TSTE19 Power Electronics

Lecture 5

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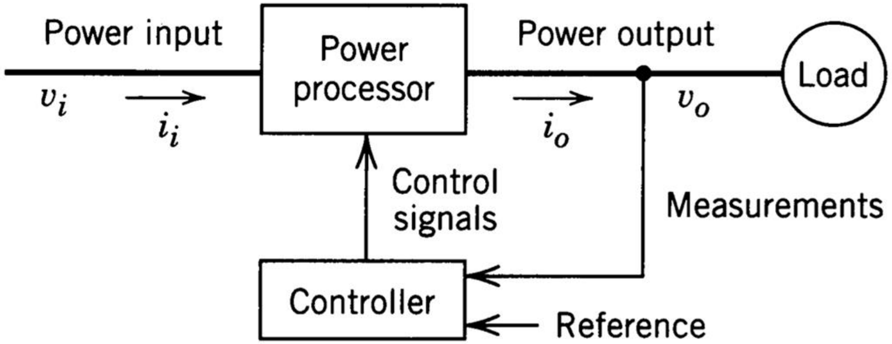
Outline

- Semiconductor switches
- Thermal aspects

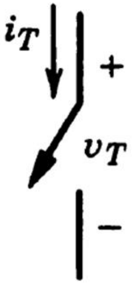
Component choice

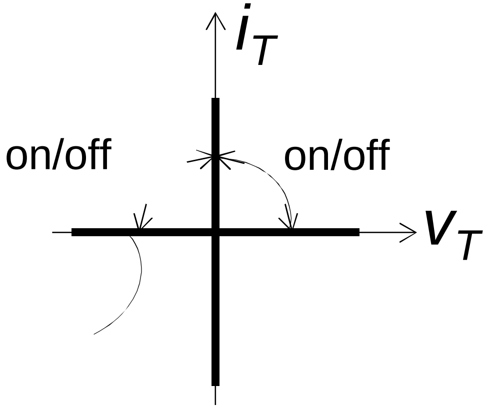
- Power processor components should not dissipate active power
    - Avoid resistances
    - Use L, C, transformers, switches (semiconductors)
- Control part may still use “ordinary” components, including resistors
    - Control is assumed to have much smaller power dissipation compared to the power processor



Ideal switch

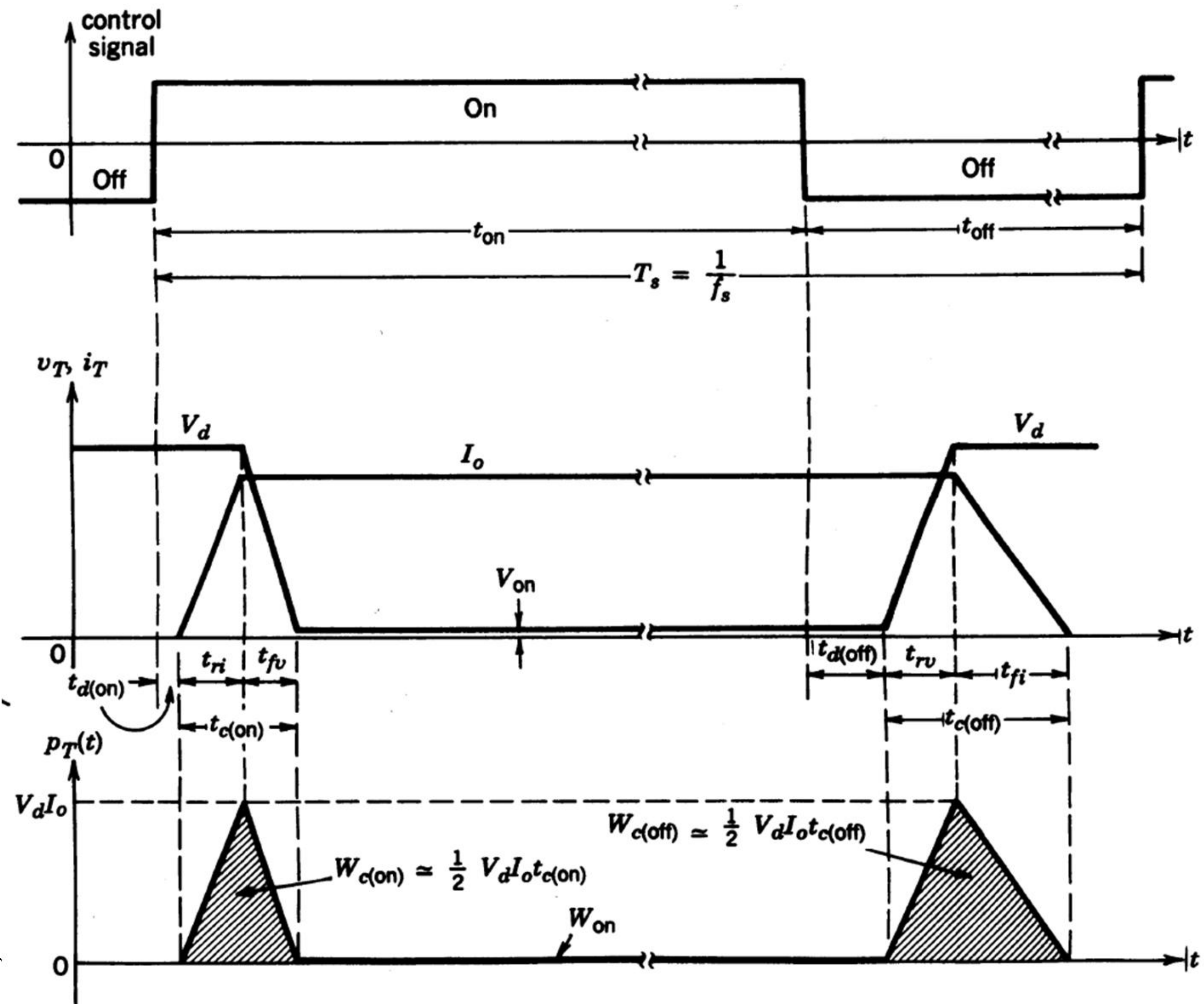
- Accept voltages of both polarities
    - Both negative and positive
- Conduct current in one direction
    - Only positive current
- No breakdown voltage
    - Perfect isolation in off state
- Zero on-resistance
    - No voltage drop over the switch
- No switch delay
- Zero energy switching
    - No power dissipated during operation

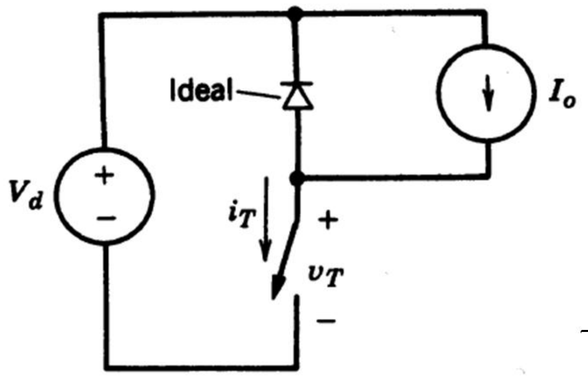




Non-ideal switch example

- Linear model
    - Rise and fall time on both V and I
    - Voltage drop V_{on}
    - I_0 models an inductor
- Power loss!





Non-ideal switch example, cont.

- Power loss during switching

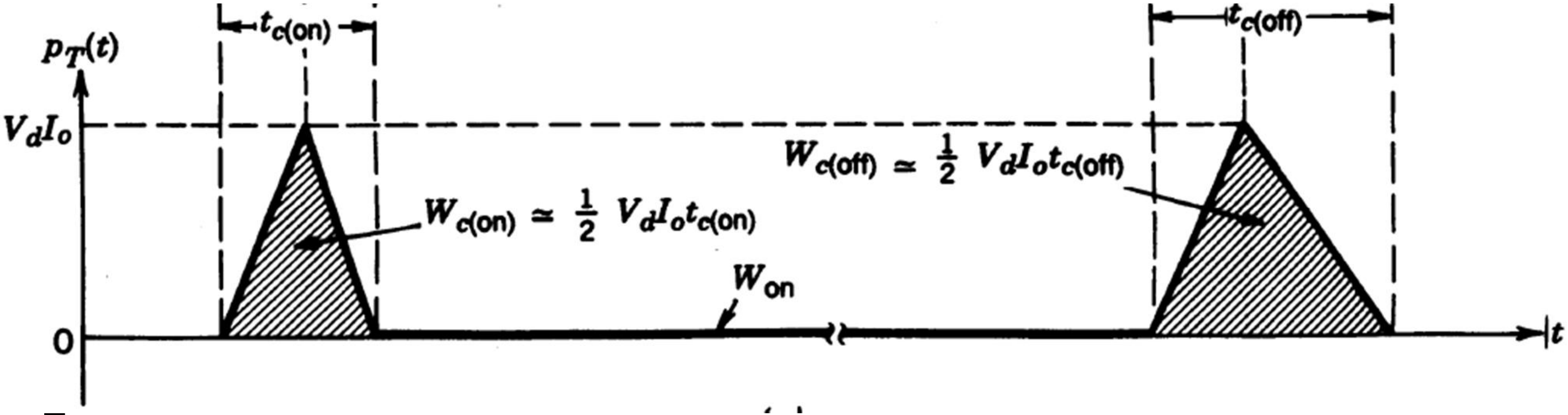
$$P_s = \frac{1}{2} V_d I_o f_s \left(t_{c(on)} + t_{c(off)} \right)$$

- Power loss during on-state

$$P_{on} = V_{on} I_o \frac{t_{c(on)}}{T_s}$$

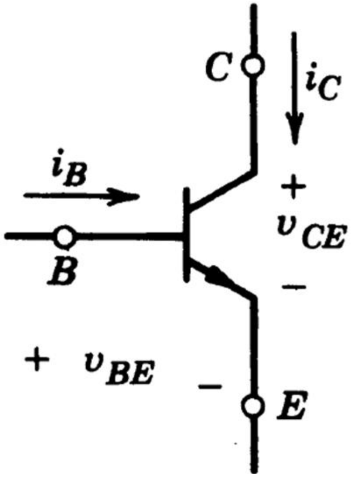
- Total power in the switch

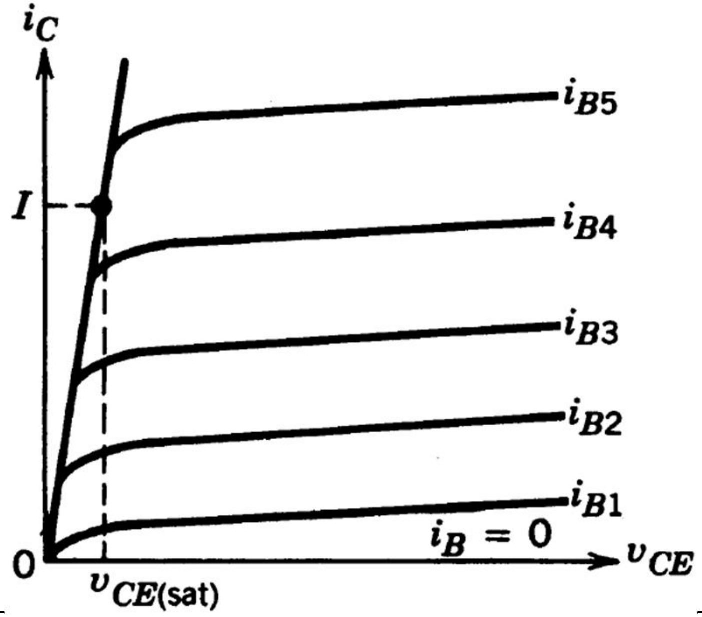
$$P_T = P_s + P_{on}$$

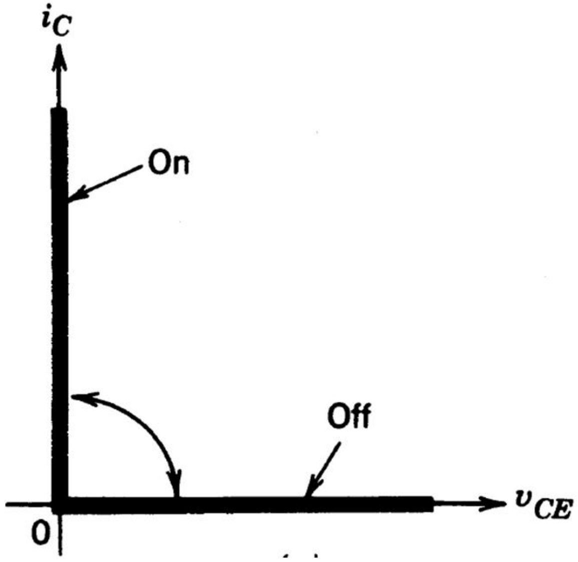


Bipolar junction transistors (BJT)

