TSTE25 Power Electronics

Lecture 4

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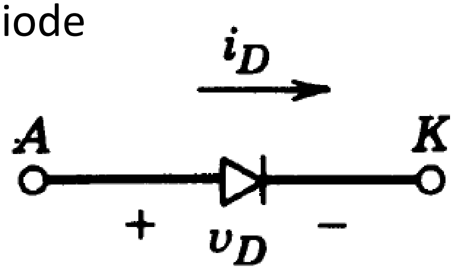
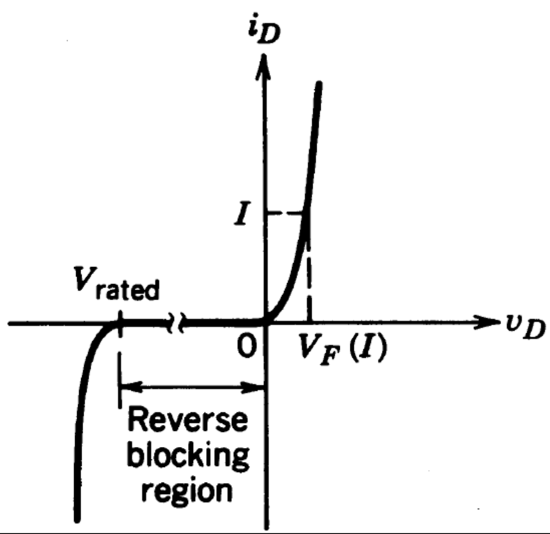
Outline

- Semiconductor switches
- Loss calculation
- Switching equivalents
- Thermal aspects

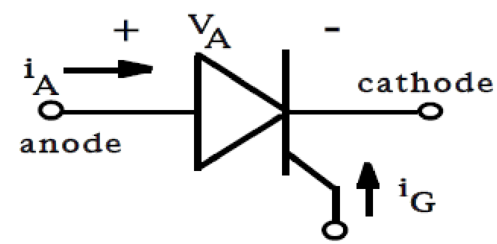
Semiconductors without turn-off capability

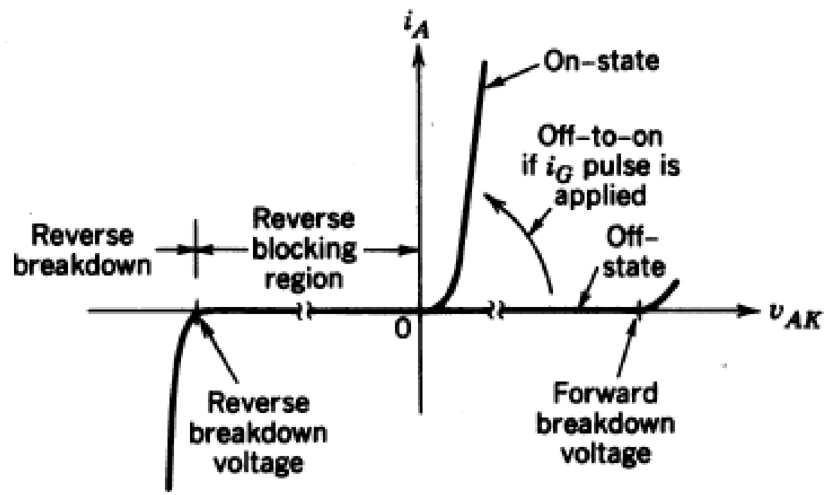
Diode





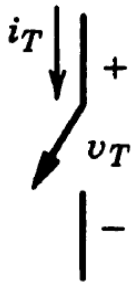
Thyristor circuit symbol.

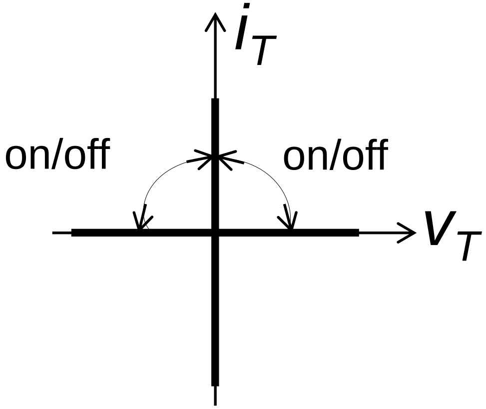




Ideal switch

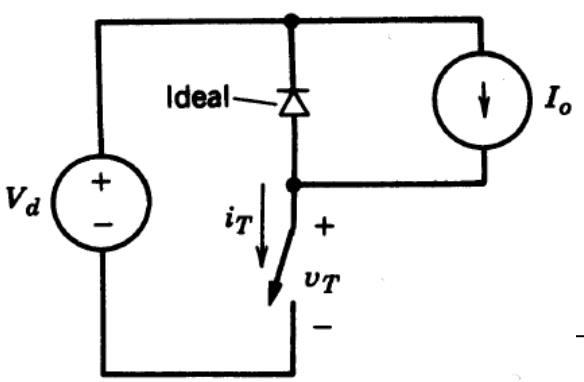
- Accept voltages of both polarities
  - Both negative and positive
- Controlled turn-on and turn-off
- Conduct current in both directions
- No breakdown voltage
  - Perfect isolation in off state
- Zero on-resistance
  - No voltage drop over the switch
- No switch delay
- Zero energy switching
  - No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

