off

■ Test Setup

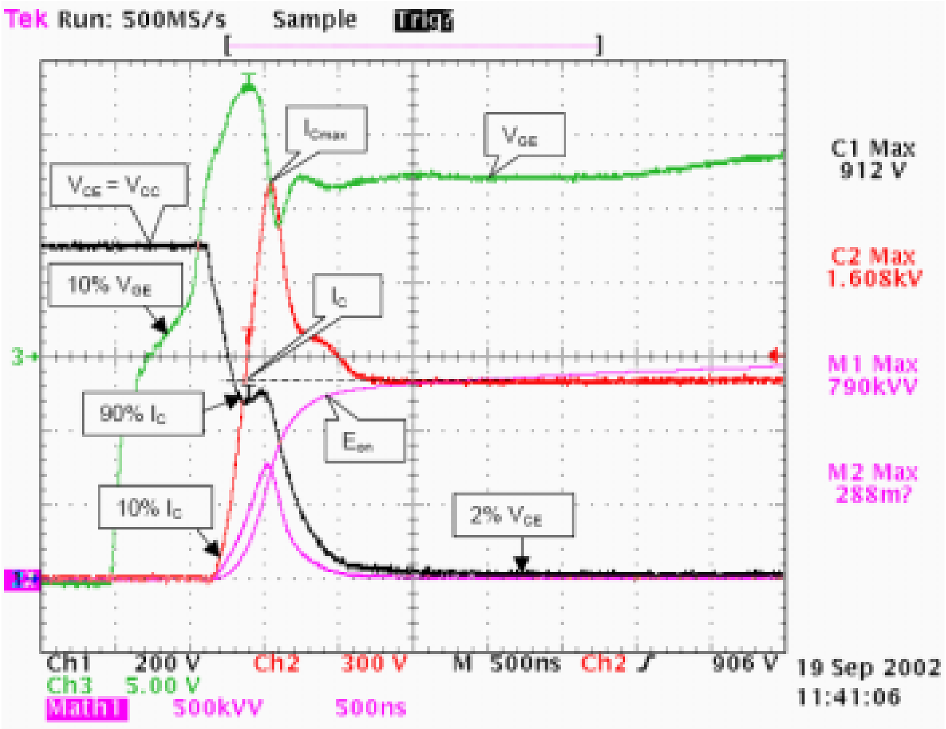


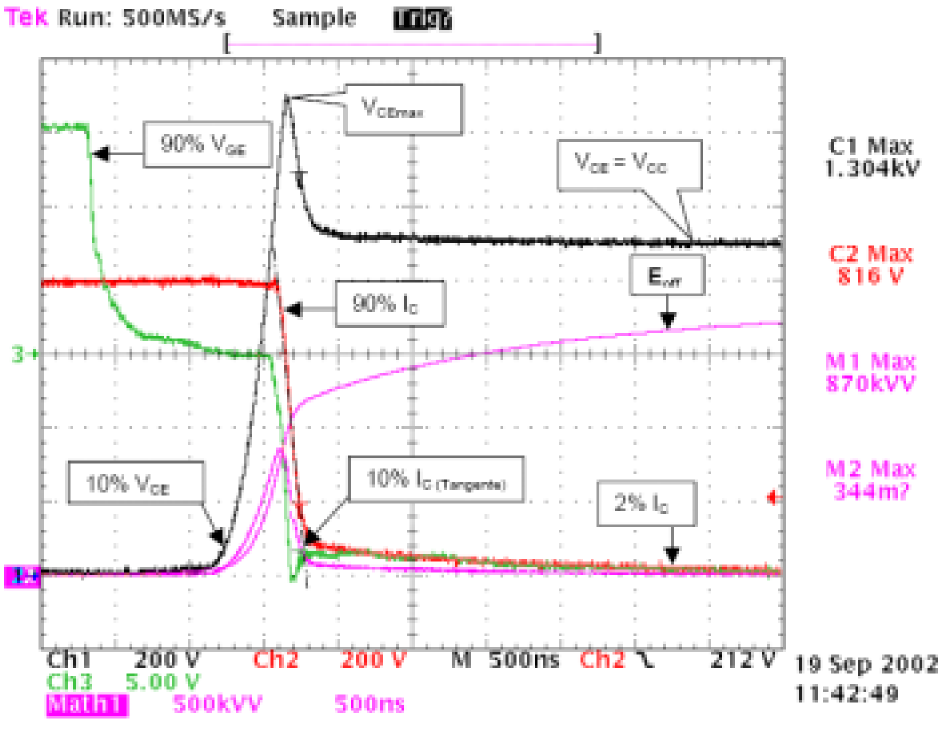
IGBT Measurements
Turn-on & Turn-off

Basic Wave Forms

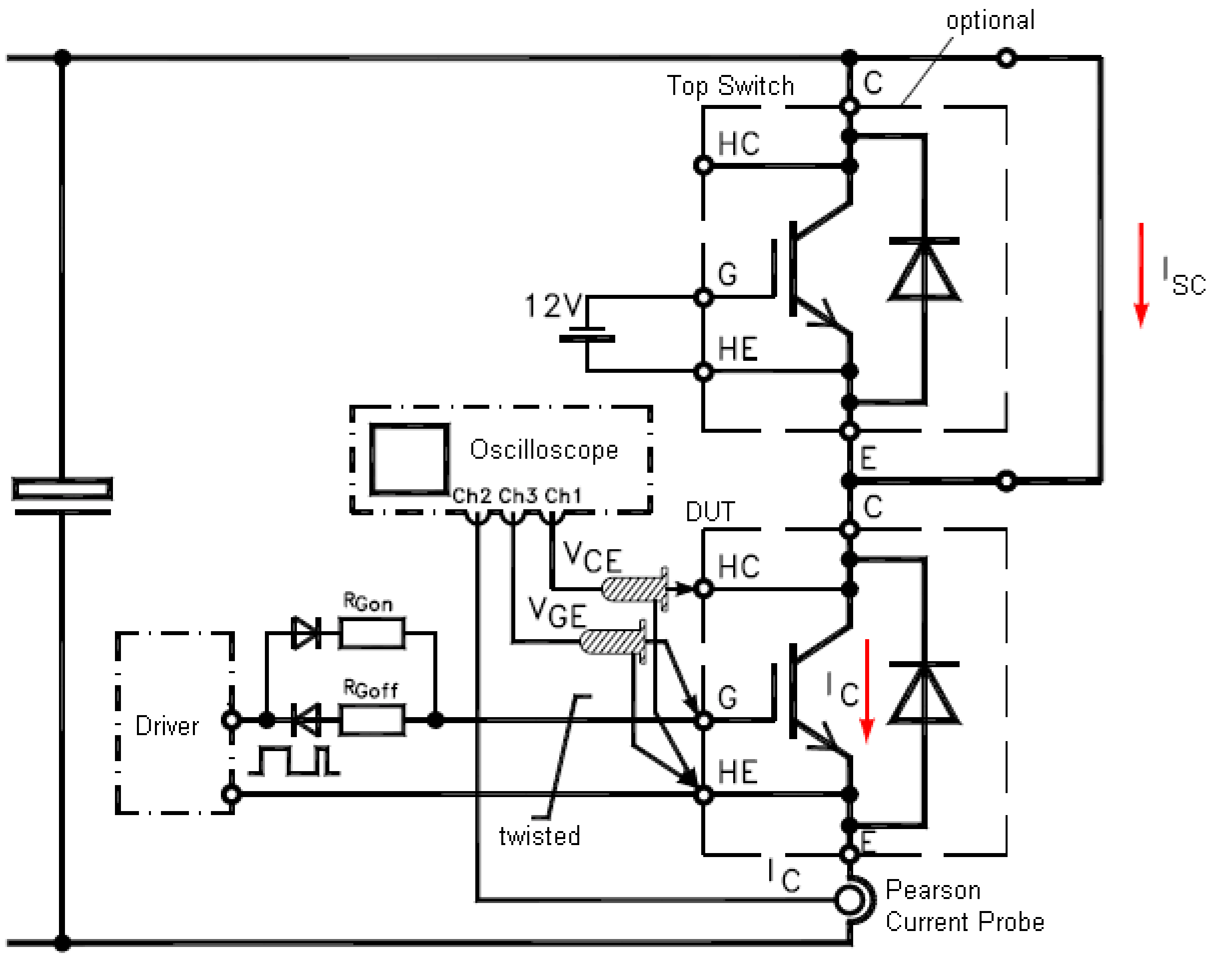


- Sample Wave Forms



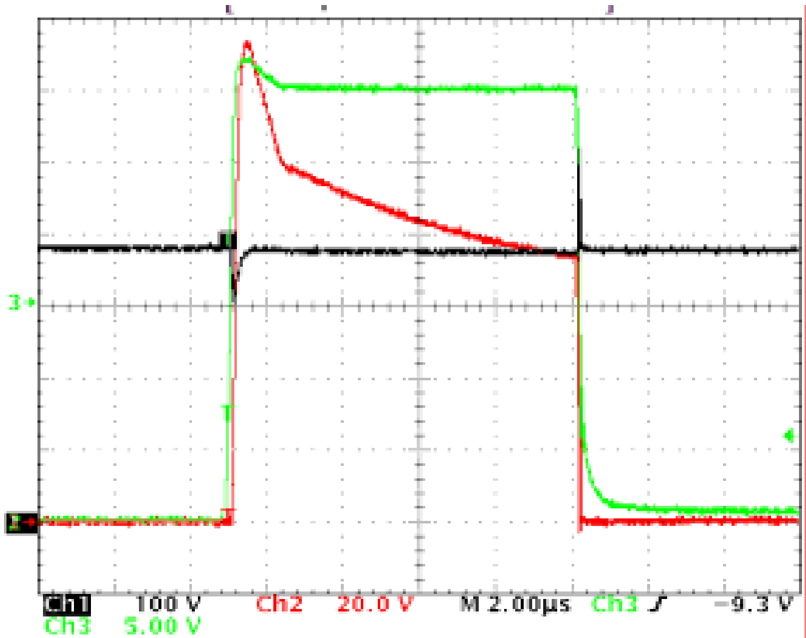


Test Setup


optional
Top Switch
C
HC
G
12V
HE
E
Isc
Oscilloscope
Ch2 Ch3 Ch1
DUT
C
VCE
HC
VGE
RGon
RGoff
Driver
G
IC
HE
twisted
E
IC
Pearson
Current Probe

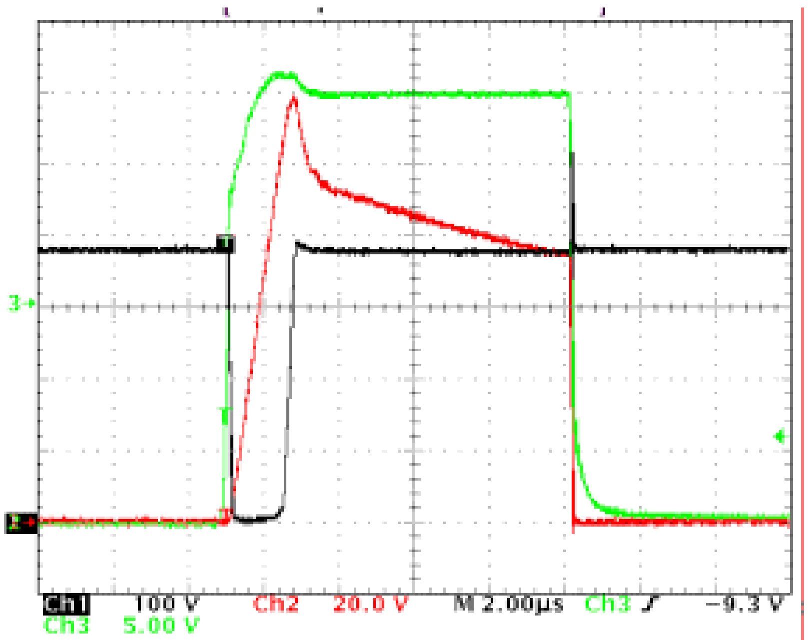
Two Types of Short-circuits

- Before short-circuit occurs, IGBT is OFF & blocks the DC-bus voltage.
- The short-circuit is created by the switch-on of the IGBT.



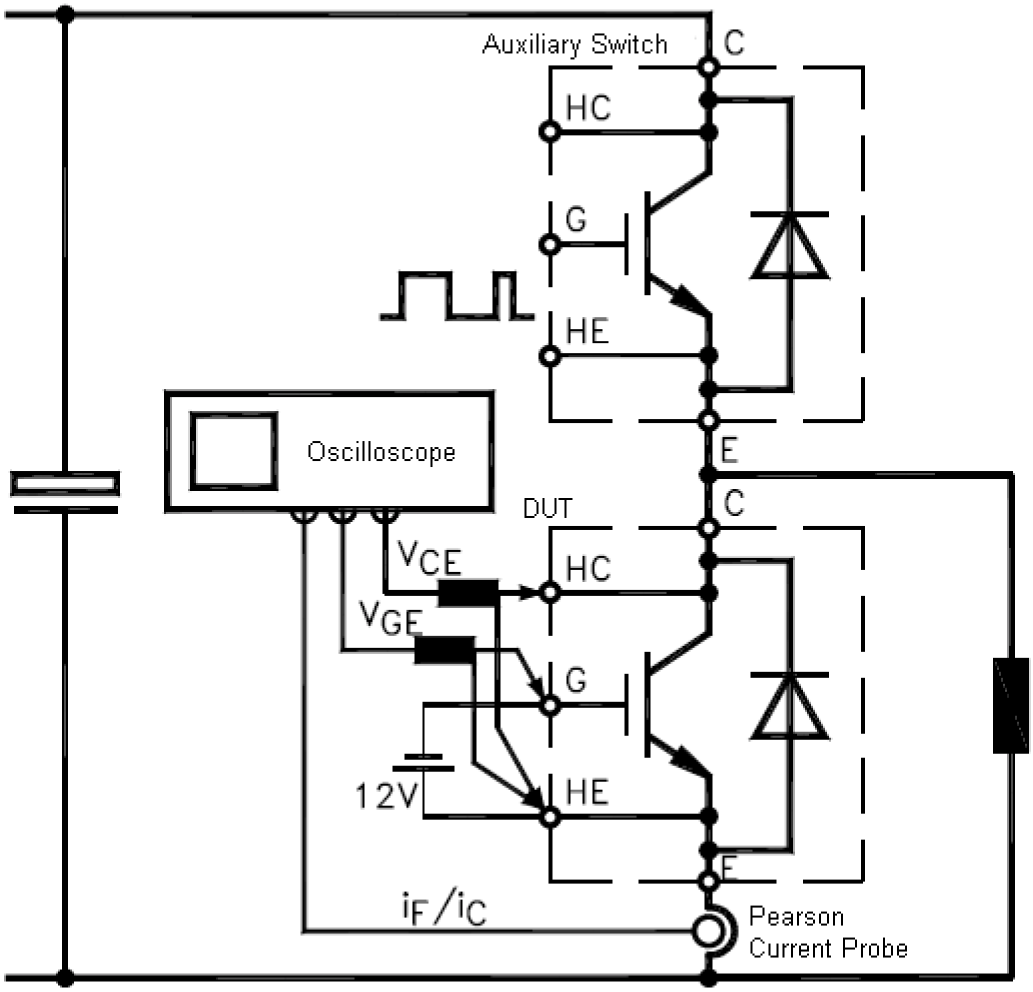
V_{CE} never reaches V_{CEsat} value!

