EE155/255 Green Electronics

Embedded Software
Power Devices
10/2/17

Prof. William Dally
Computer Systems Laboratory
Stanford University

Logistics

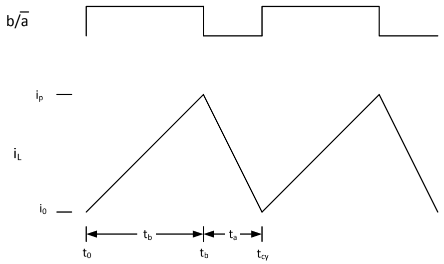
- Lab group assignments
  - Go to Canvas and group yourselves – or we will group you
- Homework 1 due Today – by 9am in box outside Sue's office
- Sign up for Lab signoff time
  - Lab 1 must be signed off this week
- Sign up for Piazza
  - piazza.com/stanford/fall2017/ee155ee255
- Discussion sections
  - Fridays 4:30-5:50PM
  - STLC 118

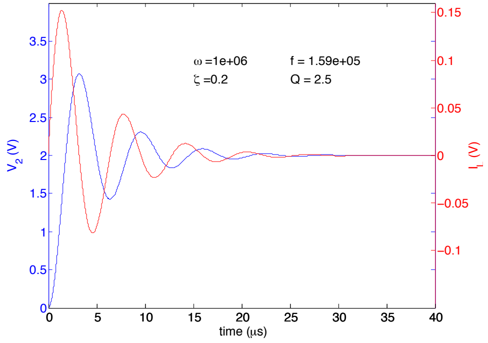
Course at a Glance

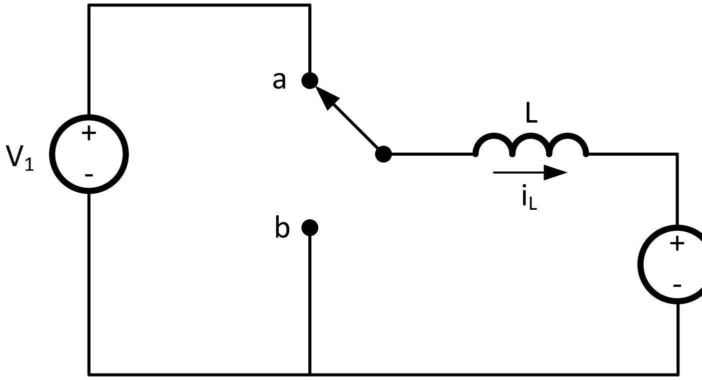
No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Wrapup						
18	11/29/17	Guest Lecture				C3		
19	12/4/17	Guest Lecture						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

PSSA in One Slide

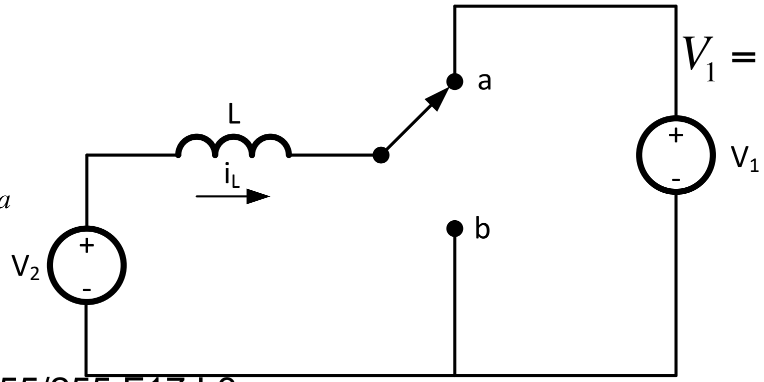
- Green energy systems are made from voltage converters
  - PV systems, electric/hybrid cars, wind power, etc…
  - Power path + intelligent control
- Separate behavior into fast and slow
  - Fast – within switching cycle
  - Slow – f << f_{cy}
- Within cycle solve for ***periodic steady state***
  - State variables the same at start and end of cycle.
- For slow transient response
  - Write difference equations
- Buck/Boost Topologies







$$V_2 = V_1 D_a$$



$$V_1 = \frac{V_2}{D_a} = \frac{V_2}{\left(1 - D_b\right)}$$

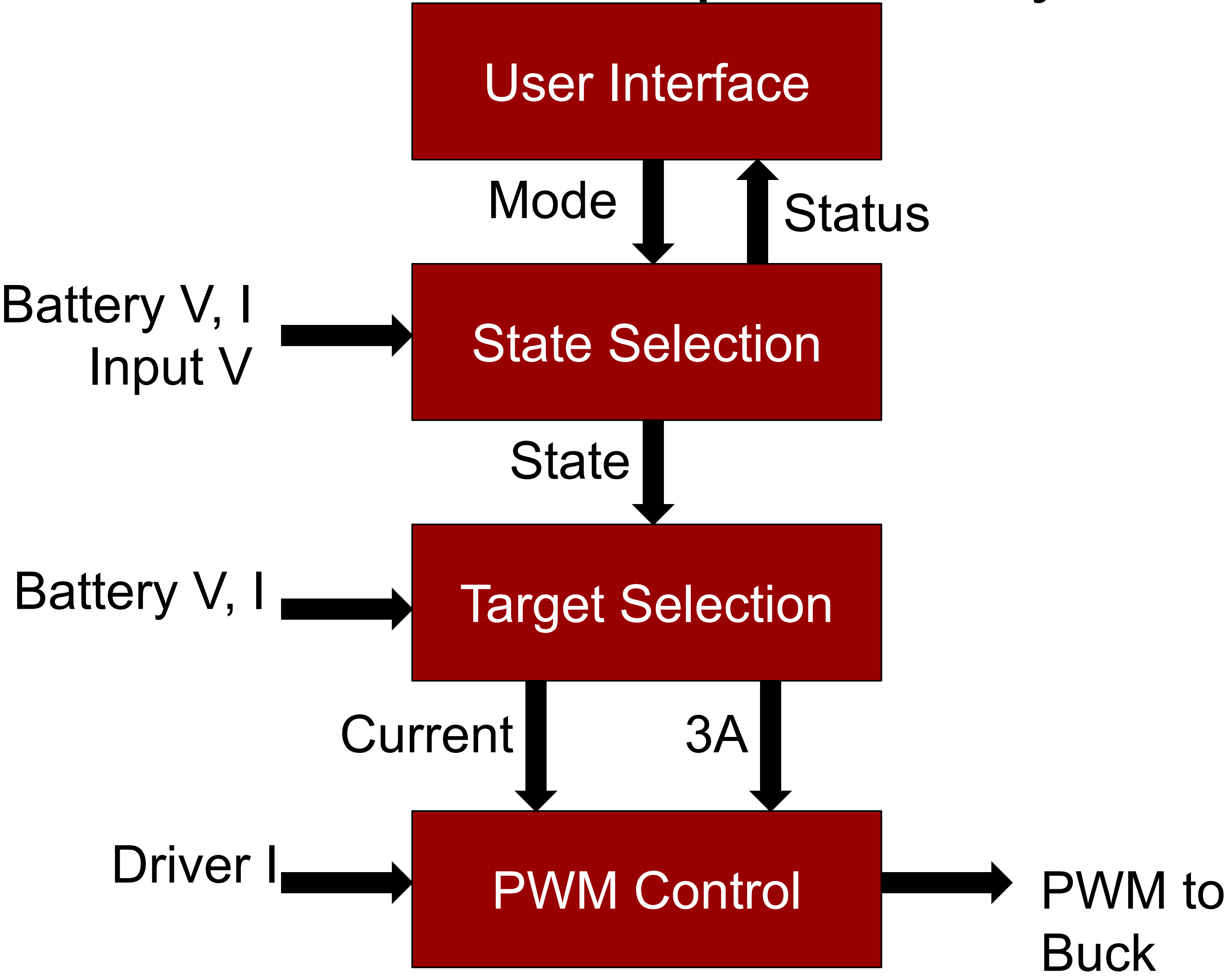
Embedded Software in One Slide

- Real-time, Event driven
  - Timer schedules periodic events (make sure work is done before next event)
  - I/O devices signal completion
- Integer and FP Arithmetic
  - Scale your numbers, avoid divides
- Layered design
  - UI – avoid modes, label buttons, it should be obvious
  - Control – at different frequencies
  - Monitoring and Housekeeping

Organization of Code

- Control
- User Input
- Display
- Monitoring
- Housekeeping

Layered Control: Example Battery Charger



User Interface

Mode

Status

Battery V, I
Input V

State Selection

State

Battery V, I

Target Selection

Current

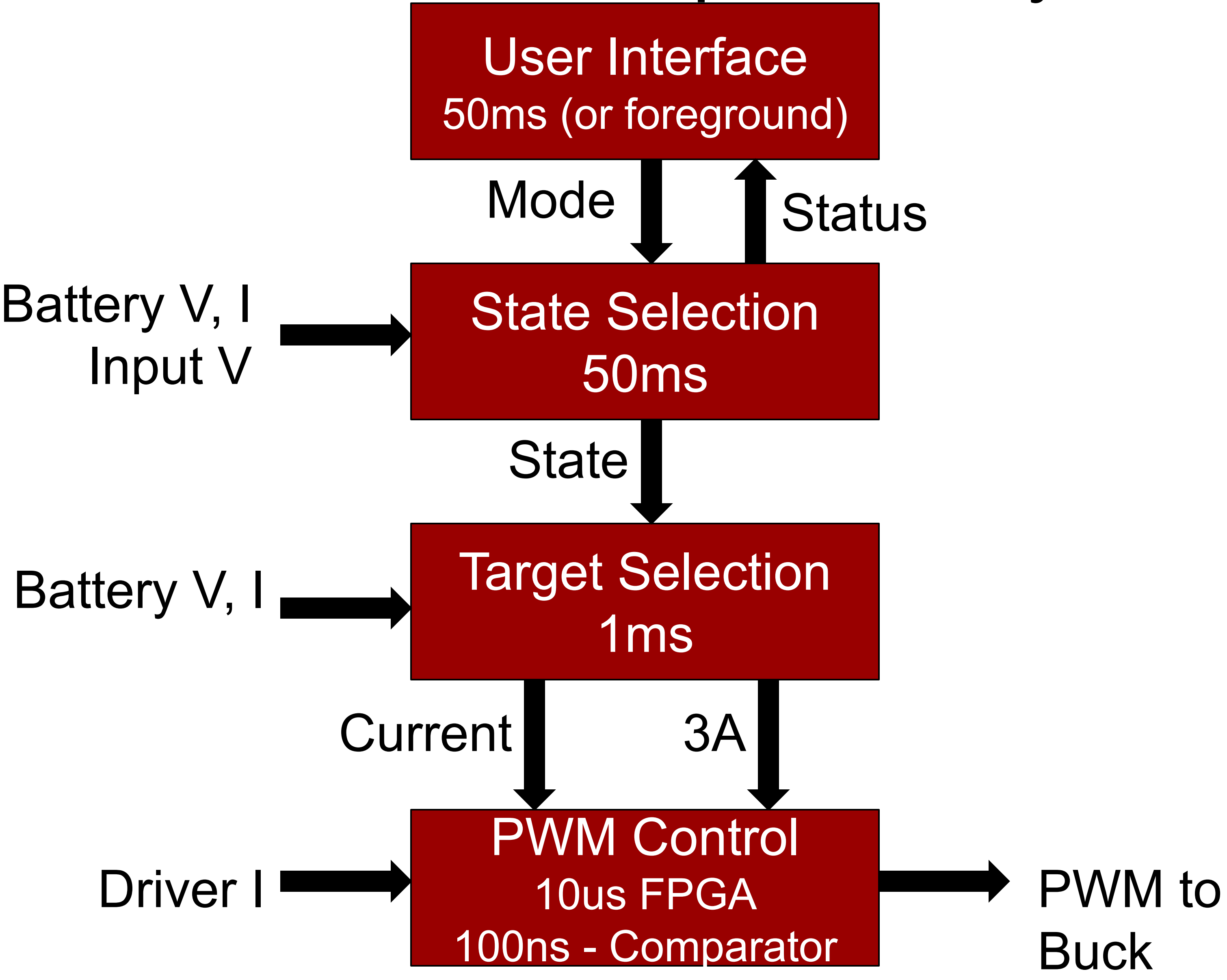
3A

Driver I

PWM Control

PWM to
Buck

Layered Control: Example Battery Charger



User Interface
50ms (or foreground)

Mode

Status

Battery V, I
Input V

State Selection
50ms

State

Battery V, I

Target Selection
1ms

Current

3A

Driver I

PWM Control
10us FPGA
100ns - Comparator

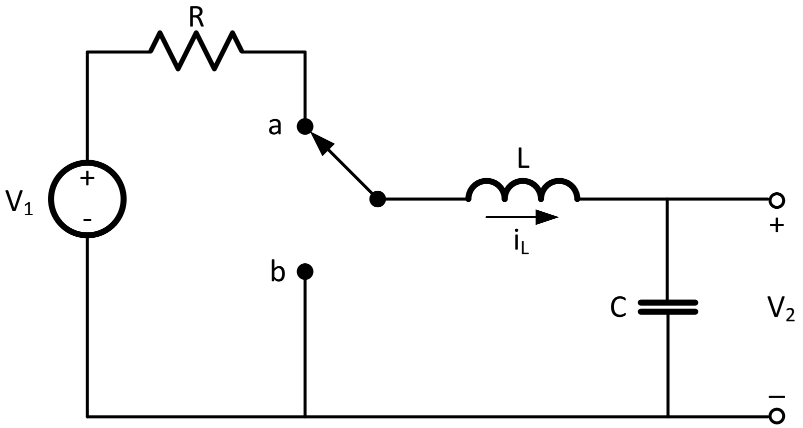
PWM to
Buck

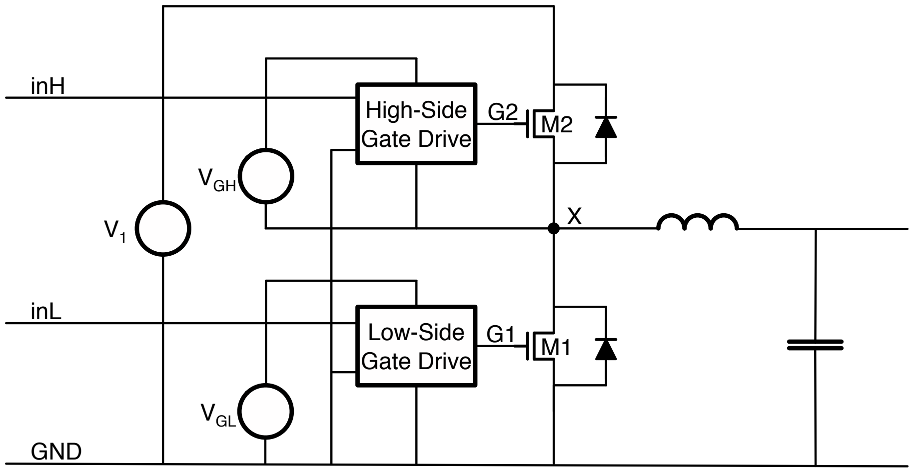
Example Photovoltaic Controller

- Mode selection
  - Line test, Panel test, MPPT, etc…
- Monitors
  - Line (current, voltage, frequency, …) (anti-islanding)
  - Internal operation (voltages, currents, temps)
  - Panels (current, voltage)
- Maximum Power-Point Tracking
  - Search algorithm for peak power point
- Inverter control
  - Convert 400V DC to 240V AC – in sync with line
- User interface
  - Display status, serial output, network connections, …

Power Electronics
Part 1 – Power Devices

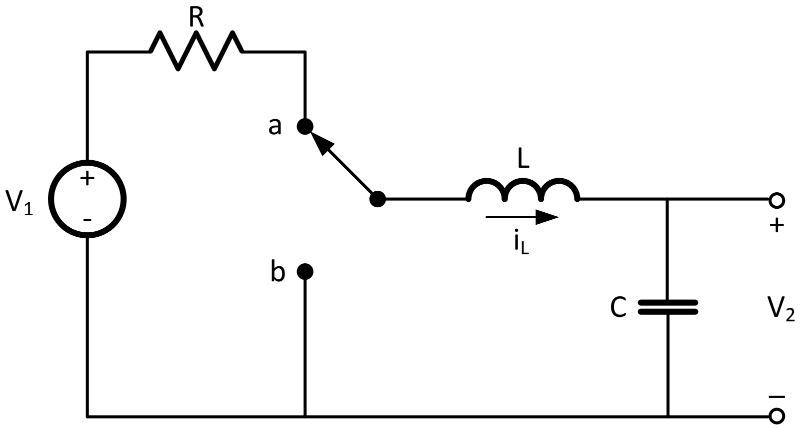
Real Switches

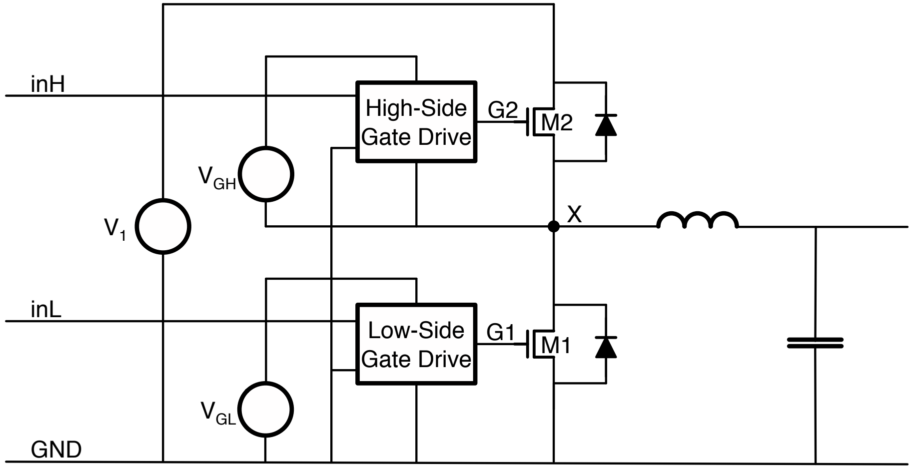




Real Switches

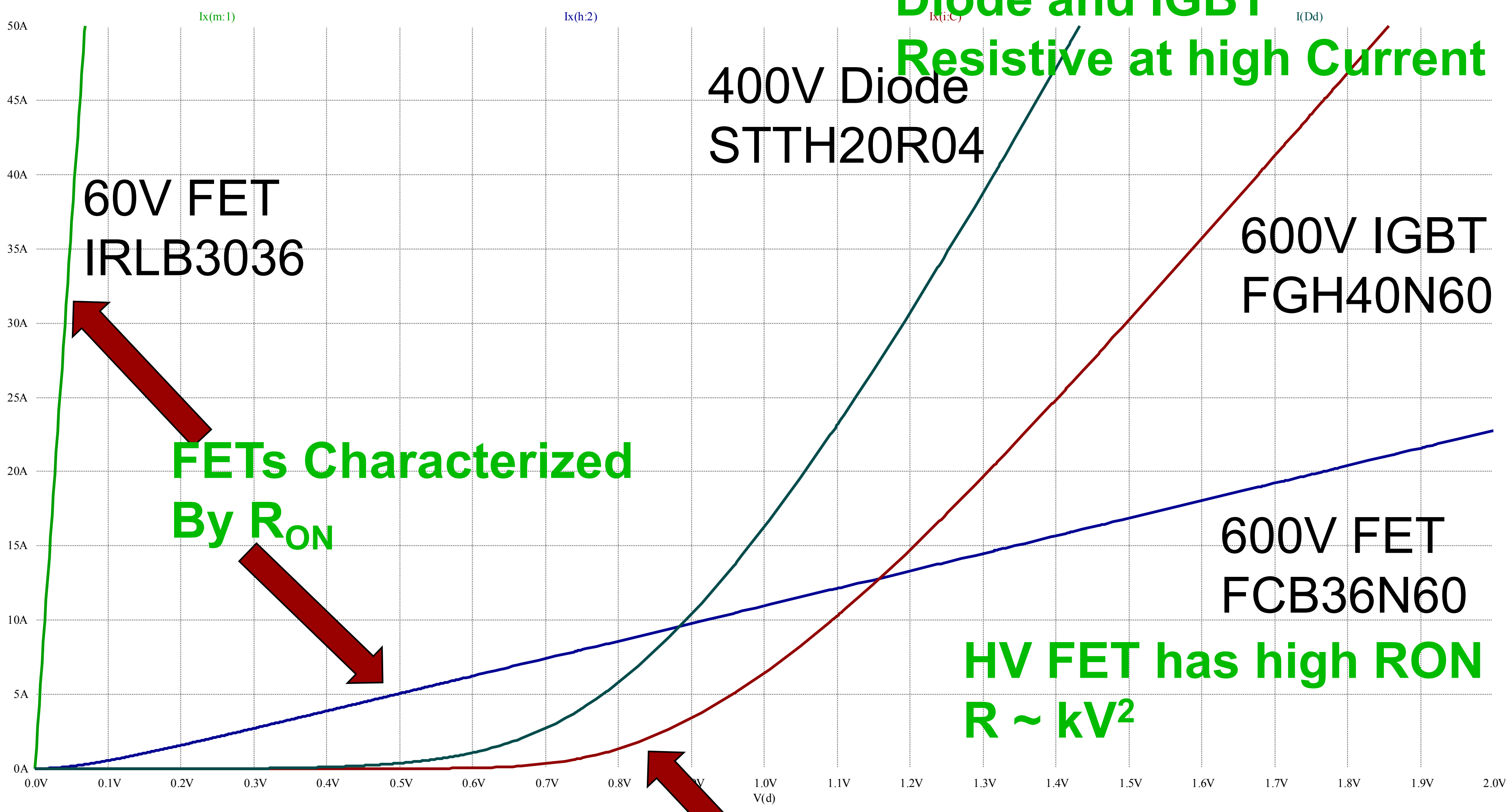
- Finite switching time
- Finite voltage blocking
- Non-zero on resistance
- Parasitic L and C
- Need gate-drive supplies