- Continuous control current when on
- $5 < h_{FE} = \frac{I_C}{I_B} < 10$ for power BJT
- Possible to turn on and off

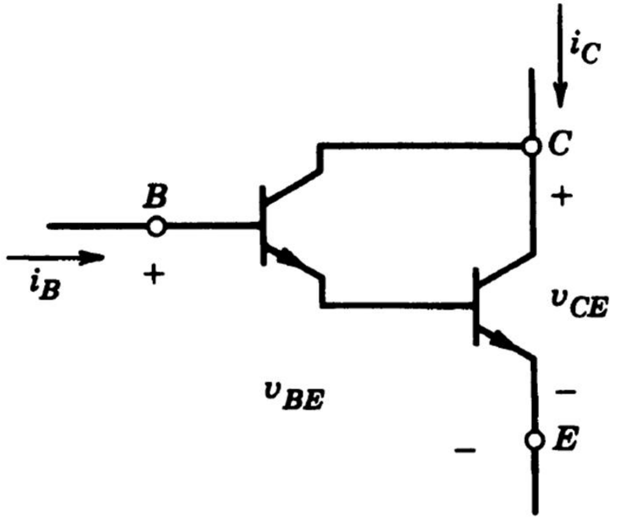


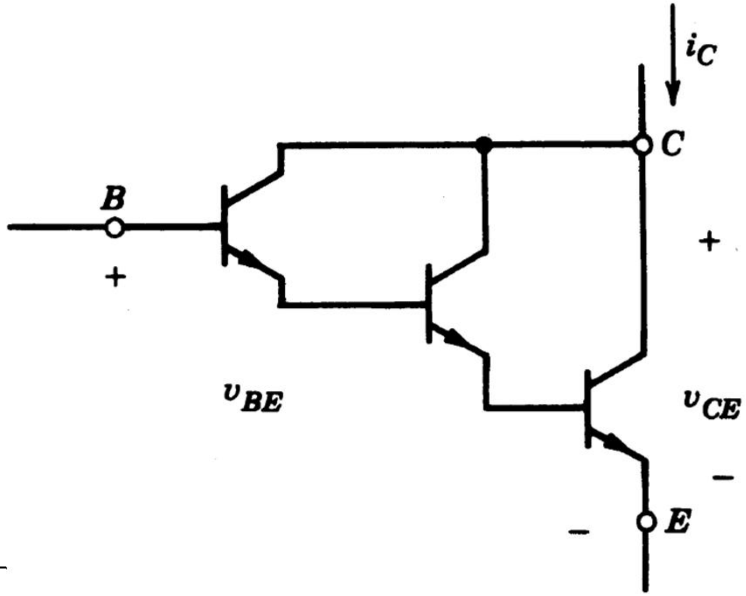




Darlington bipolar transistors

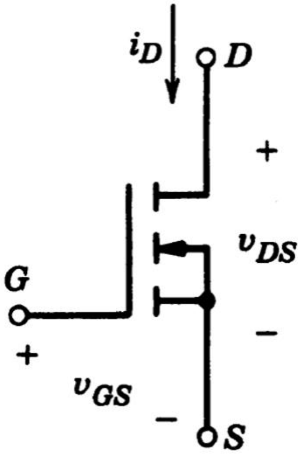
- Increase h_{FE}
- Increases also v_{CEsat}
- 0.1 us < switching time < 10 us
- Integrated on a single silicon chip

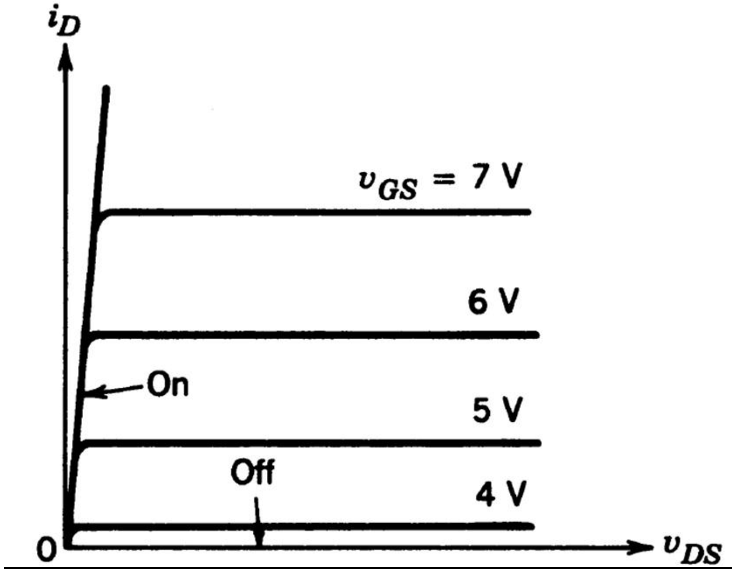


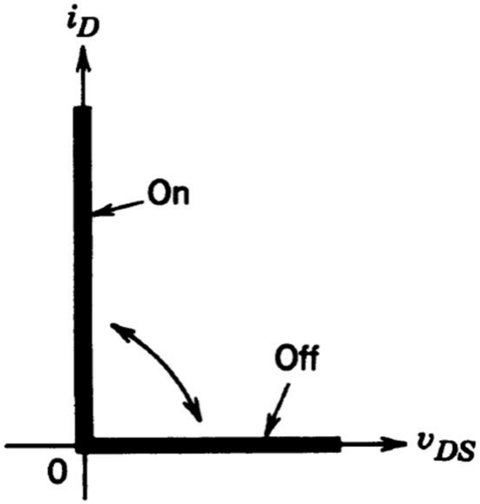


MOSFET transistors

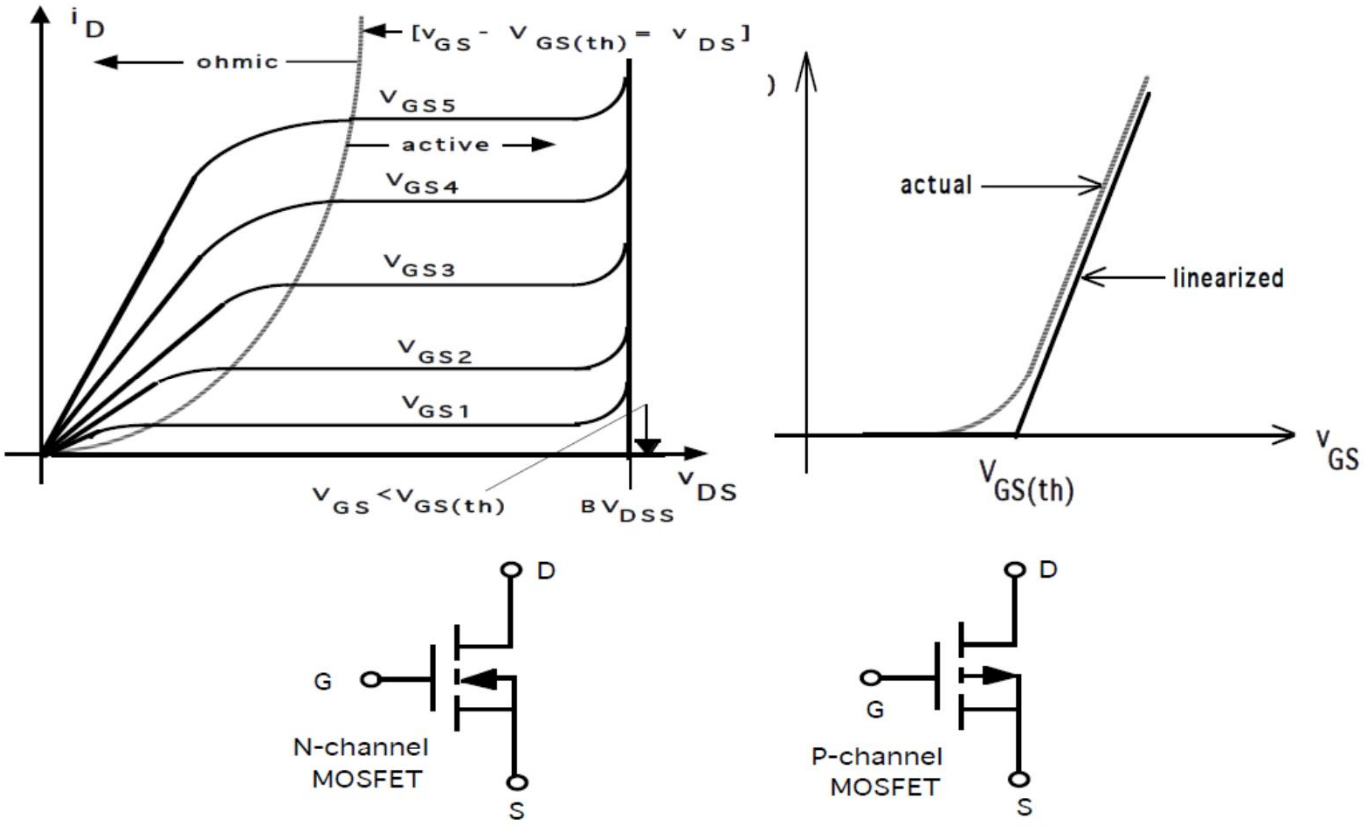
- Voltage controlled
- Fast switching
  - 10 ns < t < 500 ns
- Tradeoff R_{on} vs Blocking voltage