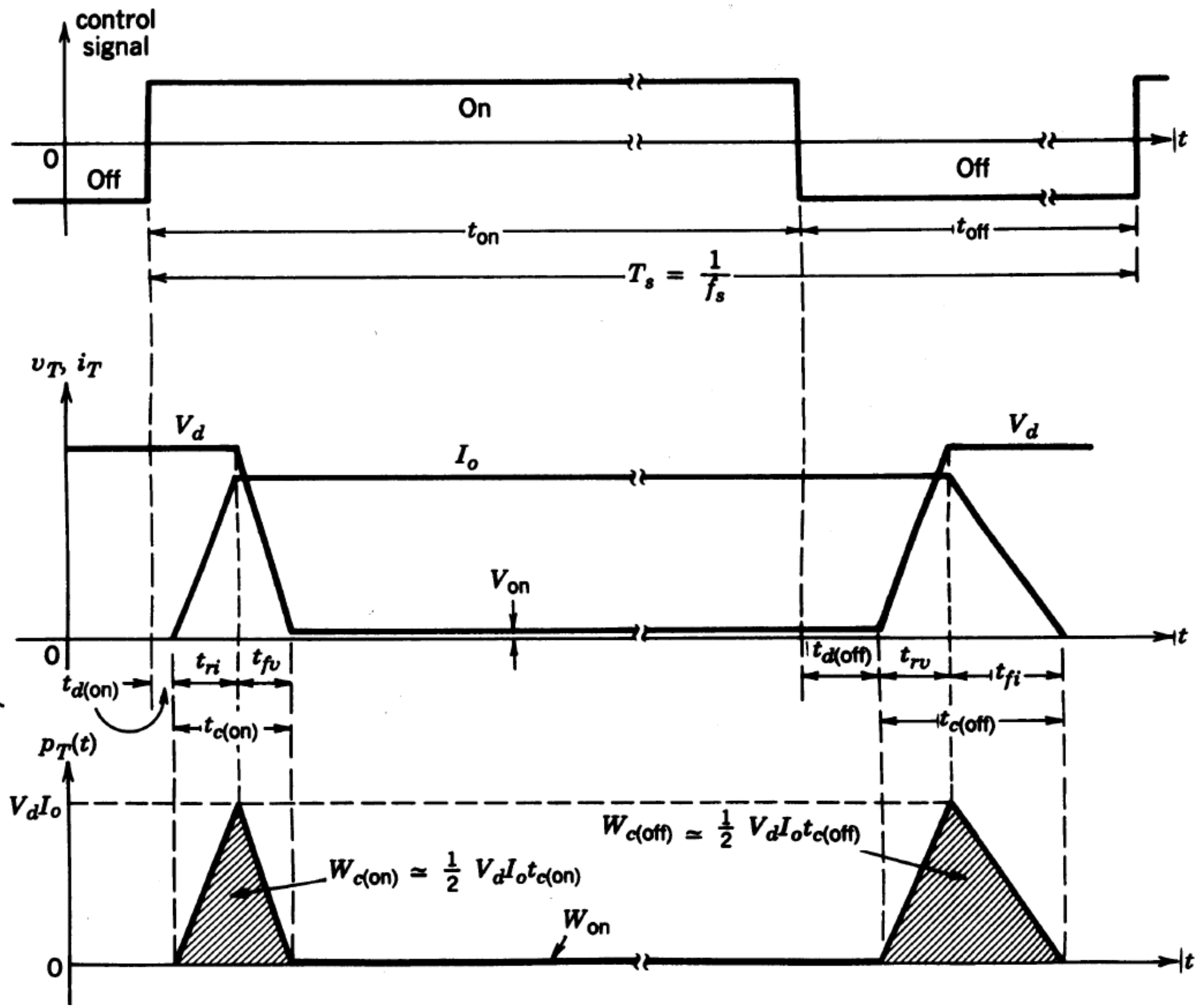




Non-ideal switch example

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





DC/DC converter losses

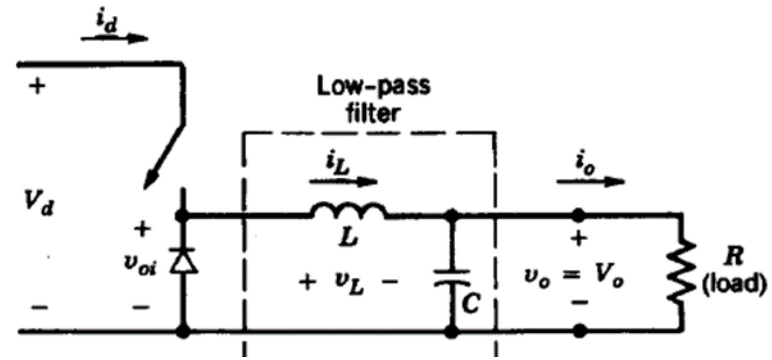
Conduction losses

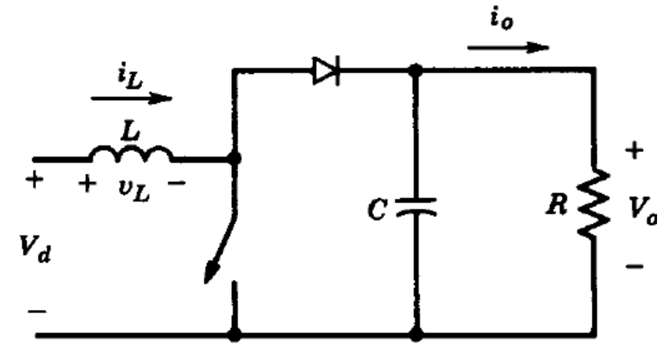
- $P_{on} = r_{ds(on)} I_{sw,rms}^2 =$
  $= D \cdot r_{ds(on)} I_{L,av}^2$

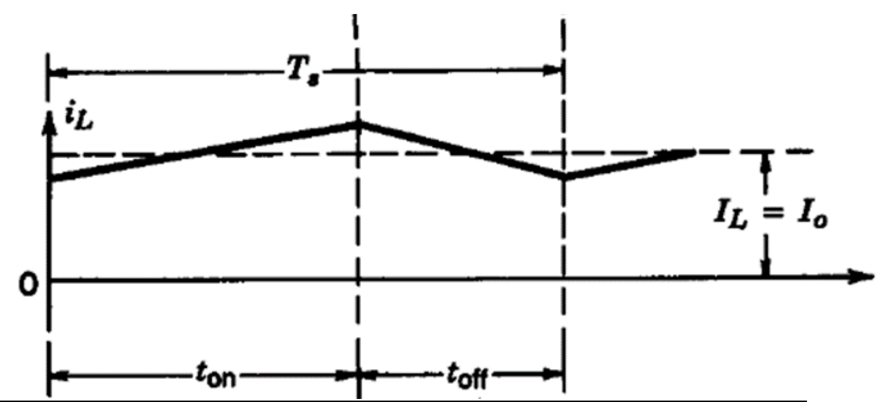
Switching losses (average)

- $P_s = \frac{1}{2} V_d I_{sw,aw} f_s \left(t_{c(on)} + t_{c(off)} \right)$
- $I_{sw,av} = I_{L,av}$

- Further reading see document "Losses" in Lisam/Tutorials

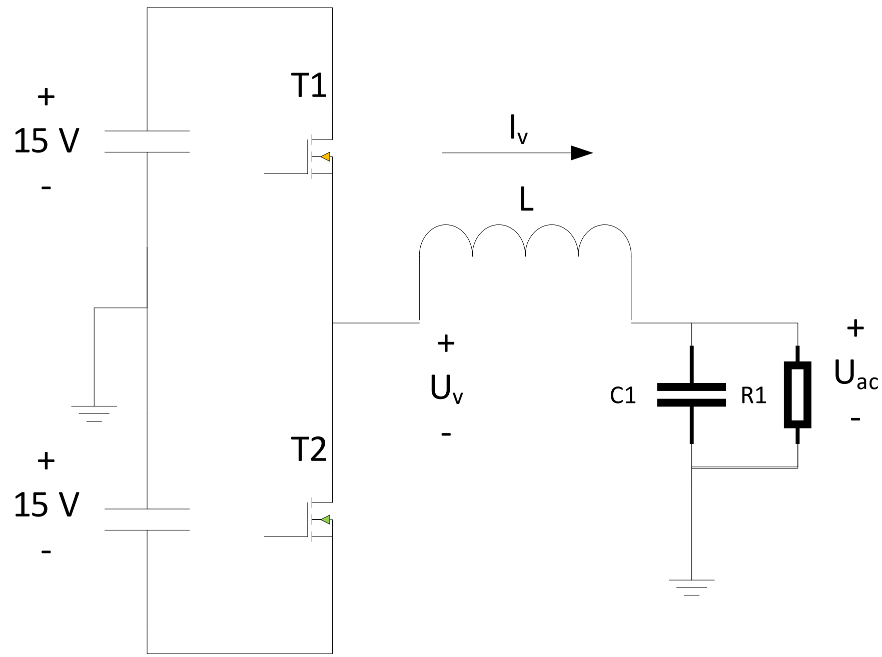






Half-bridge converter example

- Total dc-voltage, positive-to-negative side
  - $U_d = 30V$
- DC-voltage positive and negative side to ground
  - $\frac{U_d}{2} = \pm 15V$