- Before the short-circuit occurs, IGBT is ON & in saturation region.
- The short-circuit is created by applying the DC-bus voltage on C-E of the IGBT.



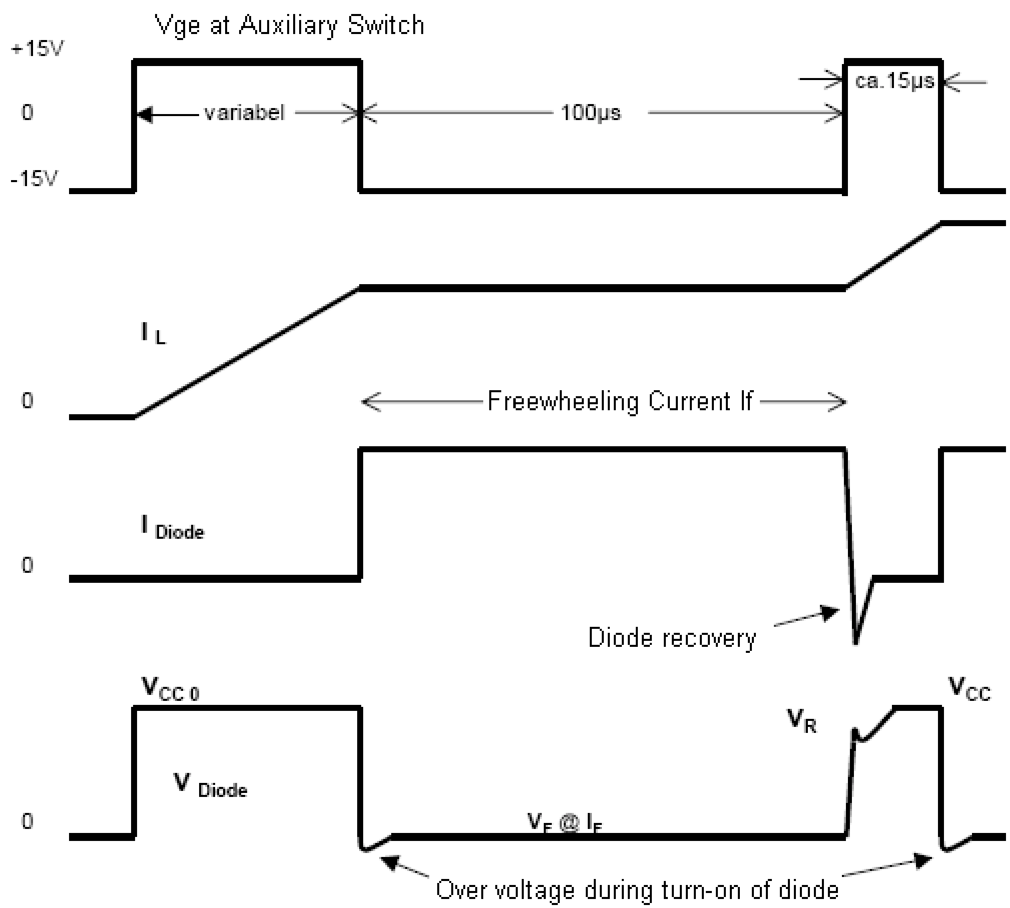
VCE de-saturates from V_{CEsat} value!

- Test Setup


Auxiliary Switch
C
HC
G
HE
E
Oscilloscope
DUT
C
HC
G
HE
E
V_{CE}
V_{GE}
12V
i_F/i_C
Pearson
Current Probe

Diode Measurements
Recovery

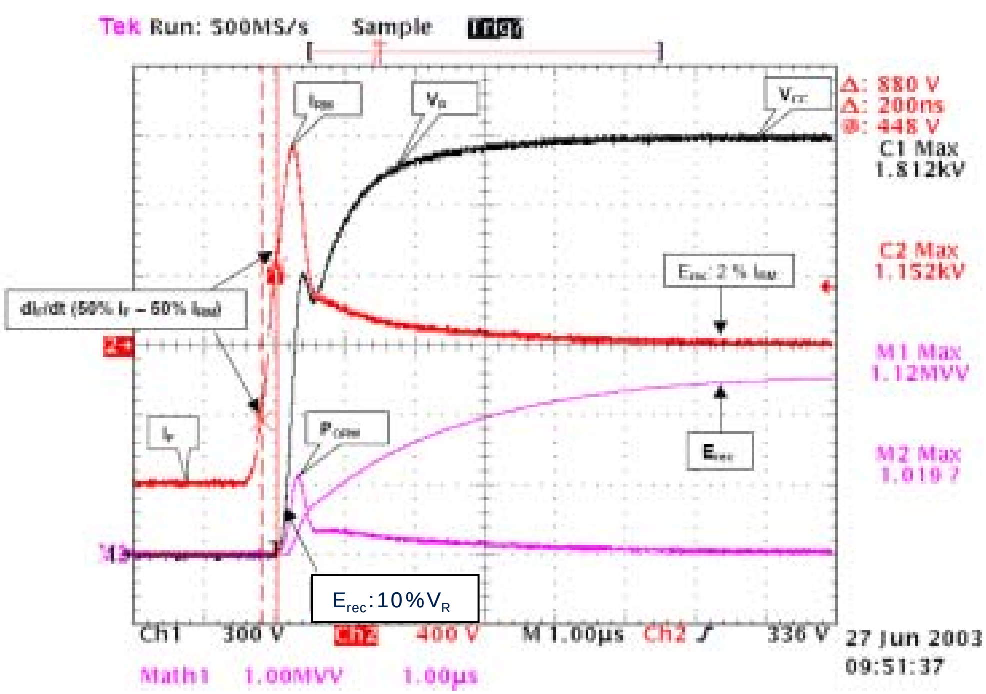
Basic Wave Forms

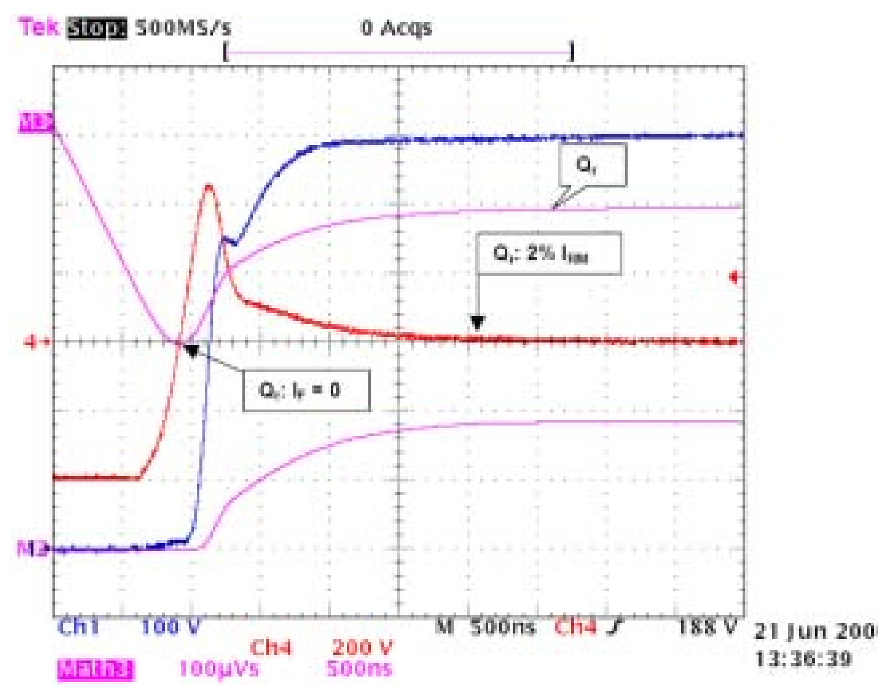


Diode Measurements Recovery

- Sample Wave Form

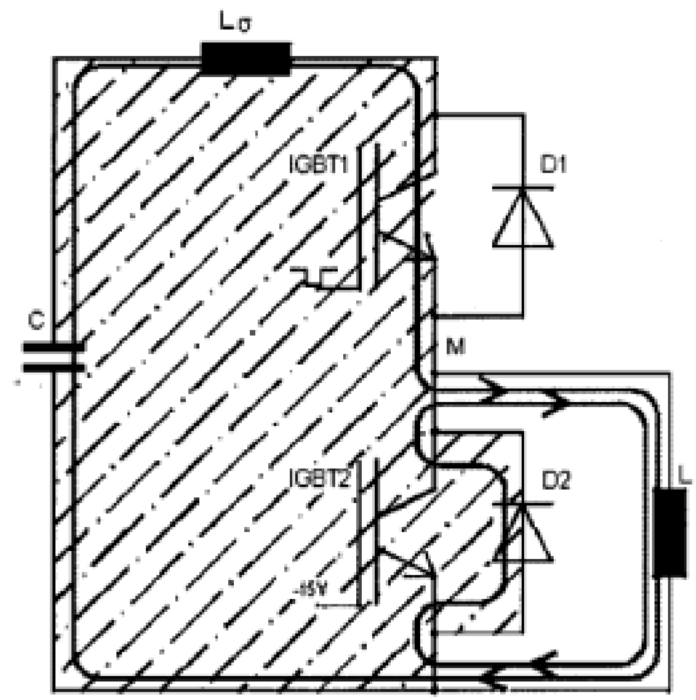
d_{iF}/dt	Erec	Qr
50% I_F-50% I_{RM}	**10% V_R-2% I_{RM}**	**I_F=0-2% I_{RM}**





Double Pulse Test

- **IGBT characterization**
  - Comparable test conditions as datasheet
  - Results close to Infineon datasheet expected.
- **Customer's application setup**
  - Helpful for further design
  - Different test conditions, and different results expected
  - Both IGBT in the (2-level) leg to be tested – different commutation loop & different behavior



IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
  - IGBT RBSOA
  - Diode SOA
  - Short circuit
  - Vge limit
  - Others – Not tested by double pulse test
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching

IGBT Safe Operation – IGBT RBSOA

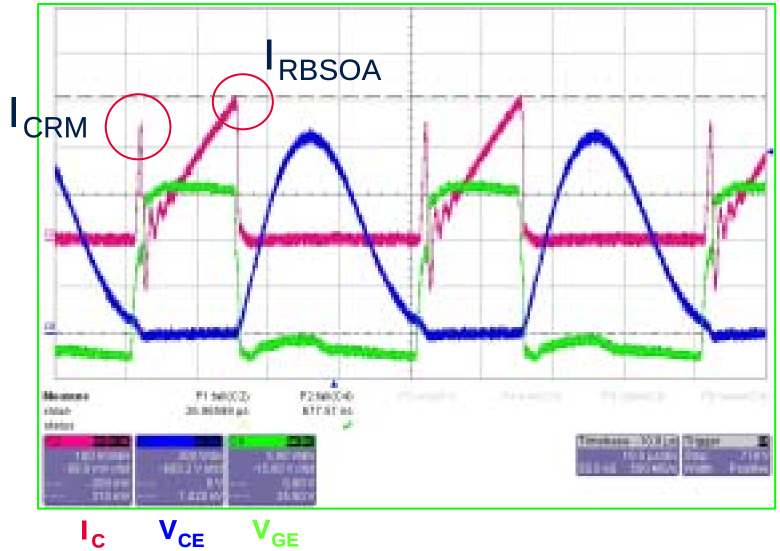
- Pulse current (ICRM IRBSOA)

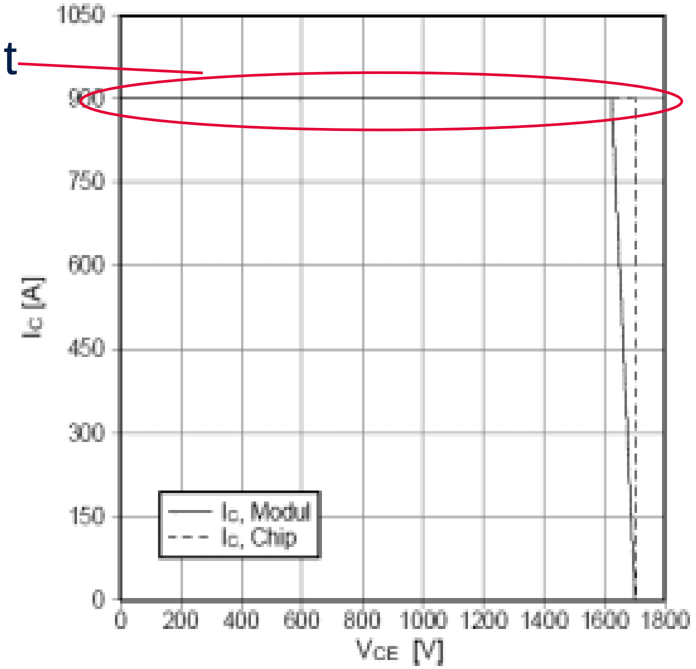
Periodischer Kollektor Spitzenstrom repetitive peak collector current	t_P = 1 ms	I_{CRM}	900	A

I_{CRM} is defined as repetitive turn on pulse current, related to IGBT thermal

I_{CRM} may be exceeded during turn on due to reverse recovery.