Quick Summary in a Few Pictures

DC I-V Characteristics of On Switches



Diode and IGBT Resistive at high Current

400V Diode
STTH20R04

60V FET
IRLB3036

600V IGBT
FGH40N60

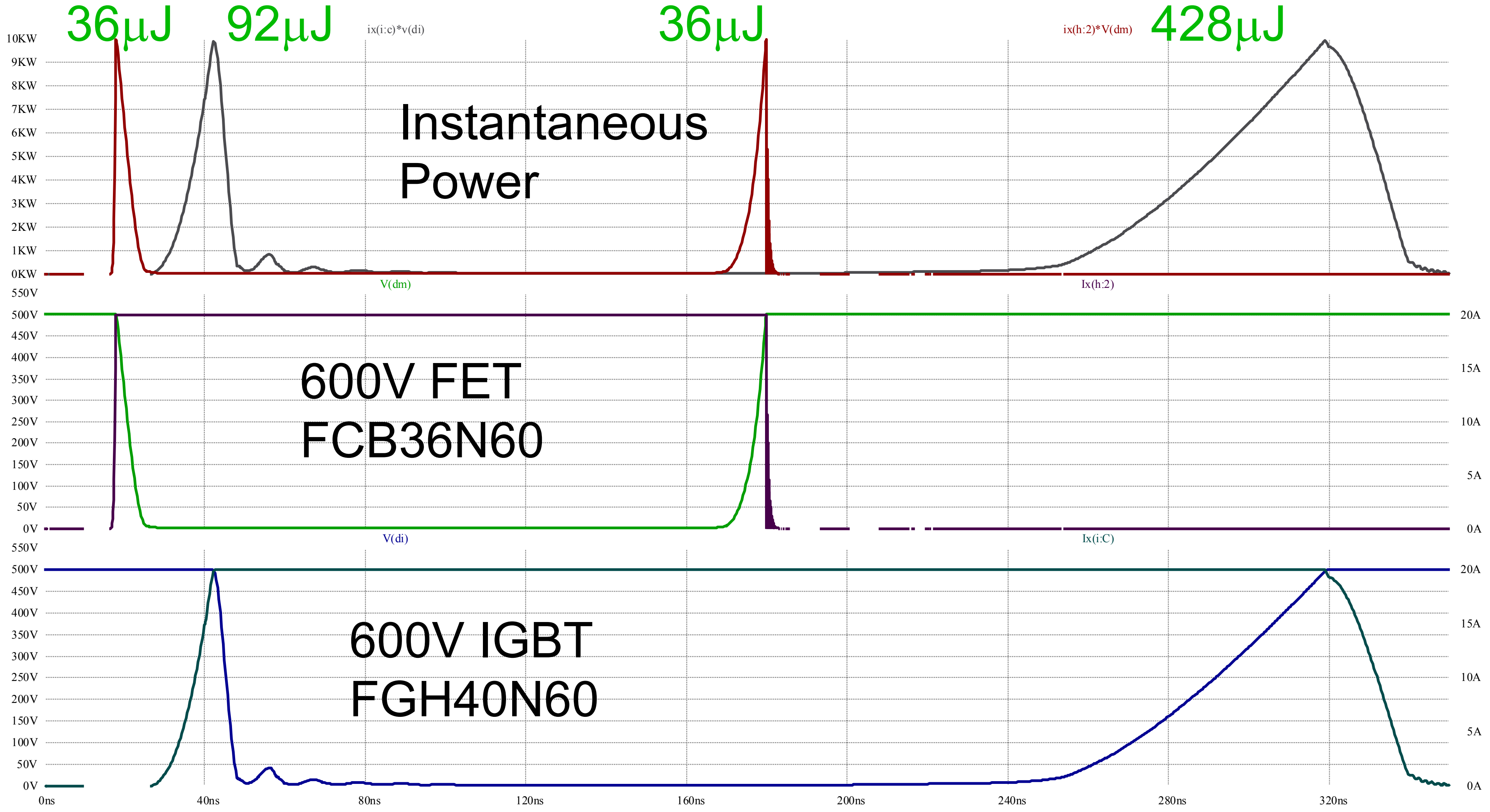
FETs Characterized By R_{ON}

600V FET
FCB36N60

HV FET has high RON
$R \sim kV^2$

IGBT Like a Diode
Little Current Until ~0.7V

Transient Response of FET and IGBT



36μJ 92μJ 36μJ 428μJ

Instantaneous Power

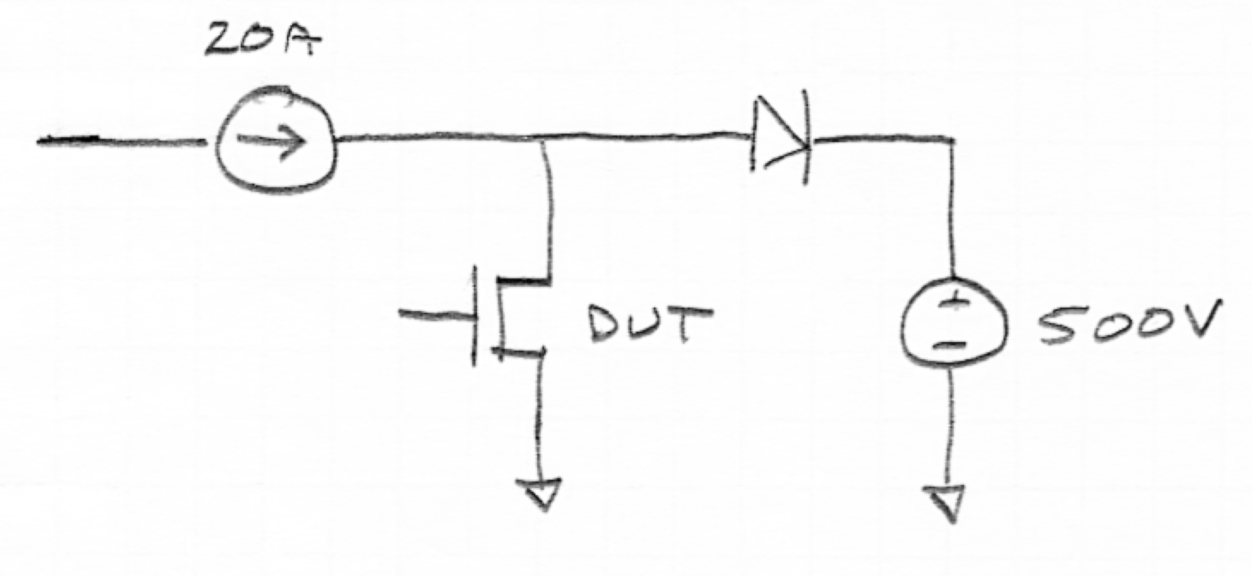
600V FET
FCB36N60

600V IGBT
FGH40N60

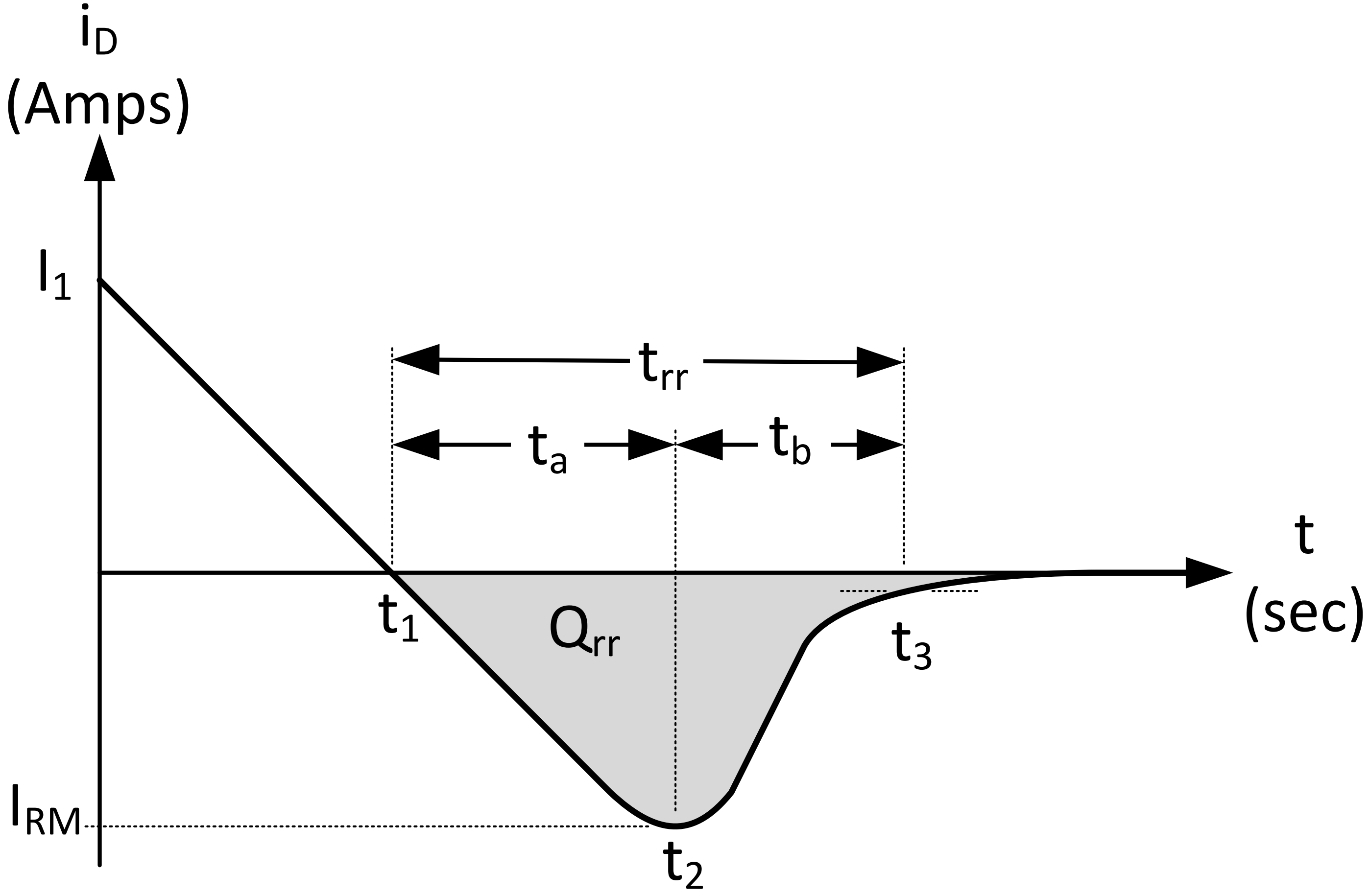
Turn On

Turn Off

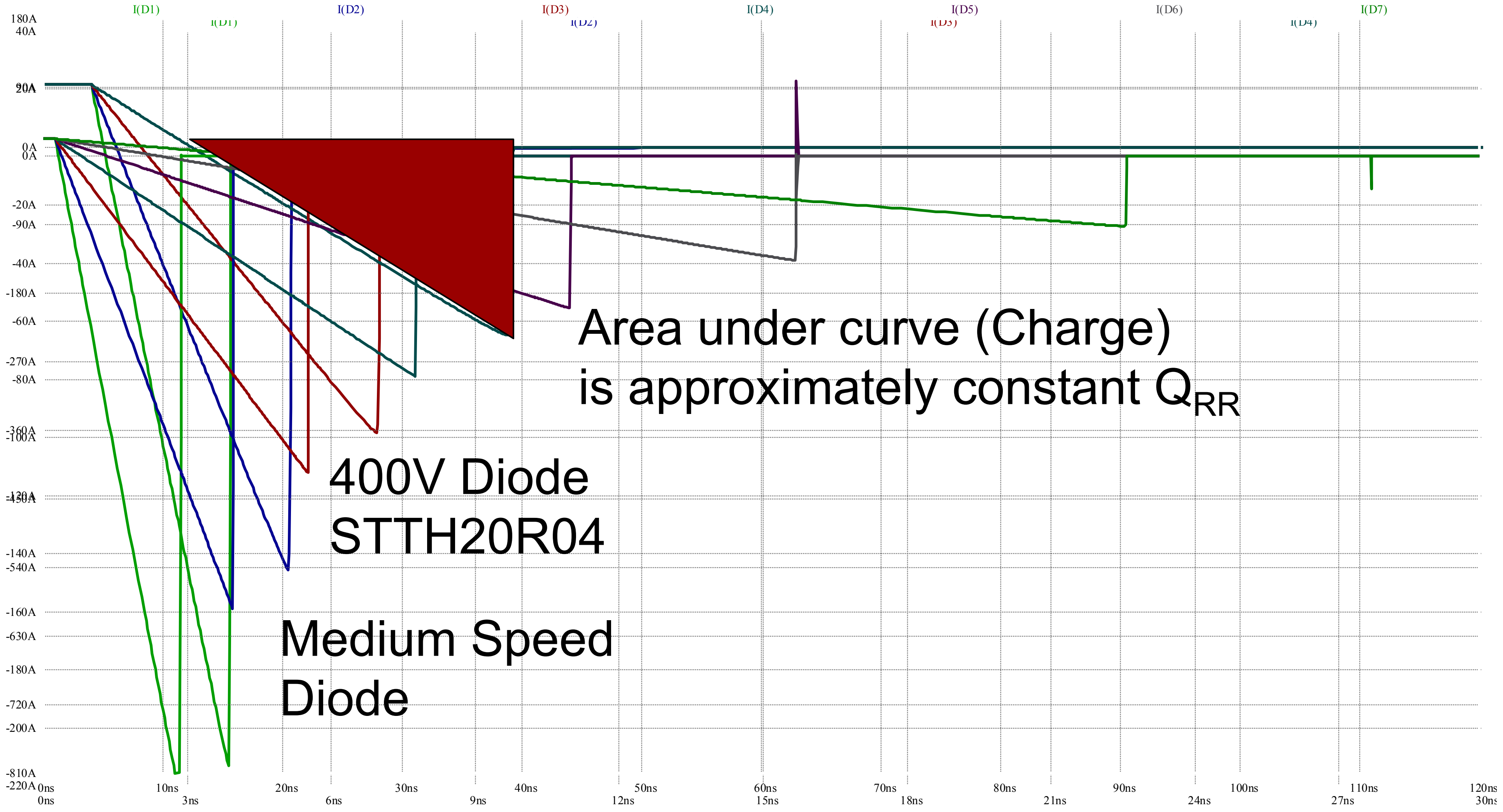
Boost Configuration for Transient Test



Diode Reverse Recovery



Diode Reverse Recovery



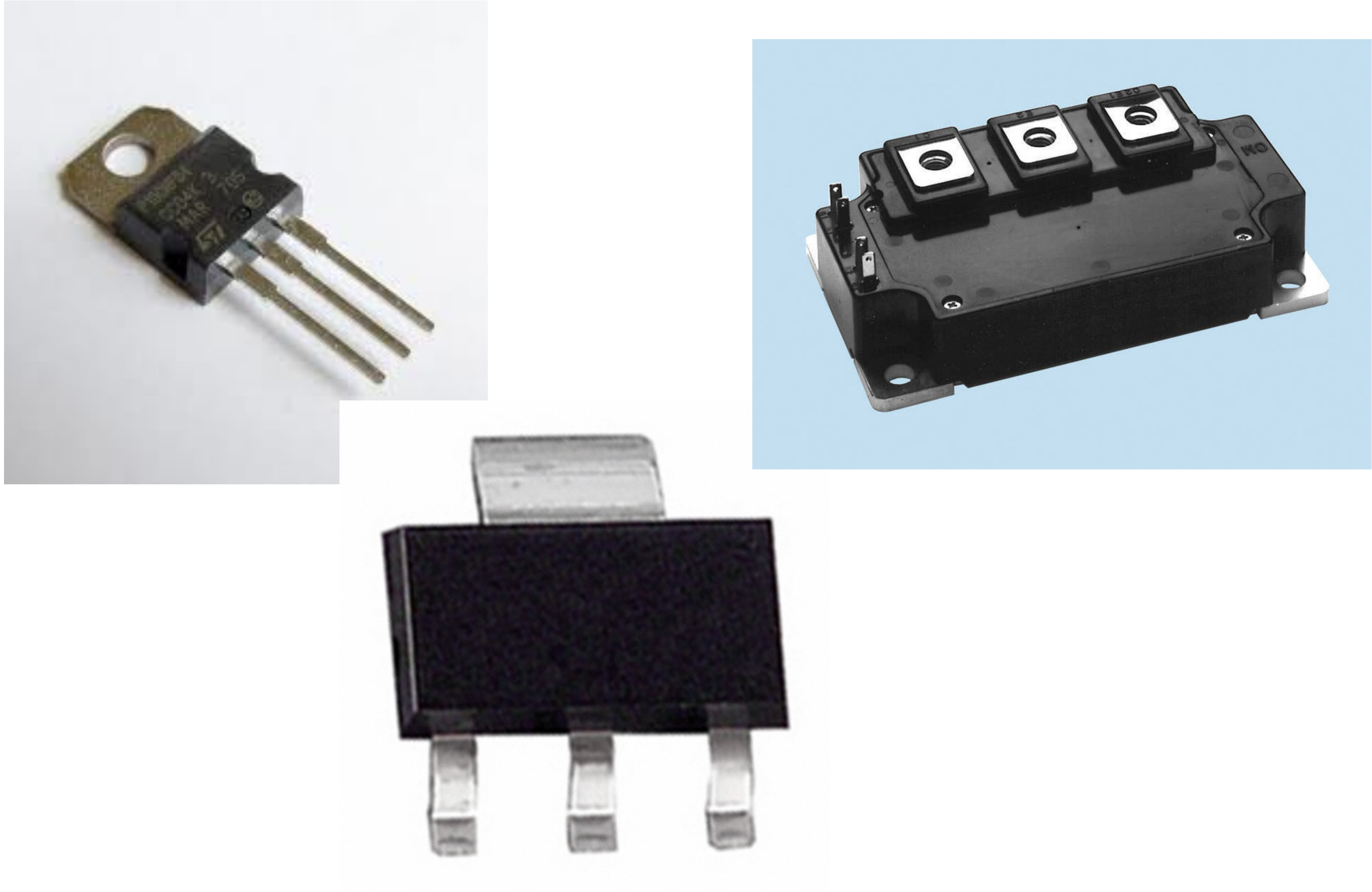
Area under curve (Charge) is approximately constant Q_{RR}

