You said f_{sw} ↑ better but . . .

4.3.4. Efficiency vs. switching frequency

W_{on} & W_{off} often   Choose diode type to set Q_{rr}

Add up all of the energies lost during the switching transitions of one switching period:

DC loss $$W_{tot} = W_{on} + W_{off} + W_D + W_C + W_L + \ldots$$ L-C Parasitics

Average switching power loss is

AC loss $$P_{sw} = W_{tot}\, f_{sw}$$

Total converter loss can be expressed as

$$P_{loss} = P_{cond} + P_{fixed} + W_{tot}\, f_{sw}$$

f > 500 kHz often the largest term for loss

BUT

SBH to the rescue

where P_{fixed} = fixed losses (independent of load and f_{sw})
P_{cond} = conduction losses

$$P_{DYNAMIC} = \frac{1}{2}(t_R + t_F) I_{LOAD} V_{IN} f_S + V_{DRIVE} Q_G f_S$$

$$P_{CONDUCTION} = I_{LOAD}^2 R_{DS(ON)} \Delta PWM$$

$$P_{DISSIPATION} = P_{DYNAMIC} + P_{CONDUCTION}$$

Gate Drive losses

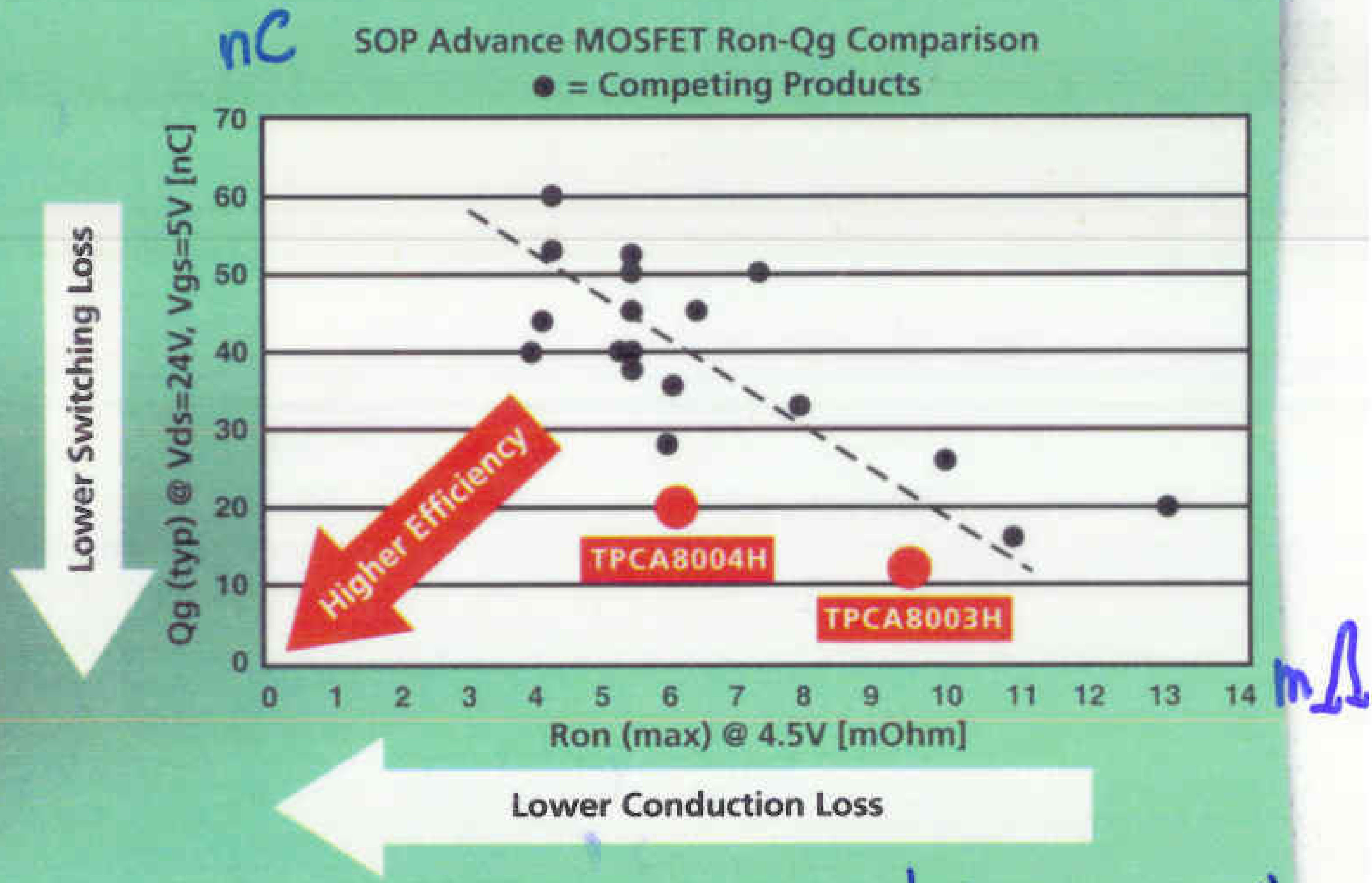
Q_G small lower losses

Want small

depend on Q_G

$R_{DS}(ON) * Q_G$

Product should be small!



$R_{DS(on)} * Q_g$ want's to be small

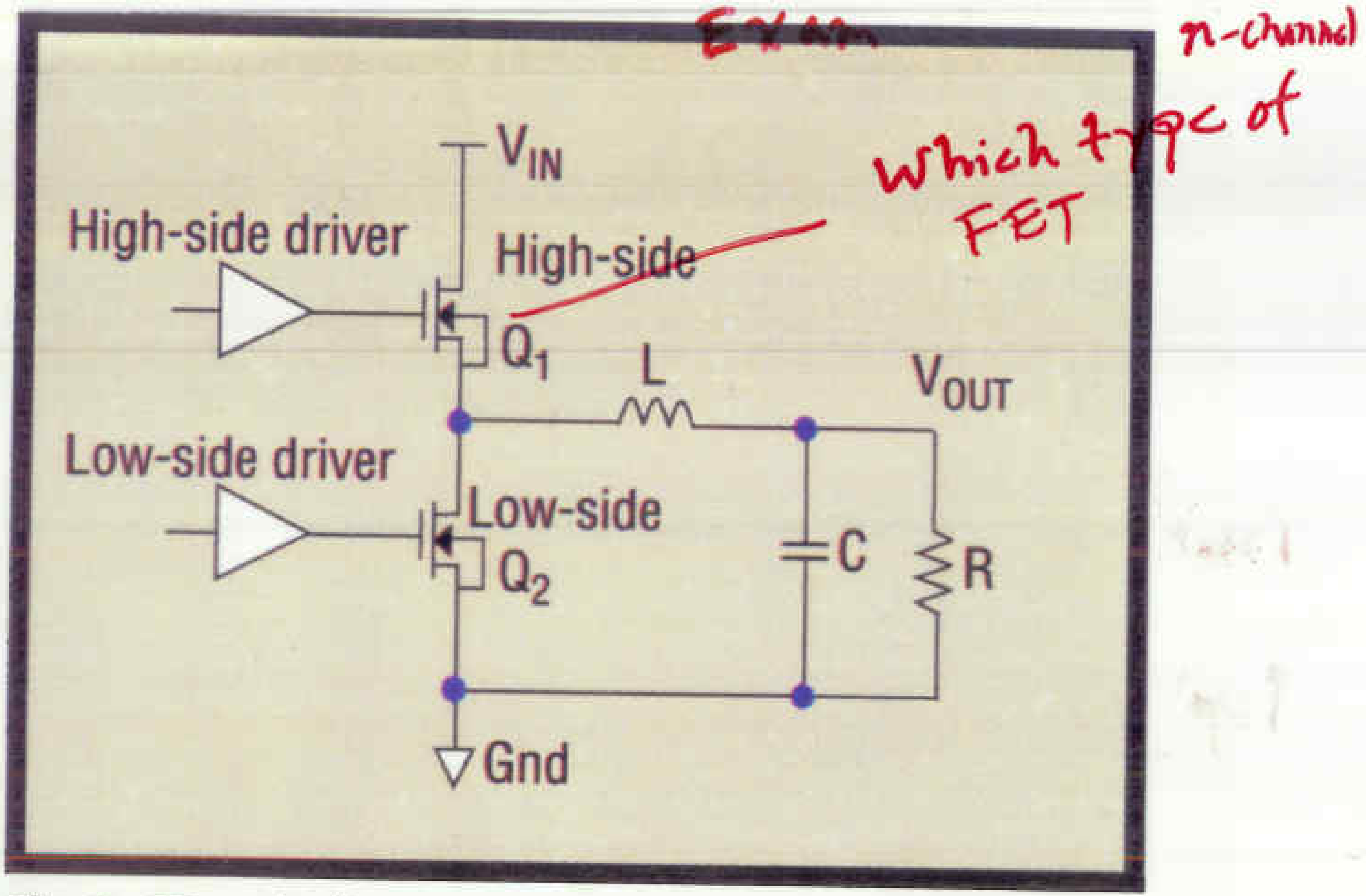
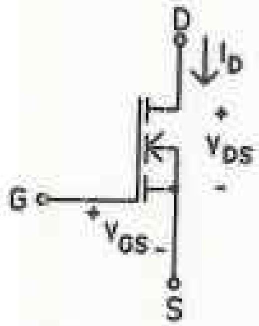
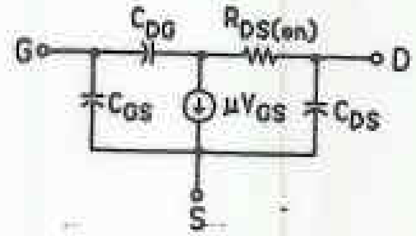