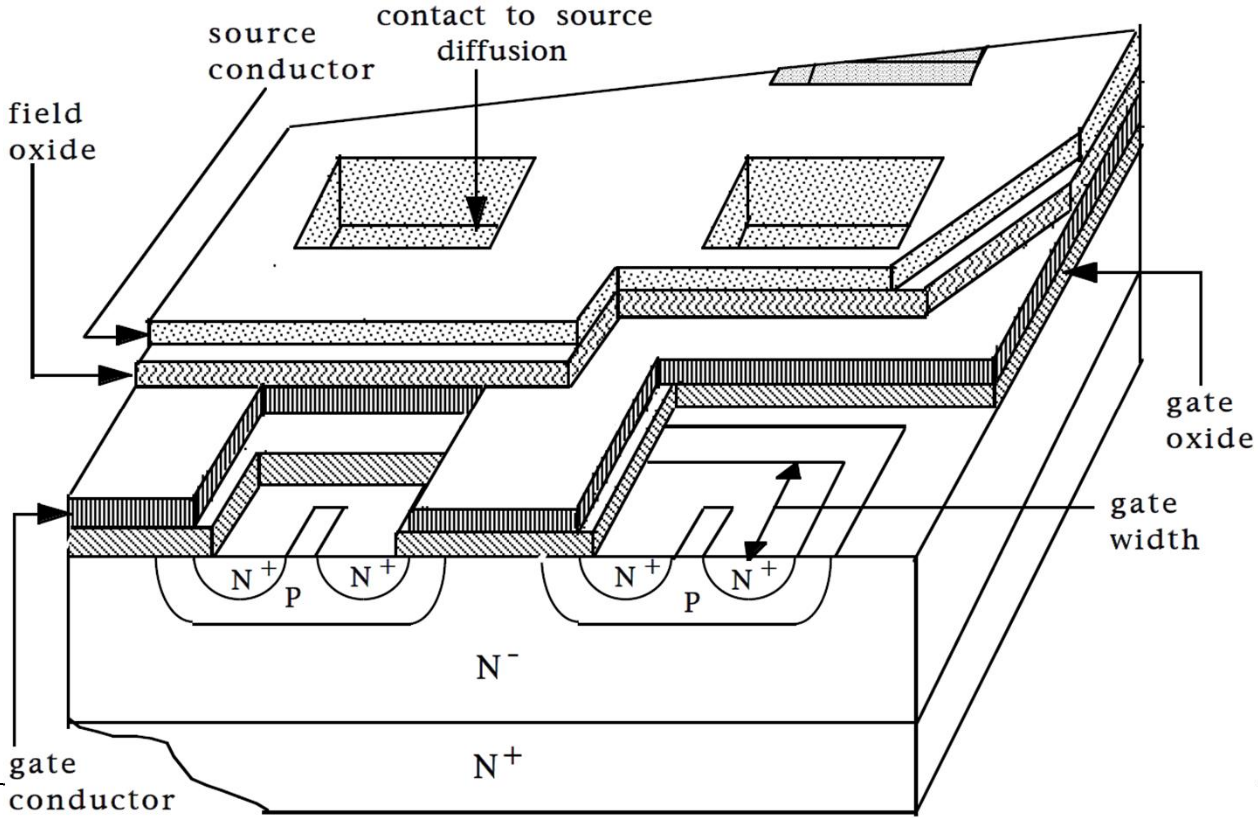


MOSFET I-V Characteristics and Circuit Symbols



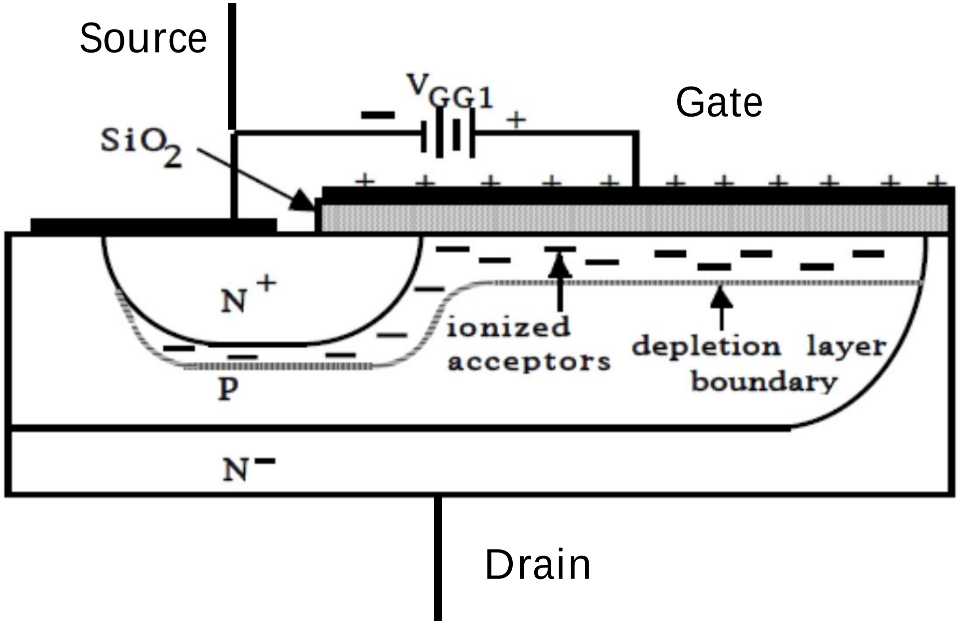
MOSFET implementation

- Thousands of cells in parallel



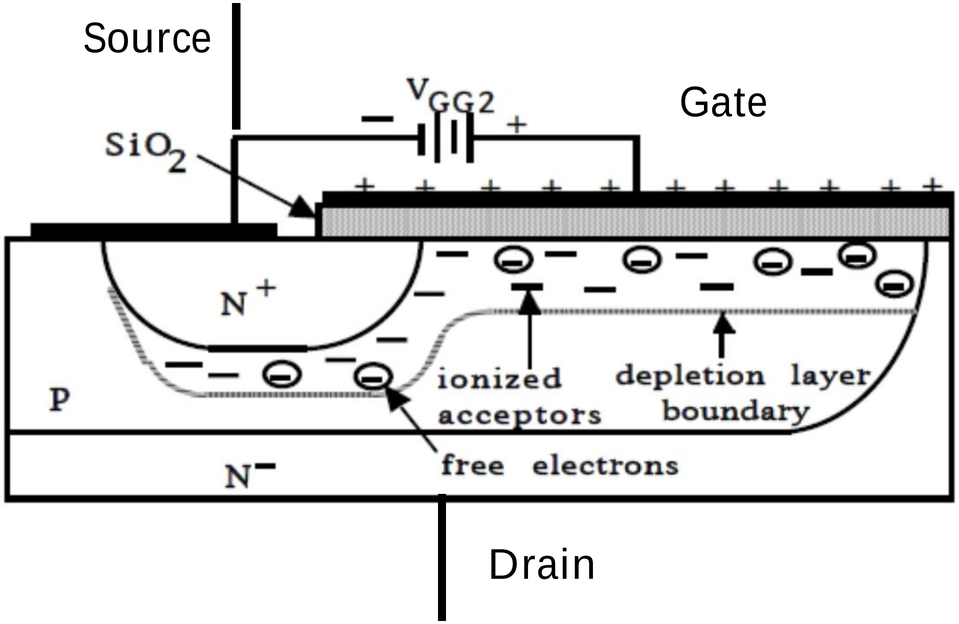
MOSFET channel conduction control

- Low gate voltage
- Inversion layer isolating drain N^- from source N^+



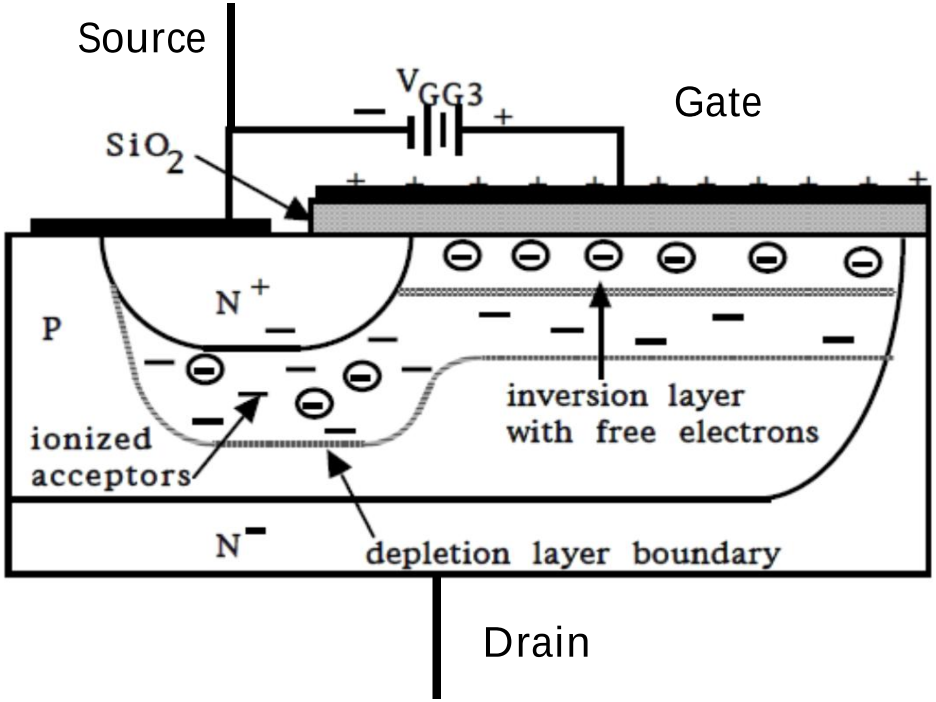
MOSFET channel conduction control

- Increasing gate voltage but below threshold
- Inversion layer with some free electrones still isolating drain N$^-$ from source N$^+$



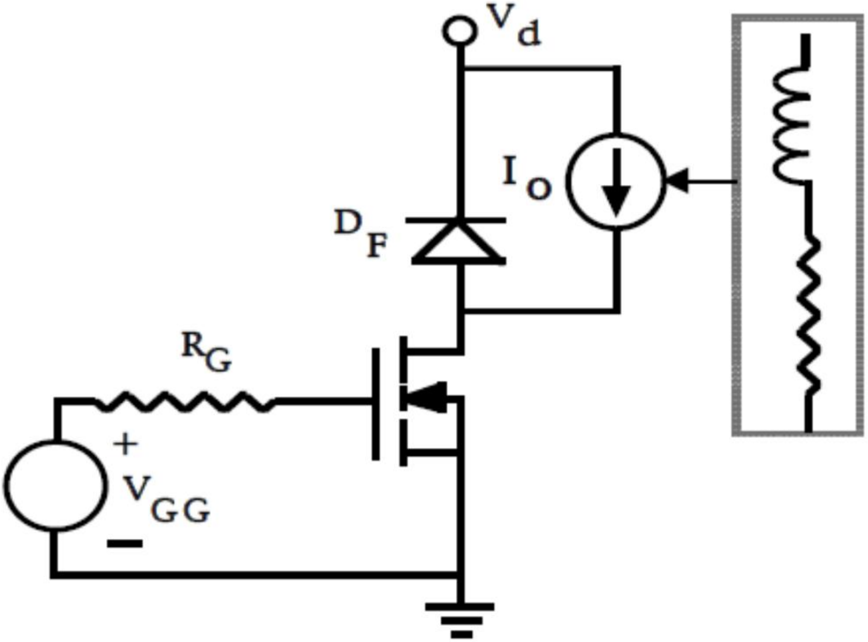
MOSFET channel conduction control

- High gate voltage above threshold
- Conductive channel of free electrons formed between drain N$^-$ and source N$^+$