400V Diode
STTH20R04

Medium Speed
Diode

Power MOSFETs

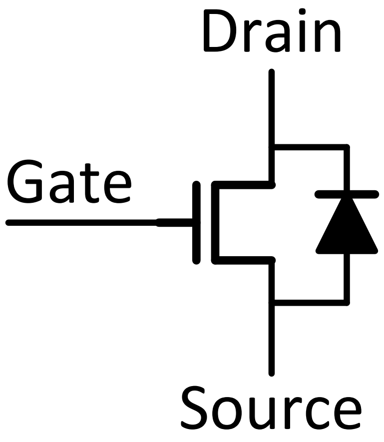
Power MOSFETs are your friends



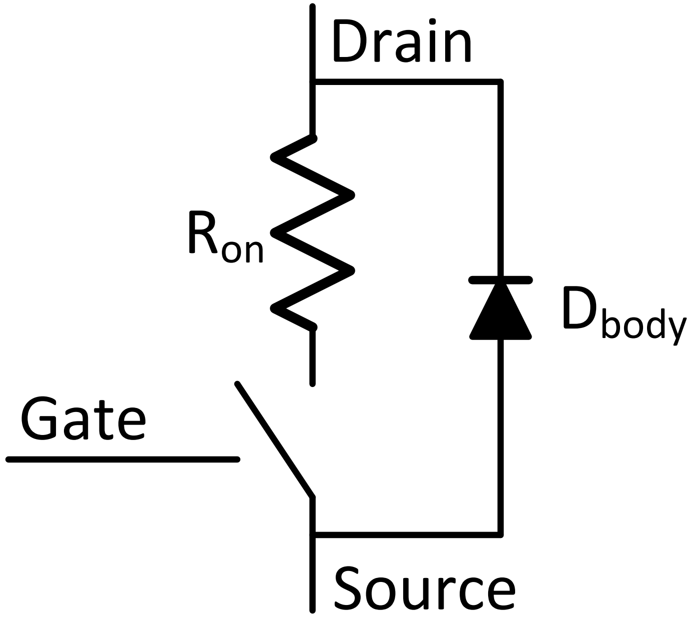
MOSFET Properties

- Fast switching time 10-50ns
  - Low switching losses
- Low conduction losses at low voltages
  - V^2/R of 1-2MW
    - e.g., at 20V R = 0.4mOhm (4mV drop at 10A)
  - Typically better than IGBT up to ~400V
- Easily paralleled for lower R_{on}, More I, or easier cooling
- Integral body diode in DMOS FET
- Avalanche breakdown can be used to “snub” overshoot

MOSFETs are Switches

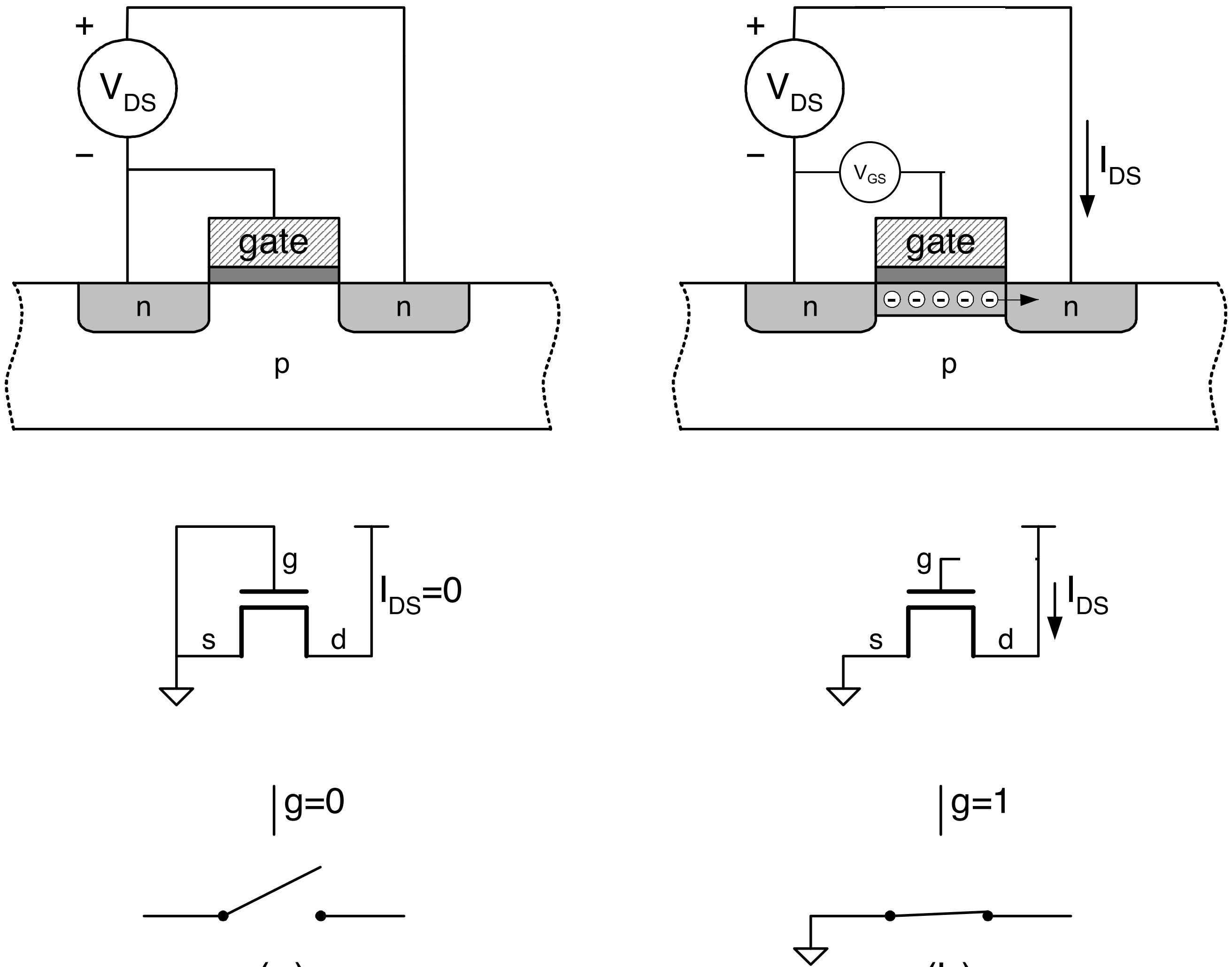


(a)



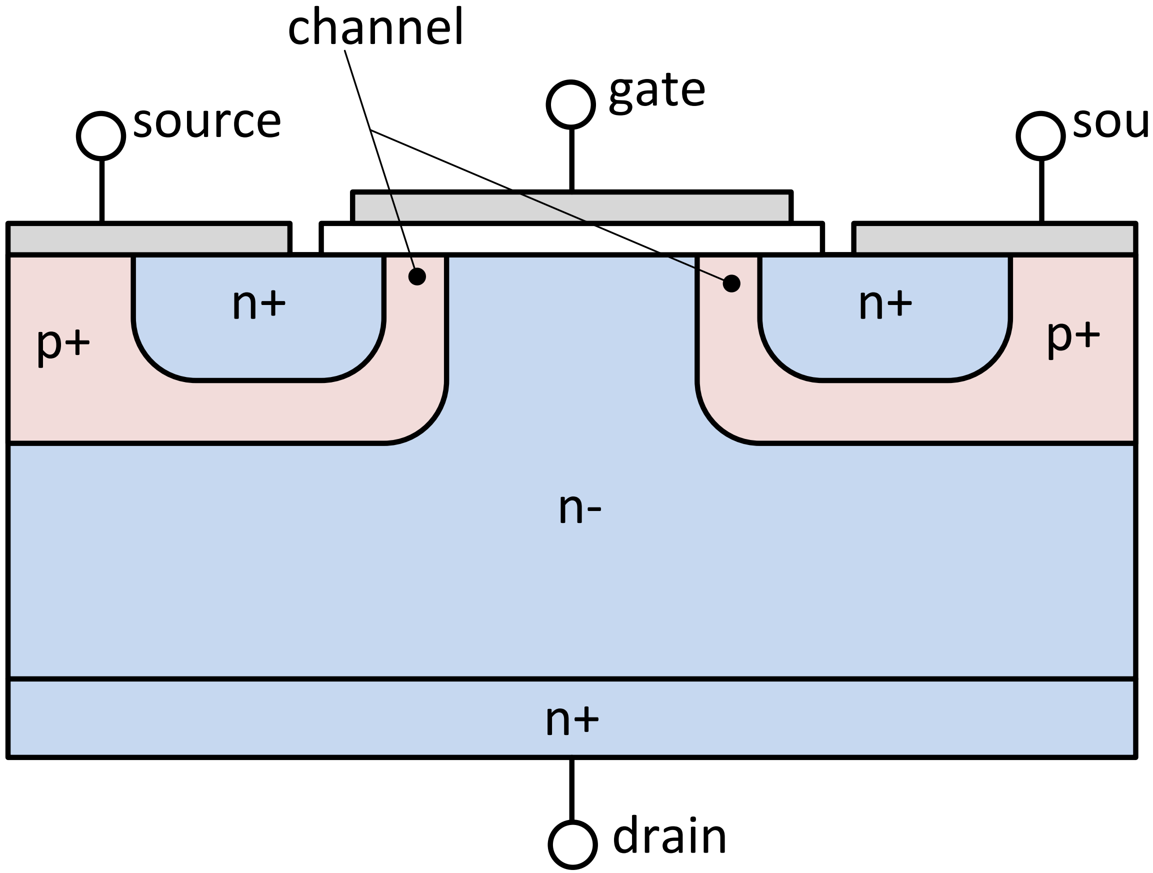
(b)

How do they Work

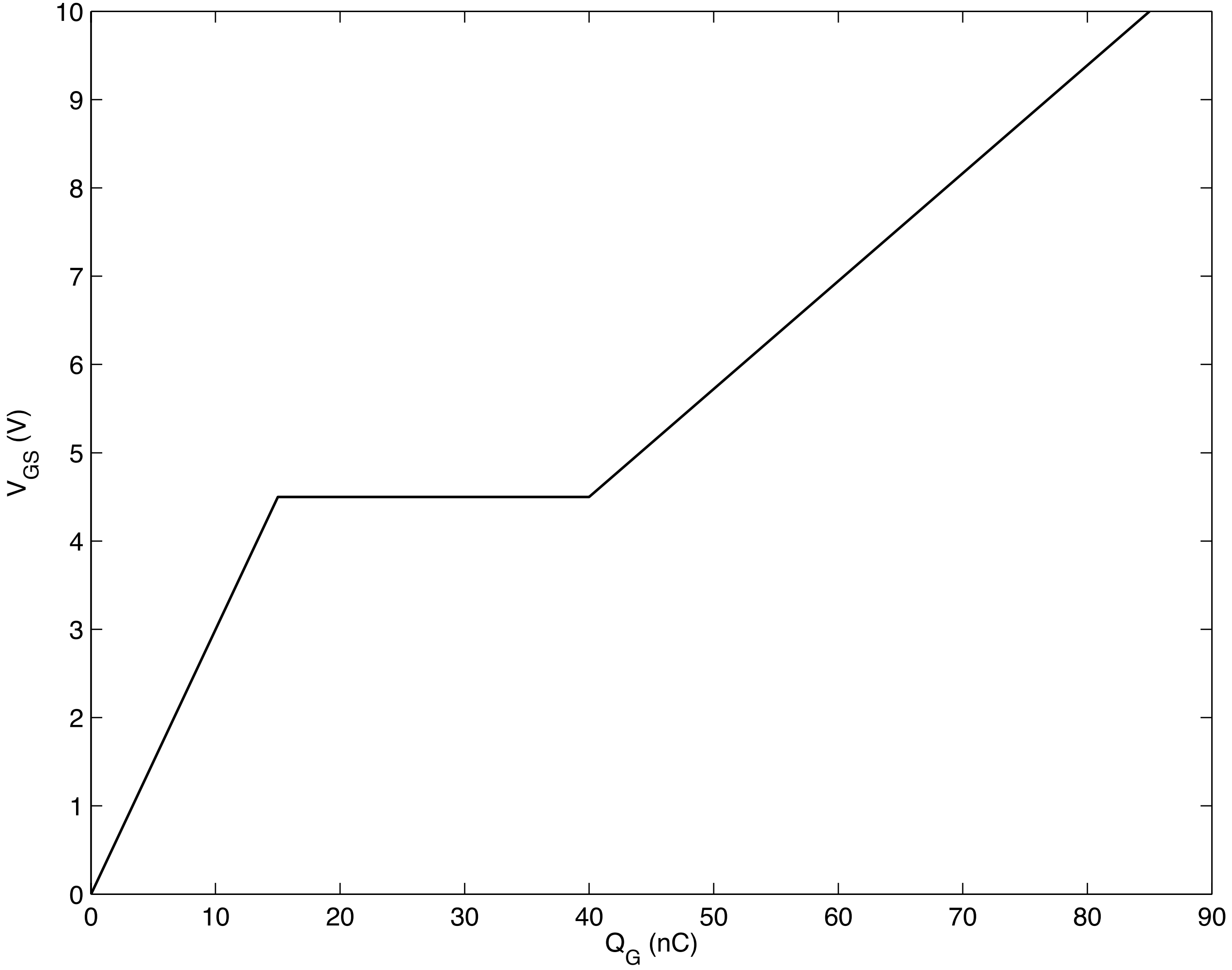


(a) (b)

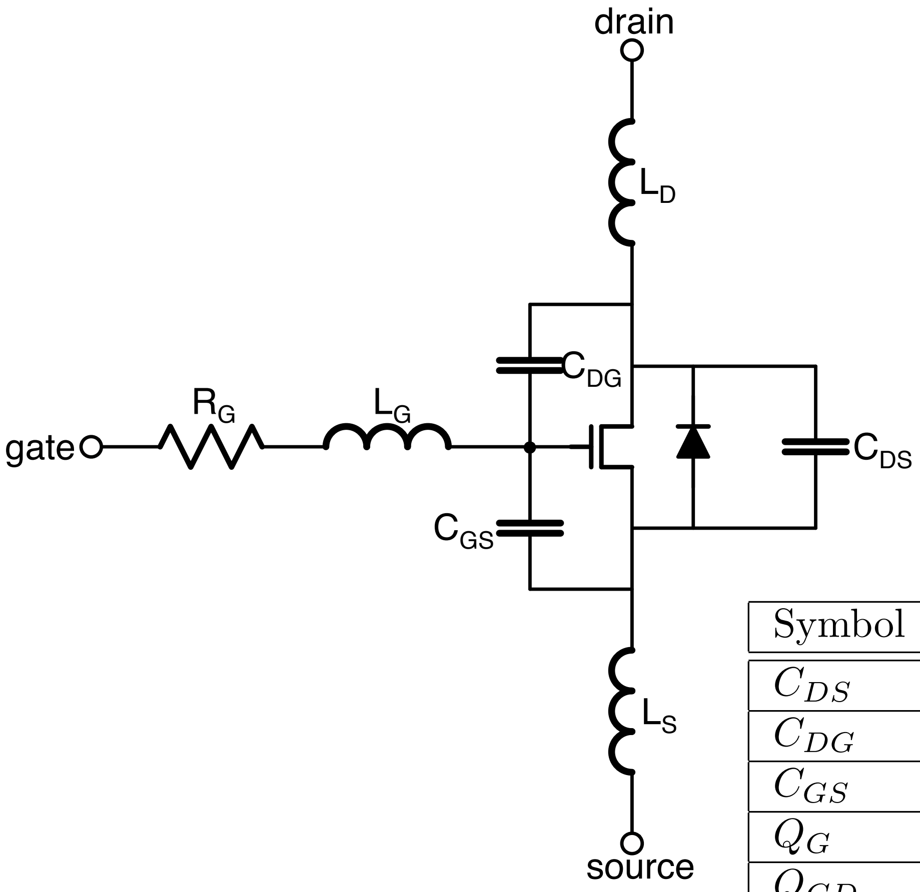
Power MOSFET (DMOS) Structure



Gate Charge vs V_{GS}



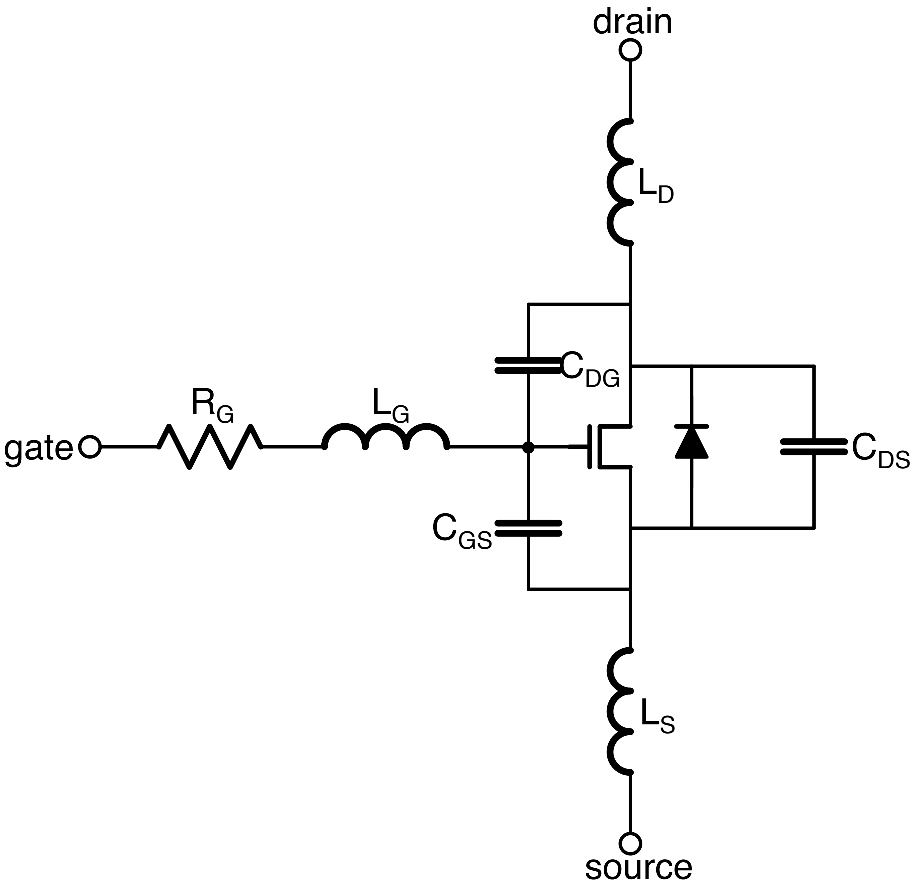
Parasitics



600V 0.1Ω FET
TO220 Package

Symbol	Value	Units	Description
C_{DS}	200	pF	Drain-source capacitance
C_{DG}	70	pF	Drain-gate (Miller) capacitance
C_{GS}	3600	pF	Gate-source capacitance
Q_G	86	nC	Total gate turn-on charge
Q_{GD}	35	nC	Gate-drain turn-on charge
L_S	7	nH	Source inductance
L_D	3	nH	Drain inductance
L_G	7	nH	Gate inductance
R_G	1.5	Ω	Gate resistance