Fig. 1. *Circuit diagram of dc-to-dc synchronous buck converter.*

Optimized W-gated Trench



Symbol

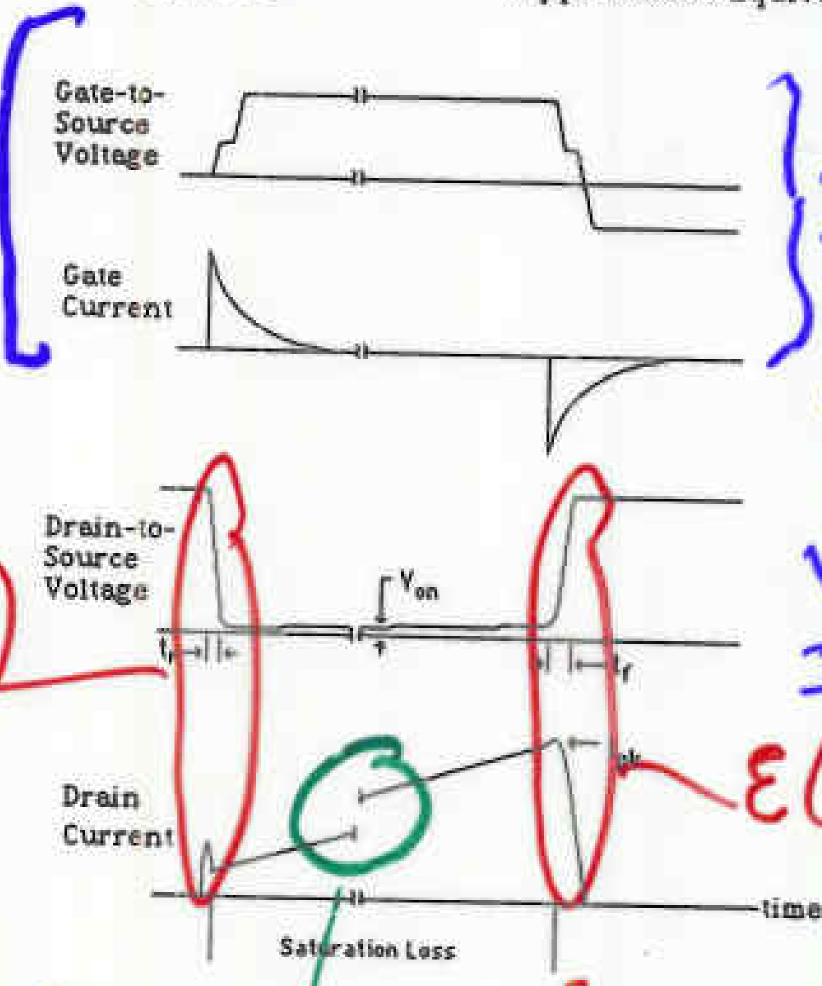


Approximate Equivalent Circuit

Gate Drive Power

$P = f_{sw}[E_{on} + E_{off}]$

neglect as V_G, I_G are low



Von rises as Ion ramps up

Waveforms for a power MOSFET in a PWM switching power supply.

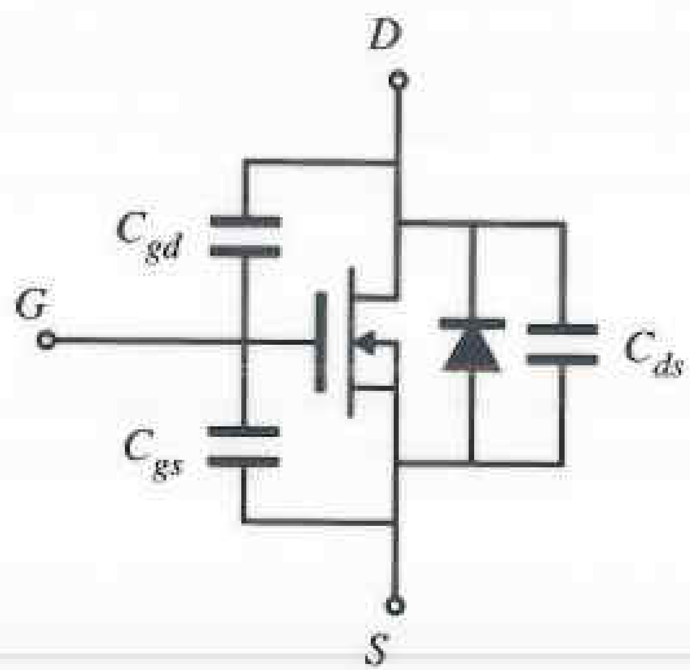
$P(\text{sw loss}) = f_{sw}[E(\text{on to off}) + E(\text{off to on})] + ?$

0 Not in Erikson

These I_d and V_{ds} waveforms will allow us to calculate switch loss for each switching cycle. The cycle includes two parts as each switch alternates on and off alternatively. We neglect switch driver losses for now.