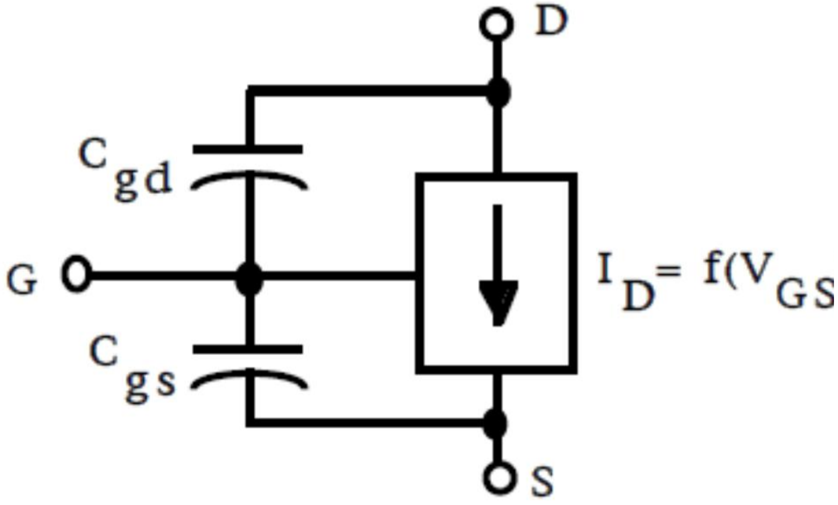


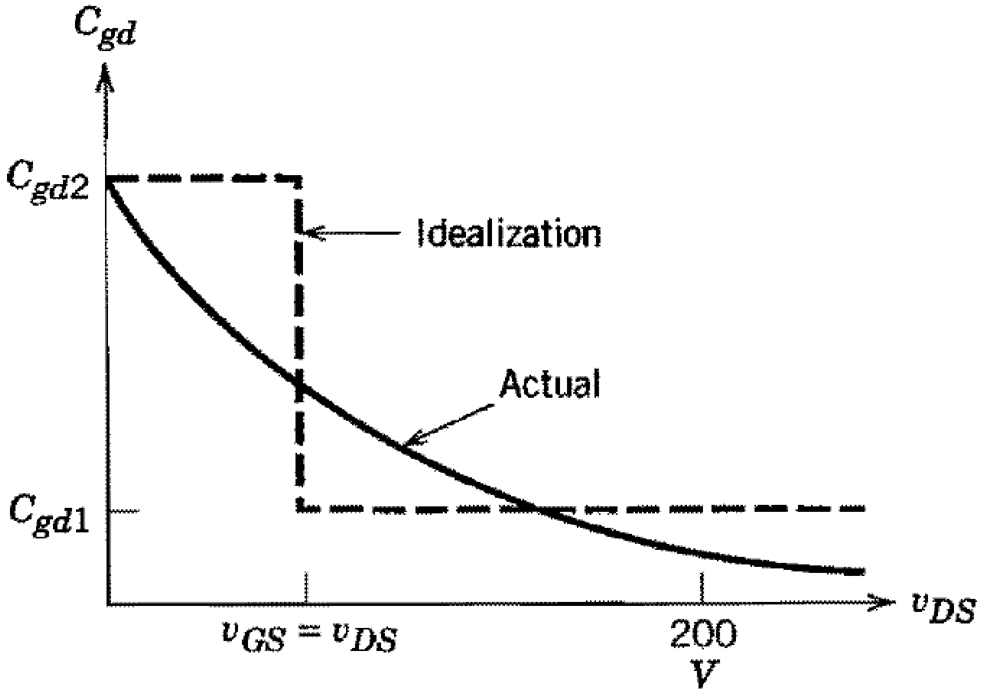
Switching MOSFET – Diode pair

- The current I_o is either conducted through the diode (when MOSFET is off) or through the MOSFET
- Turn-on: $V_{GG} >> V_{th}$
- Turn-off: $V_{GG} = 0$



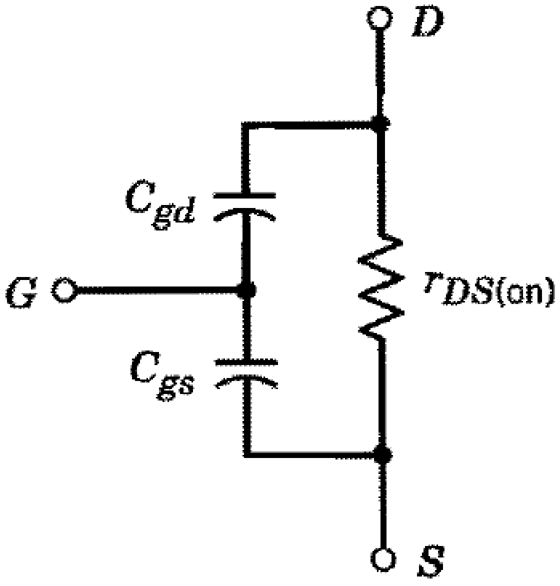
MOSFET turn-on/turn-off equivalent





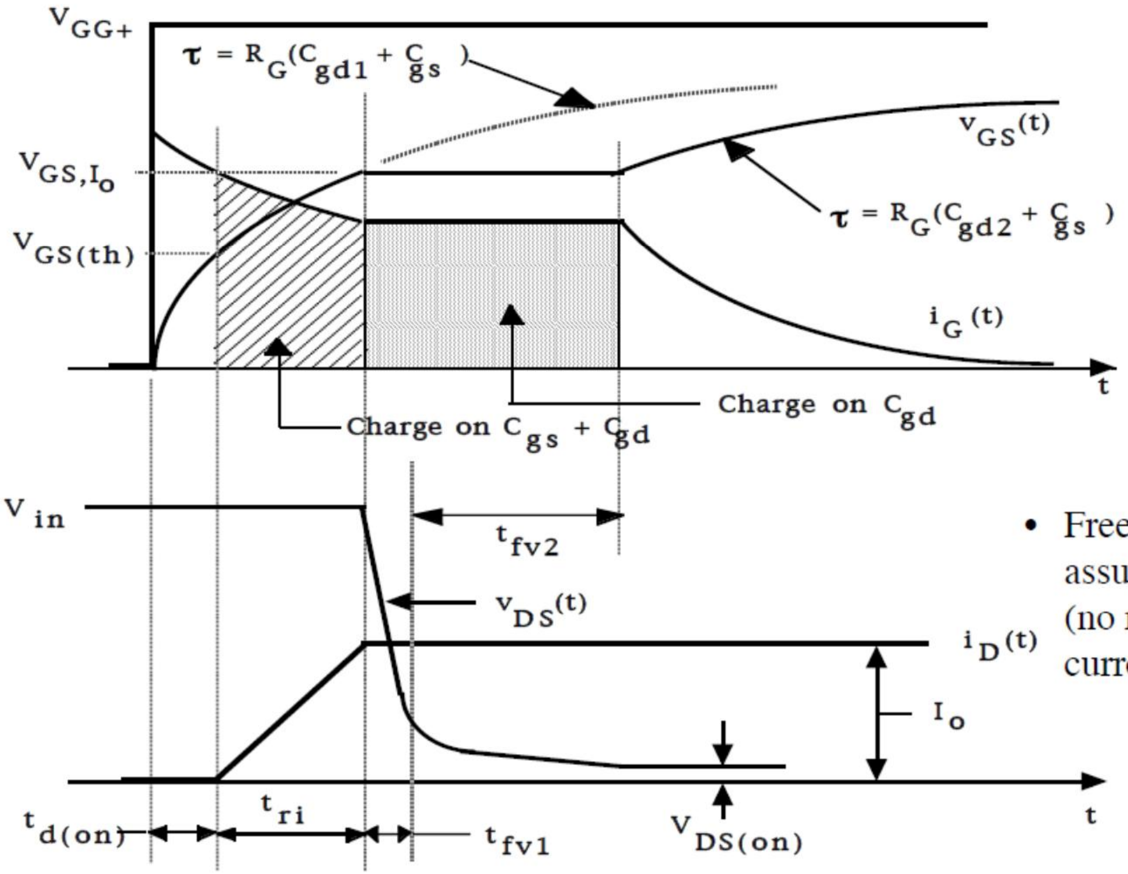
- MOSFET equivalent circuit valid for off-state (cutoff) and active region operation.

MOSFET on-state equivalent



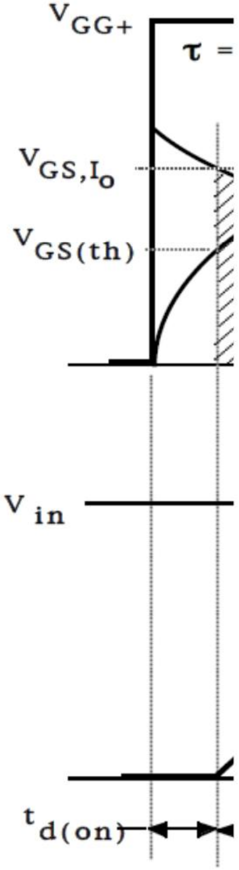
- MOSFET equivalent circuit valid for on-state (triode) region operation.

MOSFET-based Buck Converter Turn-on Waveforms

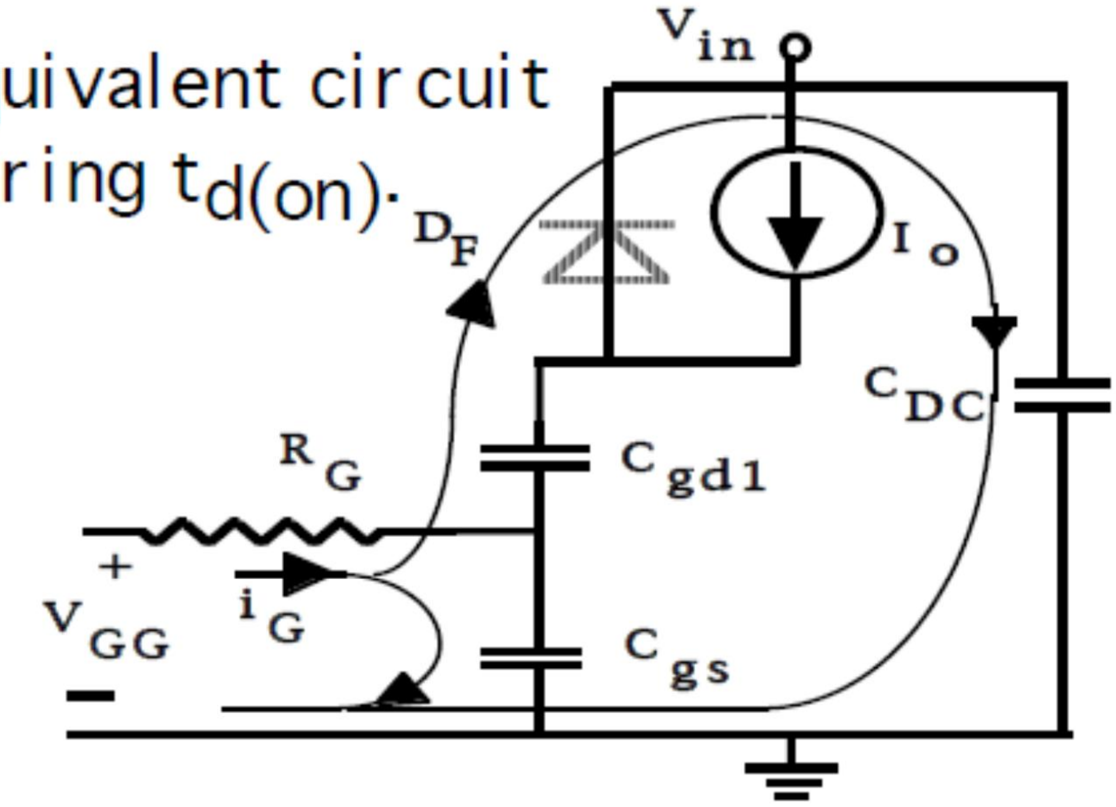


- Free-wheeling diode assumed to be ideal. (no reverse recovery current).