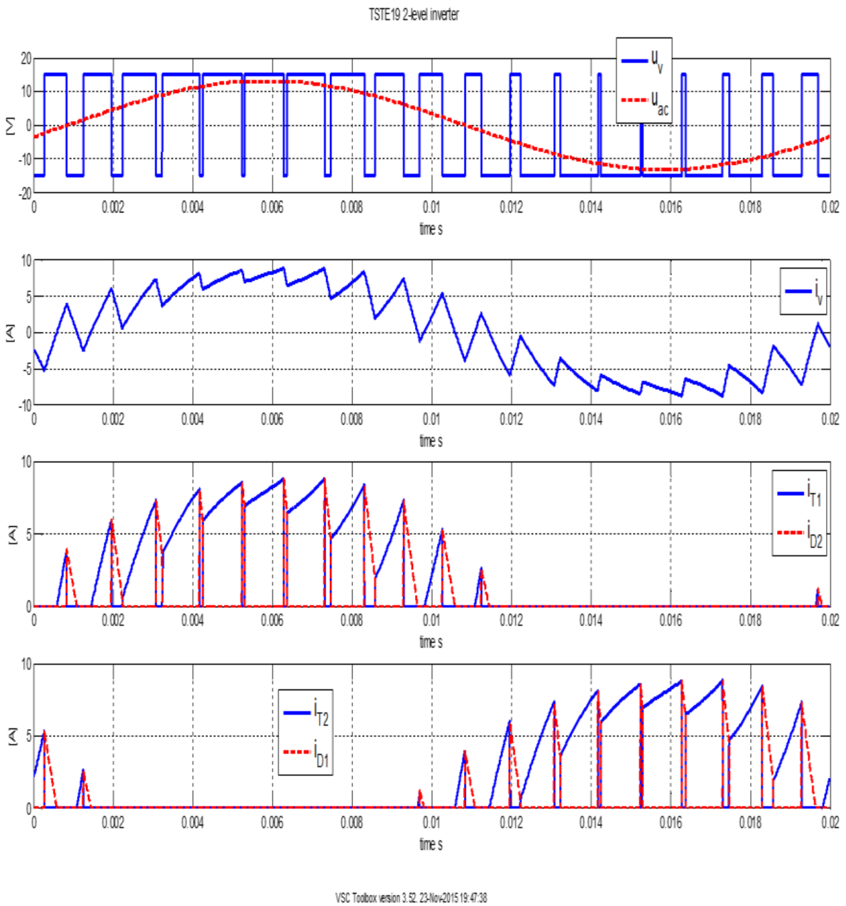
DC/AC converter losses

Conduction losses (Both switches)

- $P_{on} = 2 \cdot r_{ds(on)} I_{sw,rms}^2 =$
  $= 2D \cdot r_{ds(on)} I_{L,av}^2 =$
  $= \{D_{av} = 0.5\} = r_{ds(on)} I_{L,av}^2$

Switching losses (total average for both switches in a half-bridge)

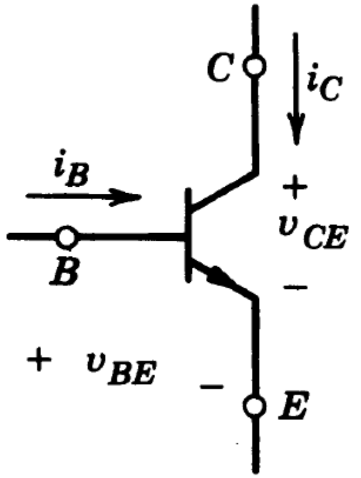
- $P_s = \frac{1}{2} V_d I_{sw,av} f_s \left(t_{c(on)} + t_{c(off)}\right)$
- $I_{sw,av} = \frac{2\sqrt{2}}{\pi} I_{v,rms} = 0.9 I_{v,rms}$
  (based on full-wave pulses)

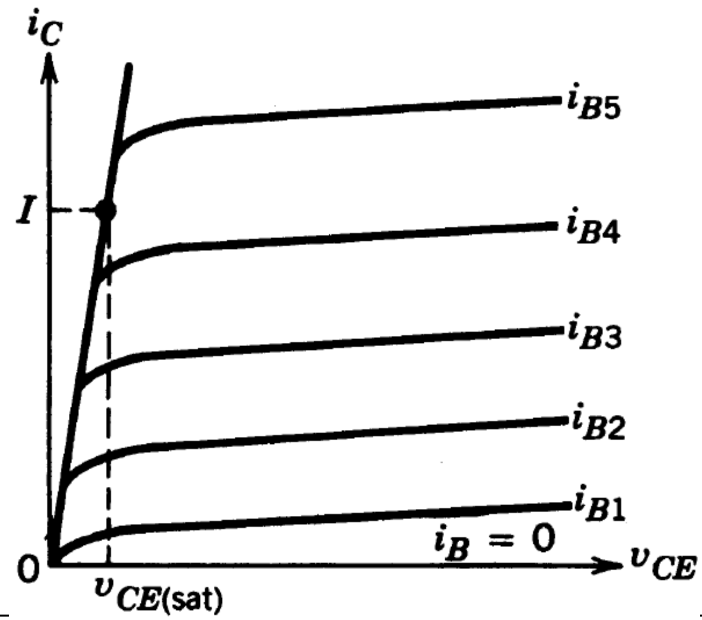


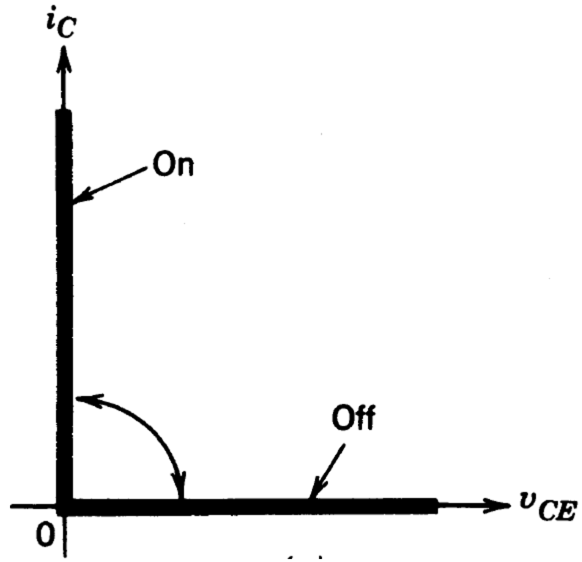
- Further reading see document "Losses" in Lisam/Tutorials

Bipolar junction transistors (BJT)

- Current controlled by base current i_B
- $5 < h_{FE} = \frac{I_C}{I_B} < 10$ for power BJT
- Possible to turn on and off

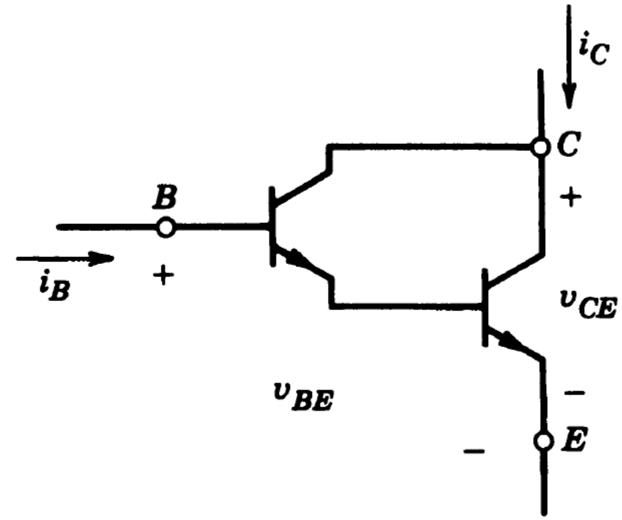


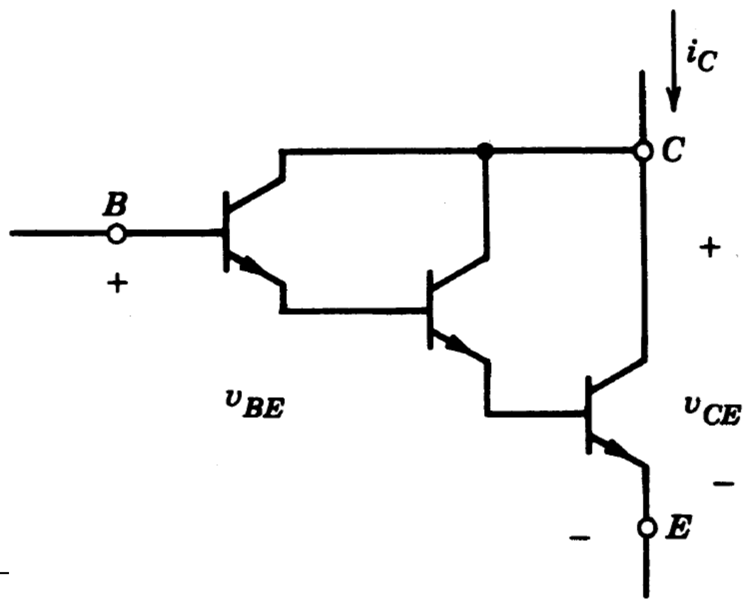




Darlington bipolar transistors

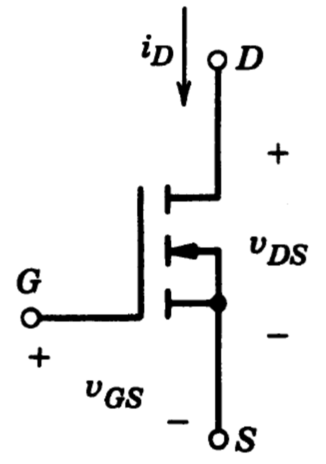
- Increase h_{FE}
- Increases also v_{CEsat}. Higher losses!
- 0.1 us < switching time < 10 us
- Integrated on a single silicon chip