I_{RBSOA} is defined as maximum turn off current





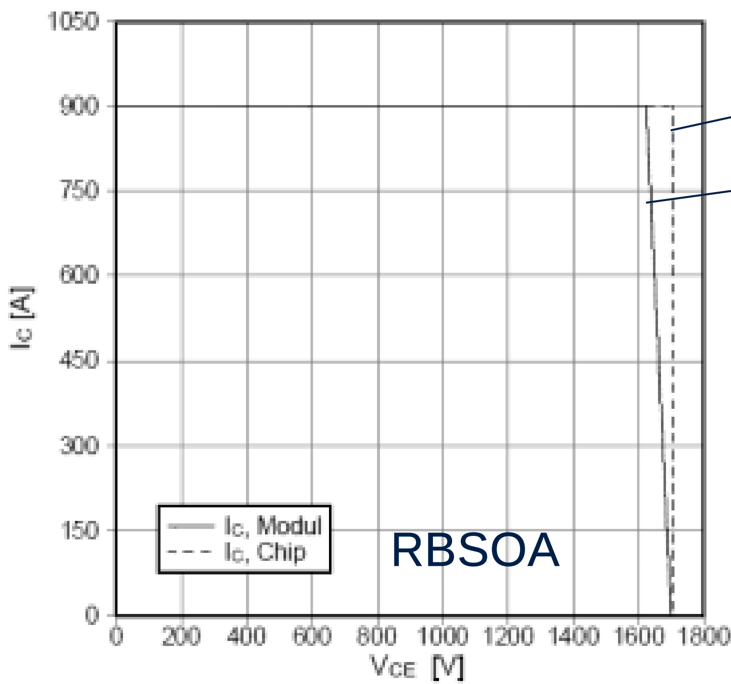
1ms is just test condition, real pulse width is depend on thermal

IGBT Safe Operation – IGBT RBSOA

- Blocking voltage (VCES)

Kollektor-Emitter-Sperrspannung collector-emitter voltage	$T_{vj} = 25°C$	V_{CES}	1700	V

V_{CES} specified at T_j=25℃. Higher T_j, higher blocking voltage



Chip level

Module level

Due to stray inductance inside module

$$\Delta V = di/dt * L_{\delta}$$

V_{CES} is easiest to be exceed during turn off, due to external and internal stray inductance

V_{CES} can not be violated at any condition, otherwise IGBT would break though

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IGBT Safe Operation – Diode SOA

- Blocking voltage (VRRM)

Periodische Spitzensperrspannung repetitive peak reverse voltage	T_{vj} = 25°C	V_{RRM}	1700	V

Similar definition of V_{CES} at T_j 25℃

- Pulse current (ICRM)

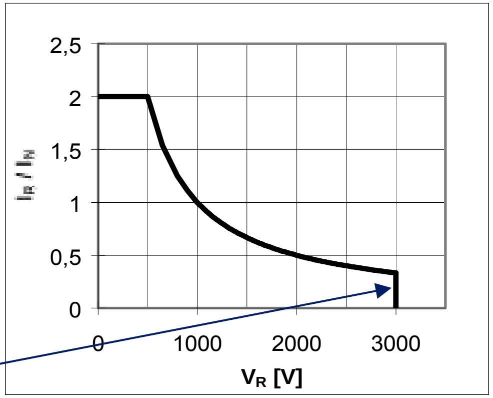
Periodischer Spitzenstrom repetitive peak forward current	t_P = 1 ms	I_{FRM}	900	A

Similar definition of I_{CRM}, two time of I_F.

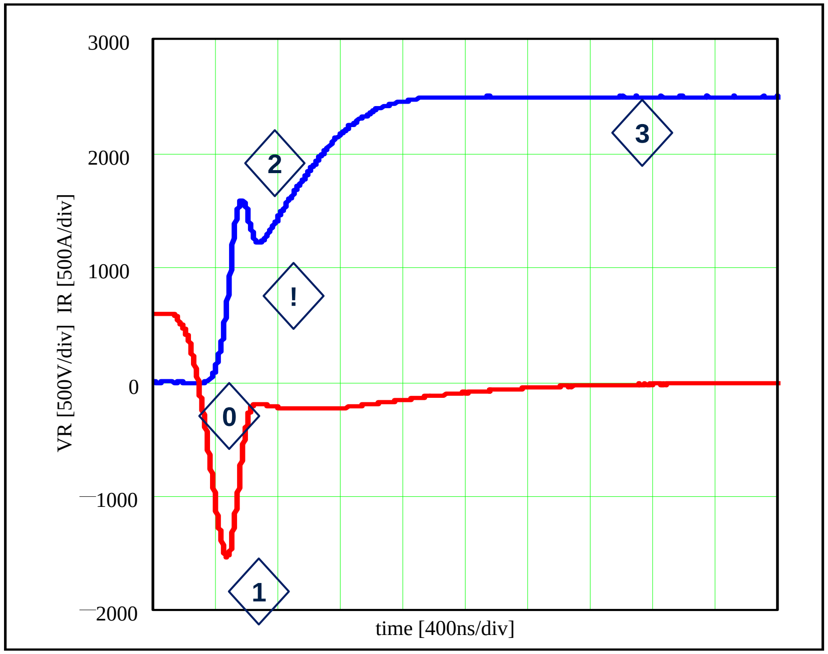
IGBT Safe Operation – Diode SOA

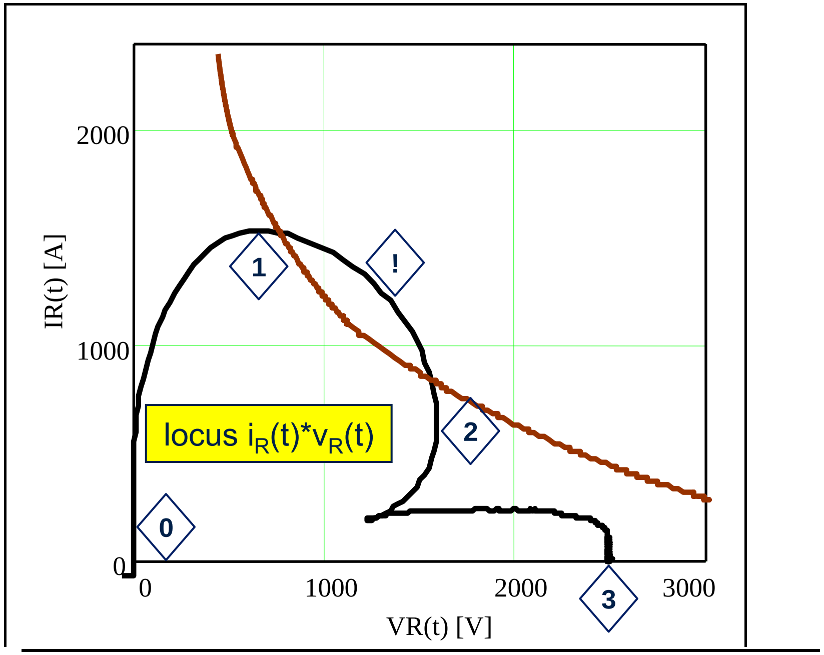
Diode SOA

High voltage module specify the SOA of diode. Not only peak current and voltage is limited, peak power also is restricted.
The instantaneous peak power should never exceed the limit for the max. power given in the SOA diagram.



More severe with small current at low temperature due to snap off and oscillation





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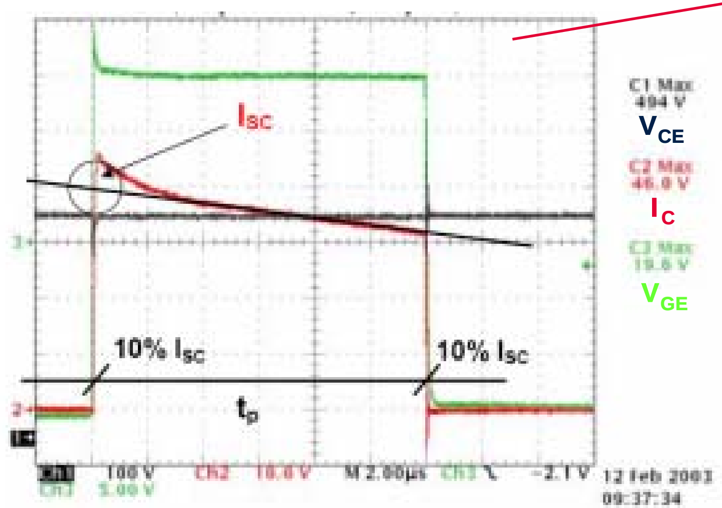
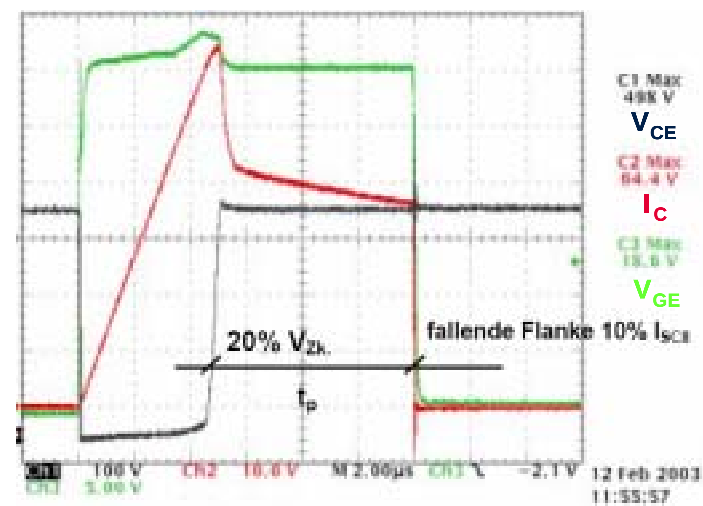
IGBT Safe Operation – short circuit

Short circuit current (ISC)

Kurzschlussverhalten SC data	$V_{GE} \le 15$ V, $V_{CC} = 1000$ V $V_{CEmax} = V_{CES} - L_{sCE} \cdot di/dt$ $t_P \le 10$ µs, $T_{vj} = 125$°C	I_{SC}		1800		A



SC1: Short before Switch On

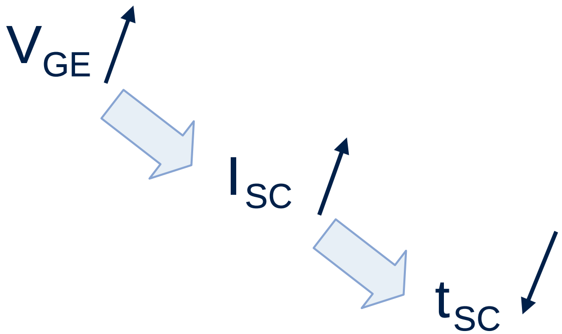


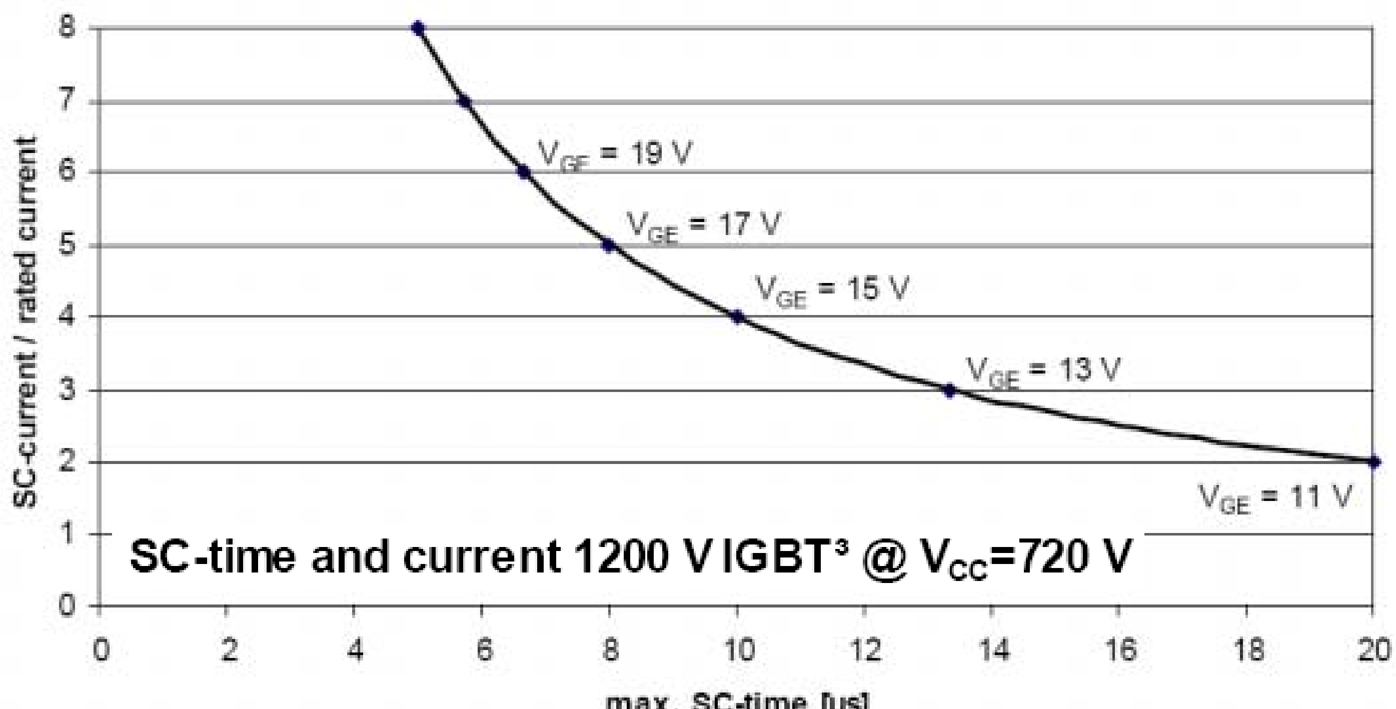
SC2: Short after Switch On

The short circuit current value is a typical value. In applications, SC1 and SC2 can only be safely turned off when desaturated, the short circuit time should not exceed 10us.