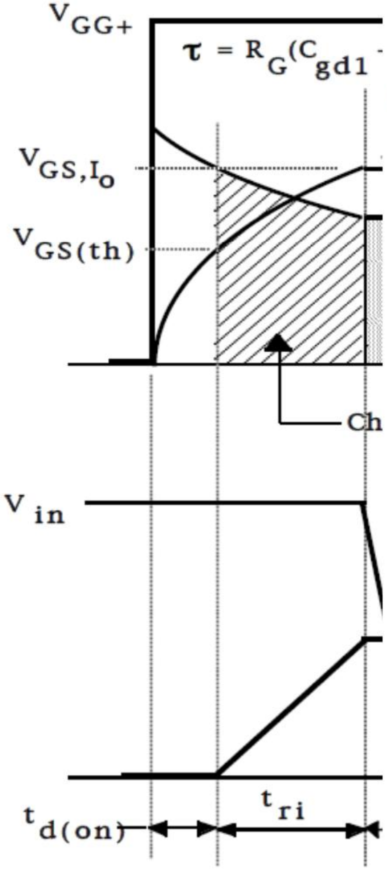
MOSFET-based Buck Converter Turn-on Waveforms



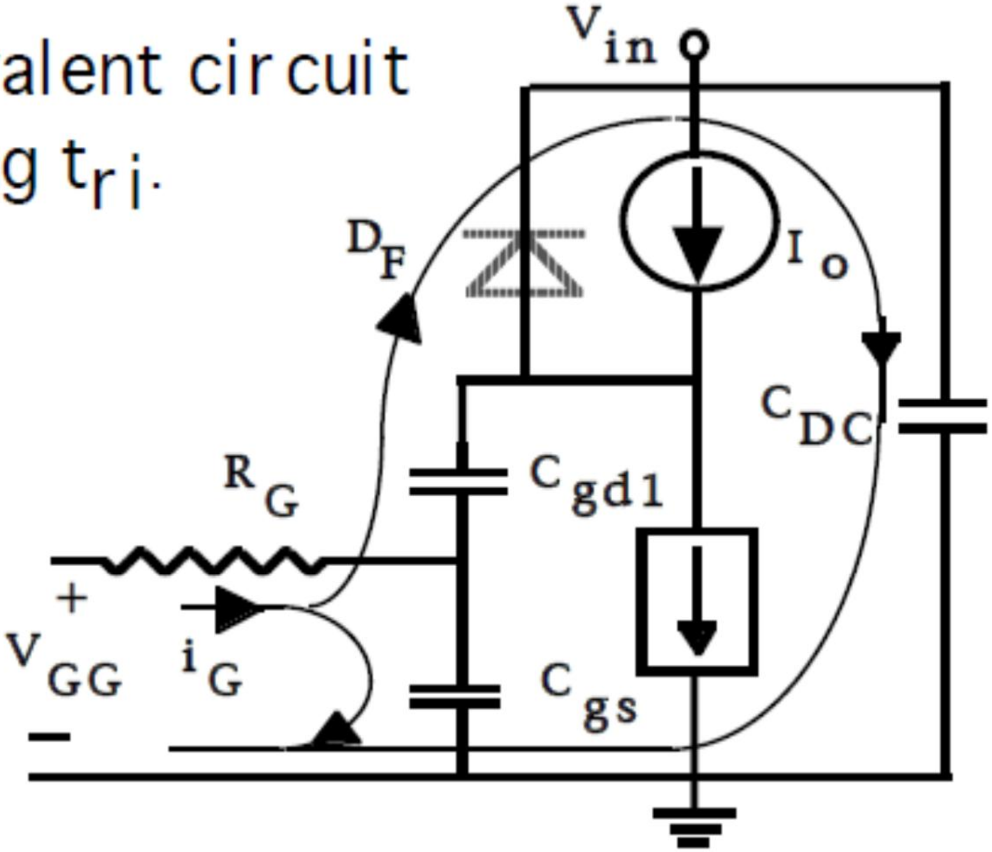
- Equivalent circuit during $t_{d(on)}$.



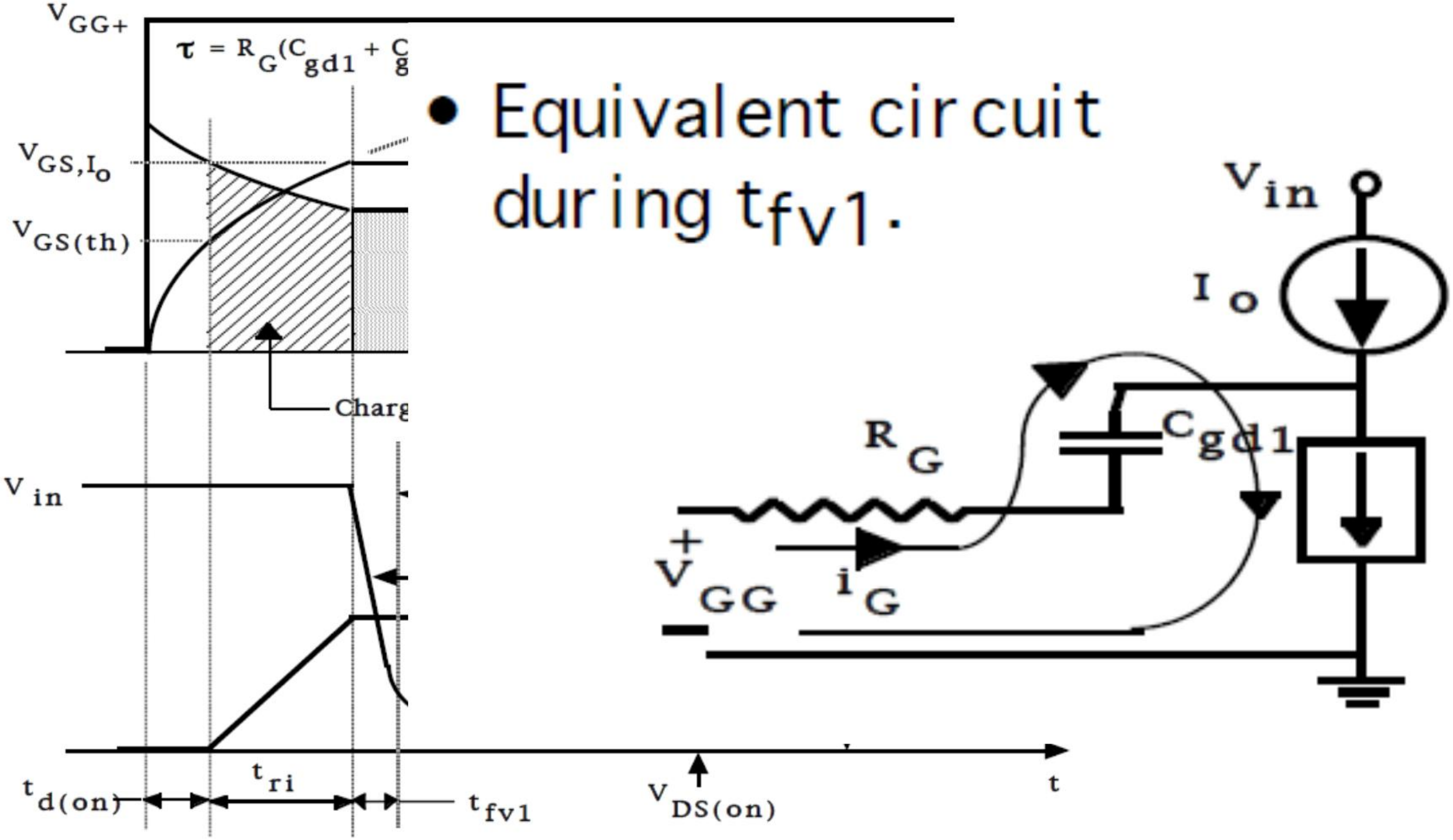
MOSFET-based Buck Converter Turn-on Waveforms



- Equivalent circuit during t_{ri}.

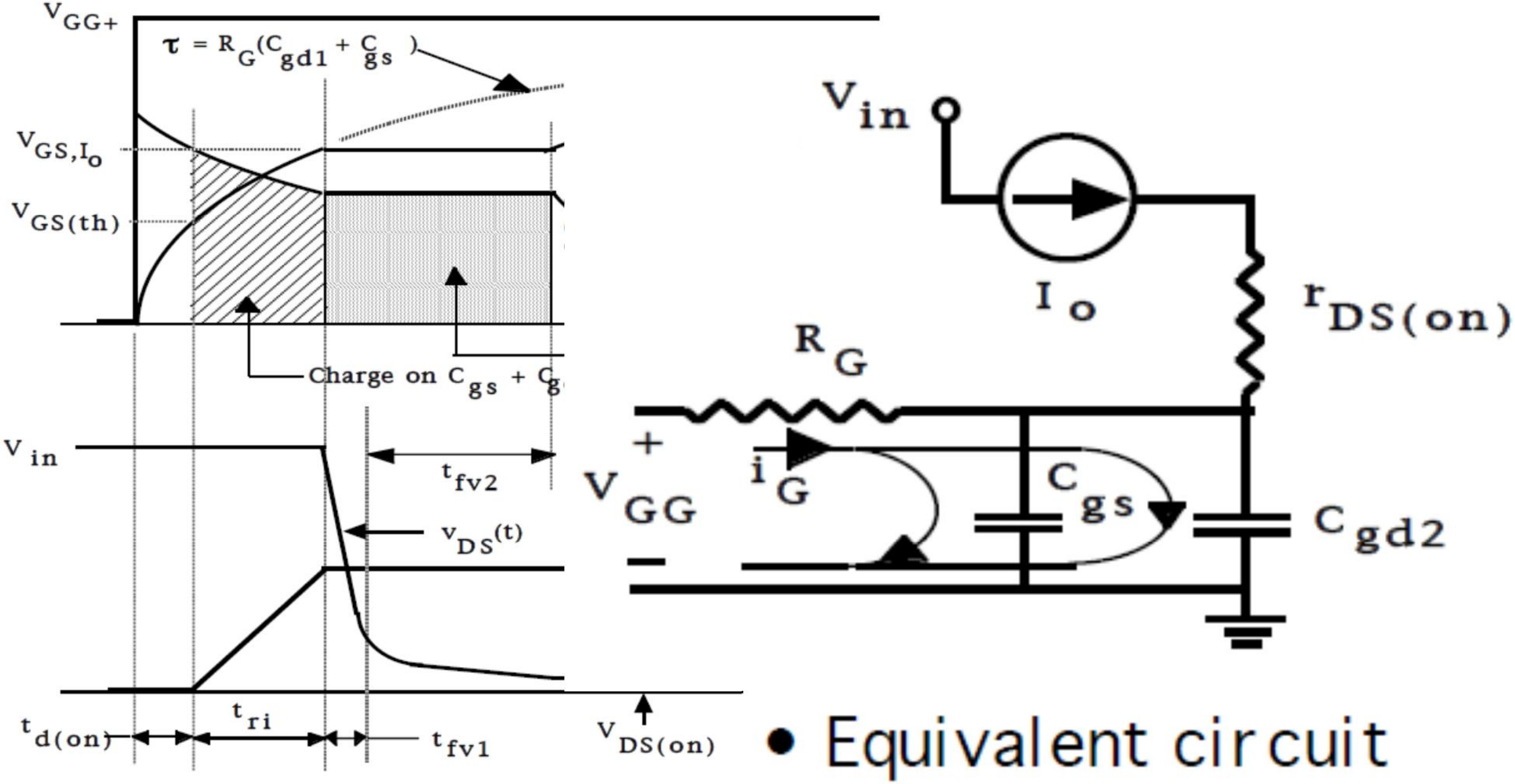


MOSFET-based Buck Converter Turn-on Waveforms



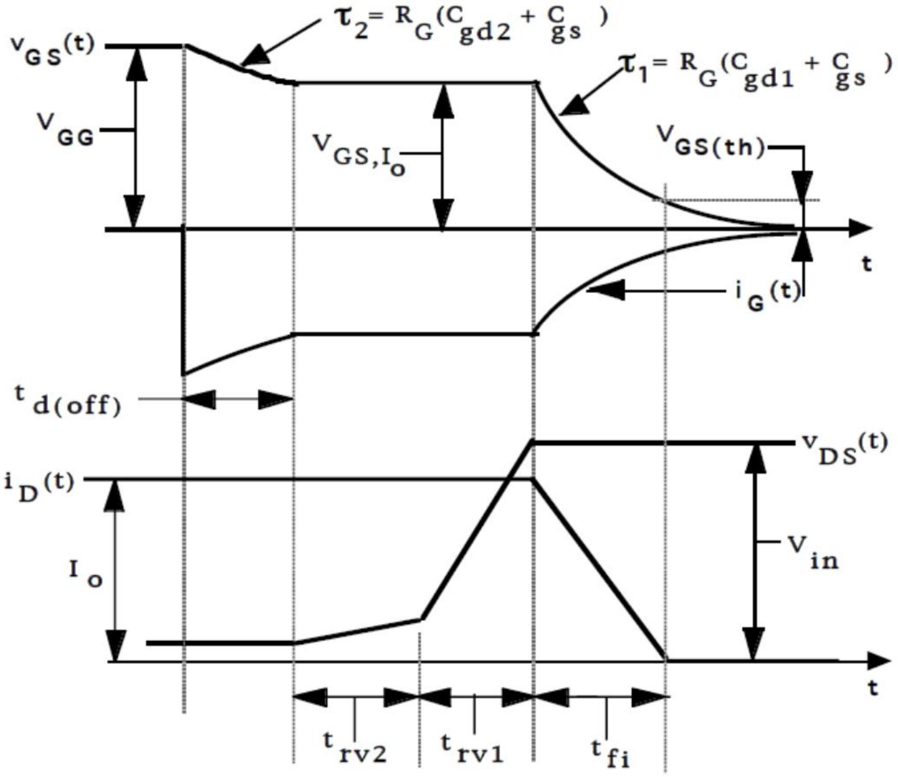
- Equivalent circuit during t_{fv1}.