$\frac{di}{dt}$ limited by $\frac{V}{L}$

A simple MOSFET equivalent circuit

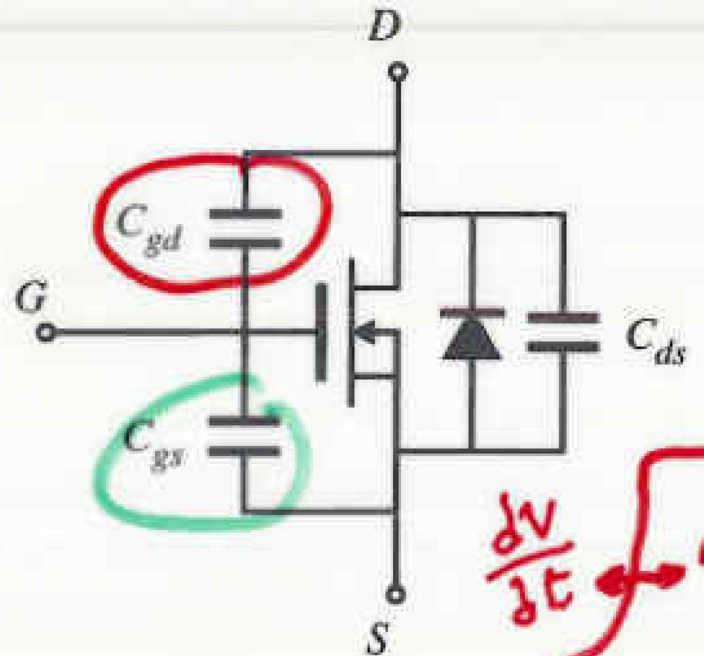


- C_{gs} : large, essentially constant
- C_{gd} : small, highly nonlinear
- C_{ds} : intermediate in value, highly nonlinear
- switching times determined by rate at which gate driver charges/discharges C_{gs} and C_{gd}

$$C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1 + \frac{v_{ds}}{V_0}}}$$

$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0'}{\sqrt{v_{ds}}}$$

A simple MOSFET equivalent circuit



- C_{gs} : large, essentially constant
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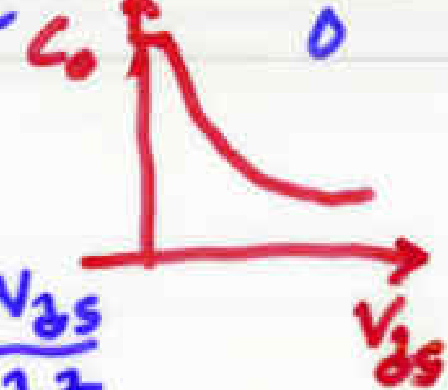
$$C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1 + \frac{v_{ds}}{V_0}}}$$

$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0'}{\sqrt{v_{ds}}}$$

MOSFET nonlinear C_{ds}

Approximate dependence of incremental C_{ds} on v_{ds} :

$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0'}{\sqrt{v_{ds}}}$$



Energy stored in C_{ds} at $v_{ds} = V_{DS}$:

$$W_{Cds} = \int v_{ds}\, i_C\, dt = \int_0^{V_{DS}} v_{ds}\, C_{ds}(v_{ds})\, dv_{ds}$$

$$W_{Cds} = \int_0^{V_{DS}} C_0'(v_{ds}) \sqrt{v_{ds}}\, dv_{ds} = \tfrac{2}{3}\, C_{ds}(V_{DS})\, V_{DS}^2$$

— same energy loss as linear capacitor having value $\tfrac{4}{3}\, C_{ds}(V_{DS})$