Parasitics



C_{DS} – CV^2 energy

L_D, L_S – I^2L energy

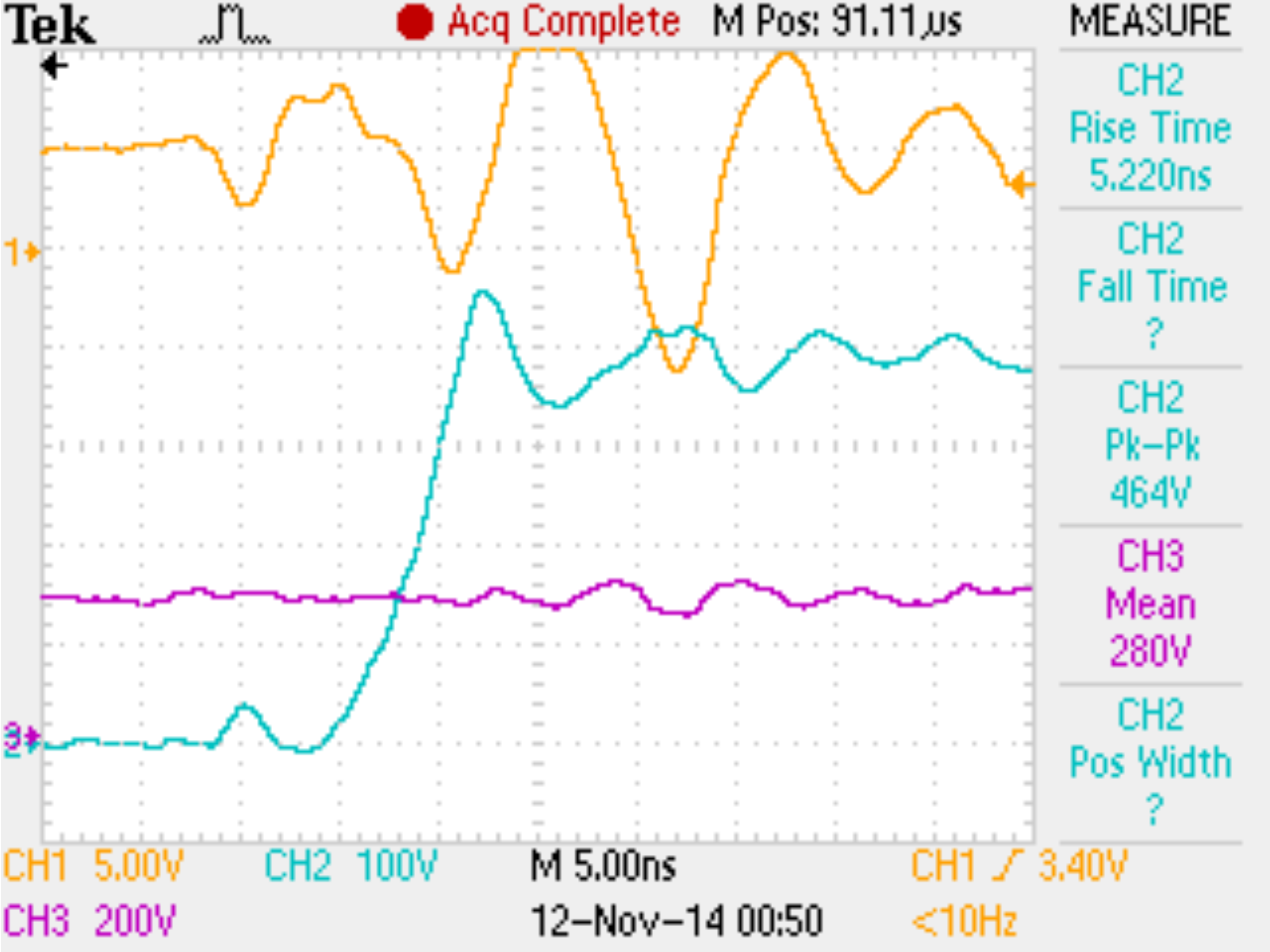
slows switching,

overshoot,

corrupts gate drive

C_{DG} – slows turn on

R_G, L_G – slow device turn-on



Tek

Acq Complete M Pos: 91.11µs

MEASURE

CH2
Rise Time
5.220ns

CH2
Fall Time
?

CH2
Pk–Pk
464V

CH3
Mean
280V

CH2
Pos Width
?

CH1 5.00V CH2 100V M 5.00ns CH1 ∕ 3.40V

CH3 200V 12–Nov–14 00:50 <10Hz

Typical MOSFETs

					GaN	SiC	
Device	20V	IRLB3036	IRFB4227	FCB36N60N	EPC2010	C2M0025120	Units
$V_{DS\max}$	20	60	200	600	200	1200	V
R_{on}		1.9	20	81	18	25	mΩ
Q_G		91	70	86	5	161	nC
C_{oss}		1020	460	80	270	220	pF
$I_{D\max}$		195	65	36	12	90	A
I_{DM}		1100	260	108	60	250	A
E_{AS}		290	140	1800			mJ
$P_{\max}$		380	330	312		463	W
V^2/R		1.9	2.0	4.4	2.2	58	MW
V^2/RQ_G		21	29	52	440	360	mV/s

Power MOSFETs should be ON or OFF They are not happy in between

- IRLB3036
- Can handle 60V (when its off)
- Can handle 195A (when its on – if you can cool it)
  - $I^2R = (195)^2(0.002) = 76W$
- But it can't handle 60V and 195A at the same time
  - $P = VI = (60)(195) = 11.7kW$
  - At least not for very long

- Turn them on and off quickly
- Best circuits are "soft switching"
  - Zero-current switching (ZCS) or zero-voltage switching(ZVS) or both.

Power Diodes

Diode Properties

- Self-controlling switch
  - Allows current in one direction
  - Turns off when current reaches zero (in theory)
- Relatively fixed voltage drop independent of current
  - 0.5 to 2.0V
  - High losses at low voltages
- Care required to operate in parallel
  - Current hogging
- Turn-off delay
  - Must clear space charge out of junction
- Turn-on delay
  - Negligible for most fast diodes, but some are problematic

Key Parameters

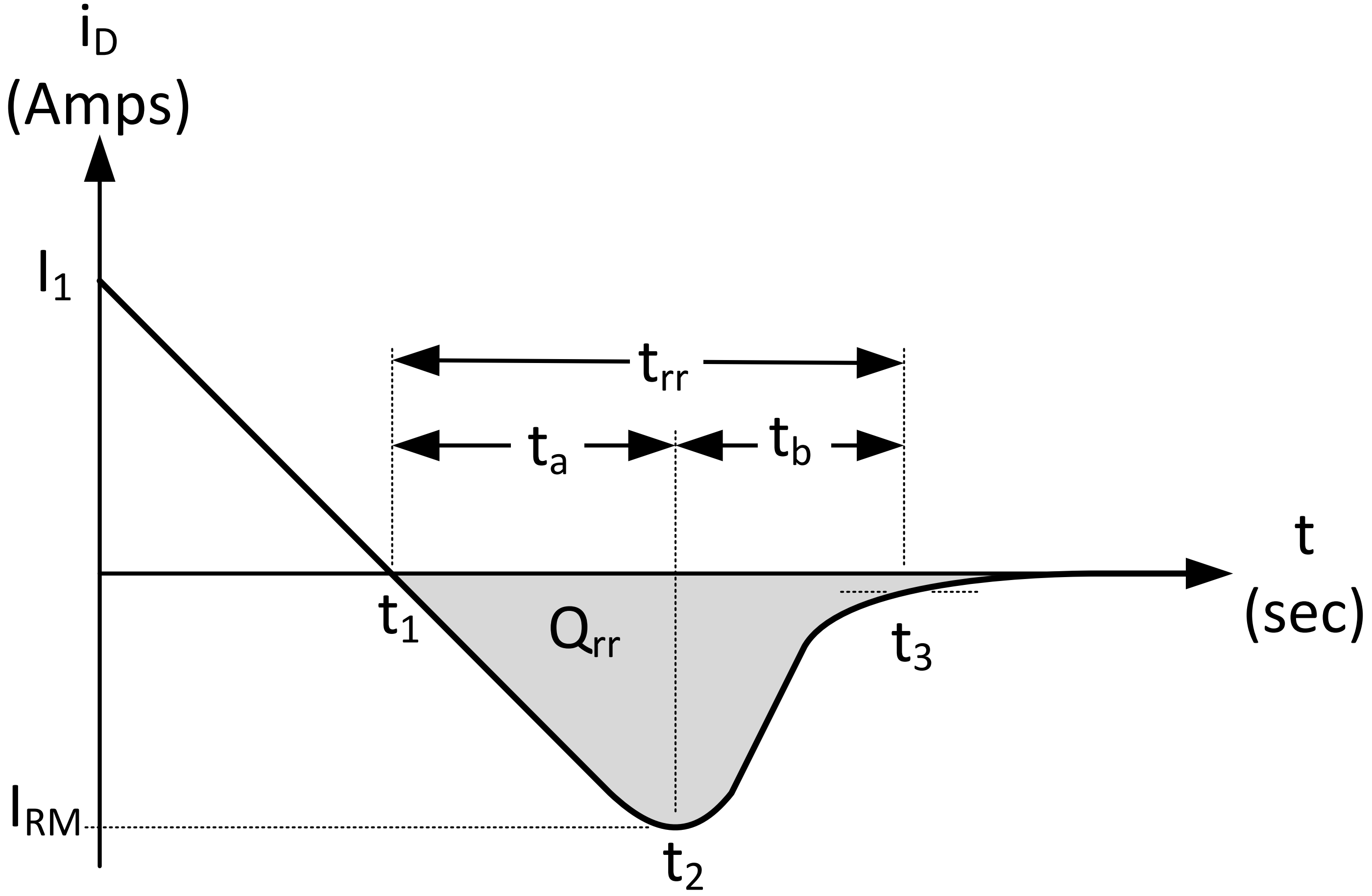
- Reverse breakdown voltage

- Maximum current

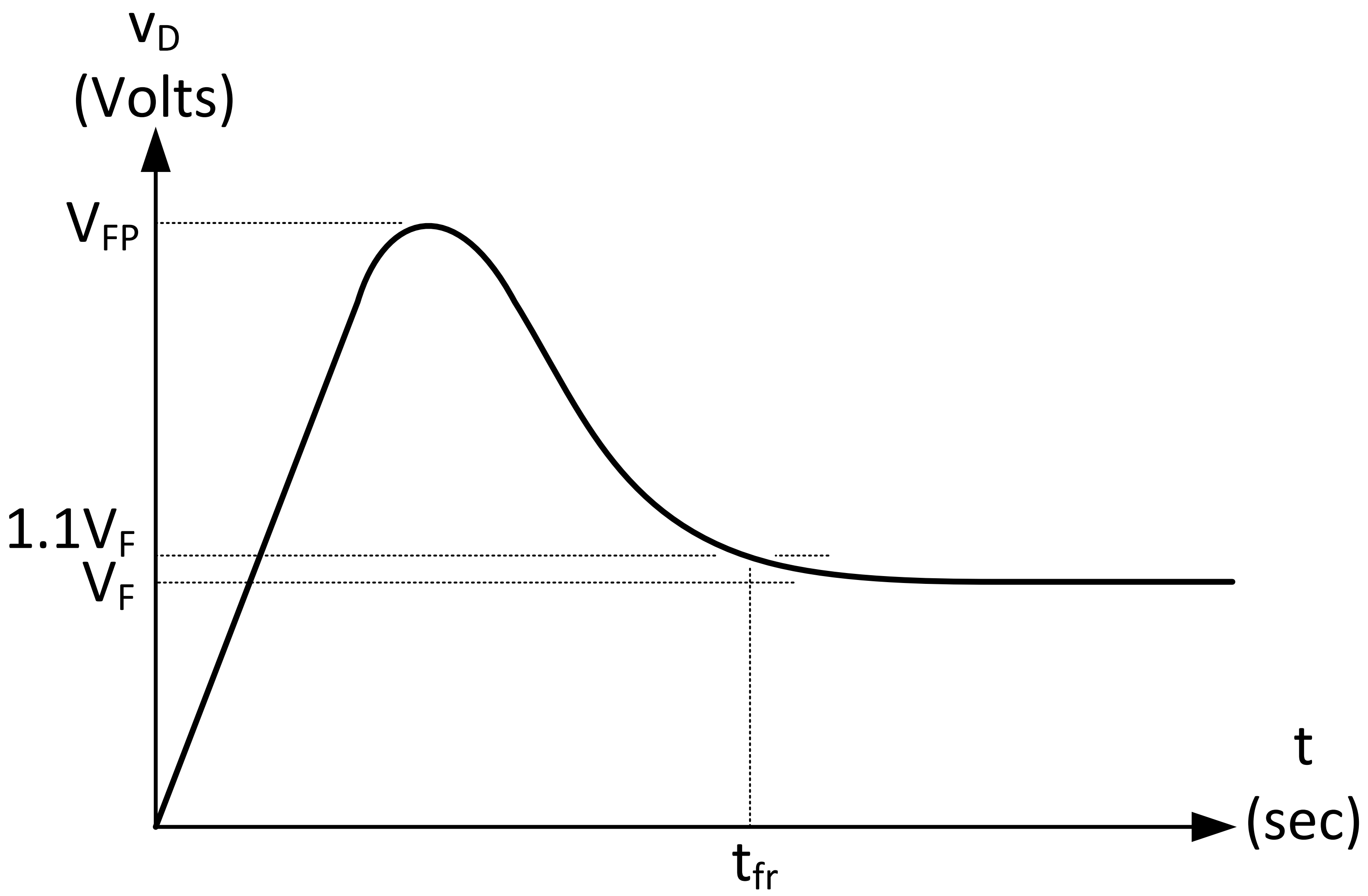
- Reverse recovery time

- Junction capacitance

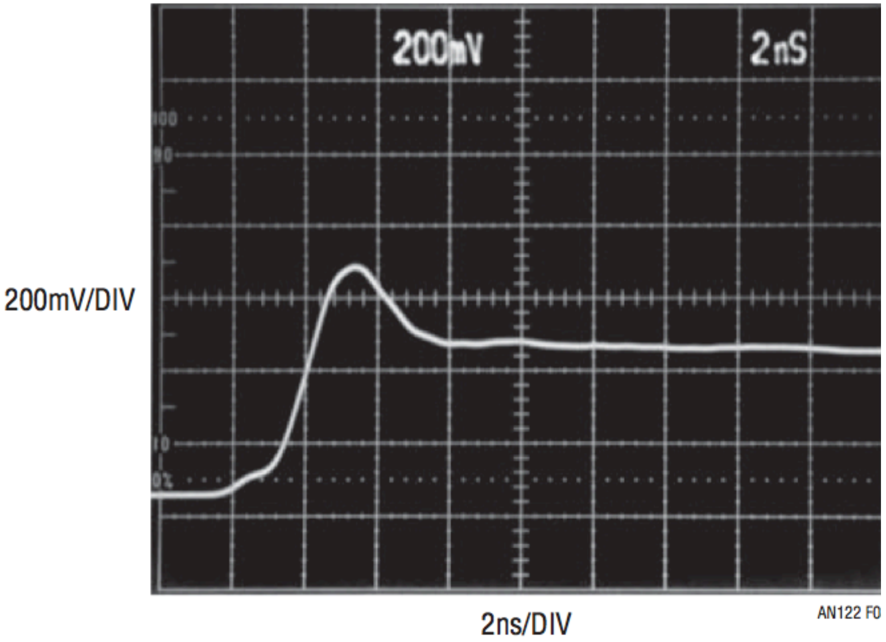
Diode Reverse Recovery



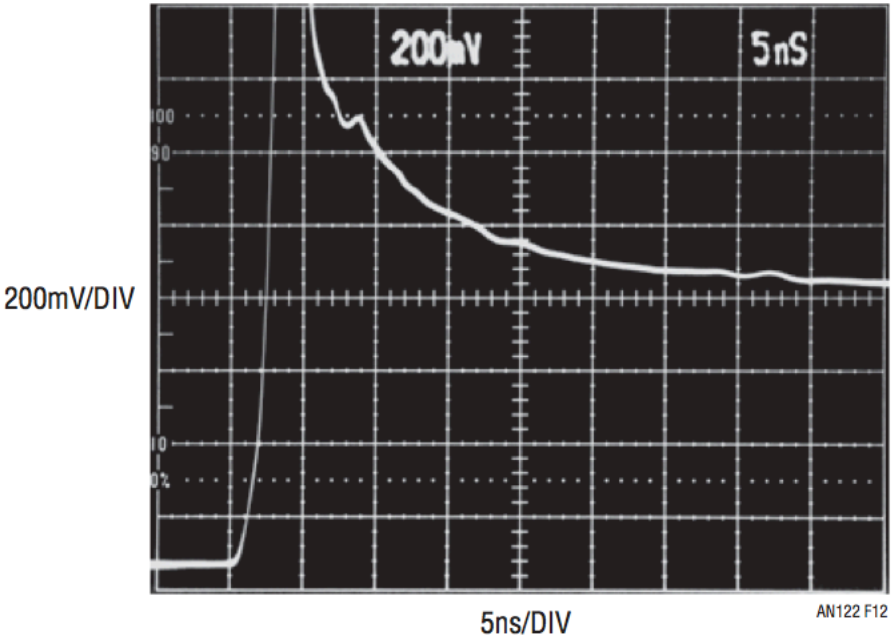
Diode Forward Recovery



Diode Forward Recovery

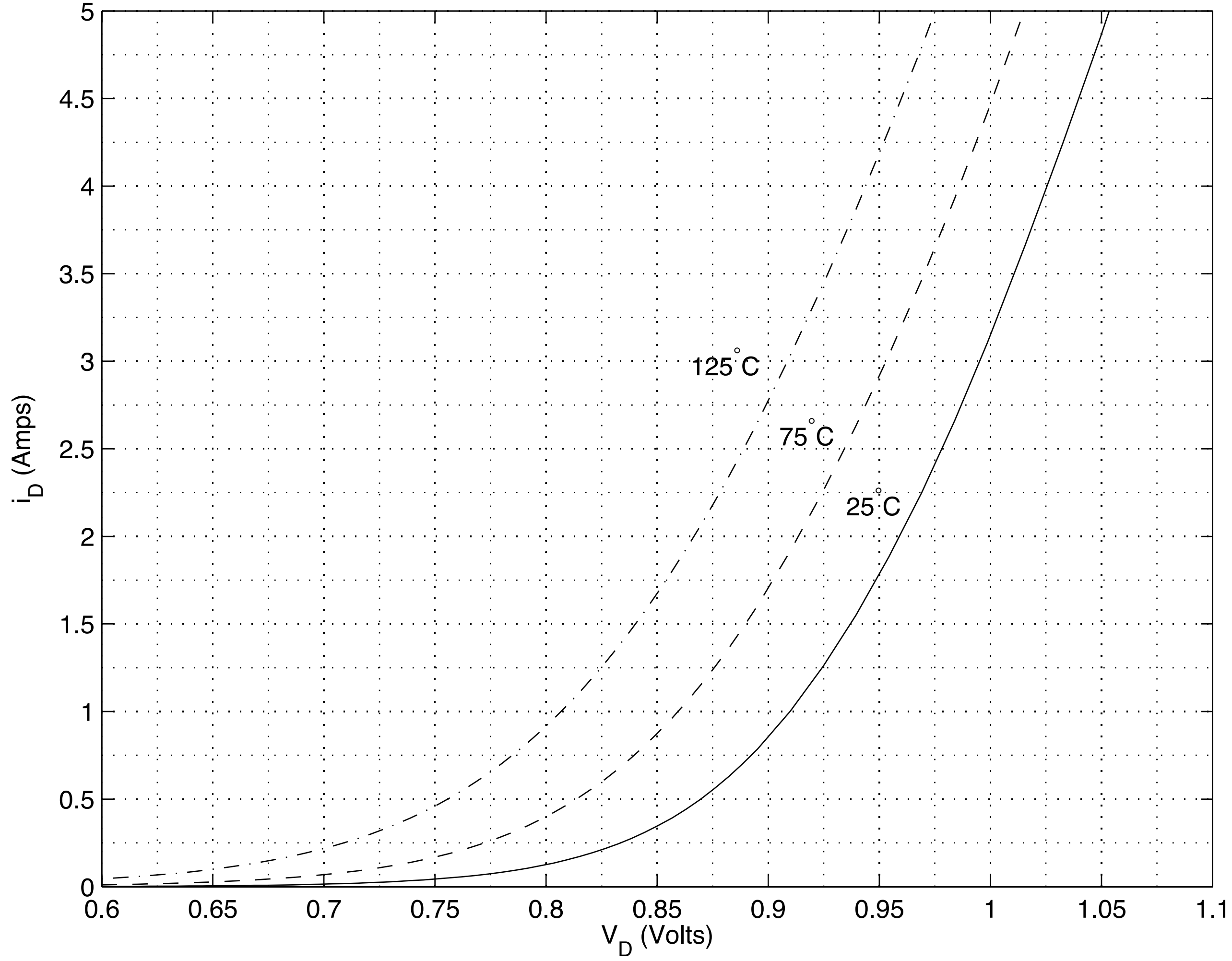


Good Diode



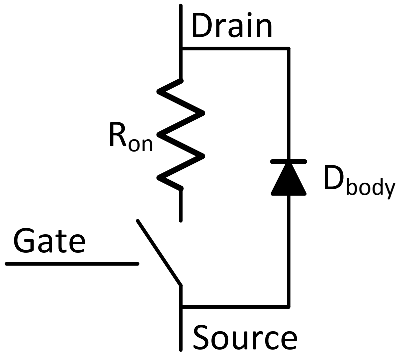
Bad Diode

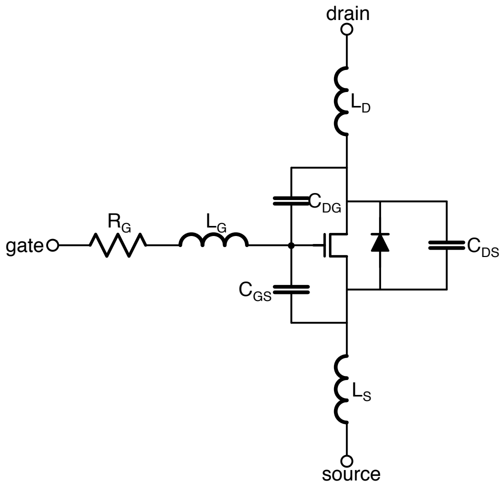
Two 2A Diodes < One 4A Diode

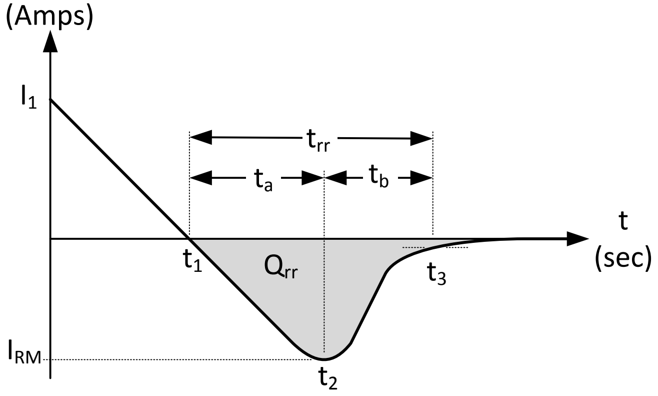


Summary – Power Devices

- Finite, non-zero
  - Switching time
  - Blocking voltage
  - On-voltage (resistance)
- Parasitics – L and C
- MOSFETs – switches
  - Turn on/off as fast as gate can be charged
  - $R = kV^2$
- Diodes
  - Self-controlled switches
  - Reverse recovery loss Q_{RR}