MOSFET-based Buck Converter Turn-on Waveforms



- Equivalent circuit during t_{fv2}.

MOSFET-based Buck Converter Turn-off Waveforms

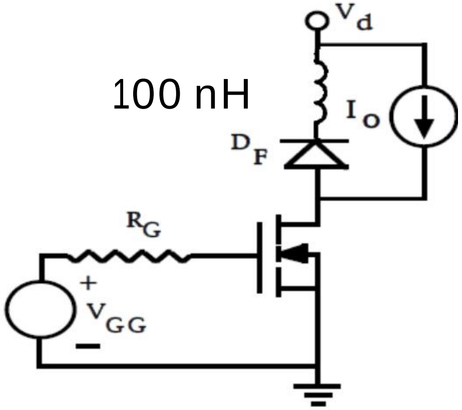


- Assume ideal free-wheeling diode.
- Essentially the inverse of the turn-on process.
- Model quanitatively using the same equivalent circuits as for turn-on. Simply use correct driving voltages and initial conditions

Lecture 5

Exercises

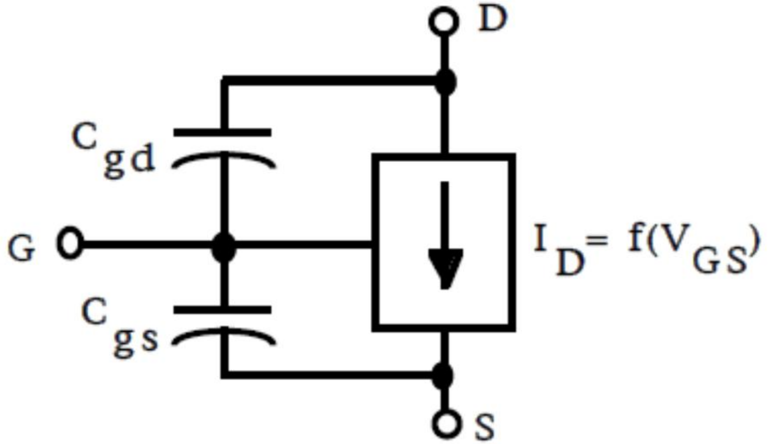
22-13

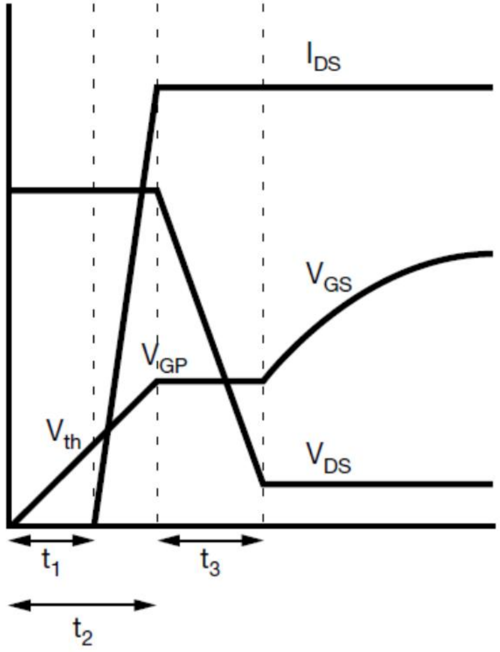


- A MOSFET step-down converter such as shown in Fig. 22-10 operates at a switching frequency of 30 kHz with a 50% duty cycle at an ambient temperature of 50°C.
- The power supply $V_d = 100$ V and the load current $I_0 = 100$ A.
- The free-wheeling diode is ideal but a stray inductance of 100 nH is in series with the diode.
- The MOSFET characteristics are listed below: $B_{VDSS} = 150$ V; $T_{j,max} = 150°$C; $R_{th,j\text{-}a} = 1$ K/W; $r_{DS(on)} = 0.01$ ohm, $t_{ri} = t_{fi} = 50$ ns; $t_{rv} = t_{fv} = 200$ ns; $I_{D,max} = 125$ A
- Is the MOSFET overstressed in this application and if so, how? Be specific and quantitative in your answer.

5-100

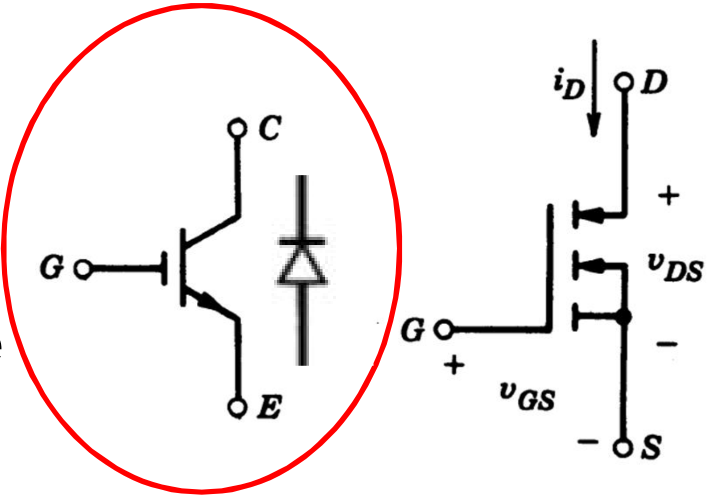
- For the step-down converter in 22-13 the dV/dt during turn-on is defined by V_d (assume $V_{dson}=0$) and t_{fv}.
- The gate-drain capacitance, C_{gd} = 120 pF. The miller platteau voltage V_{GP} = 4V
- Calculate the gate resistance, R_G for a gate drive giving V_{GG} = 10V.

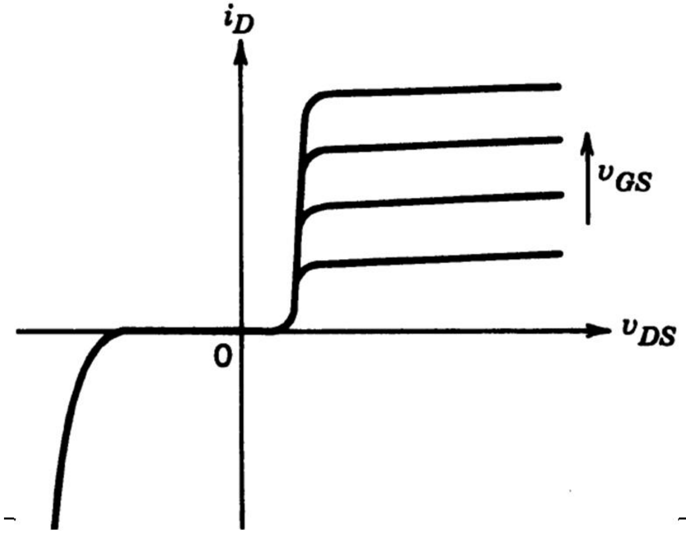


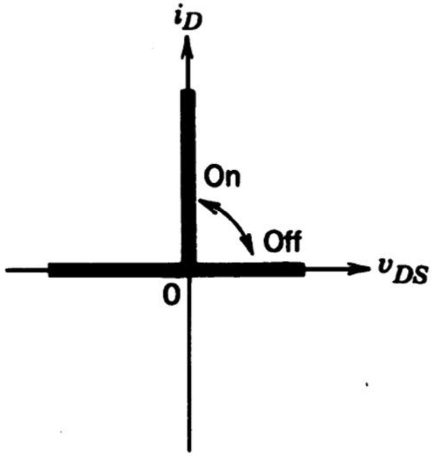


Insulated gate bipolar (IGBT)

- High input impedance
- Small on-state voltage
- Large blocking voltage
- Combined with anti-parallel diode







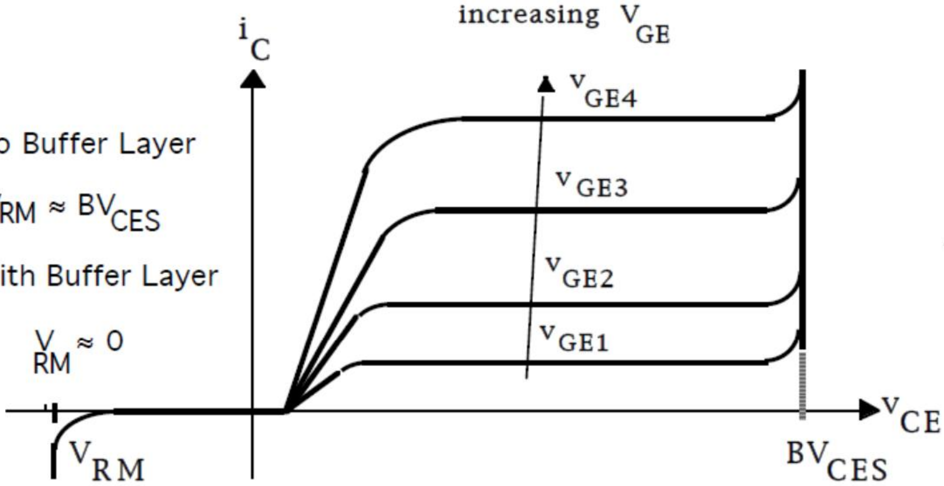
IGBT I-V Characteristics and Circuit Symbols