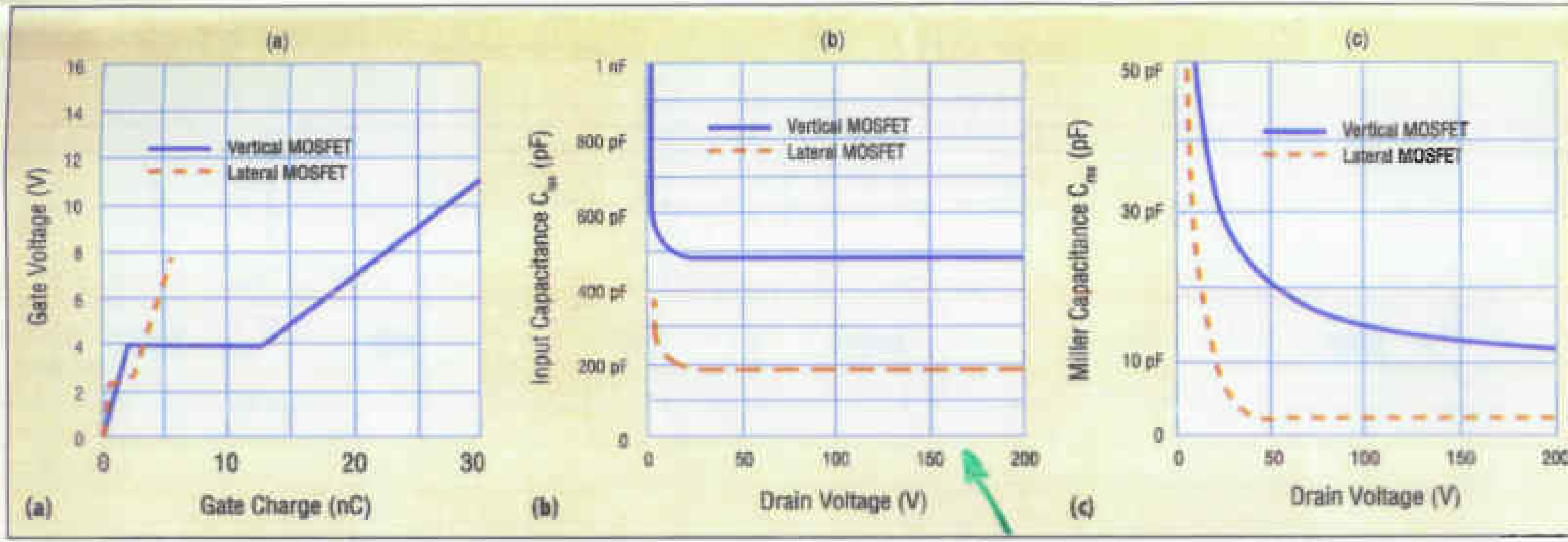
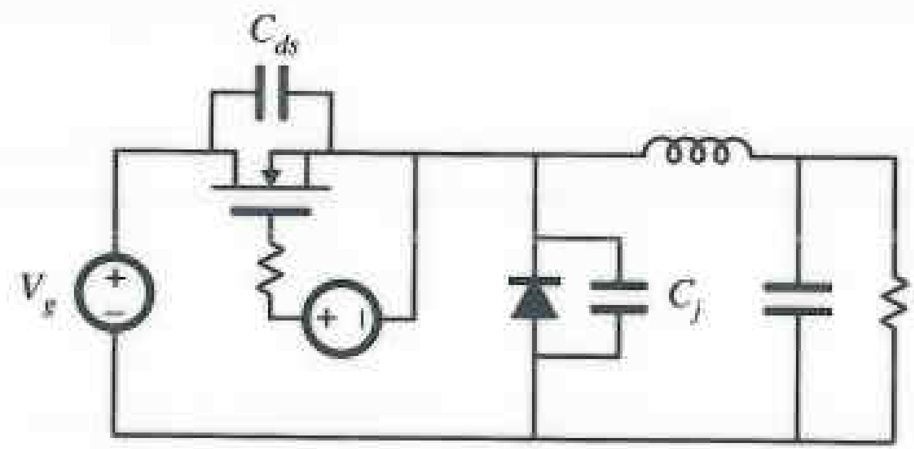


Fig. 3. *Standard vertical MOSFET versus an integrated lateral MOSFET: (a) gate charge, (b) input capacitance and (c) Miller capacitance.*

Switching loss caused by semiconductor output capacitances

Buck converter example



Energy lost during MOSFET turn-on transition (assuming linear capacitances):