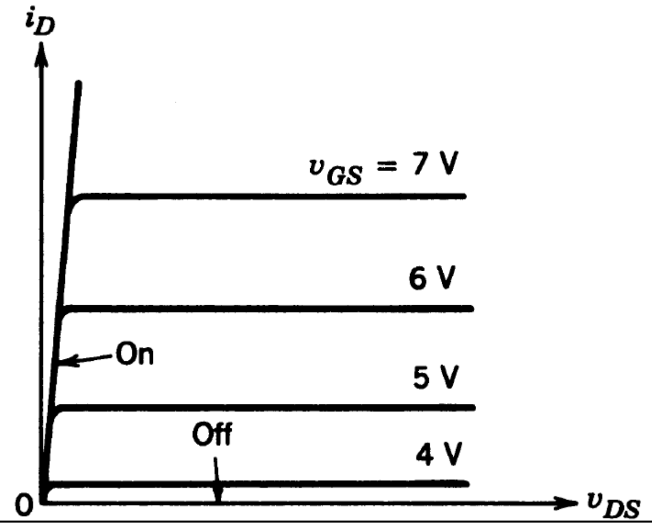


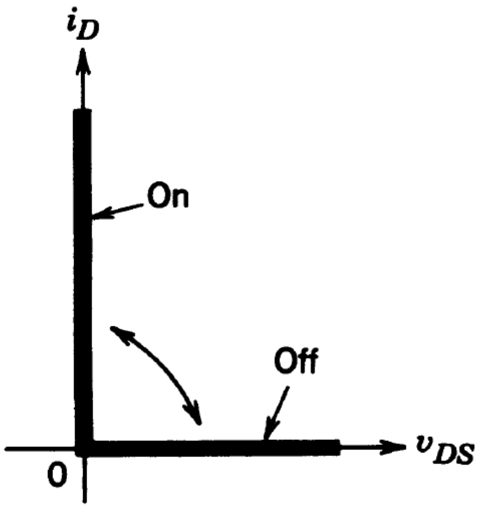


MOSFET transistors

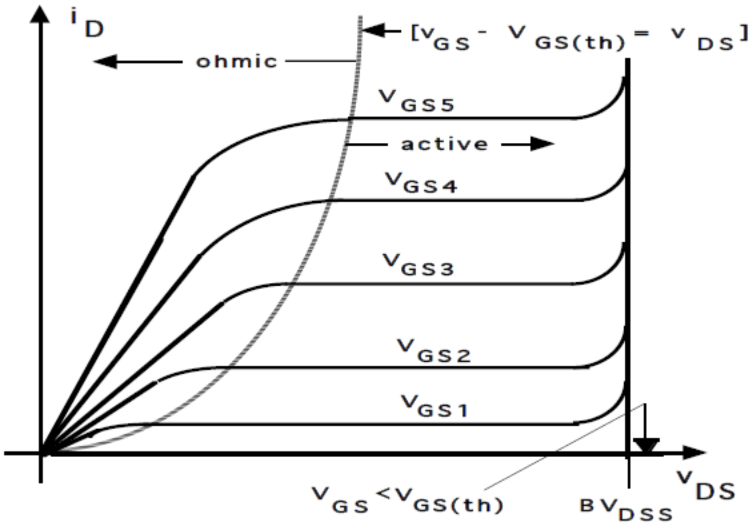
- Voltage controlled, $V_{GS} > V_{GS(th)}$
- Fast switching
  - 10 ns < t < 500 ns
- Tradeoff R_{on} vs Blocking voltage
- Bidirectional current conduction
- Built in “body” diode

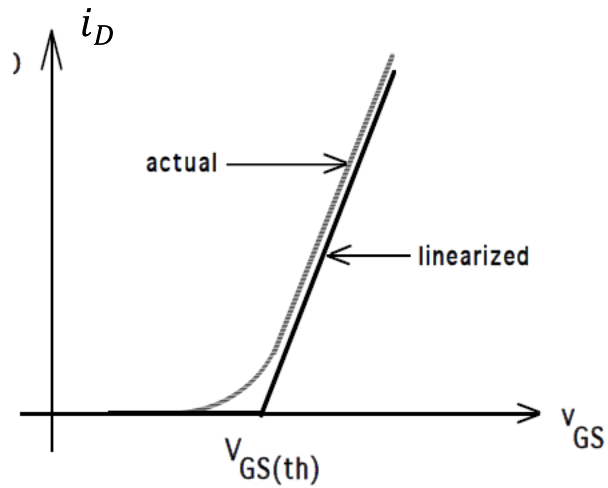


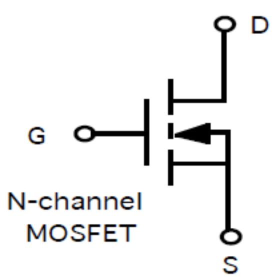




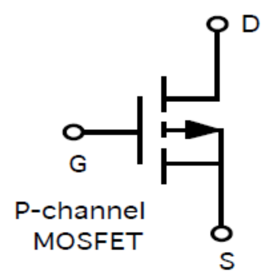
MOSFET I-V Characteristics and Circuit Symbols