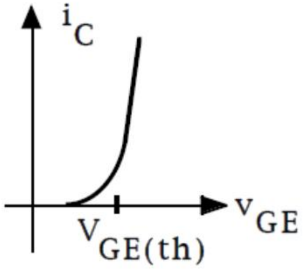
- No Buffer Layer

  $V_{RM} \approx BV_{CES}$

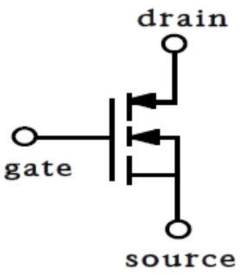
- With Buffer Layer

  $V_{RM} \approx 0$

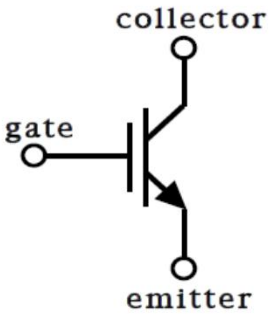




- Transfer curve

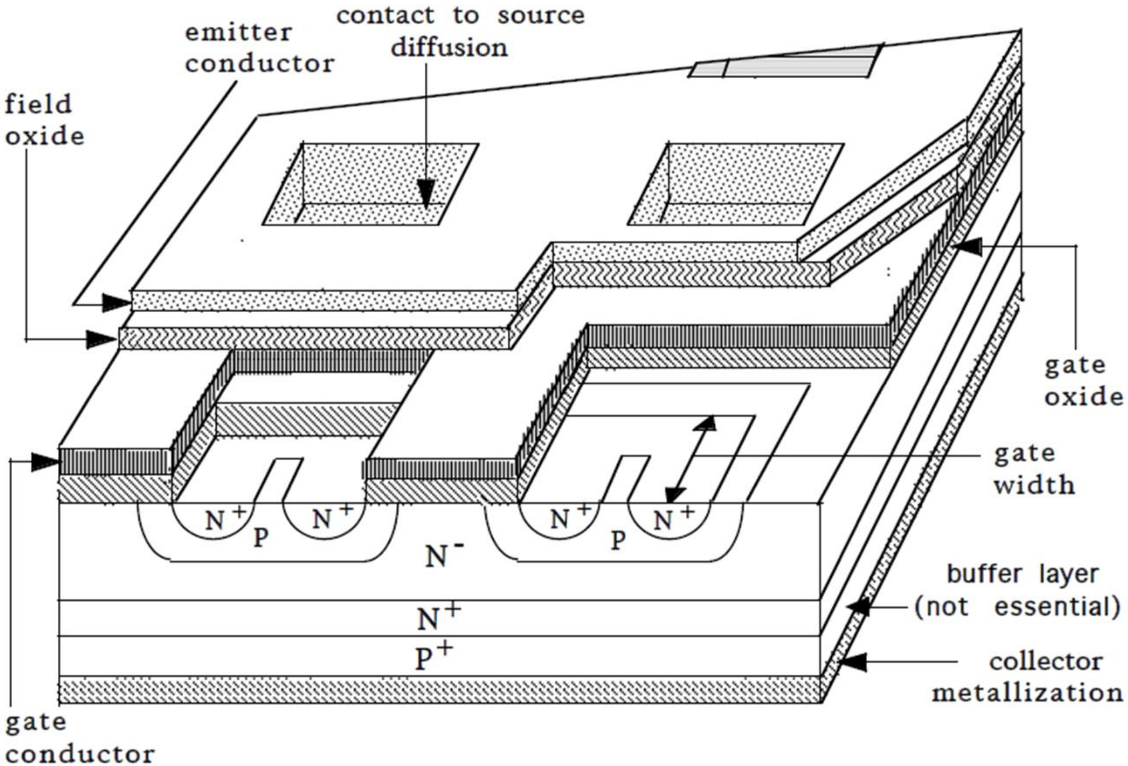


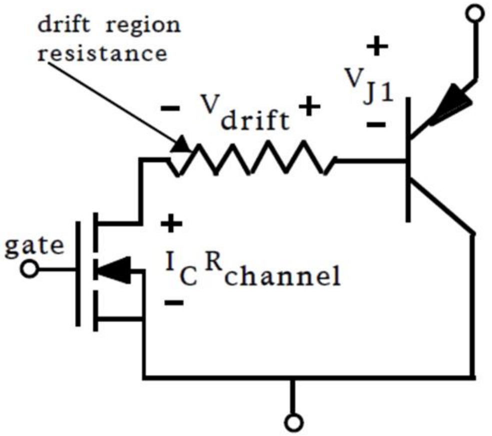
- N-channel IGBT circuit symbols



Insulated gate bipolar (IGBT) implementation

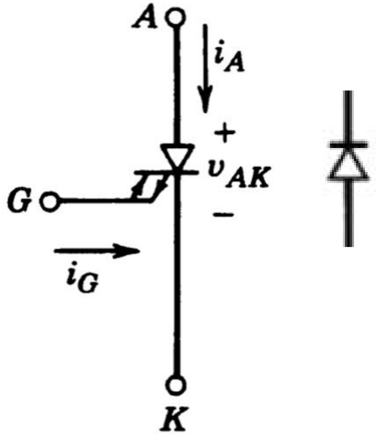
- Chip view, and approximate equivalent circuit

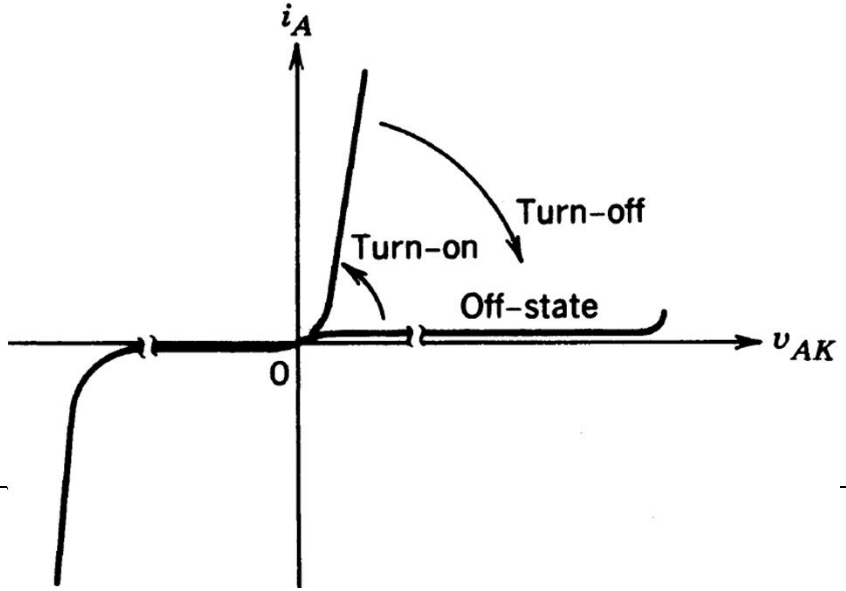




Gate-turn-off Thyristor (GTO)

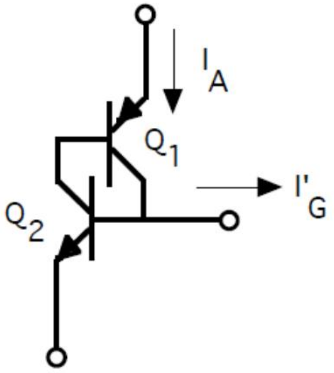
- Thyristor possible to turn off
- Slow switch time (1 us < toff < 25 us)
- High voltage and currents
  - 4.5 kV, 2-3 kA
- Combined with anti-parallel diode

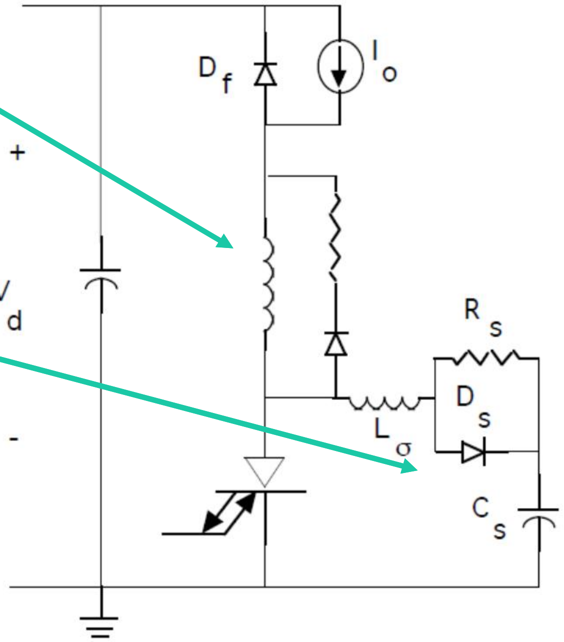




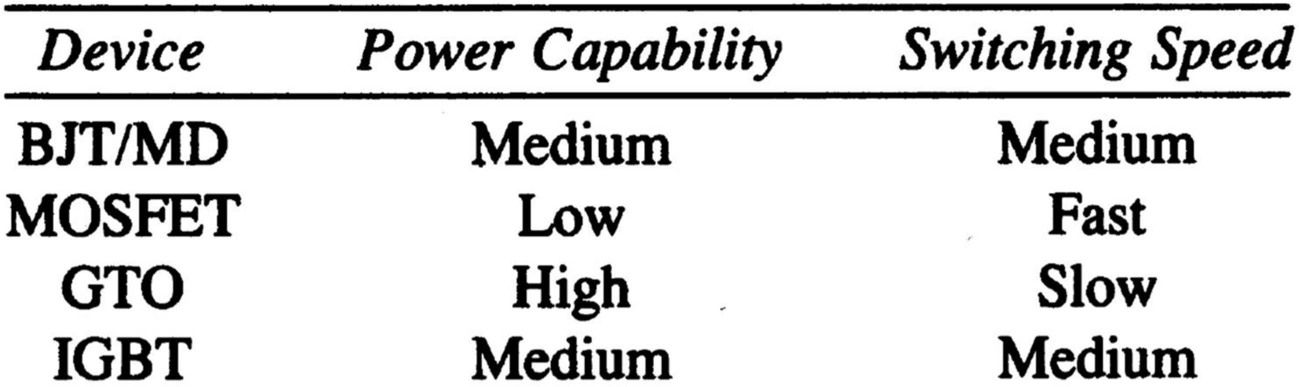
Gate-turn-off Thyristor

- High gate current required at turn-off. $I_G \approx I_A$.
- Turn-on inductor required to limit dI/dt
- Turn-off snubber required to limit over-voltage related to stored energy in the turn-on inductor



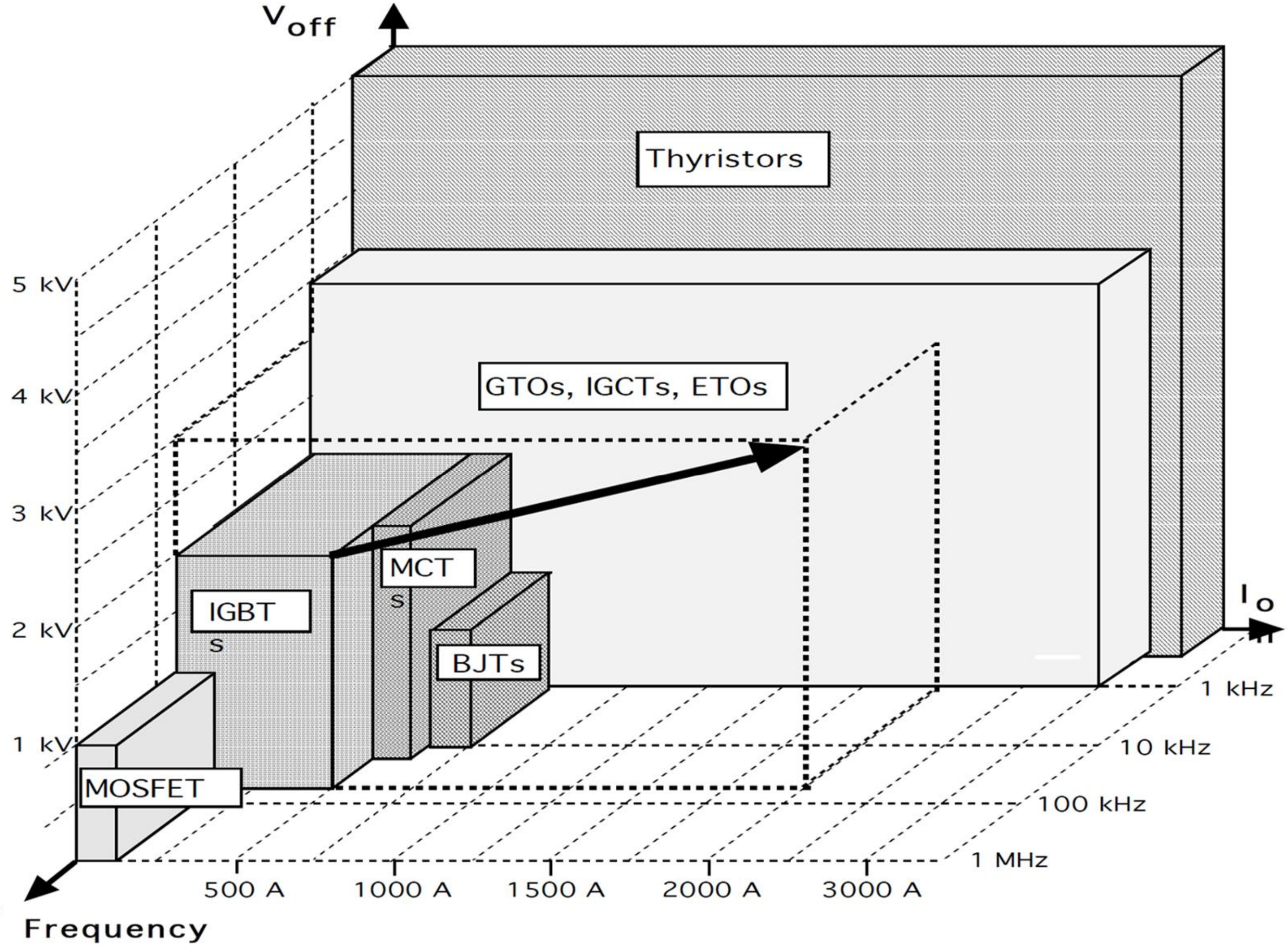


Controllable switch comparison



Device	*Power Capability*	*Switching Speed*
BJT/MD	Medium	Medium
MOSFET	Low	Fast
GTO	High	Slow
IGBT	Medium	Medium

Controllable switch comparison, cont.