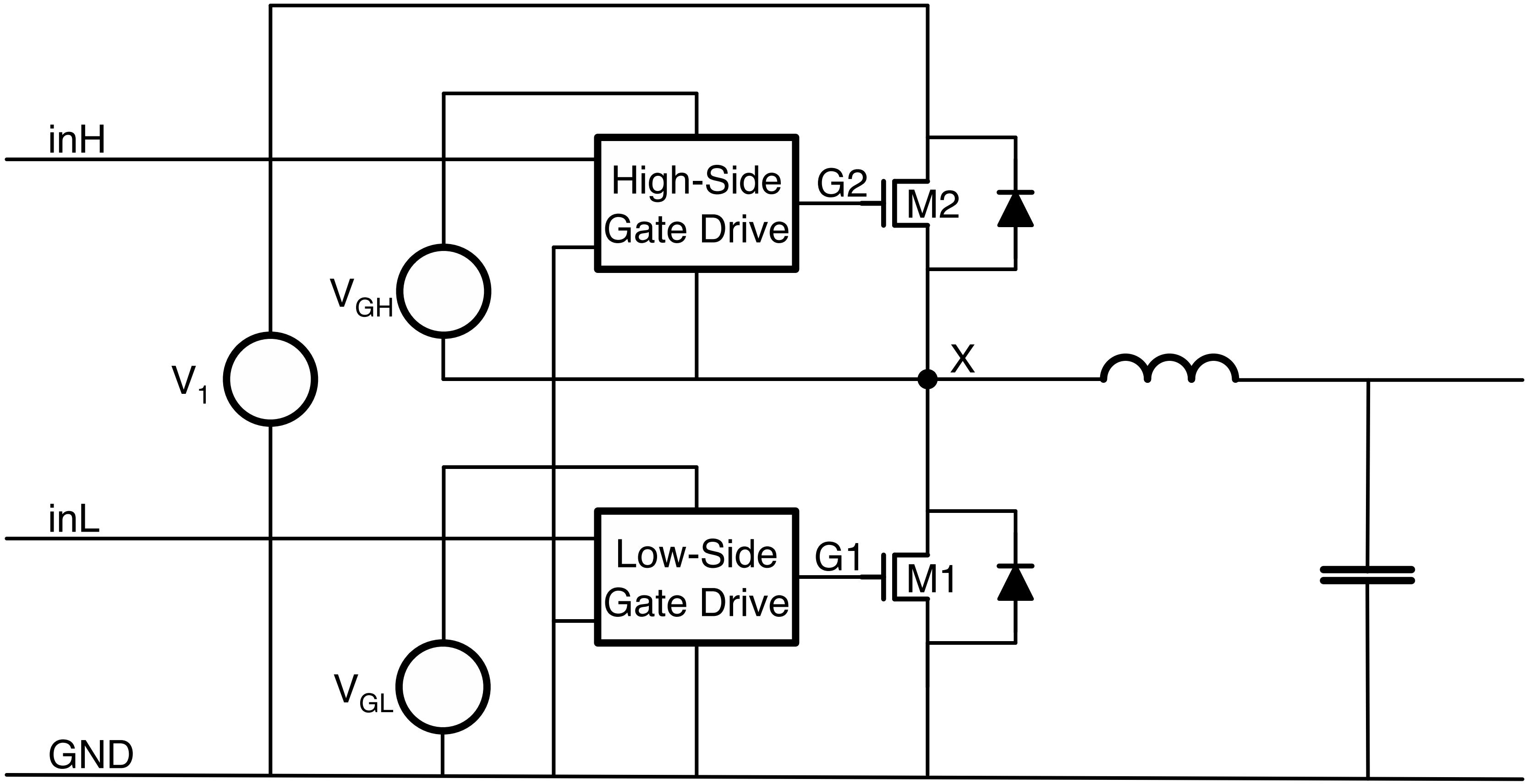




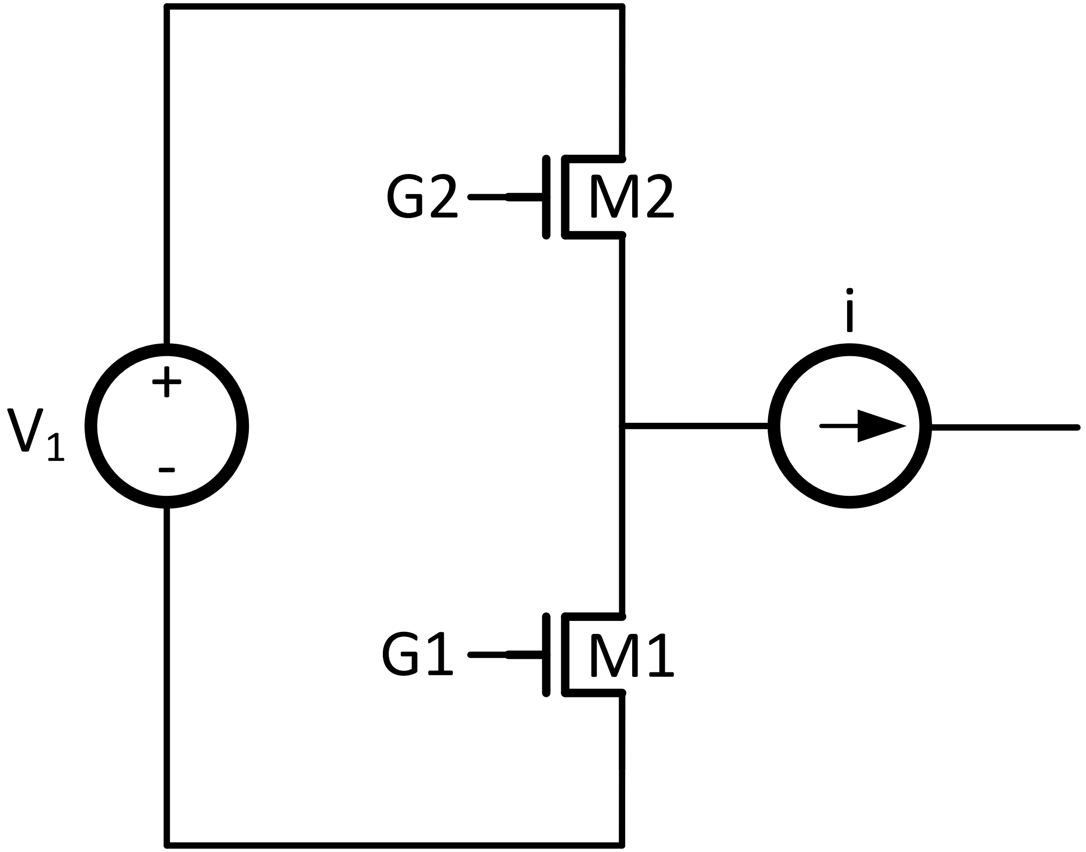


Power Circuits

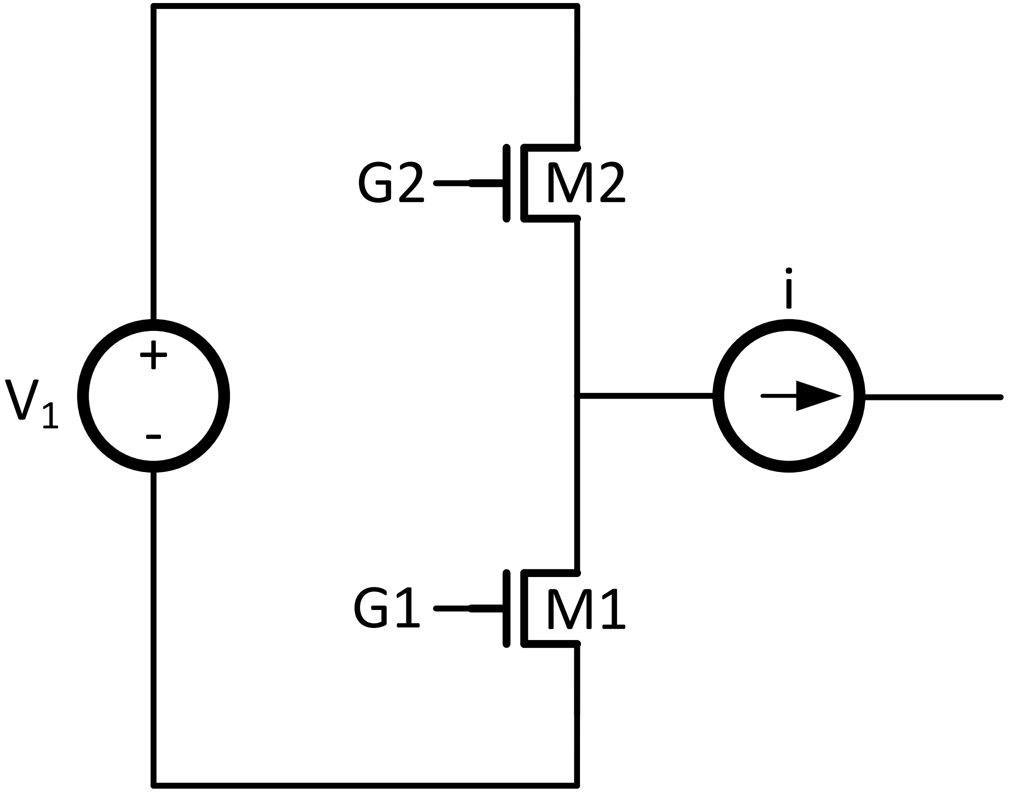
Practical Buck Converter



Simple Model



One Switch May be a Diode



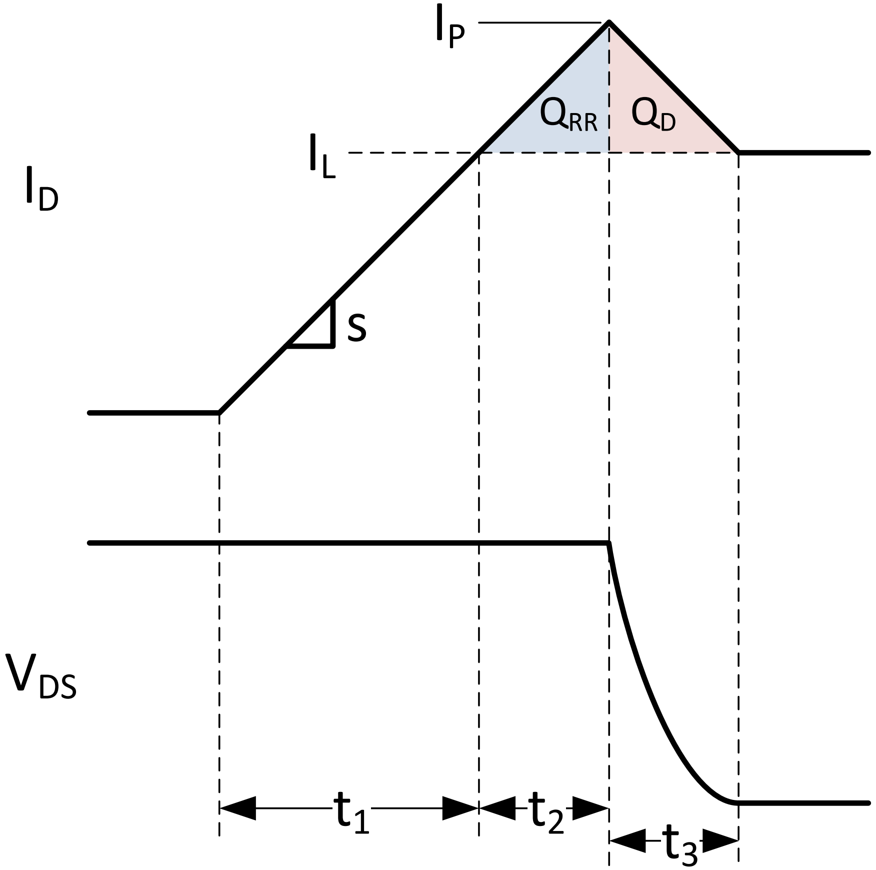
Lower switch for buck

Upper switch for boost

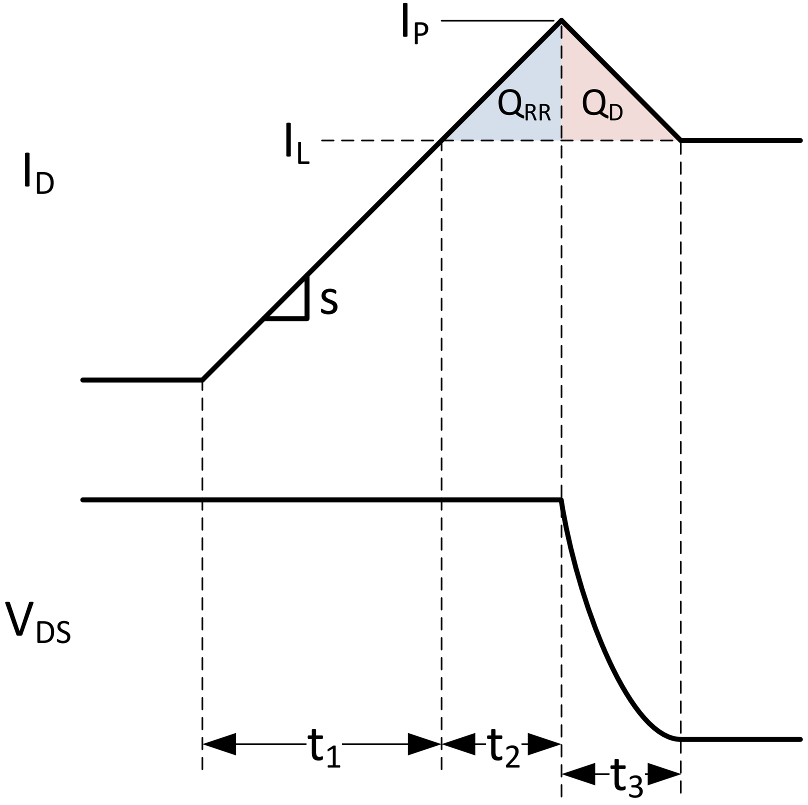
Other switch does most of the work

Synchronous rectification may be used to reduce loss

Turn-On Loss



Turn-On
Buck w/ Diode



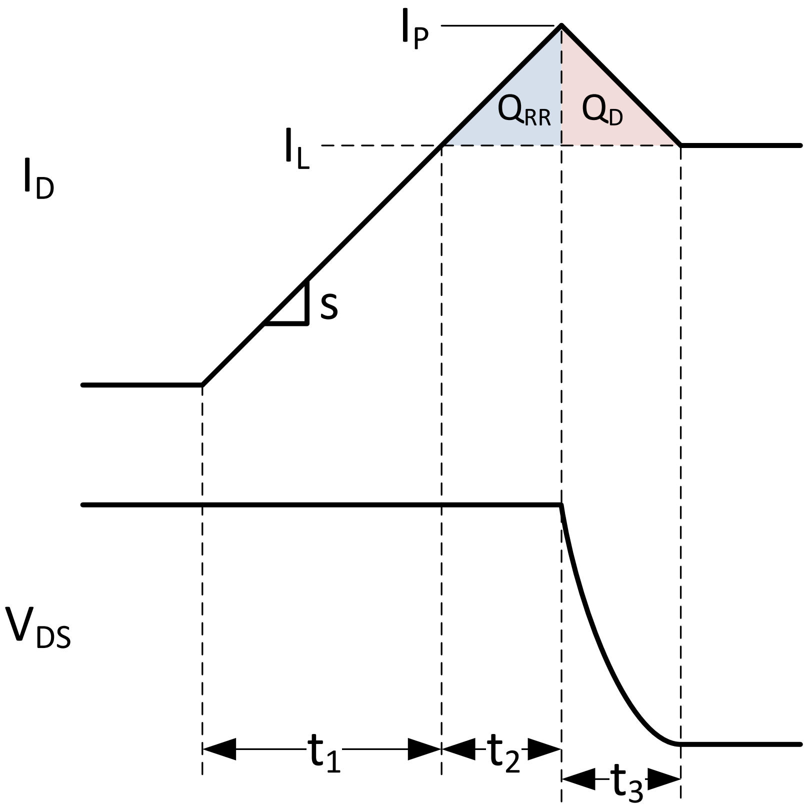
t_1 – ramp current to I_L

t_2 – diode reverse recovery

t_3 – discharge drain
capacitance

Current waveform in t_2 and t_3 may vary

Turn-On
Buck w/ Diode



$$t_1 = \frac{I_L}{s}$$

$$E_1 = 0.5 V_{DD} I_L t_1 = \frac{0.5 V_{DD} I_L^2}{s}$$

$$t_2 = \sqrt{\frac{2Q_{RR}}{s}}$$

$$E_2 = V_{DD} t_2 \left(I_L + 0.5 t_2 s \right)$$

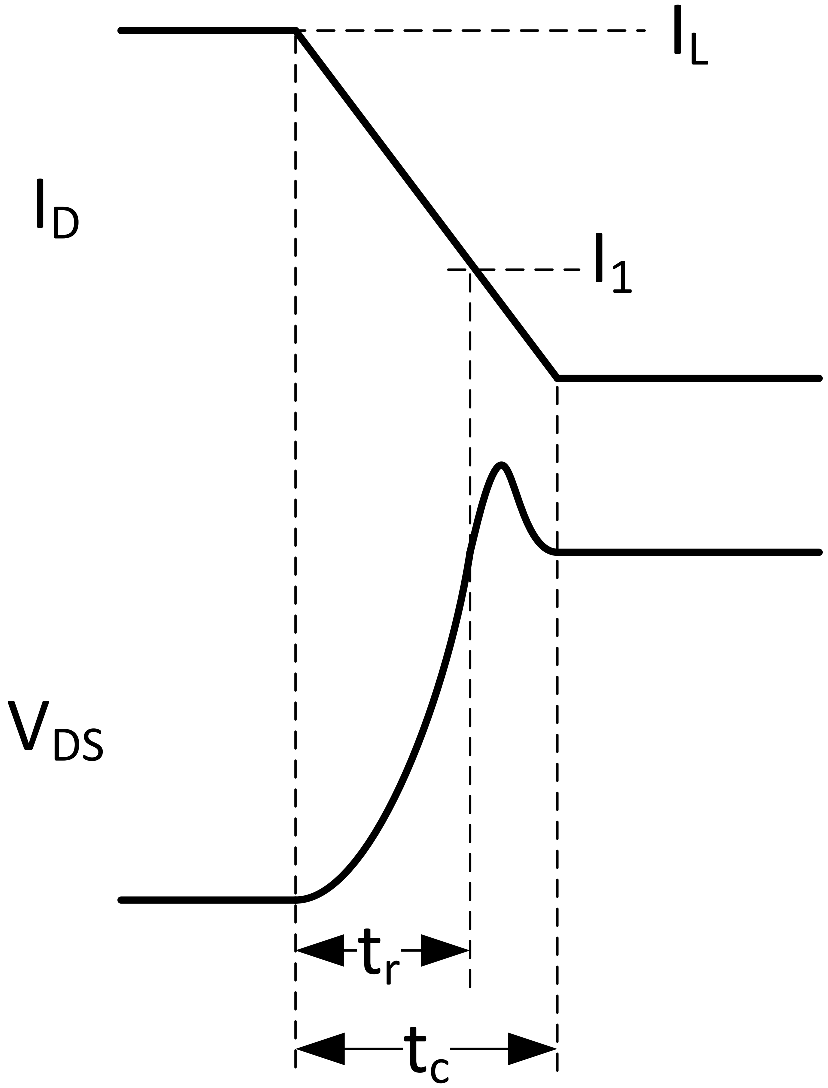
$$t_3 \approx \frac{2I_P}{Q_D}$$

T3 is upside down

T3 = 2Qd/Ip