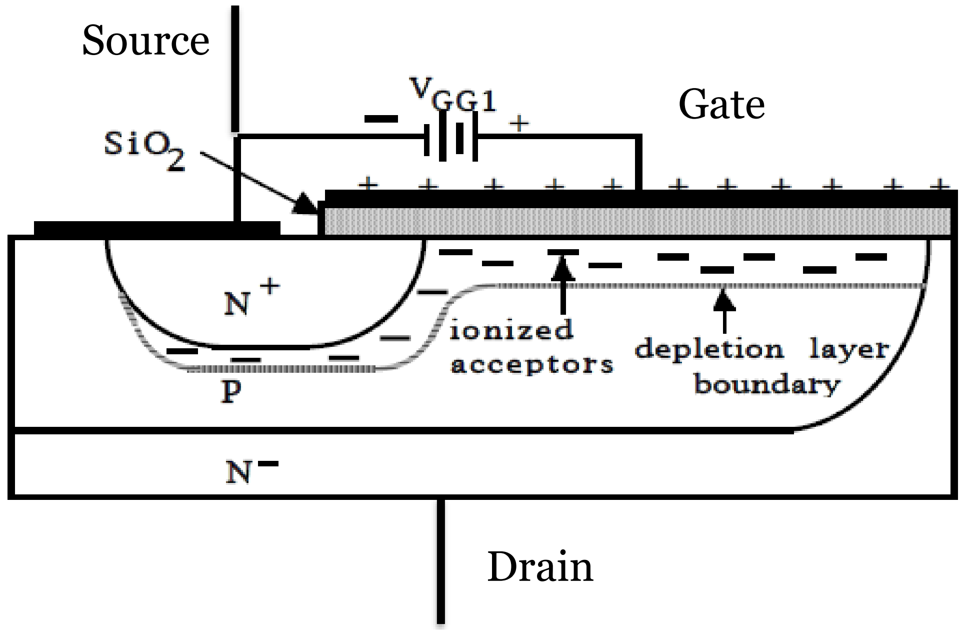
N-channel
$V_{GS}>0$



P-channel
$V_{GS}<0$

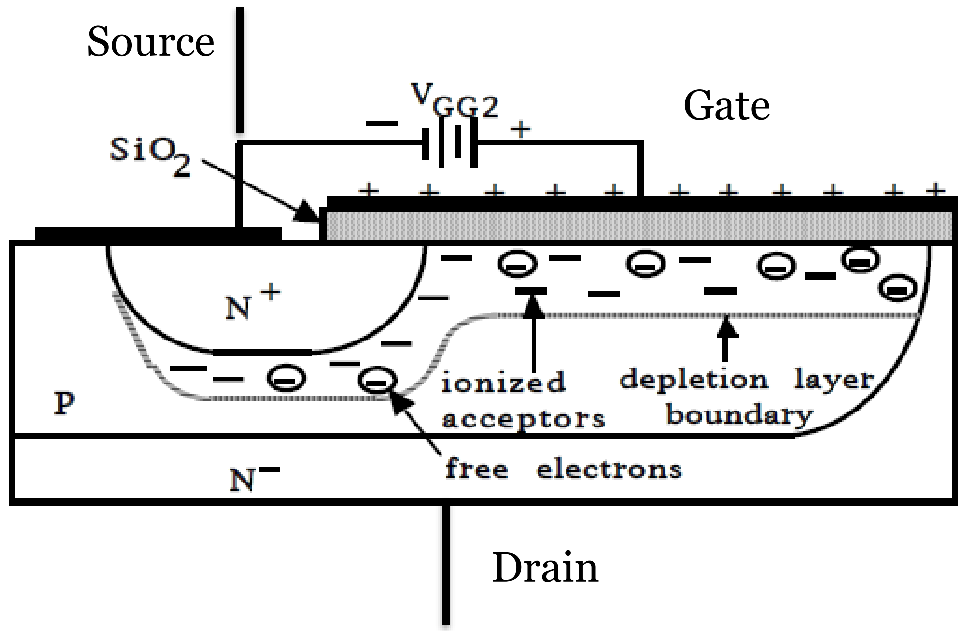
MOSFET channel conduction control

- Low gate voltage
  - $V_{GS} << V_{GS(th)}$
- Inversion layer isolating drain N^- from source N^+



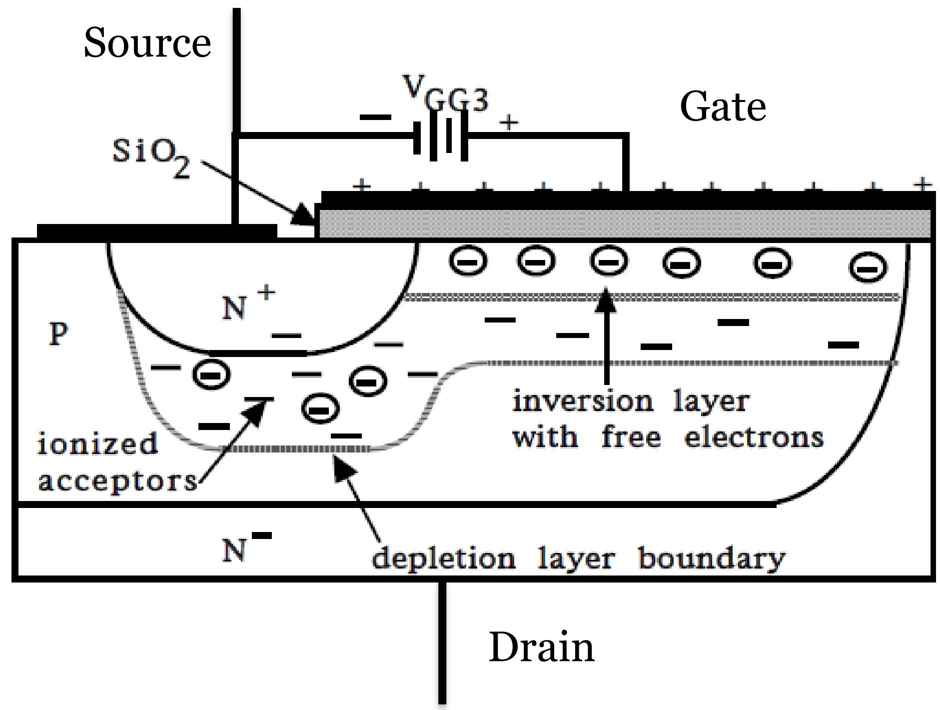
MOSFET channel conduction control

- Increasing gate voltage but below threshold
  - $V_{GS} < V_{GS(th)}$
- Inversion layer with some free electrones still isolating drain N^- from source N^+



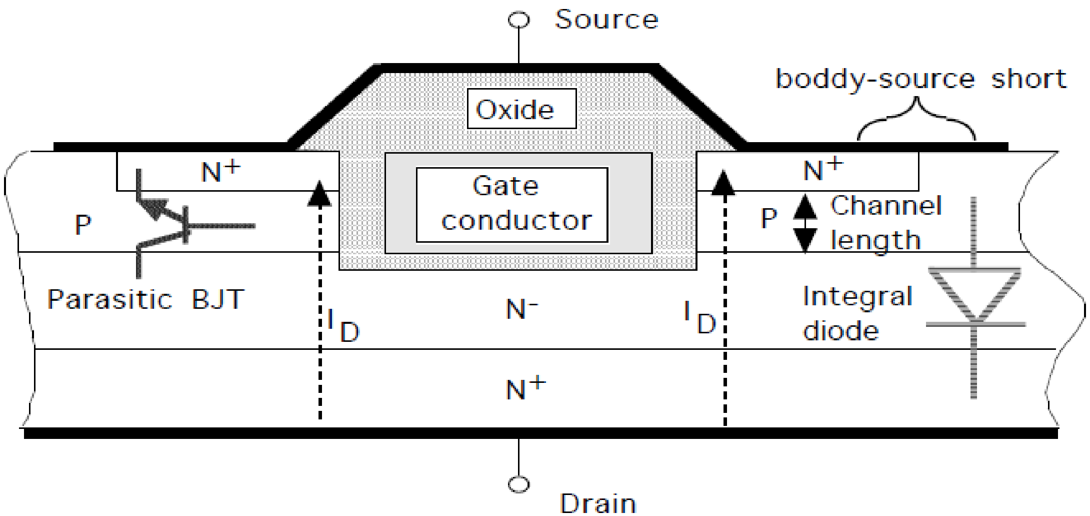
MOSFET channel conduction control

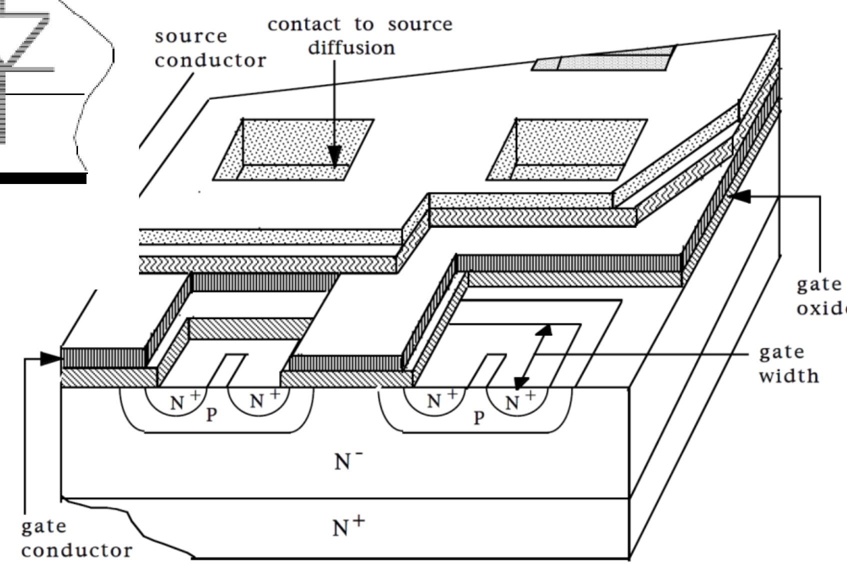
- High gate voltage above threshold
- $V_{GS} > V_{GS(th)}$
- Conductive channel of free electrons formed between drain N^- and source N^+