IGBT Safe Operation – short circuit

- Short circuit condition:
  - VGE: gate voltage (15V)
  - VCC: DC bus voltage
  - Tvj: short circuit start temperature





It is important to clamp gate voltage during short circuit

IGBT Double Pulse Test

- Basic principle of double pulse test
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  - IGBT RBSOA
  - Diode SOA
  - Short circuit
  - Vge limit
  - Others – Not tested by double pulse test
- What can be done with double pulse test
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IGBT Safe Operation – Vge limit

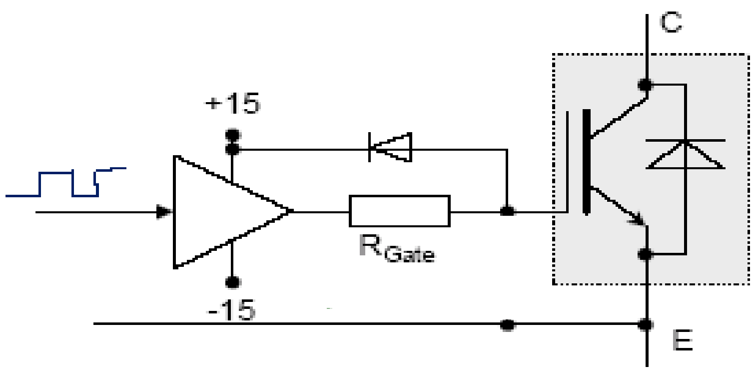
Gate-emitter voltage (Vge)

Gate-Emitter-Spitzenspannung gate-emitter peak voltage		V_{GES}	+/-20	V

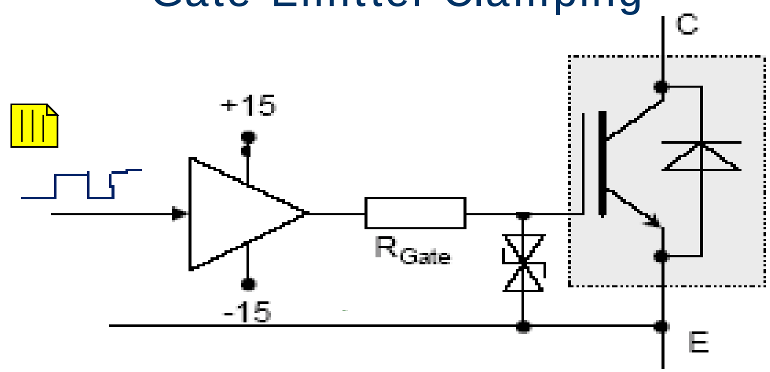
Gate Clamping:

- Limitation of increase of gate voltage due to positive feedback over C_{GC}
- An issue with long durations regarding gate oxide break down
- Limitation of short circuit currents

Methode 1
Gate-Supply Clamping



Methode 2
Gate-Emitter Clamping



IGBT Double Pulse Test

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  - Short circuit
  - Vge limit
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IGBT Safe Operation – Others, not tested by two-pulse test

Höchstzulässige Sperrschichttemperatur maximum junction temperature	Wechselrichter, Brems-Chopper / Inverter, Brake-Chopper	$T_{vj\ max}$			175	°C
Temperatur im Schaltbetrieb temperature under switching conditions	Wechselrichter, Brems-Chopper / Inverter, Brake-Chopper	$T_{vj\ op}$	-40		150	°C

- Maximum junction temperature
  - IGBT & Diode loss estimation
  - Thermal impedance
- Reliability
  - DC stability

Kollektor-Emitter-Gleichsperrspannung DC stability	T_{vj} = 25°C, 100 fit	$V_{CE\ D}$	2100	V

  - Thermal cycling & power cycling
- Min switching time

Mindesteinschaltdauer minimum turn-on time		$t_{Fon\ min}$	10,0	µs

- … …

IGBT Double Pulse Test

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- What can be done with double pulse test
  - Check switching waveforms – oscillation?
  - Measurement of loss, switching time, stray inductance
  - Verify IGBT RBSOA, diode SOA
  - Verify short-circuit protection
  - IGBT Paralleling
  - Optimize Driver design
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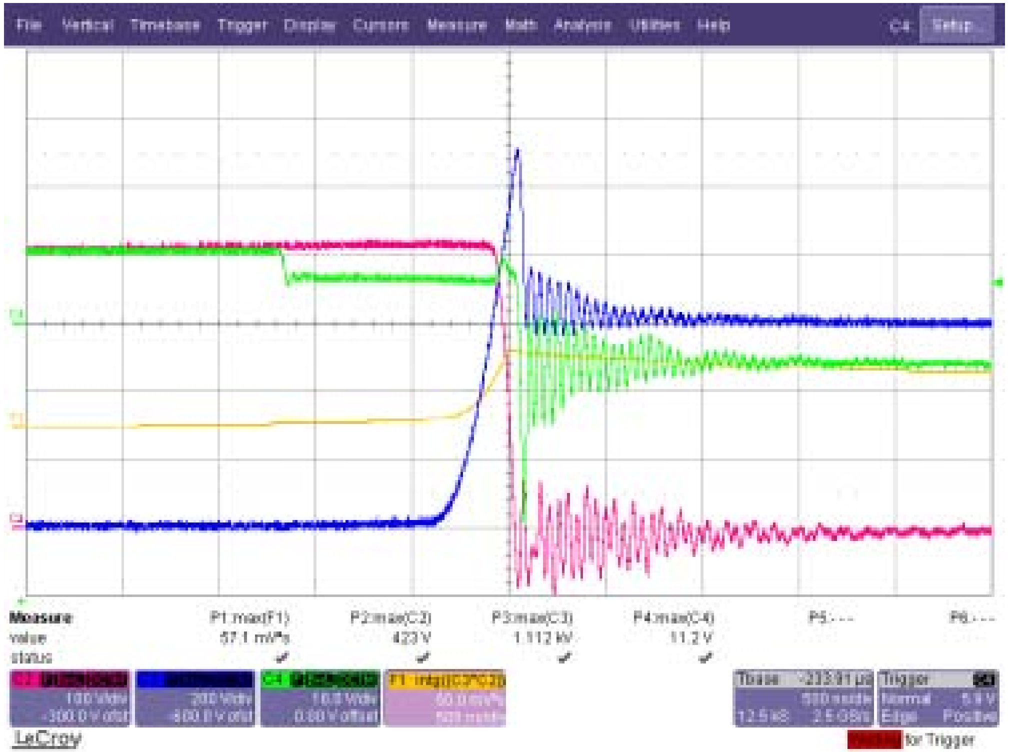
Double pulse test – waveforms



Both too small Rg and too large Rg can lead to oscillations.

IGBT Double Pulse Test

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- **What can be done with double pulse test**
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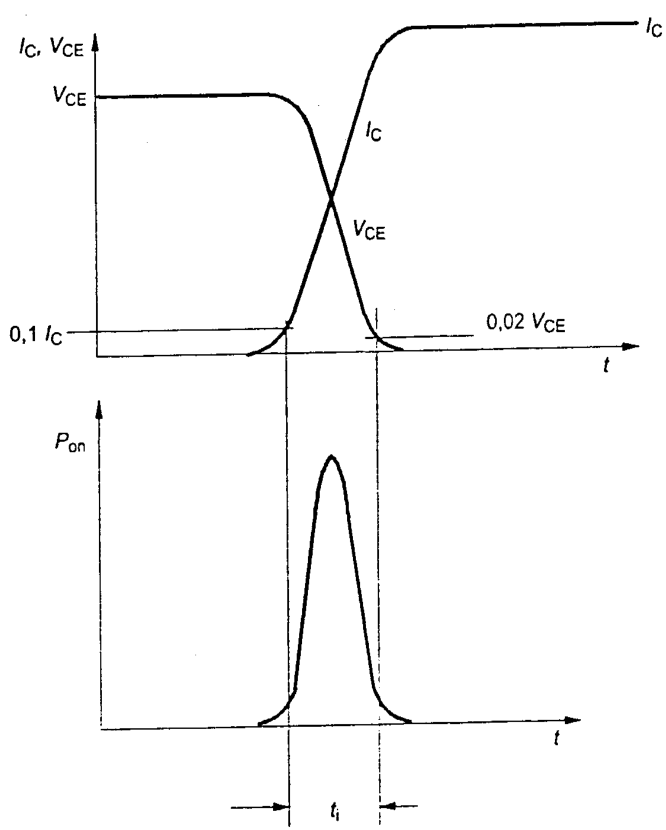
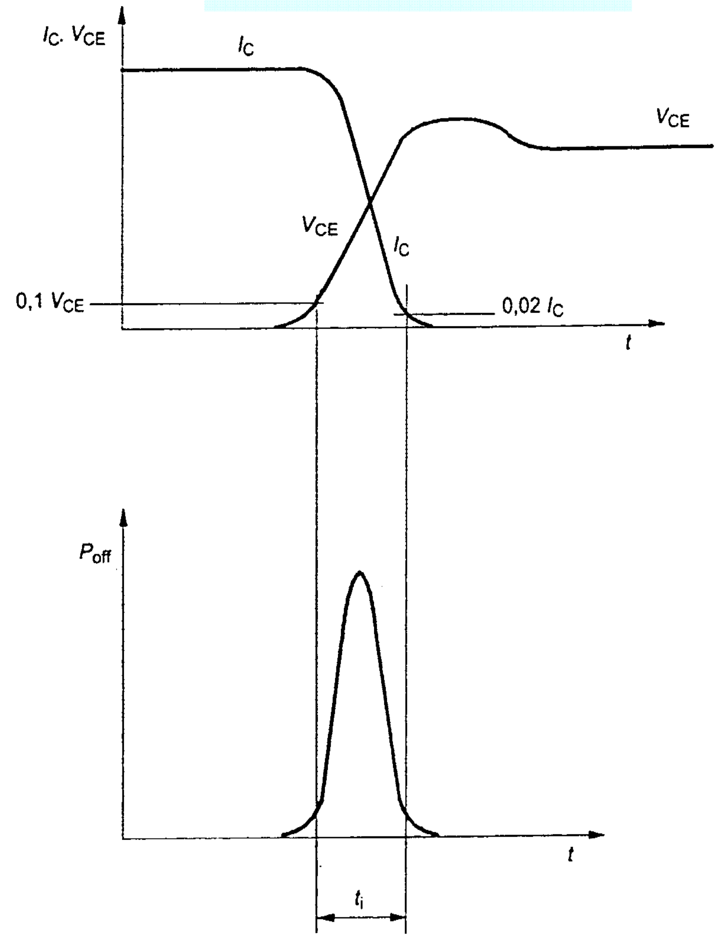
Definition of Eon and Eoff_IEC60747-9

Eon definition



10 % Ic to 2 % Vce

Eoff definition



10 % Vce to 2 % Ic

Definition of Eon and Eoff

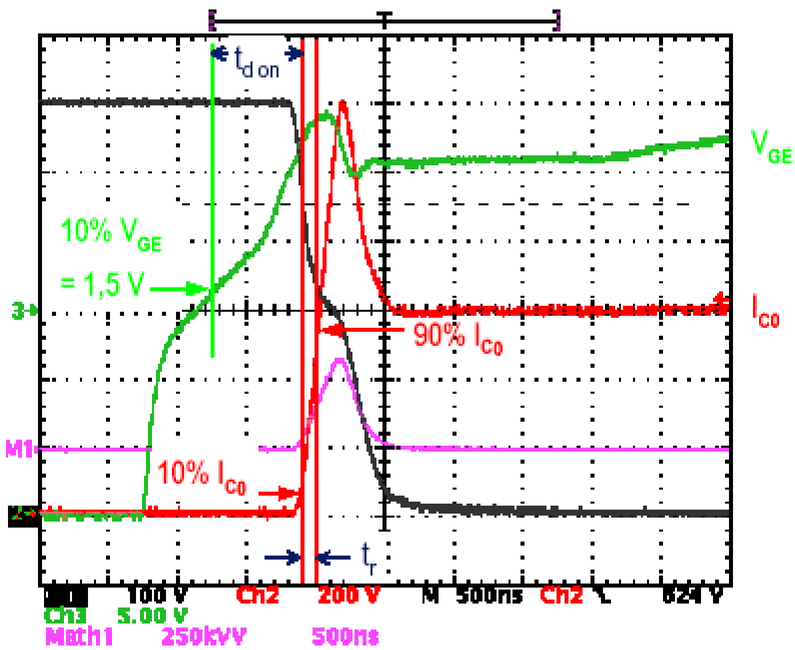
	Eon	Eoff	Notes
IEC60747-9	10%Ic-2%Vce	10%Vce-2%Ic	
IEC60747-9 Ed2 2005-06-10	10% Vge-2%Vce	90%Vge-2%Ic	
Infineon Module	10%Ic-2%Vce	10%Vce-2%Ic	
Infineon Discrete	10%Vge-3%Vce	90%Vge-1%Ic	Incl. 0-10% Ic at full Vce
IR Discrete	10%Ic-5%Vce	10%Vce-5%Ic	
Fairchild Discrete	10%Vge-0%Vce	90%Vge-0%Ic	
Tyco Module	10%Vge-3%Vce	90%Vge-1%Ic	

- IGBT module datasheets give two/three E_{on} & E_{off} values at T_j = 25°C & T_j = 125°C/150°C, respectively, all for $I_{C,nom}$ & around ½ V_{ces}, V_{GE} = ±15V.
- E_{on} & E_{off}, especially E_{on} increases with increase of R_G
- E_{on} & E_{off} increase with the rising of T_j