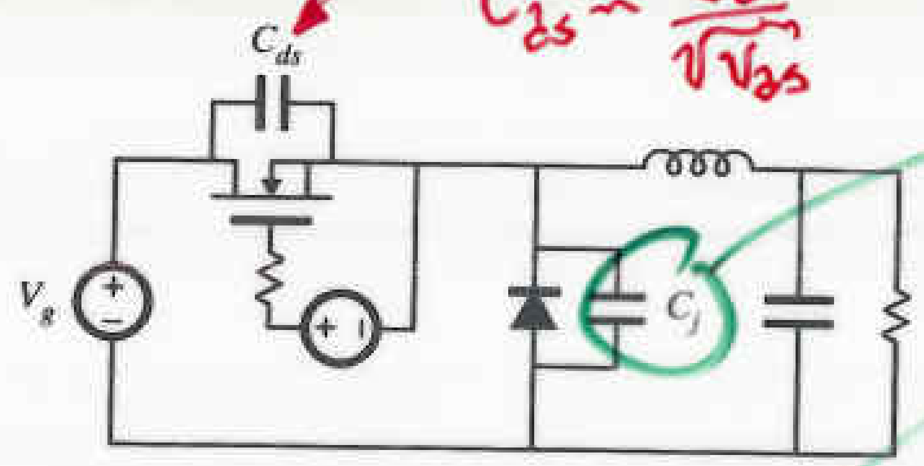
$$W_C = \frac{1}{2}\,(C_{ds} + C_j)\,V_g^2$$

C_{DS} = min ⇒ low Q

Fig 4.52 pg 98

Example: semiconductor output capacitances

Buck converter example



Energy lost during MOSFET turn-on transition (assuming linear capacitances):

$$W_C = \frac{1}{2}\,(C_{ds} + C_j)\,V_g^2$$

TR was off is C_{ds} max or min?
storing charge
TR must "eat" this during turn-on

Some other sources of this type of switching loss

Schottky diode

- Essentially no stored charge $I_{rr} \to 0$
- Significant reverse-biased junction capacitance

Transformer leakage inductance

- Effective inductances in series with windings
- A significant loss when windings are not tightly coupled

Interconnection and package inductances

- Diodes
- Transistors
- A significant loss in high current applications

Wiring PCB

① V_{drop}

② V_{stress} on turn-off due to "L kick"