MOSFET implementation

- Thousands of cells in parallel

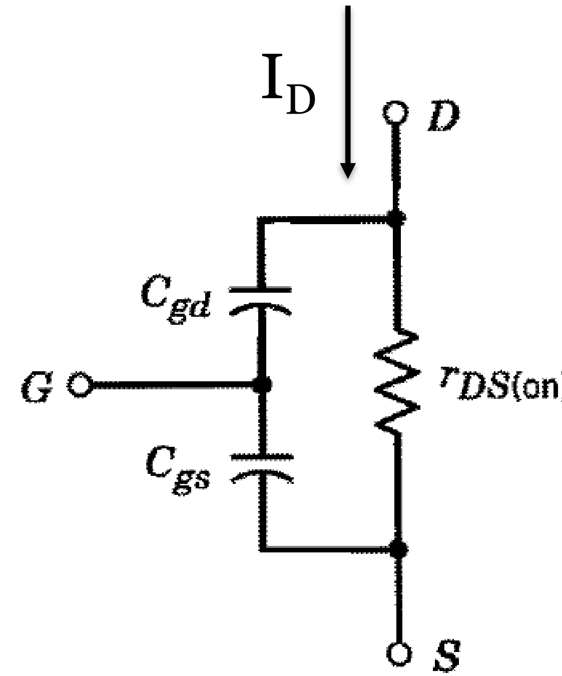




MOSFET on-state equivalent

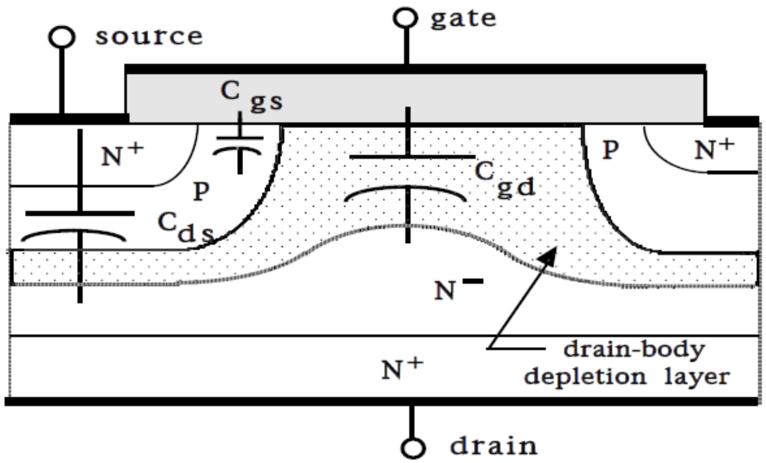
- On-state conduction losses

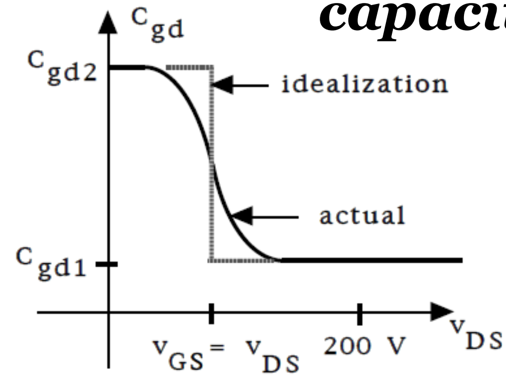
$$P_{on} = r_{DS(on)} I_D^2$$



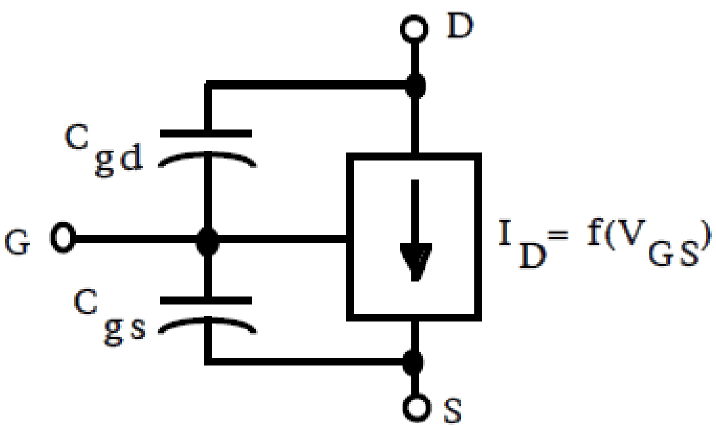
MOSFET equivalent circuit for on-state operation

MOSFET turn-on/turn-off equivalent





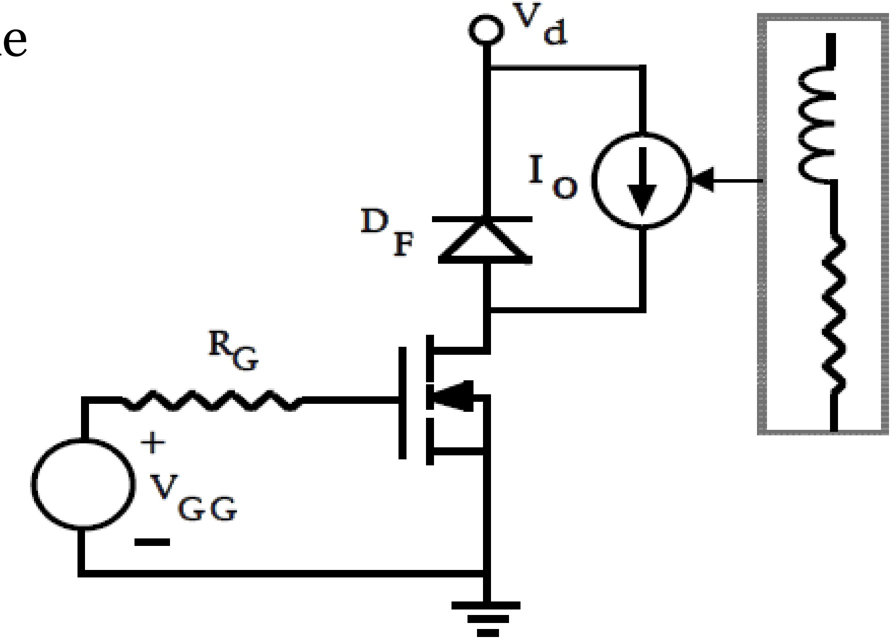
C_{gd}: "Miller capacitance"