$$E_3 = 0.5 V_{DD} Q_D + 0.33 V_{DD} I_L t_3$$

Turn-Off
Buck with Diode

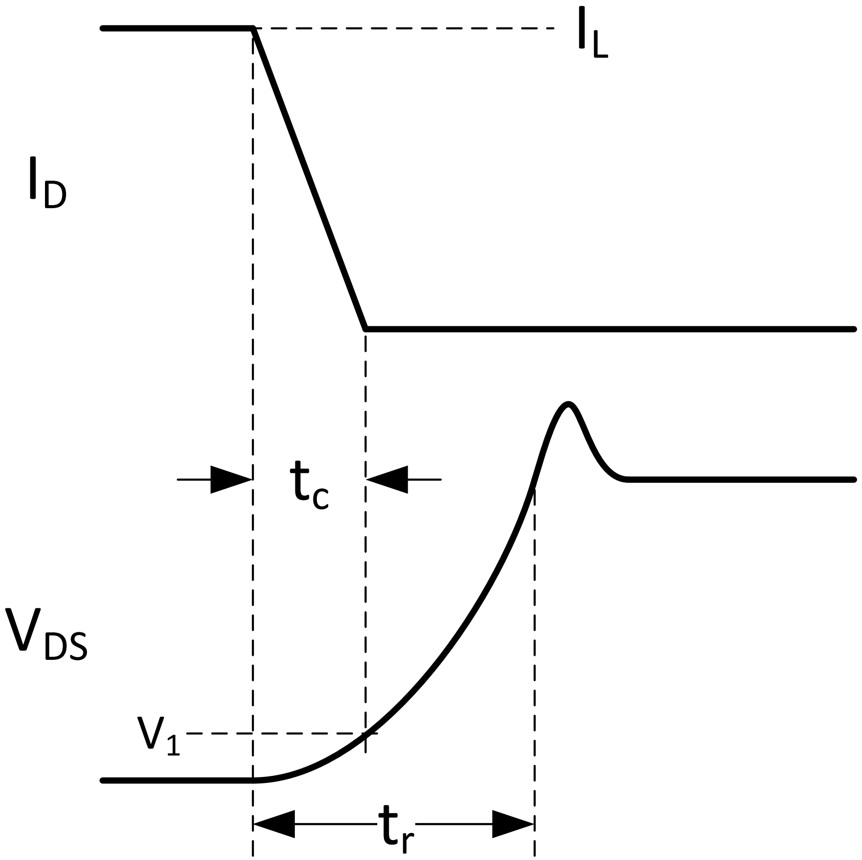


Excess current charges drain node.

Integrate to get switching energy

$$E = V_{DD} t_r \left(\frac{1}{6} I_L + \frac{1}{3} I_1 \right)$$

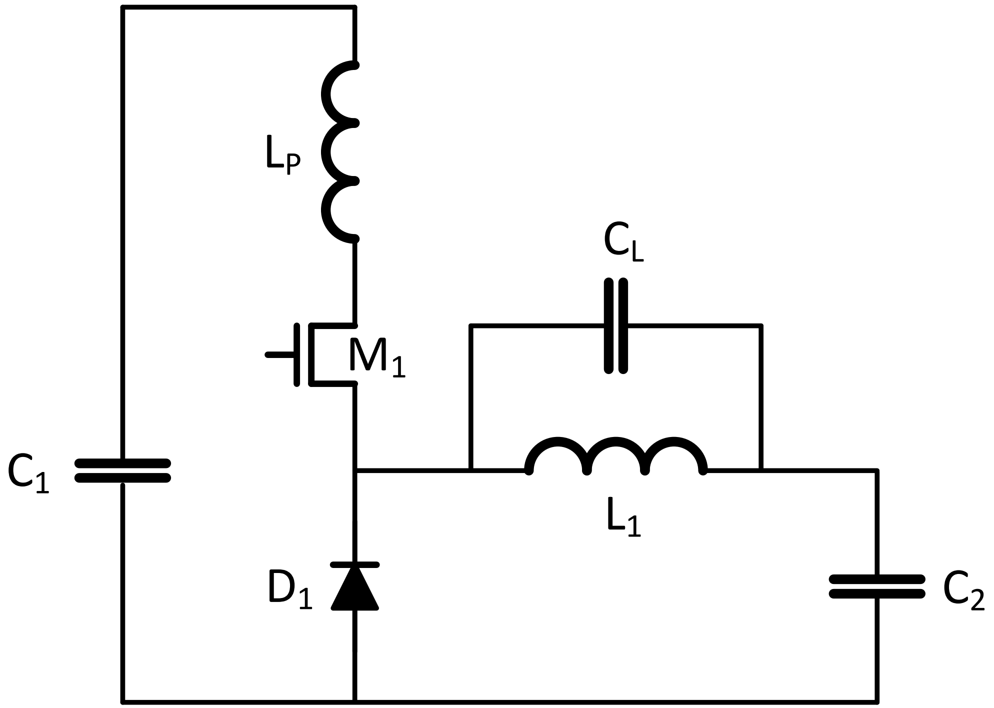
Turn-Off
Buck with Diode



If current ramps faster than voltage nearly ZVS

$$E = \frac{1}{6} V_1 I_L t_c$$

Parasitic Losses

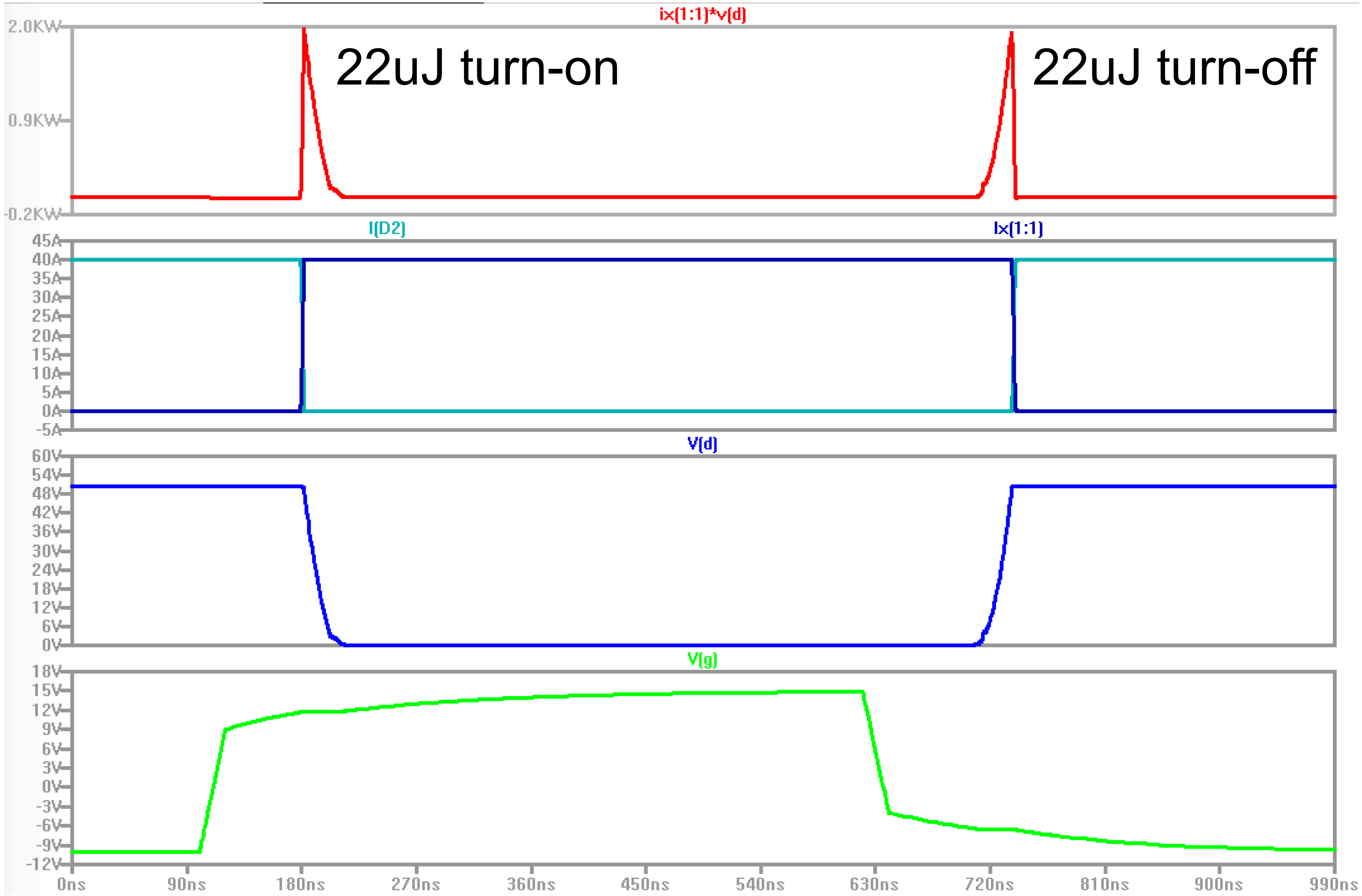


Switching Loss with SPICE

Simulation Setup

- Boost configuration 40A, 50V
- IRLB3036 – 60V, 2mΩ FET

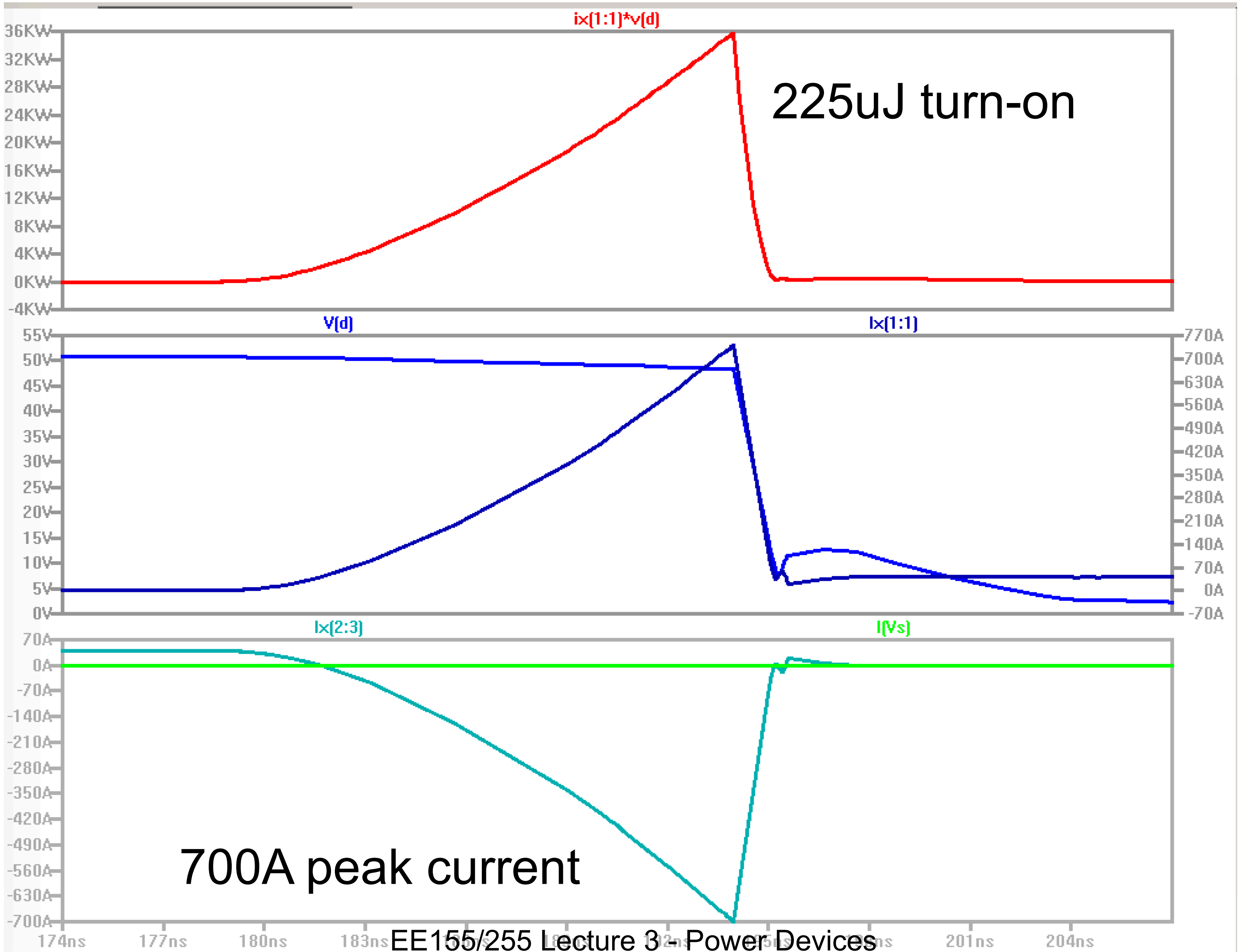
Ideal Diode, No Parasitics



22uJ turn-on

22uJ turn-off

Body Diode of IRLB3036

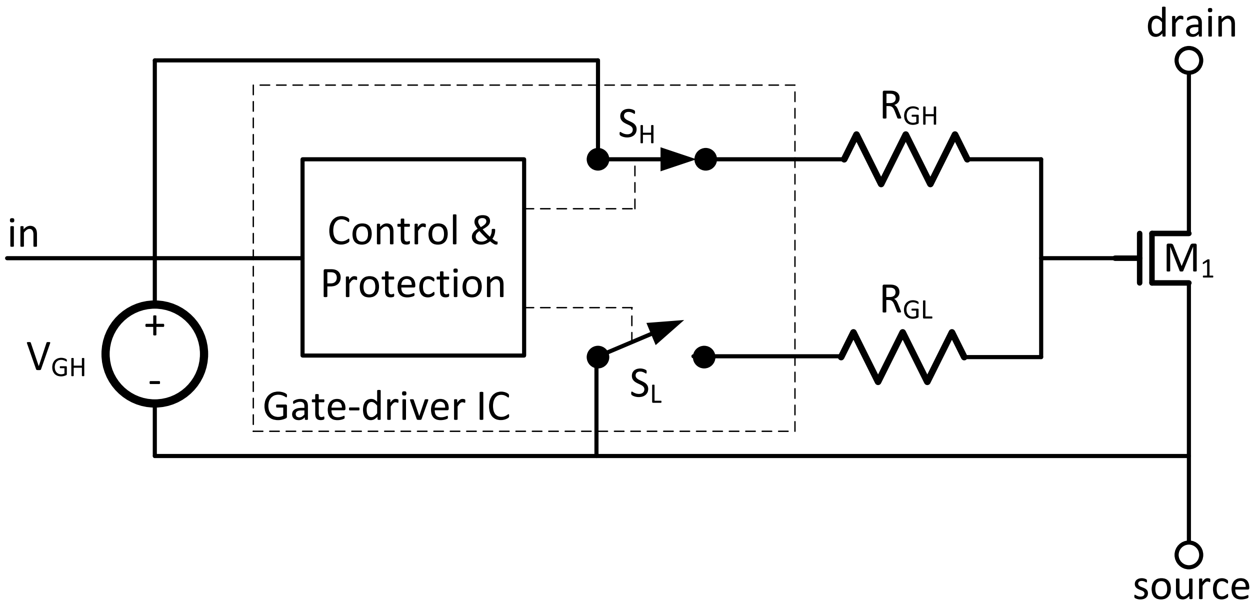


225uJ turn-on

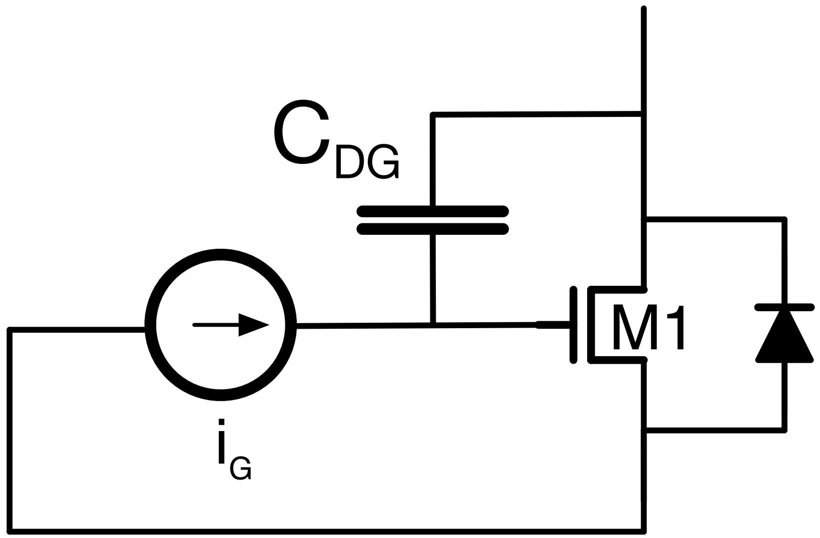
700A peak current

Gate Drive

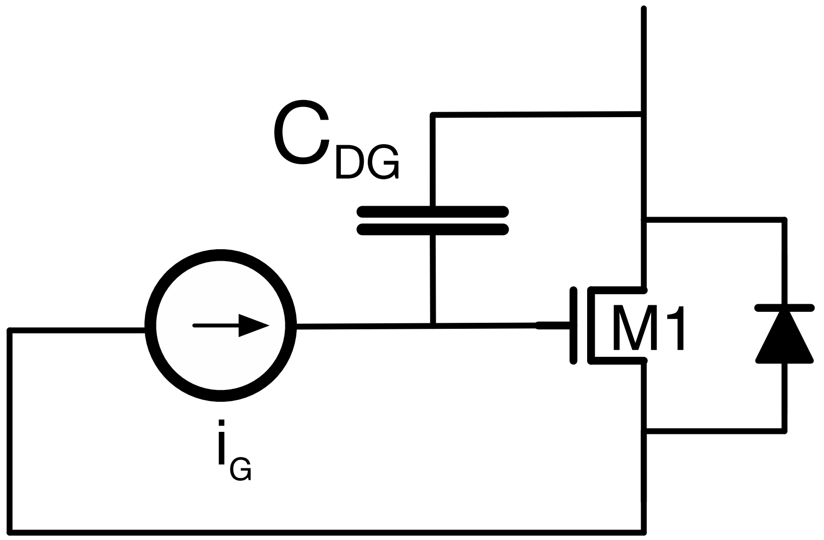
Gate Driver


drain
R_{GH}
S_H
in
Control &
Protection
M_1
R_{GL}
V_{GH}
+
-
S_L
Gate-driver IC
source