$V_{IN} \to V_{IN} + V_L$

Inside a failed Power MOSFET

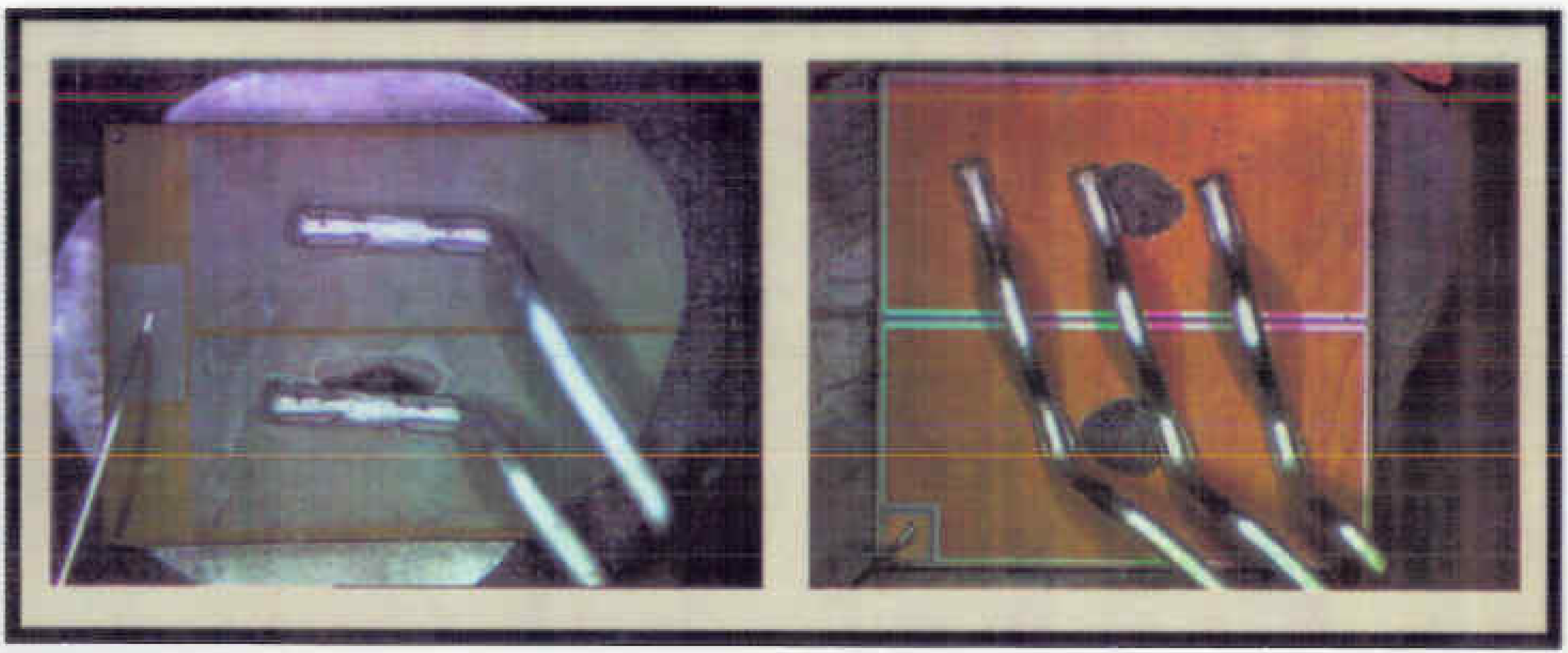


Fig. 6. *FETs destroyed by the capacitor-dump test. Planar is on the left; Trench is on the right. Note the dual damage sites on the trench part.*

MOSFET: conclusions

- A majority-carrier device: fast switching speed — to 3 MHz
- Typical switching frequencies: tens and hundreds of kHz — 600 kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive — $V_{DS} = 600$, $R_{ON} = 1/4\,\Omega$
- The device of choice for blocking voltages less than 500V
- 1200 — 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating

Summary of chapter 4

1. How an SPST ideal switch can be realized using semiconductor devices depends on the polarity of the voltage which the devices must block in the off-state, and on the polarity of the current which the devices must conduct in the on-state.
2. Single-quadrant SPST switches can be realized using a single transistor or a single diode, depending on the relative polarities of the off-state voltage and on-state current.
3. Two-quadrant SPST switches can be realized using a transistor and diode, connected in series (bidirectional-voltage) or in anti-parallel (bidirectional-current). Several four-quadrant schemes are also listed here.
4. A "synchronous rectifier" is a MOSFET connected to conduct reverse current, with gate drive control as necessary. This device can be used where a diode would otherwise be required. If a MOSFET with sufficiently low R_{on} is used, reduced conduction loss is obtained.

Summary of chapter 4

5. Majority carrier devices, including the MOSFET and Schottky diode, exhibit very fast switching times, controlled essentially by the charging of the device capacitances. However, the forward voltage drops of these devices increases quickly with increasing breakdown voltage.
6. Minority carrier devices, including the BJT, IGBT, and thyristor family, can exhibit high breakdown voltages with relatively low forward voltage drop. However, the switching times of these devices are longer, and are controlled by the times needed to insert or remove stored minority charge.
7. Energy is lost during switching transitions, due to a variety of mechanisms. The resulting average power loss, or switching loss, is equal to this energy loss multiplied by the switching frequency. Switching loss imposes an upper limit on the switching frequencies of practical converters.

Summary of chapter 4

8. The diode and inductor present a "clamped inductive load" to the transistor. When a transistor drives such a load, it experiences high instantaneous power loss during the switching transitions. An example where this leads to significant switching loss is the IGBT and the "current tail" observed during its turn-off transition.
9. Other significant sources of switching loss include diode stored charge and energy stored in certain parasitic capacitances and inductances. Parasitic ringing also indicates the presence of switching loss.