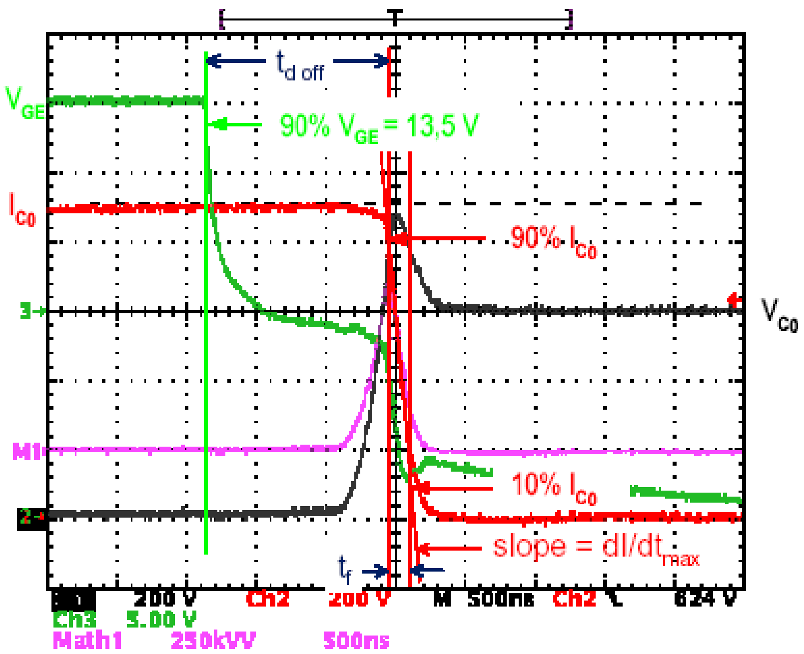
Definition of t_{don}, t_r, t_{doff} and t_f

t_{don}	t_r	t_{doff}	t_f
10% Vge-10%Ic	**10%Ic-90%Ic**	**90%Vge-90%Ic**	**90%Ic-10%Ic**

IGBT Turn on

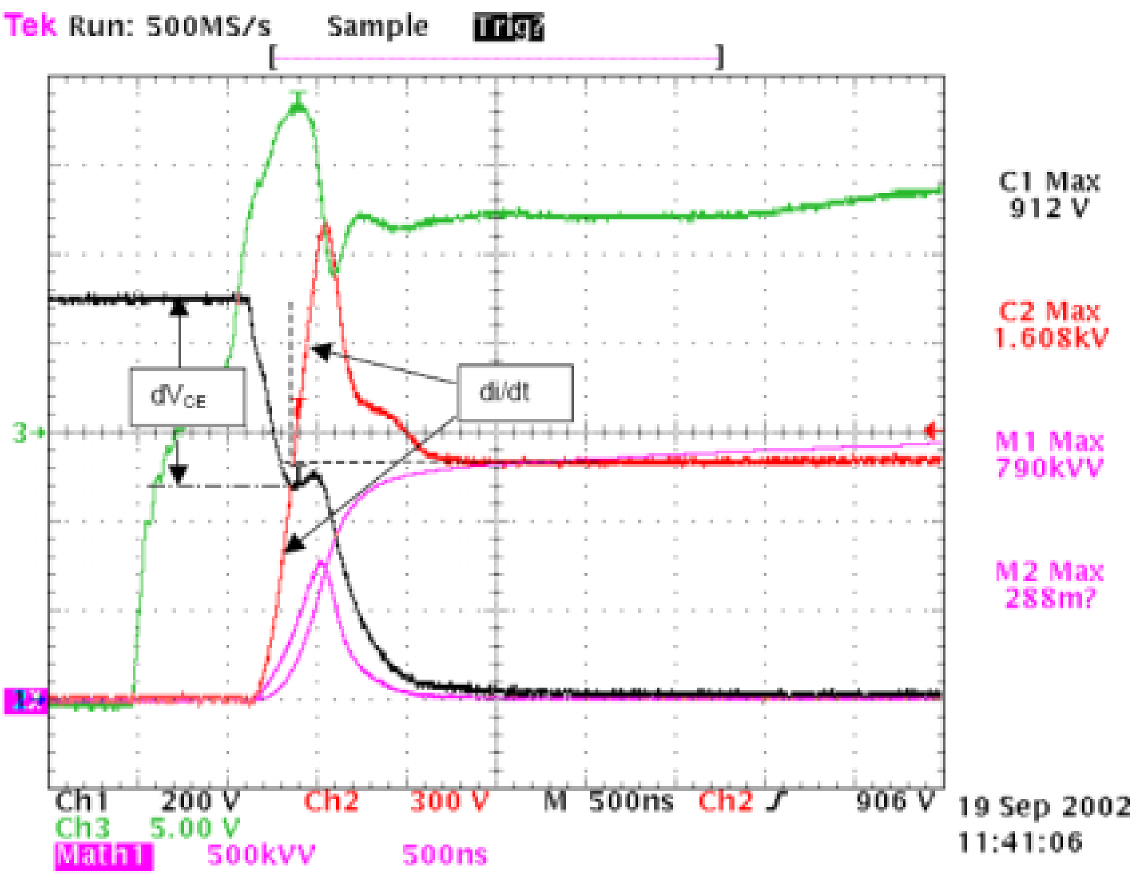


IGBT Turn off



Stray Inductance
System Stray Inductance

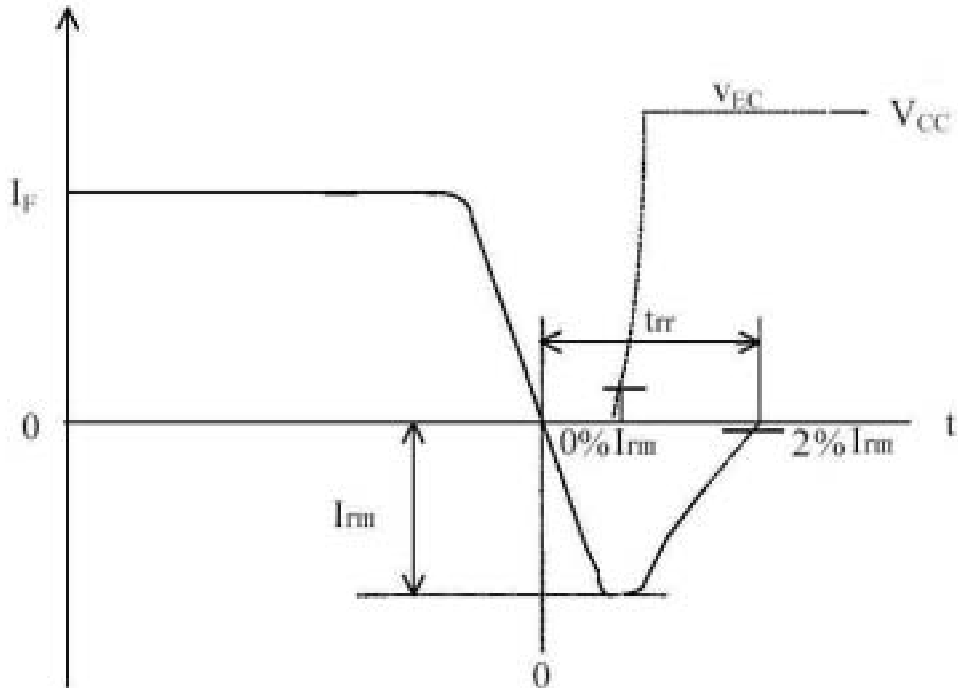
- Sample Wave Form



$$L_\sigma = dV_{CE} \cdot \frac{dt}{di}$$

Note: connect to power terminal when measuring external busbar stray inductance.

Diode switching measurement



$$E_{rec} = -\int_{V_{EC}=0.1\cdot V_{CC}}^{I_F=0.02\cdot I_{rm}} V_{EC}(t)\cdot I_F(t)\,dt$$

$$Q_{rr} = -\int_{I_F=0.02\cdot I_{rm}}^{I_F=0\cdot I_{rm}} I_F(t)\,dt$$

$$t_{rr} = t\,(I_C = 0.02\ I_{rm}) - t\,(I_C = 0\ I_{rm})$$

- IGBT module datasheets give two/three Erec values under Tj = 25°C & Tj = 125°C/150°C, all under IF,nom & ½ VCES, VGE = -15V
- Erec decreases with the increase of RG
- Erec increases with the rising of Tj

Dead Time Estimation

$$t_{DT} = [\underbrace{(t_{doff}(max) + t_f(max) - t_{don}(min))}_{\text{IGBT}} + \underbrace{(t_{PHLmax} - t_{PLHmin})}_{\text{Driver}}]*\underbrace{1.2}_{\text{Margin}}$$

- T_j, I_c, and R_g has small impact on T_{don}
  - Min T_{don} typically at small I_c, small R_g
- T_j, I_c, R_g, and V_{ge} has significant impact on T_{doff}
  - Max T_{doff} at: small current I_c

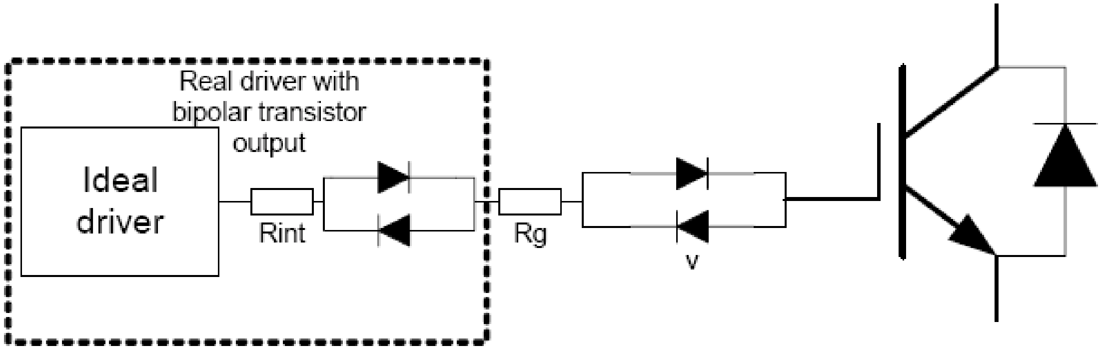
    High temperature T_j

    Variation of V_{th} should be considered

    Big R_g

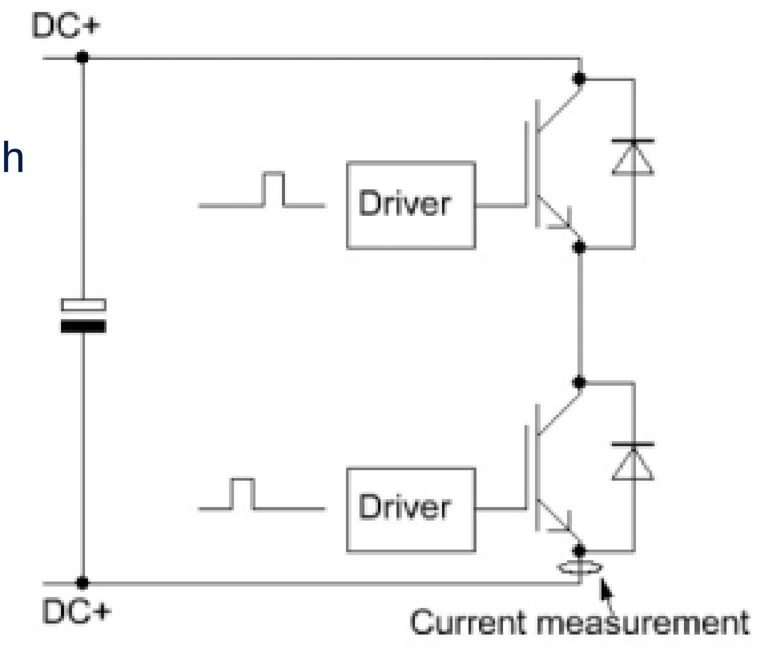
    Unipolar V_{ge}
- T_f can be neglected because it is typically very small
- Propagation delay time of driver must be considered to calculate t_{DT}

Dead Time Estimation



Block diagram of test to simulate variation of vth and driver with bipolar output

Varification of Dead Time, both high temperature and low temperature should be tested



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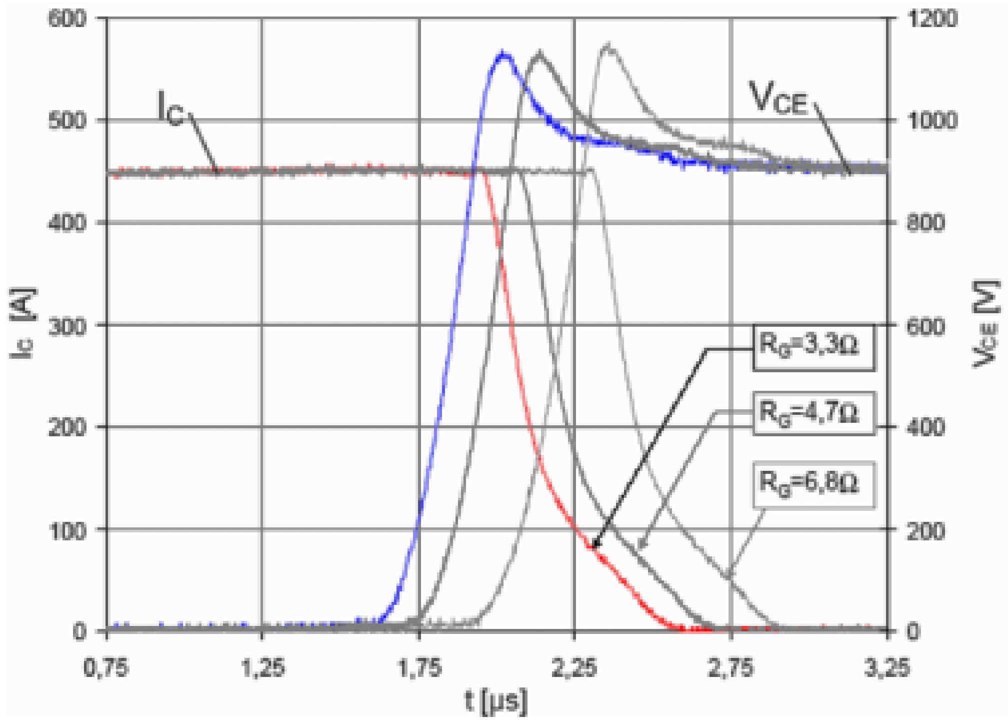
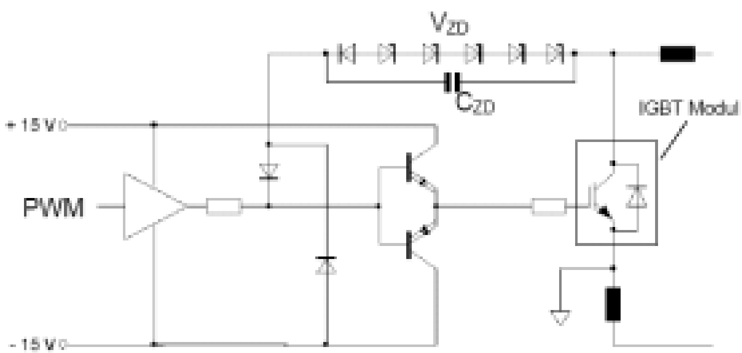
Verify IGBT RBSOA