Effect of Miller Cap on Rise Time



Effect of Miller Cap on Rise Time

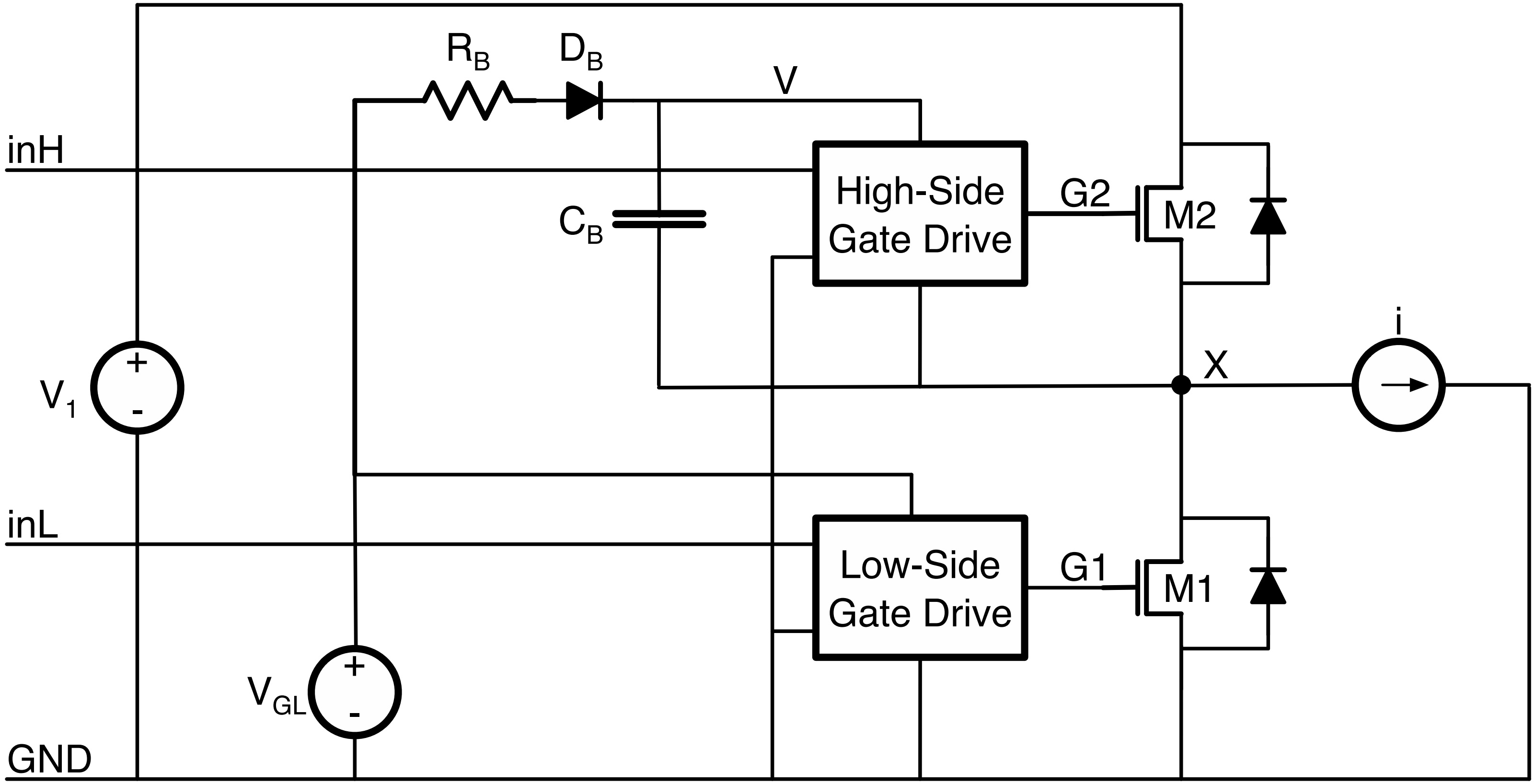


$$\frac{dV_D}{dt} = \frac{i_G}{C_{DG}}$$

$$\Delta t = \frac{\Delta V_D C_{DG}}{i_G}$$

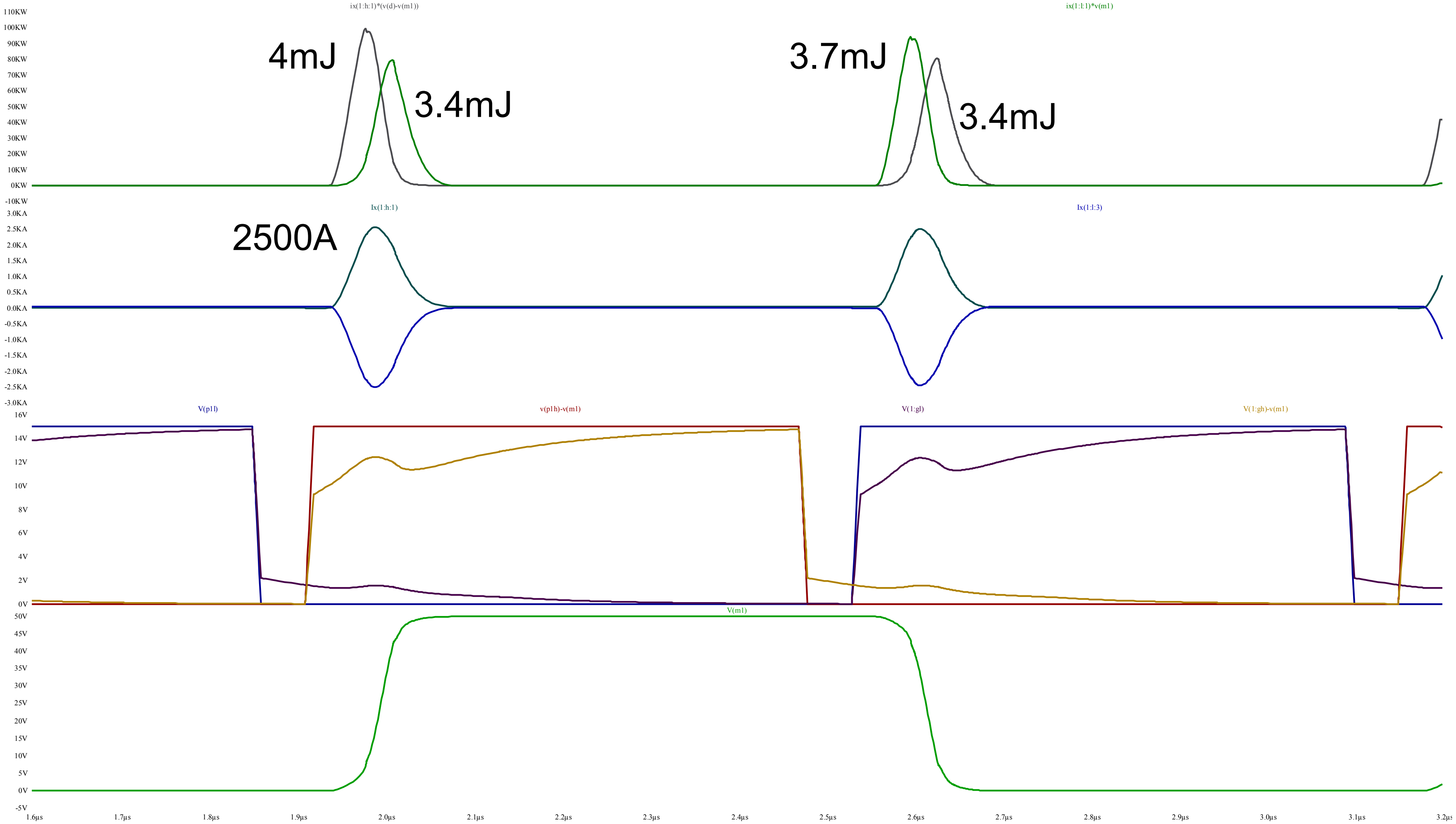
Example: i = 0.5A, C = 100pF, ΔV = 400V

Bootstrap Supply

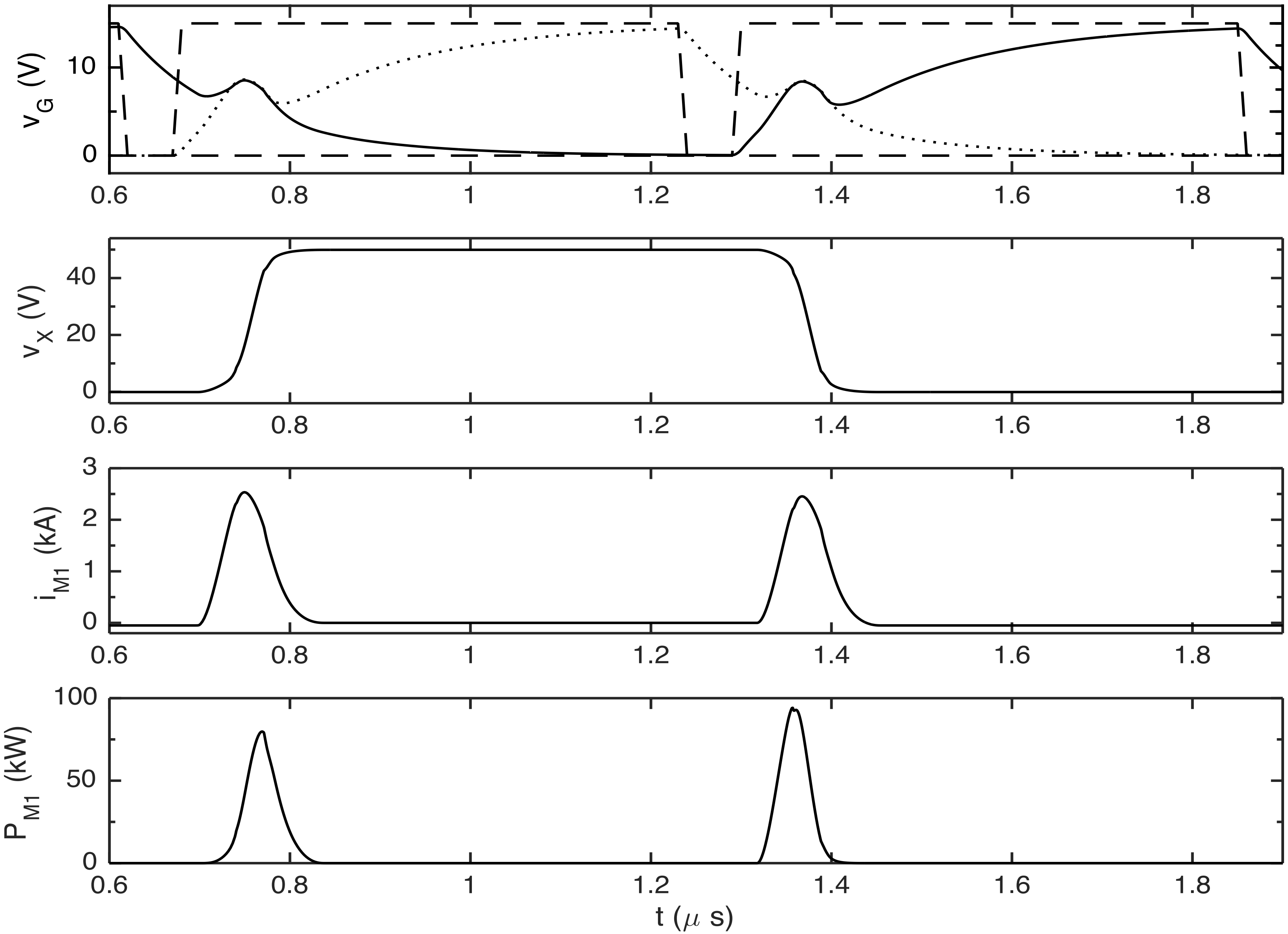


Dead Time

Too Little Dead Time (11.6kW loss)

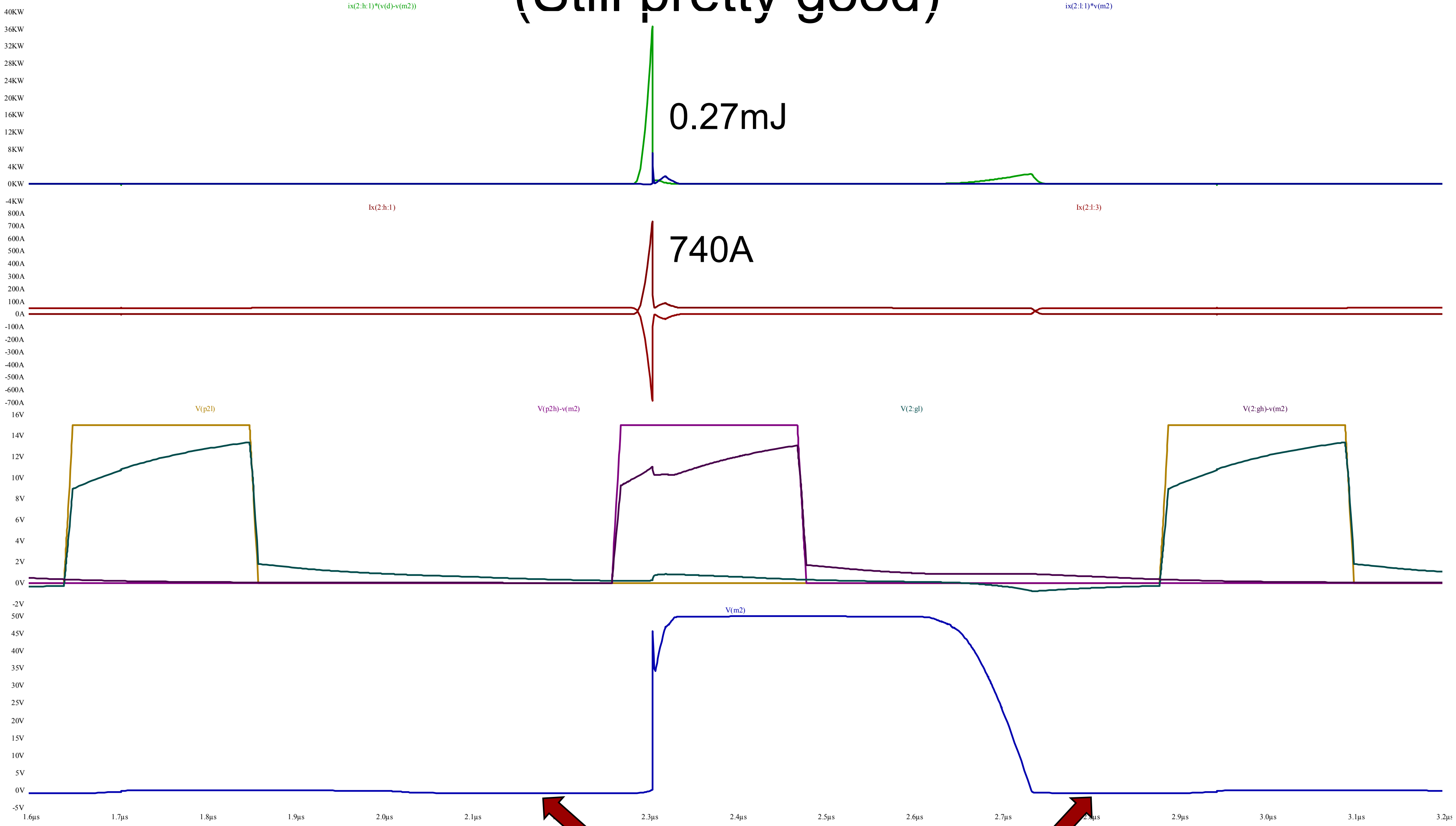


The “Real” Gate Signal



Too Much Dead-Time (340W loss)

(Still pretty good)

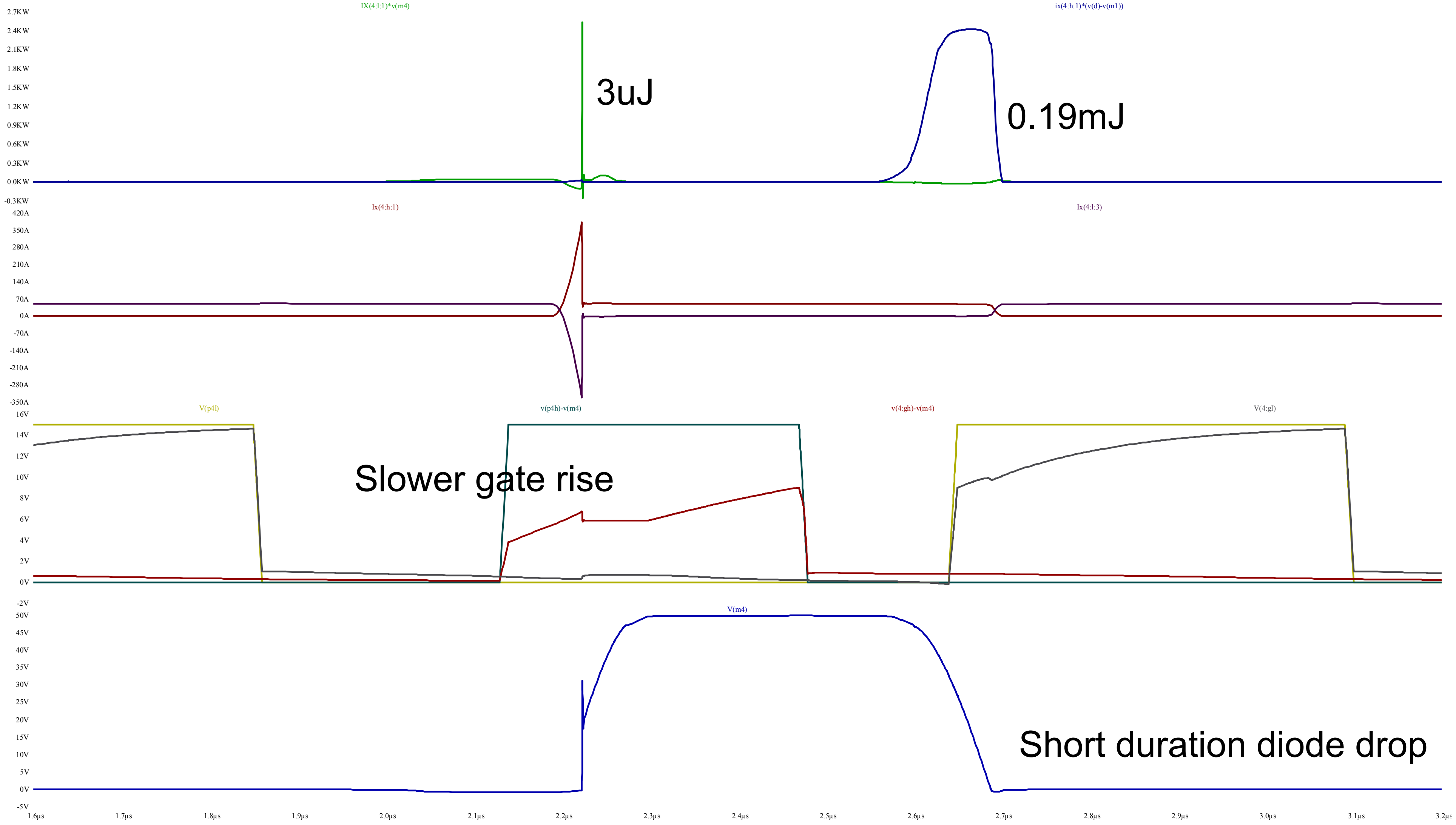


0.27mJ

740A

700mV diode drop

Just Right (310W loss)