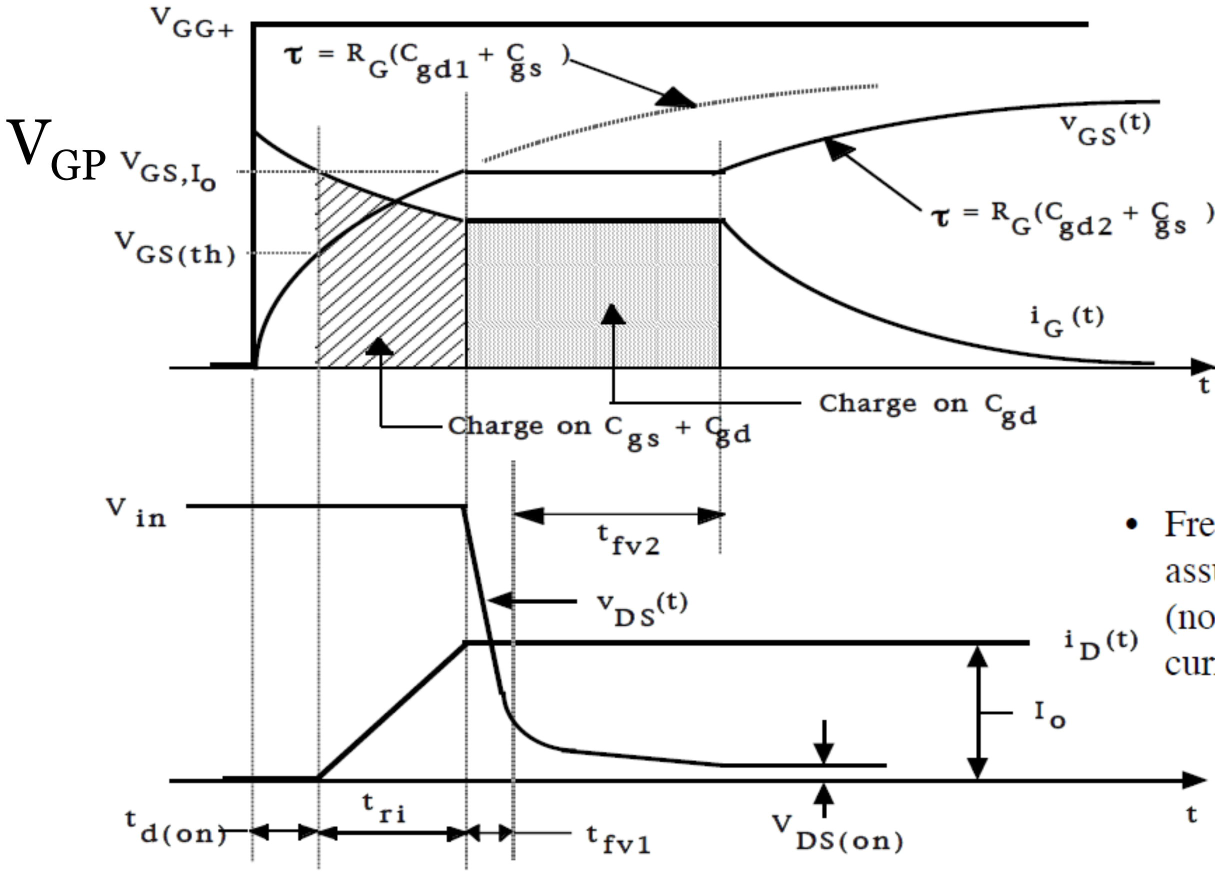
MOSFET equivalent circuit for off-state and active region operation

Switching MOSFET – Diode pair

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



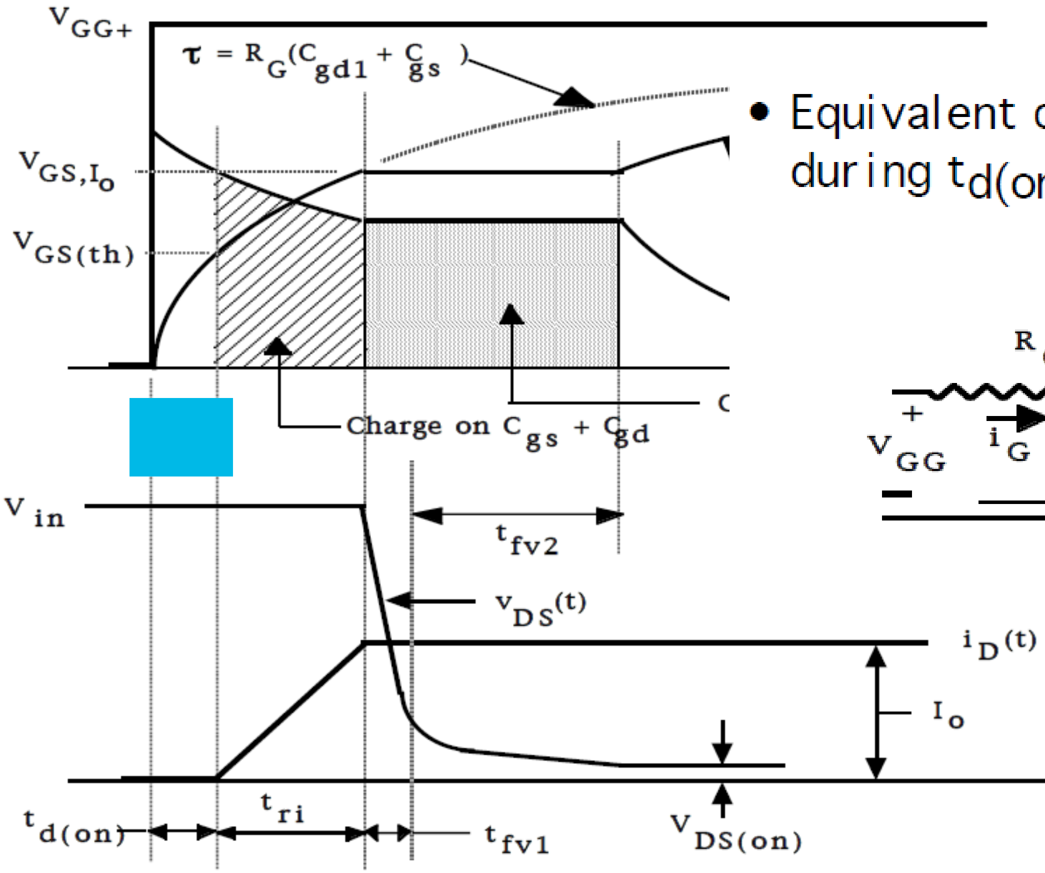
MOSFET-based Buck Converter Turn-on Waveforms



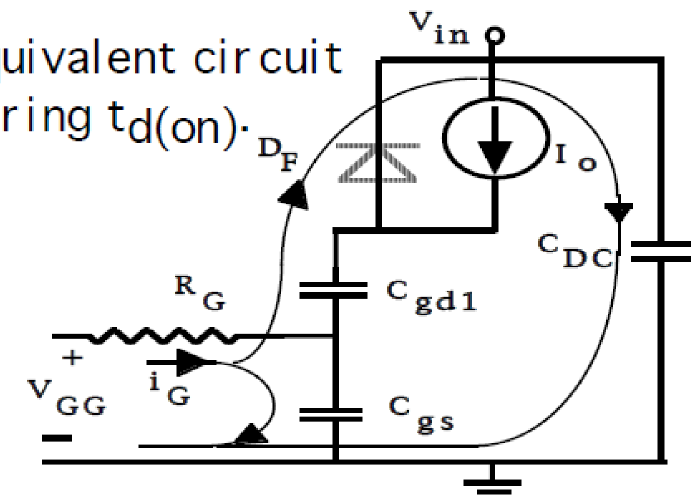
"Miller plateau"