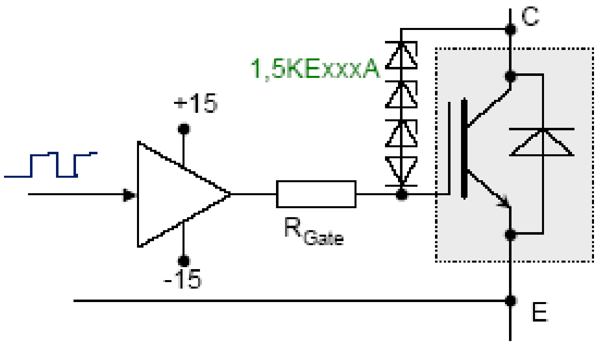


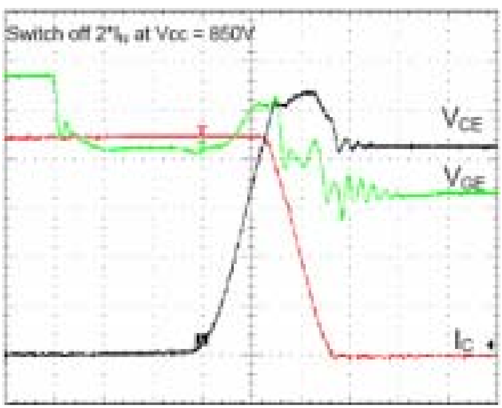
- For 3rd and 4th IGBT, Rgoff has little impact on Eoff, dv/dt, and di/dt
- $^{di}/_{dt}$ is only controllable if the gate voltage doesn't drop below the Miller Plateau level before I_C starts to decrease
- dv/dt and di/dt are controllable by the gate resistor when Rgoff is very large
- A larger resistor will result in a smaller dv/dt and di/dt

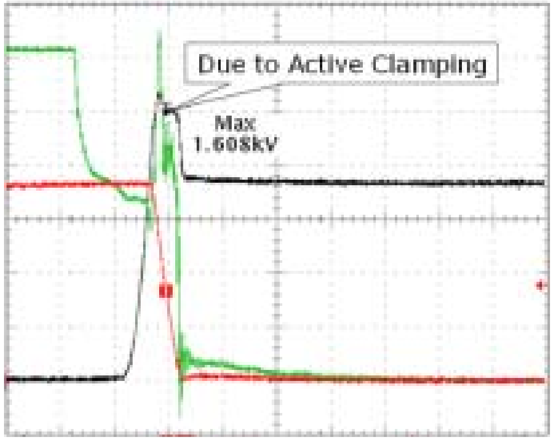
Verify IGBT RBSOA

- In no case shall over voltages exceed the maximum breakdown voltage of the IGBT
- To control the IGBT it is necessary that the gate voltage hasn't dropped below the Miller Plateau level



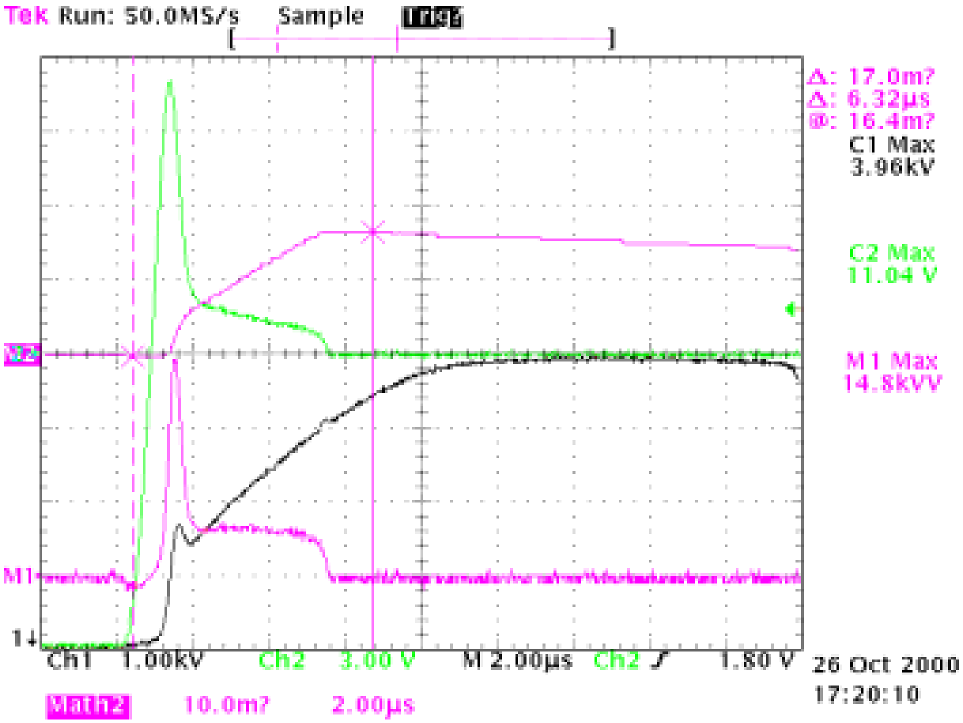


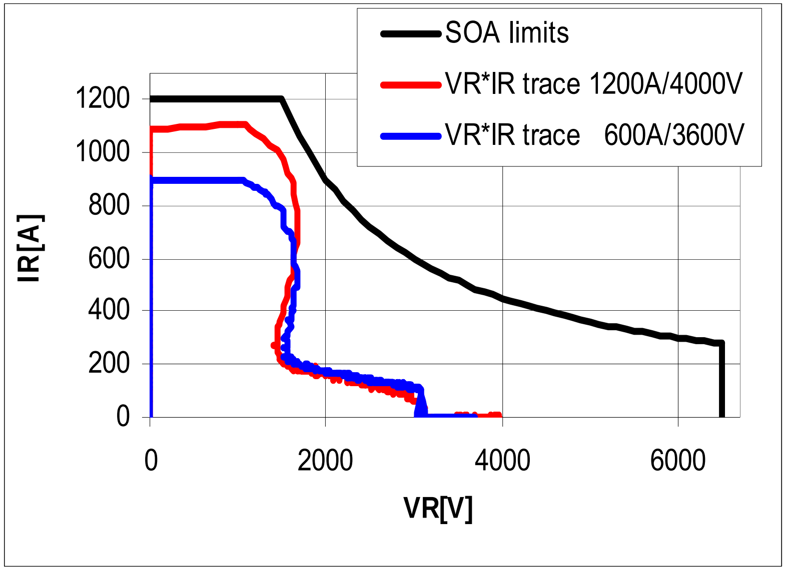




Verify Diode SOA

example: 600A / 6500V module



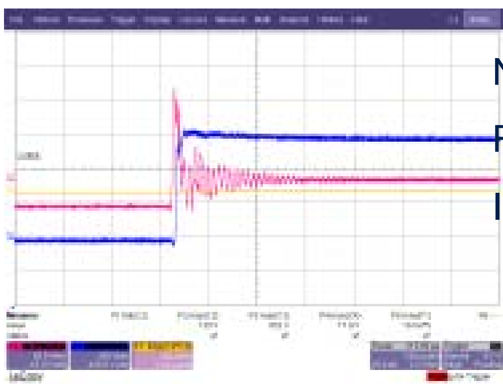


measured: $i_R(t)$ and $v_R(t)$

calculated: $p_{peak}(t) = i_R(t) \cdot v_R(t)$

Verify Diode SOA

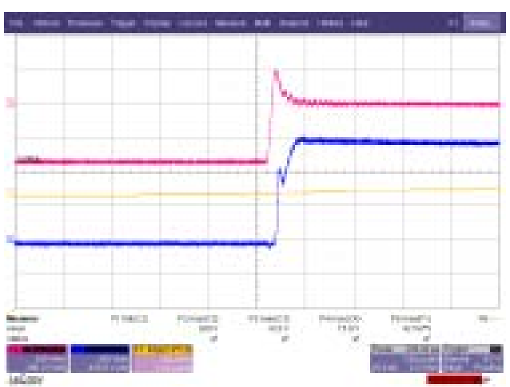
- Erec, Irr, dv/dt, and di/dt will be decreased with increasing Rg
- Erec, Irr, dv/dt, and di/dt will be decreased with increasing Cg
- Higher Tj lead to decreased dv/dt and di/dt
- Diode tends to snap off with small current



No Cge, t/div=1us

Ron=Roff=1.8 Ω

Ic= $^{1}/_{10}$ Inom



No Cge, t/div=1us

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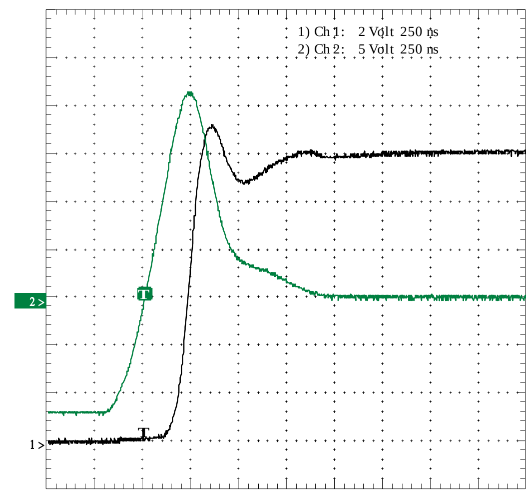
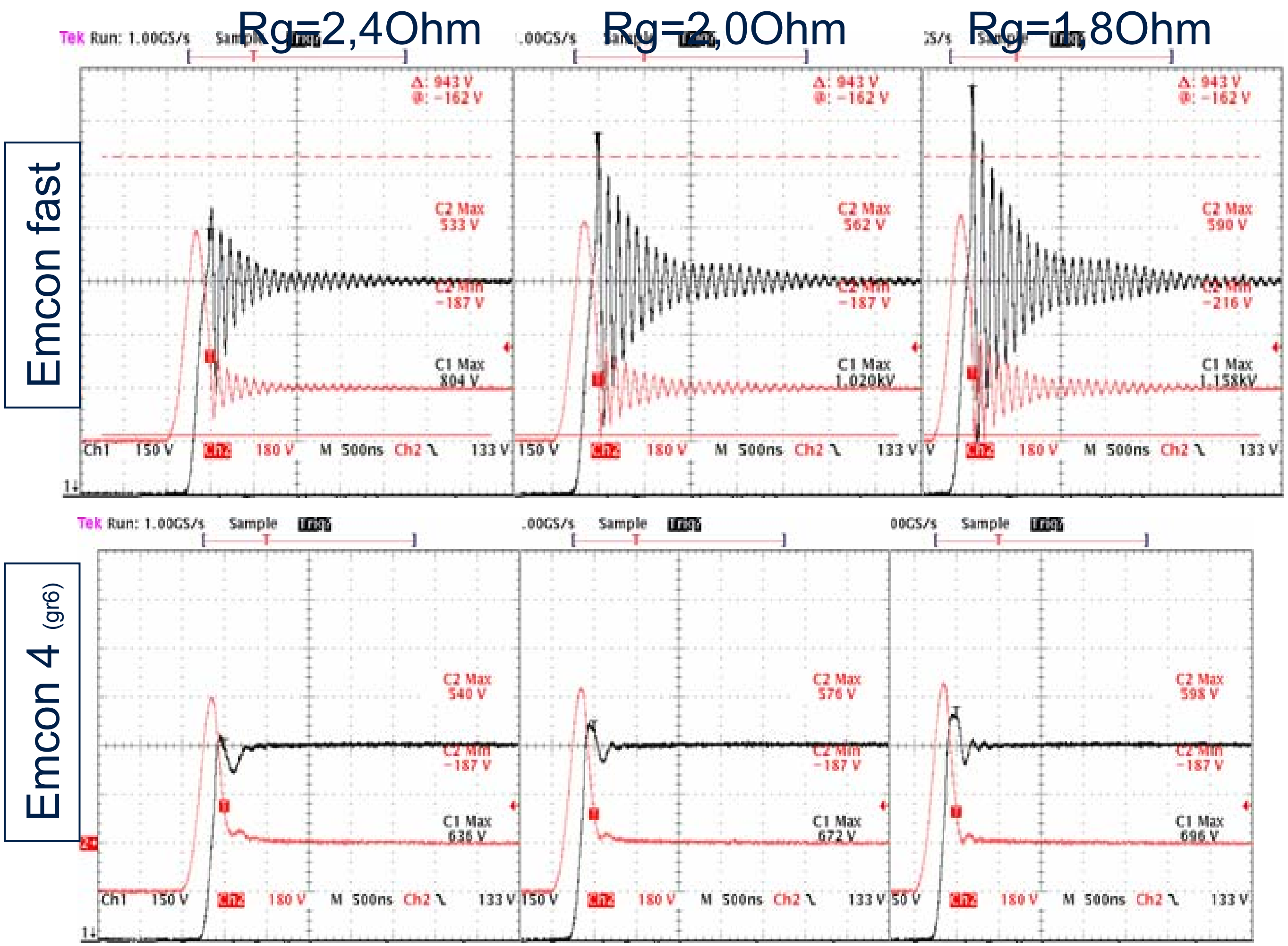