3uJ

0.19mJ

Slower gate rise

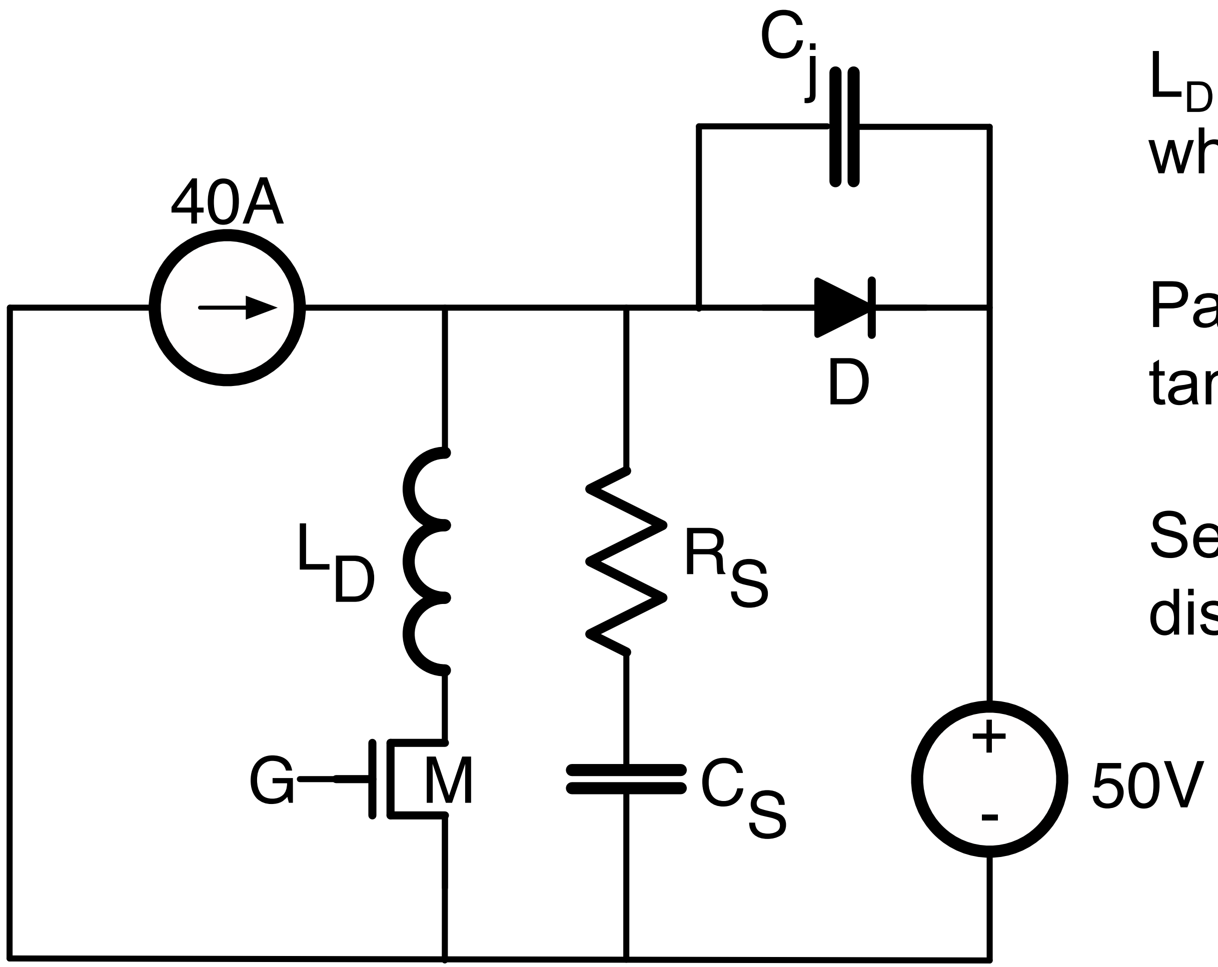
Short duration diode drop

Conduction loss is $I^2R = 50^2 \times 1m \sim 25W$

Too much dead time is better than too little

Snubbers

Dampen Ringing Nodes

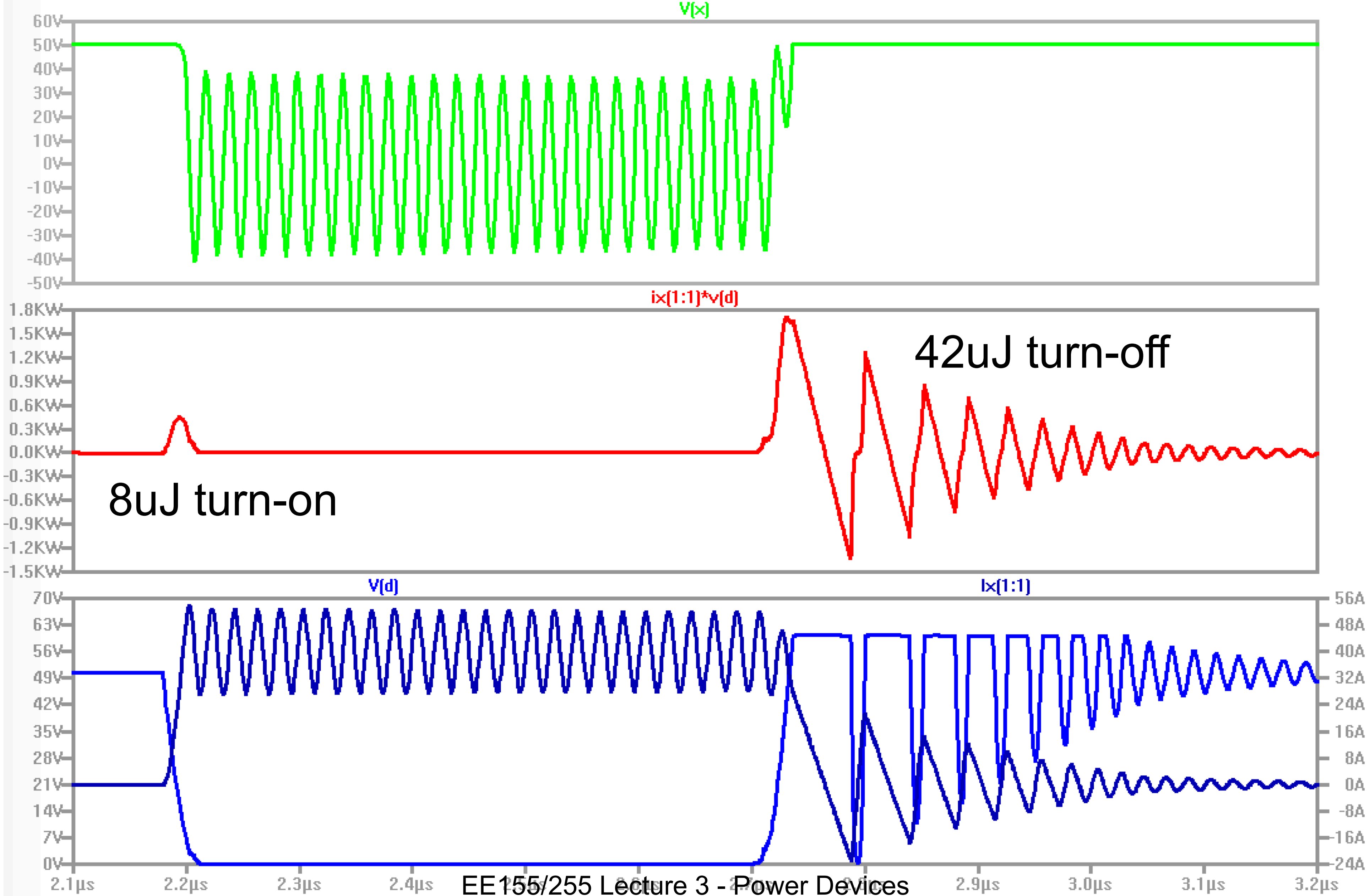


L_D and C_j resonate when M is on

Parallel RS dampens tank

Series C_S limits dissipation

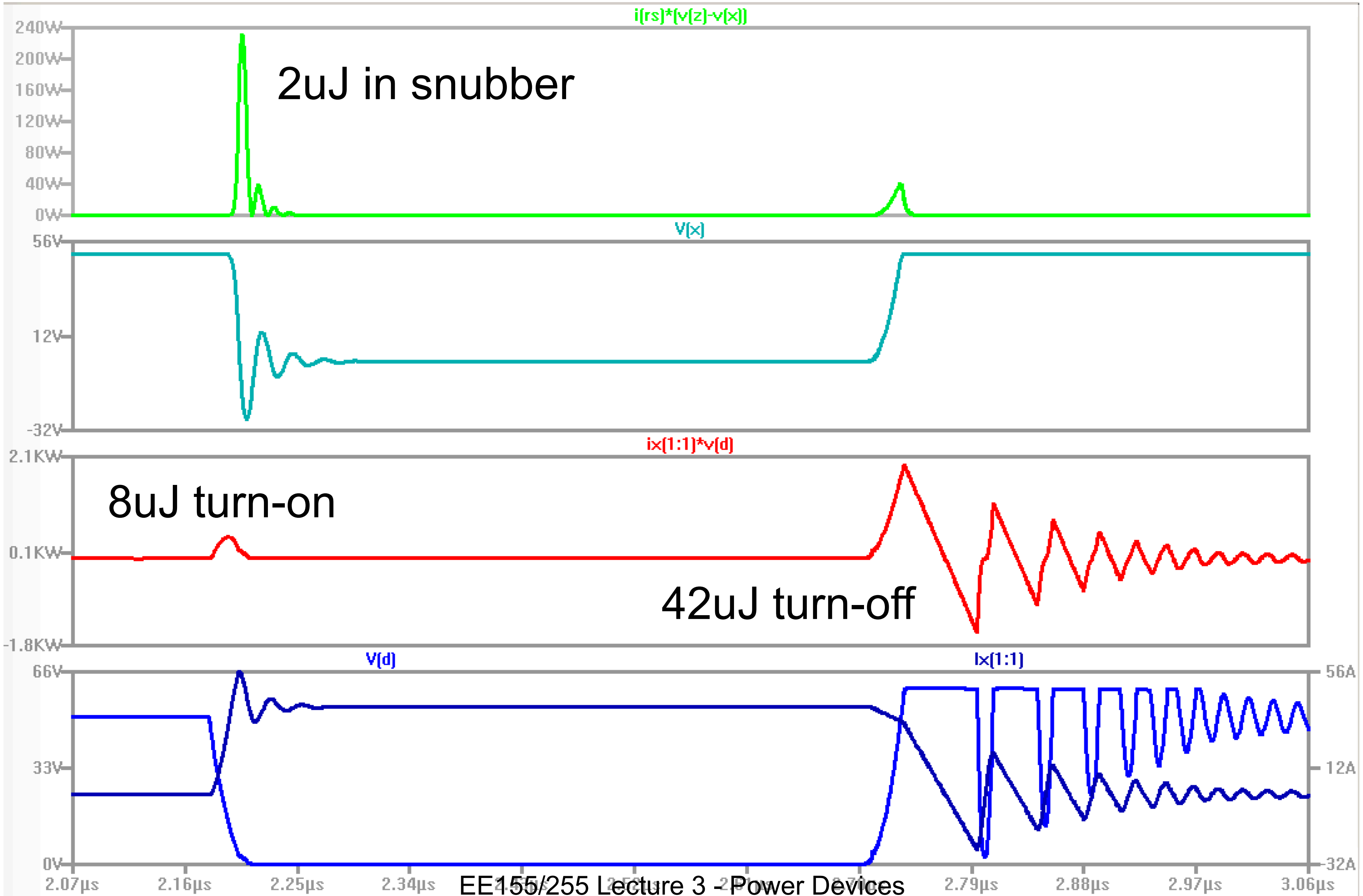
Inductance on Drain



42uJ turn-off

8uJ turn-on

With Snubber (1nF, 5Ω)

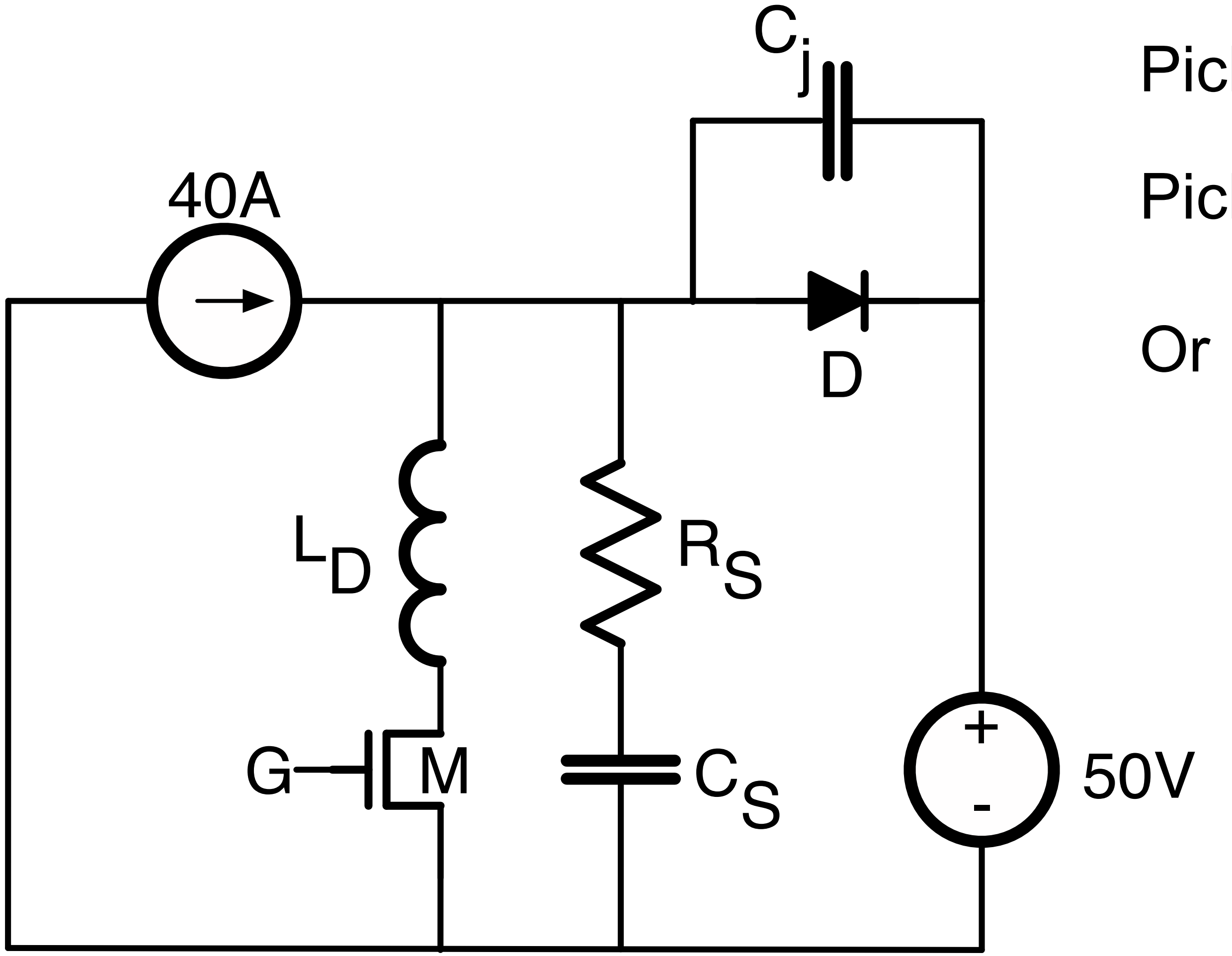


2uJ in snubber

8uJ turn-on

42uJ turn-off

Design Procedure



Pick $R_S \sim 1/\omega C_j$

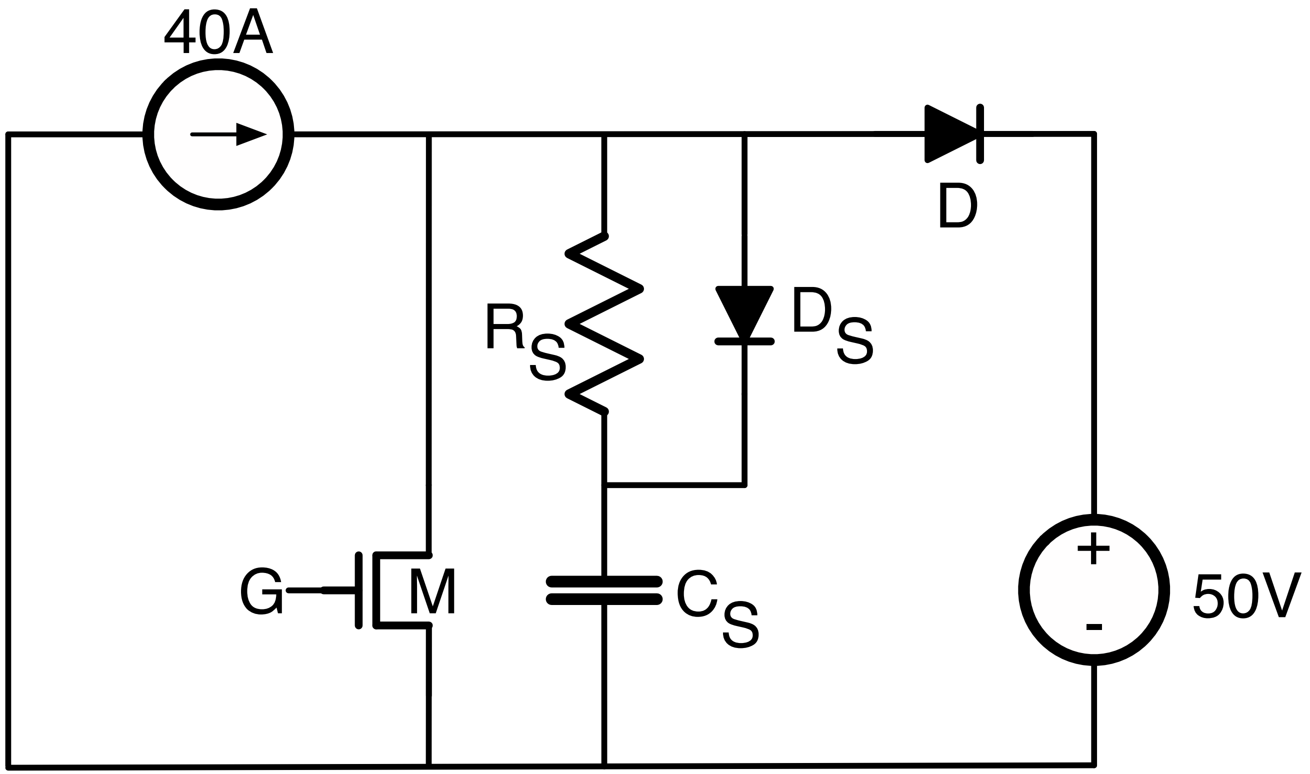
Pick C_S so

$\tau >= \pi/\omega$

Or

$E_s = C_S V^2/2$

Move Turn-Off Dissipation to Passive Device



C_S slows rise time of drain

$C_SV^2/2R_S$ dissipated in R_S when C_S discharges

Rarely used today

Other forms slow fall time and rising/falling current

Summary

- Real switches have limitations
  - Conduction losses (R_{ON} for FETs, V_{CE} for IGBTs, Diode drop)
  - Switching losses (finite t_{on}, t_{off}, t_{rr})
    - With current source load, current ramps, then voltage falls
    - And voltage rises before current falls
    - May be dominated by reverse recovery time
    - Complicated by inductance
- Power MOSFETs
  - Switch quickly, have linear I-V, integral diode
- IGBTs
  - Diode-like I-V, slower switching
- Diodes
  - Have reverse recovery time
- Switches operate in pairs
  - For one-way converters, one switch may be a diode
  - Synchronous rectification – make both switches FETs to reduce loss
  - Need “dead time” to avoid “shoot through” current
- Gate-drive circuits control rise and fall times
- Bootstrap supply needed for high-side driver
- Snubbers dampen voltage and current transients

Course at a Glance

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Wrapup						
18	11/29/17	Guest Lecture				C3		
19	12/4/17	Guest Lecture						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						