Cooling requirement motivation

- Component failure rate increase with temperature increase
- Components degrade/fail rate increase due to high temperature
- Capacitors
  - Electrolyte evaporate reate increase with temperature
- Magnetic components
  - Losses in magnetic components increase when T > 100 degrees
  - Winding insulation degrades when T > 100 degrees
- Semiconductors
  - Breakdown voltage decrease
  - Leakage current and switching time increases
  - Power sharing problems when parallel or serial devices

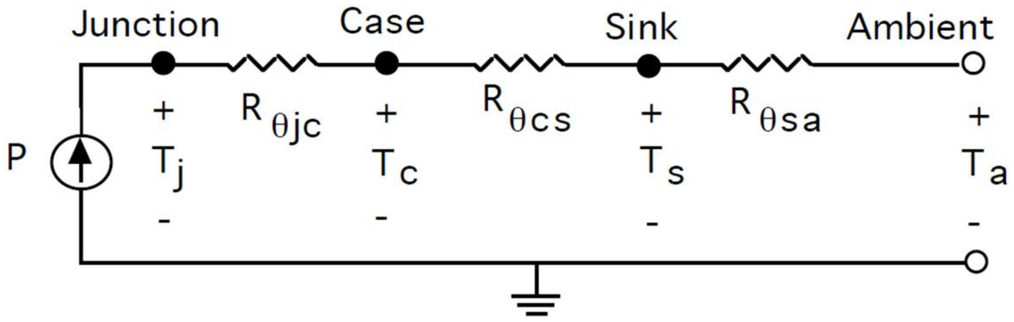
Electric analogy model

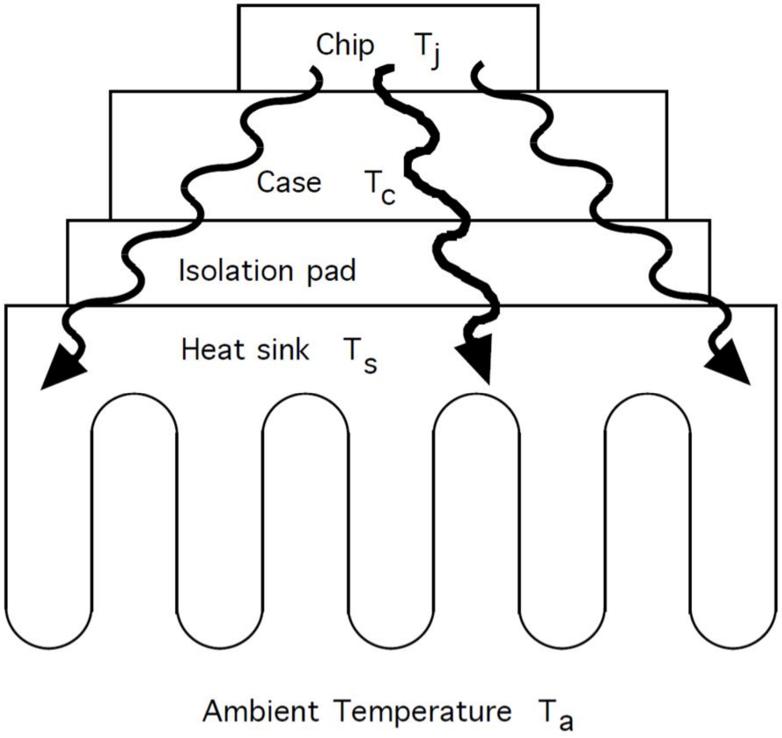
- Voltage corresponds to temperature, current corresponds to power, R_Θ (or R_{th}) corresponds to power conductivity resistance

$$R_{\Theta,cond} = \frac{\Delta T}{P_{cond}} [\mathrm{K}/W]$$

Multiple layer structure model

- Typical cooling setup
  - Different sizes and materials
- Electric model of the power transfer from power source to the environment

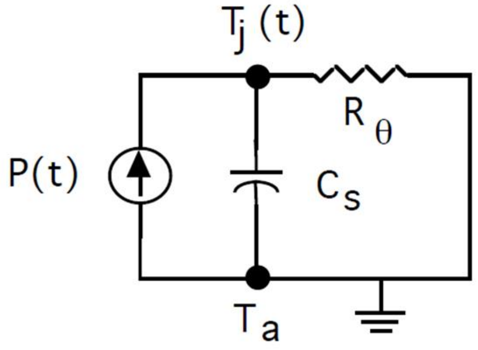




Transient thermal impedance

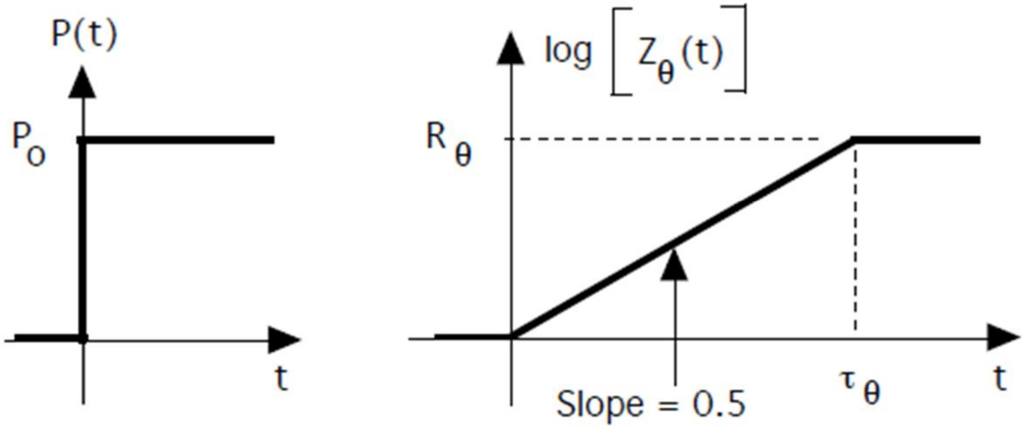
- Short increase in power dissipation may not lead to overtemperature...
- Heat capacity per unit volume Cv
  - Heat energy density Q
  - Volume V

$$C_v = \partial Q / \partial T$$
$$C_s = C_v V$$



- Corresponding electric model

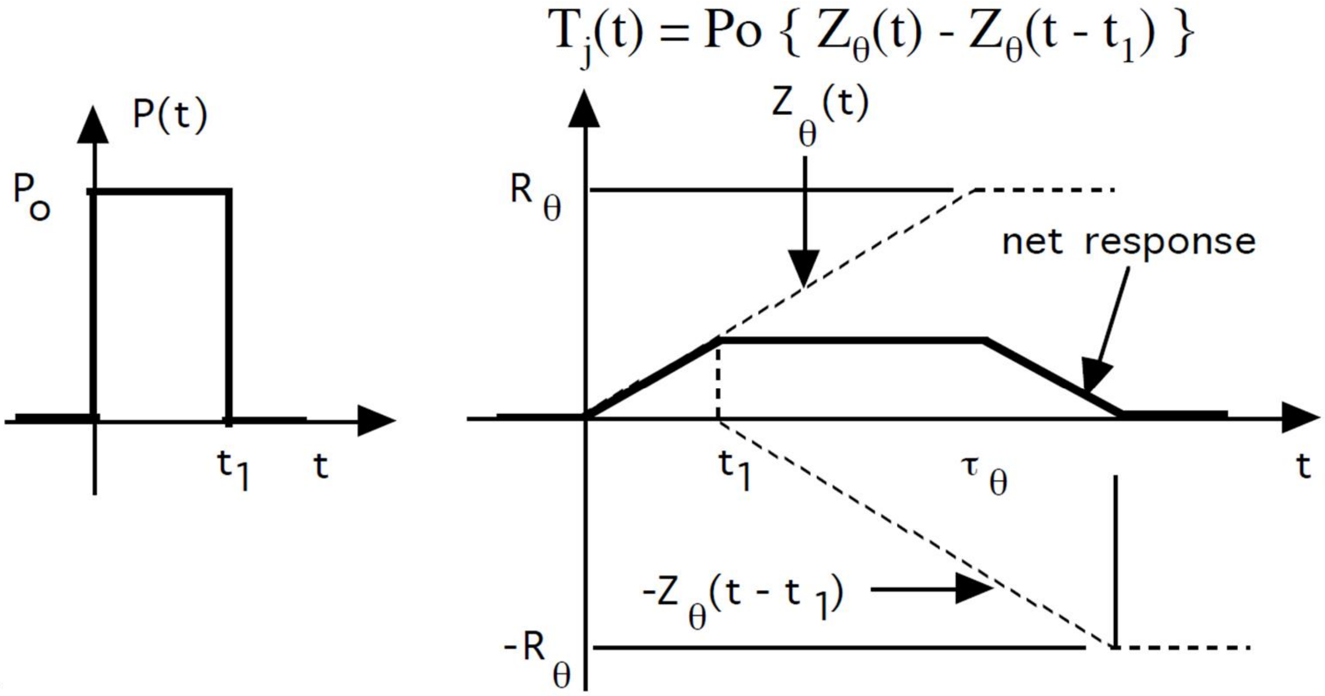
$$Z_\theta(t) = [T_j(t) - T_a]/P(t)$$



- $\tau_\theta = \pi R_\theta C_s / 4$ = thermal time constant
- $T_j(t = \tau_\theta) = 0.833 P_o R_\theta$

Transient thermal example

- Short pulse, power increase by Po



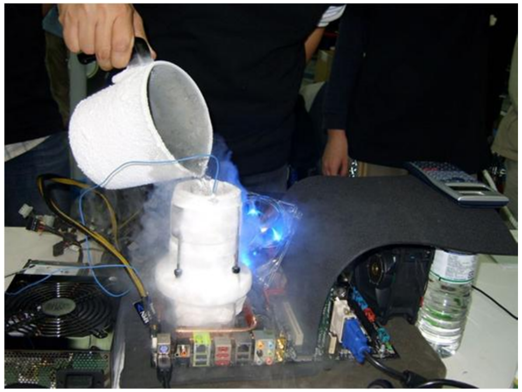
$$T_j(t) = Po\ \{\ Z_\theta(t) - Z_\theta(t - t_1)\ \}$$

Heat sinks

- Different shapes and material
- Based on convection and radiation
    - Natural convection
    - Forced-air convection
- Examples: Computers, trains, ...

Other cooling approaches

- Liquid cooling
  - Allow larger heatsinks,
    placed away from power source
- Thermal towers, heatpipes
  - Similar principle as in a refrigerator (phase shifting)
  - Connect a larger heatsink without large thermal resistance
- Liquid nitrogen
  - Force temperature down below Ta
  - Expensive
  - Water condensation problems
  - Material stress problems



Lecture 5

Exercises

29-6

- A MOSFET used in a step-down converter has an on-state loss of 50 W and a switching loss given by $10^{-3} f_s$ (in watts) where f_s is the switching frequency in hertz.
- The junction-to-case thermal resistance $R_{th,jc}$ is 1 K/W and the maximum junction temperature $T_{j,max}$ is 150°C.
- Assuming the case temperature is 50°C, estimate the maximum allowable switching frequency.

29-7

- The MOSFET of Problem 29-6 is mounted on a heat sink and the ambient temperature T_a = 35°C.
- If the switching frequency is 25 kHz, what is the maximum allowable value of the case-to-ambient thermal resistance $R_{th,ca}$ of the heat sink.
- Assume all other parameters given in Problem 29-6 remain the same except the case temperature which can change.

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