Soft recovery behavior

Verify Diode SOA – diode snap off

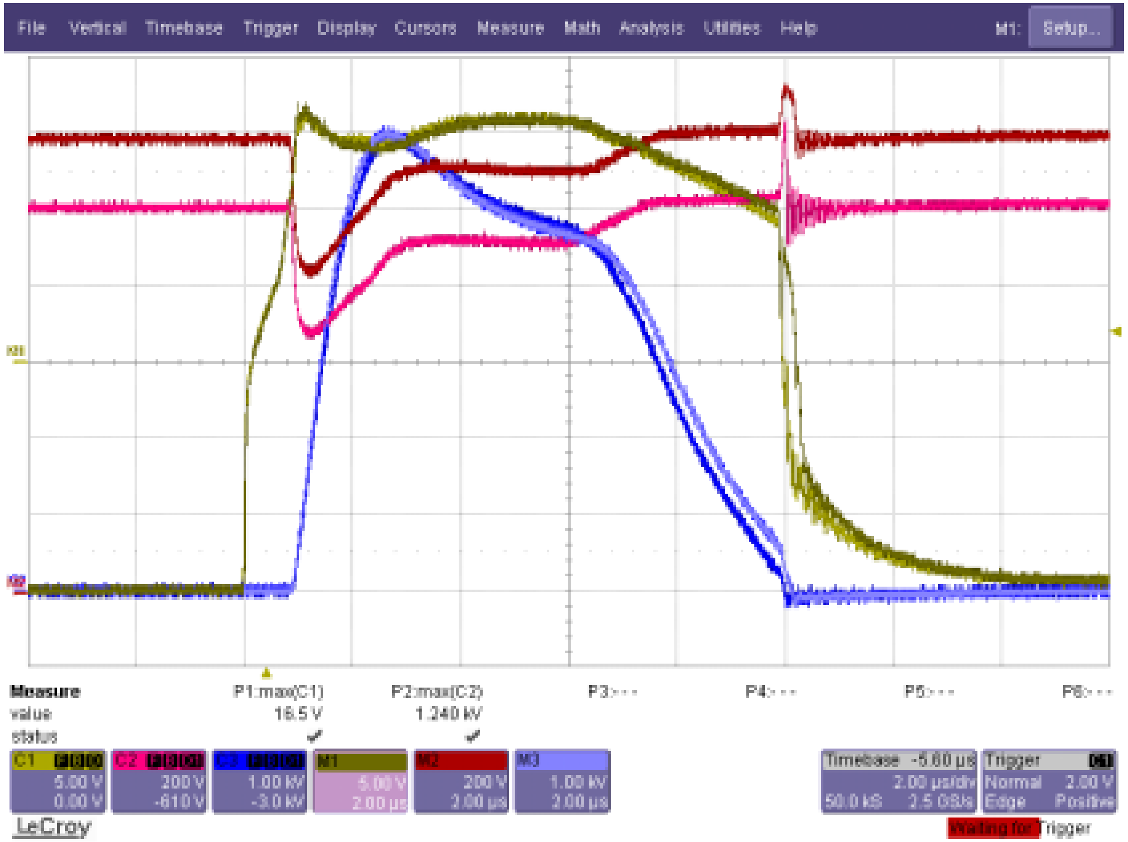


Can lead to high voltage with small current at low temperature

IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
  - Check switching waveforms – oscillation?
  - Measurement of loss, switching time, stray inductance
  - Verify IGBT RBSOA, diode SOA
  - Verify short-circuit protection
  - IGBT Paralleling
  - Optimize Driver design
- Impact of Rg, Cge on IGBT switching

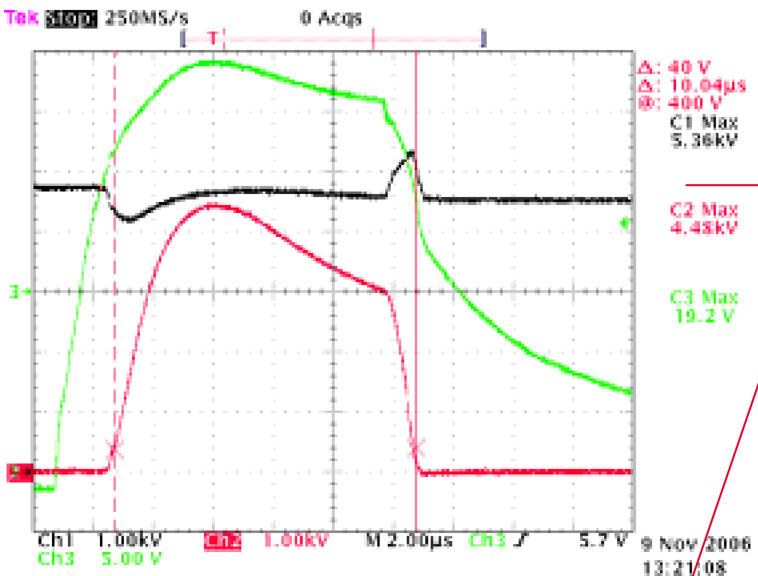
IGBT short circuit protection – turn off voltage overshoot

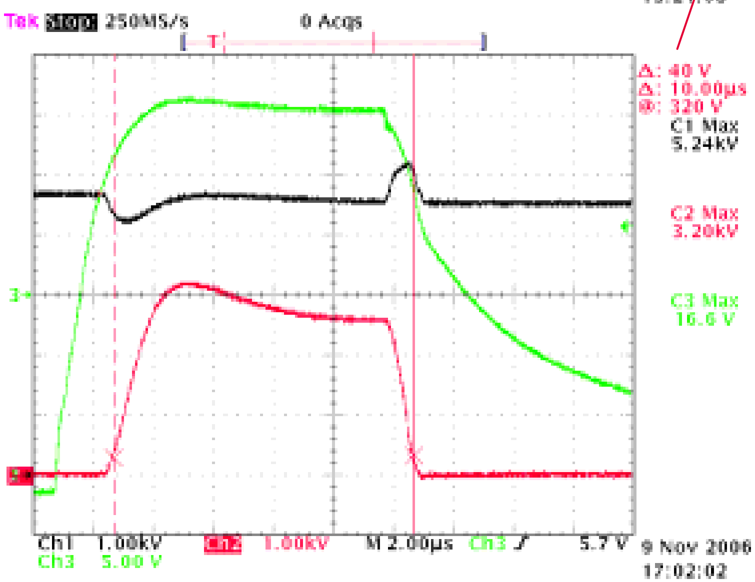


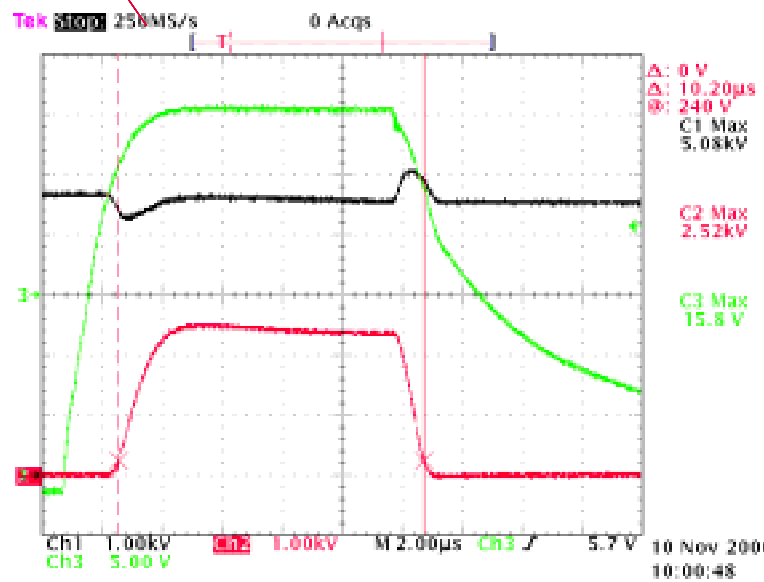
Soft turnoff SC1 – reduce voltage overshoot

IGBT short circuit protection – gate clamping

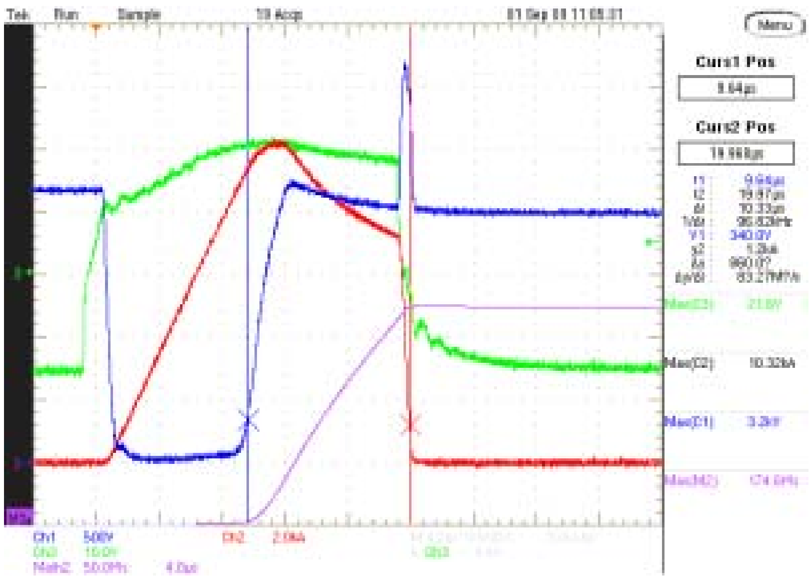
- Without clamping
- With TVS clamping between GE
- With clamping to Vcc

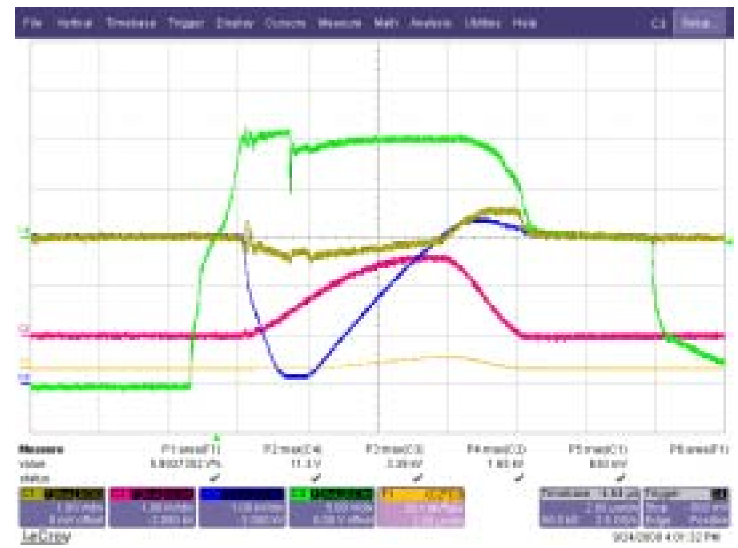






IGBT short circuit protection – short circuit II





Turn off SC-II only when desaturated.

IGBT Double Pulse Test

- Basic principle of double pulse test
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  - Check switching waveforms – oscillation?
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  - Verify IGBT RBSOA, diode SOA
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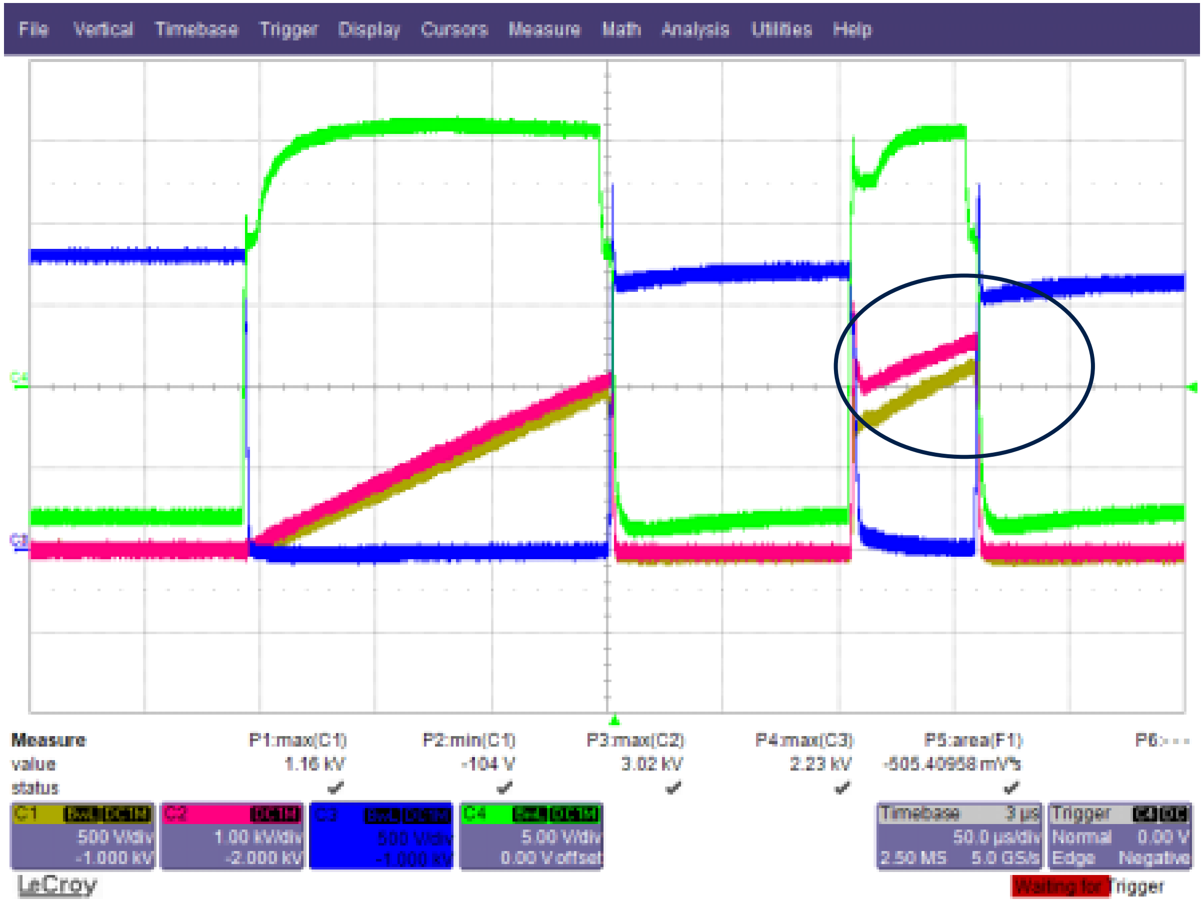
  - Optimize Driver design
- Impact of Rg, Cge on IGBT switching

IGBT parallel



C1: the left IGBT

C2: I_{DC} totally

C3: V_{CE}

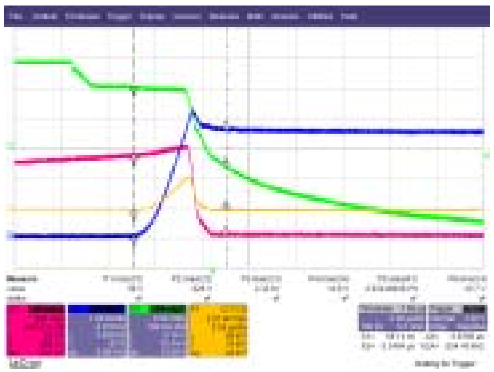
C4: V_{GE}

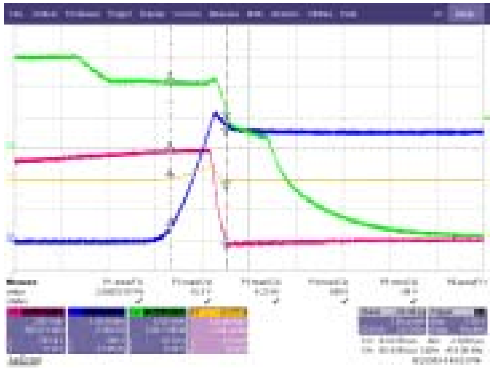
The difference between paralleled IGBT becomes smaller and smaller

IGBT Double Pulse Test

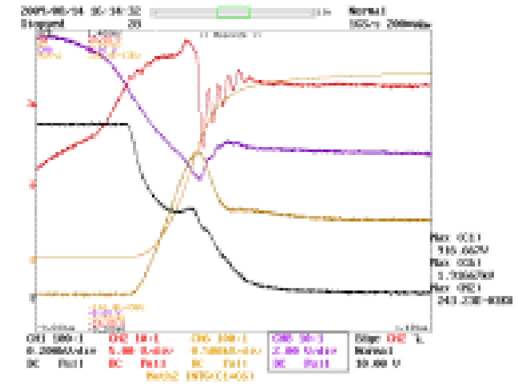
- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
  - Check switching waveforms – oscillation?
  - Measurement of loss, switching time, stray inductance
  - Verify IGBT RBSOA, diode SOA
  - Verify short-circuit protection
  - IGBT Paralleling
  - Optimize Driver design
- Impact of Rg, Cge on IGBT switching

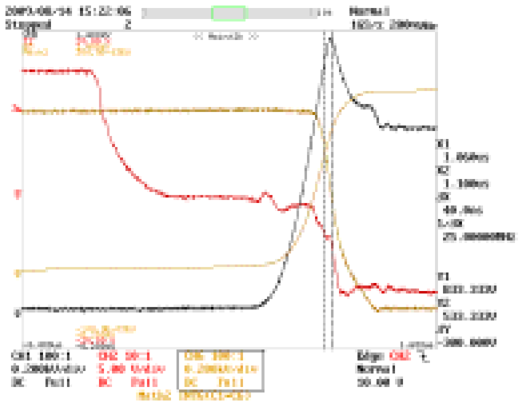
Optimize Driver Design



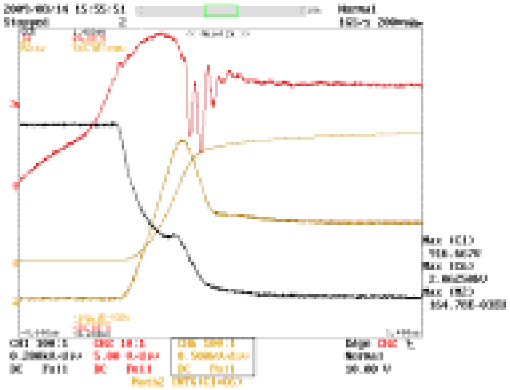


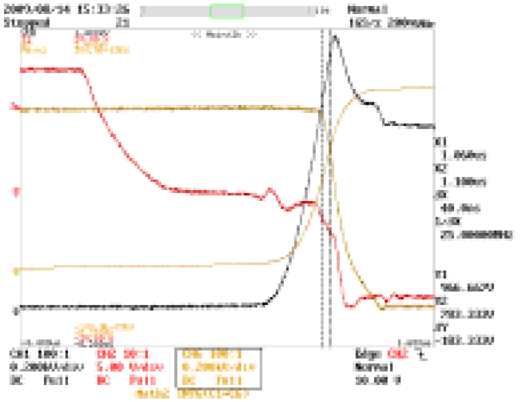
Driver comparison





6cm Gate cable



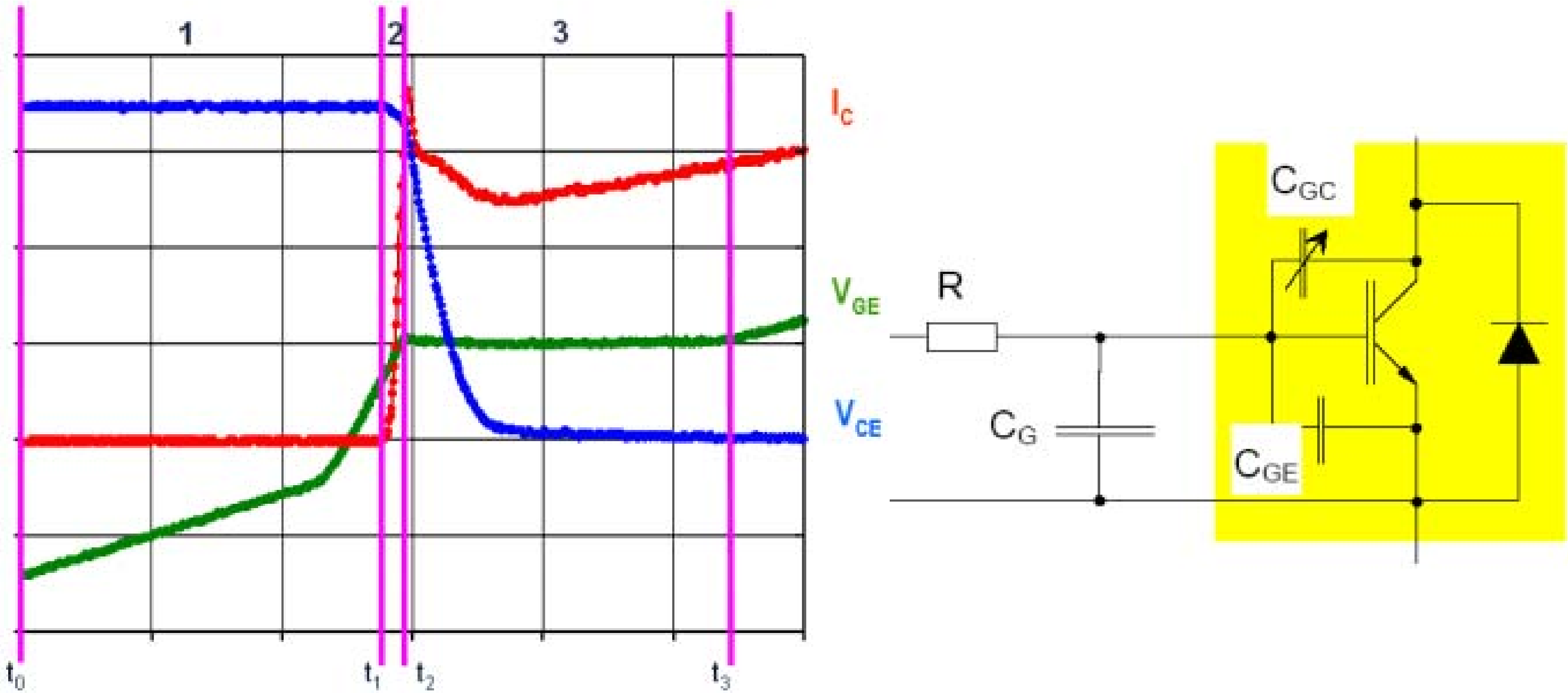


50cm Gate cable

IGBT Double Pulse Test

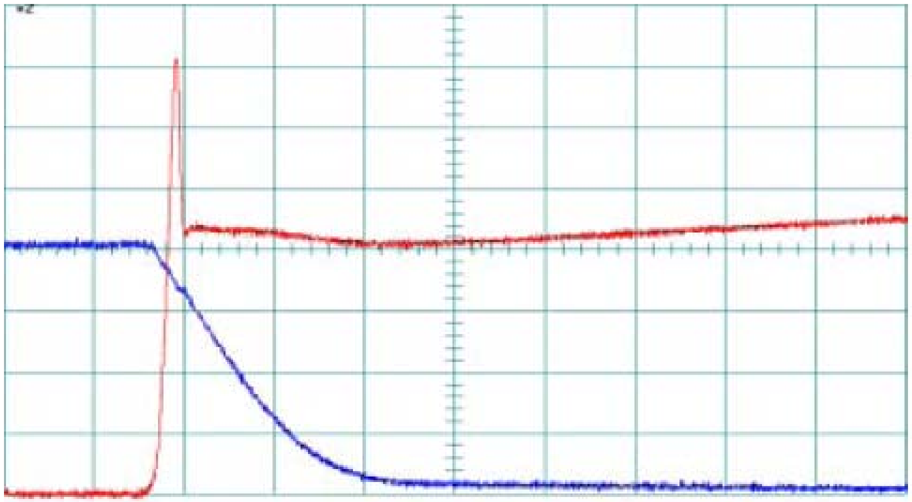
- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching

Control turn on di/dt (diode reverse recover) and dv/dt (Eon) independently

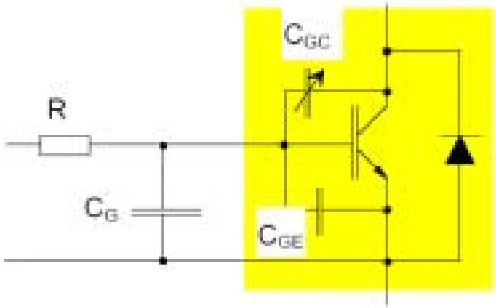


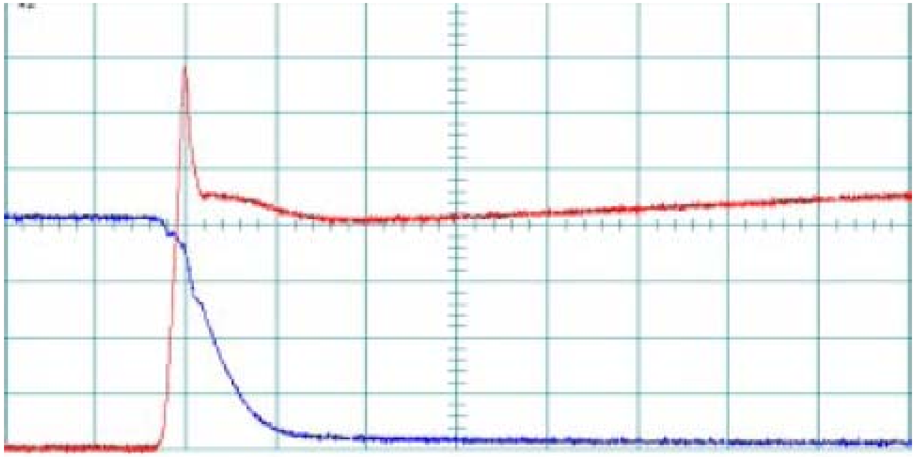
Range	Determined by	Condition	Influenced by	Influence on
1	$V_{GE} < V_{GEth}$	C_{iss} = const	R_G, $C_{GE} \parallel C_G$	t_{don}
2	$V_{GEth} < V_{GE} < V_{GEM}$	C_{iss} = const	R_G, $C_{GE} \parallel C_G$	$^{di}/_{dt}$
3	$V_{GE} = V_{GEM}$	V_{GE} = const	R_G, C_{GC} ($C_{GC} >> C_G$)	$^{dv}/_{dt}$

Control turn on di/dt (diode reverse recover) and dv/dt (Eon) independently

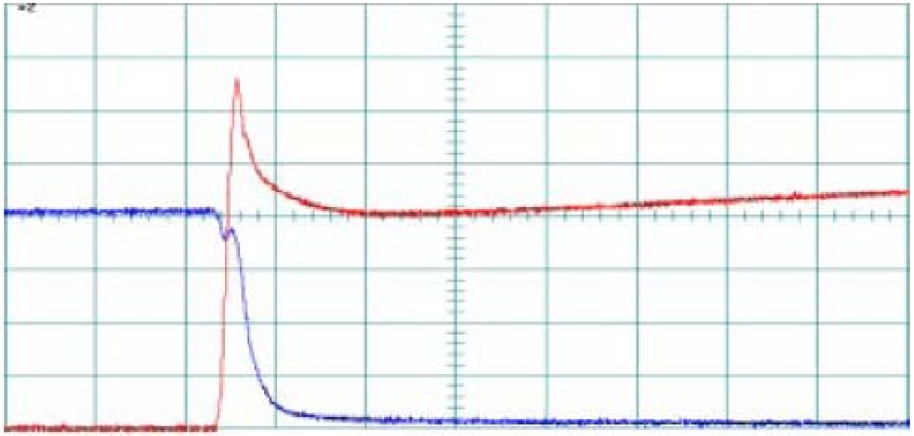


R_G=8,2Ω, C_G=0, I_C/dt= 5kA/µs, dV_{CE}/dt=0,6kV/µs, E_{on}=6,4J





R_G=3,3Ω, C_G=100nF, I_C/dt= 4,5kA/µs, dV_{CE}/dt=1kV/µs, E_{on}=4,1J



R_G=1,0Ω, C_G=330nF, I_C/dt= 5,1kA/µs, dV_{CE}/dt=2,8kV/µs, E_{on}=2,8J

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Never stop thinking