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

MOSFET-based Buck Converter Turn-on Waveforms

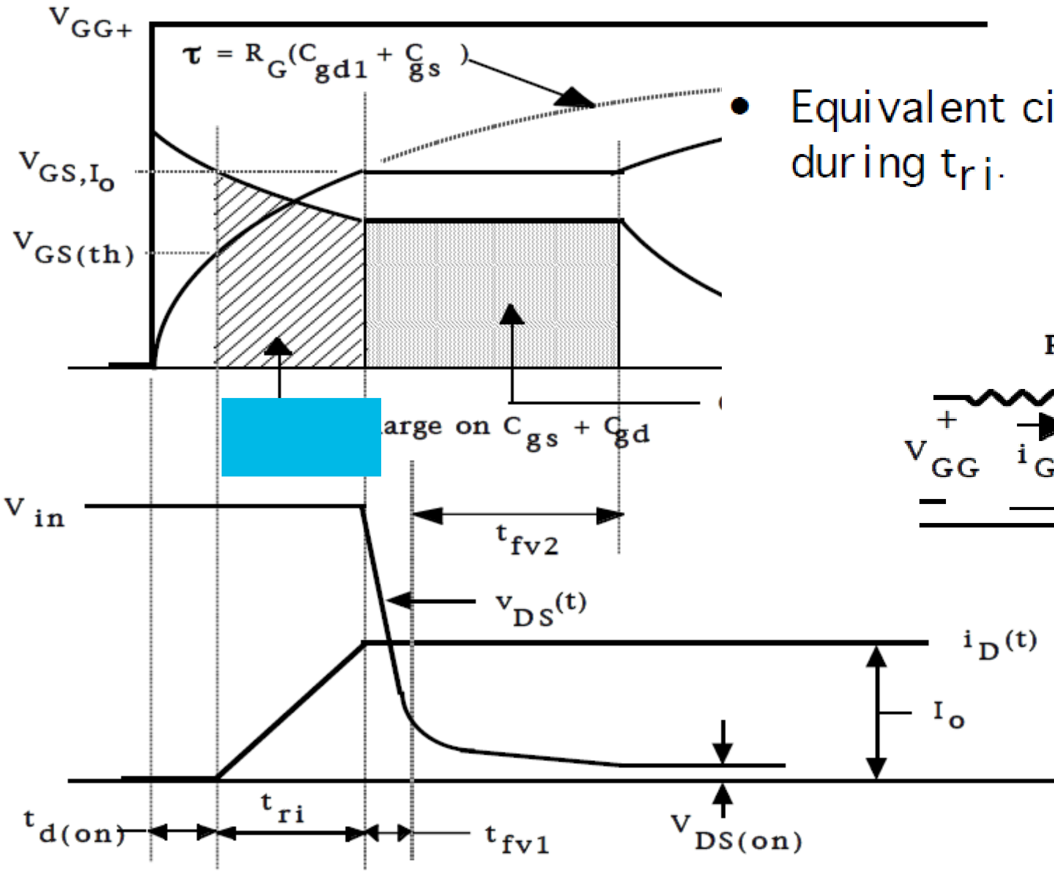


- Equivalent circuit during $t_{d(on)}$.

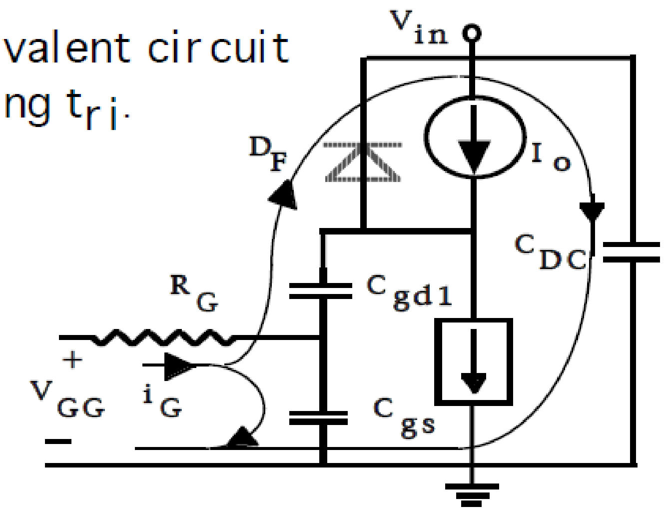


- $V_{gs} = V_{GG}\left(1 - e^{\frac{-t}{RC}}\right)$
- $R = R_g$
- $C = C_{gs} + C_{gd}$

MOSFET-based Buck Converter Turn-on Waveforms

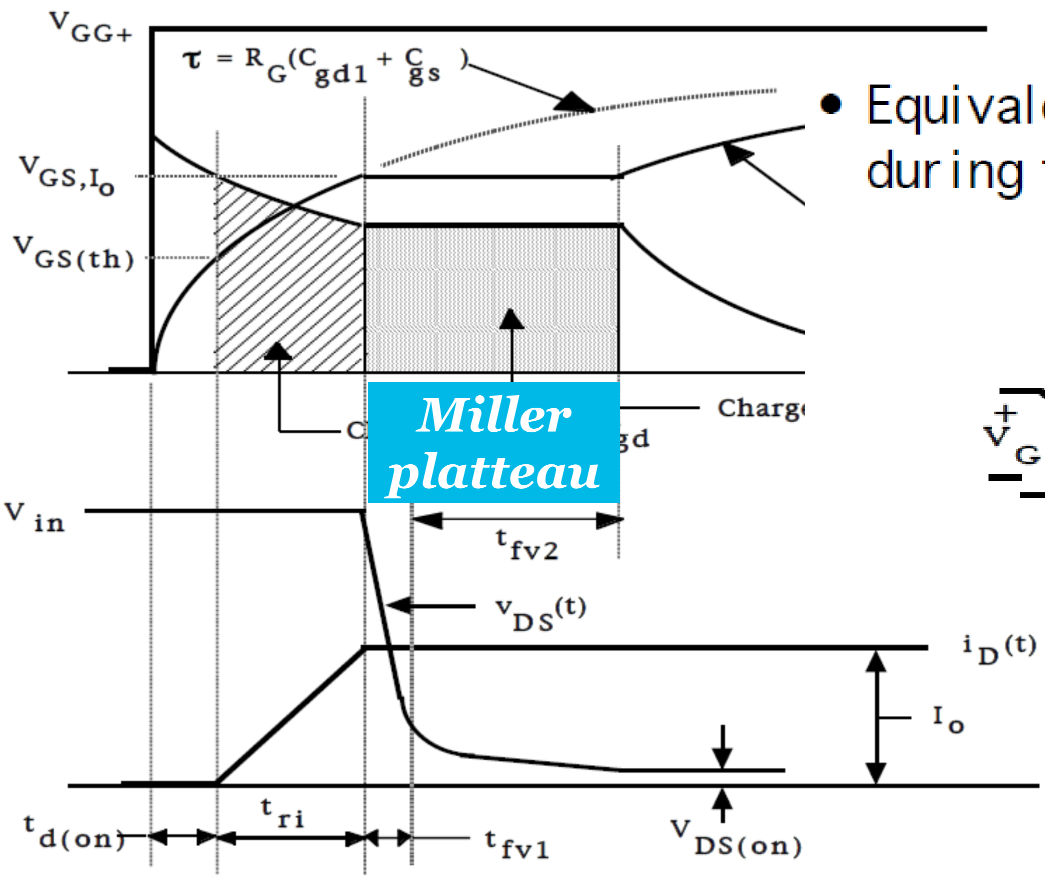


- Equivalent circuit during t_{ri}.

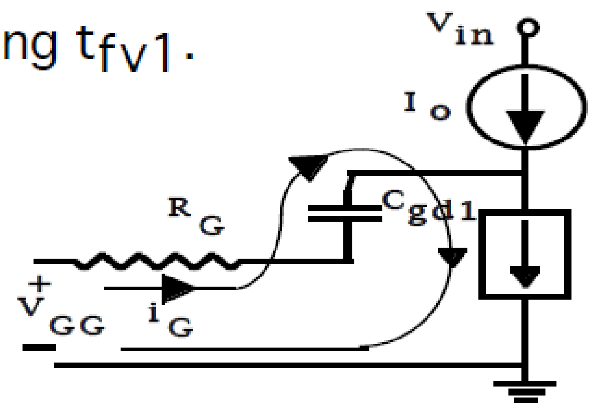


- $V_{gs} = V_{GG}\left(1 - e^{\frac{-t}{RC}}\right)$
- $R = R_g$
- $C = C_{gs} + C_{gd}$

MOSFET-based Buck Converter Turn-on Waveforms

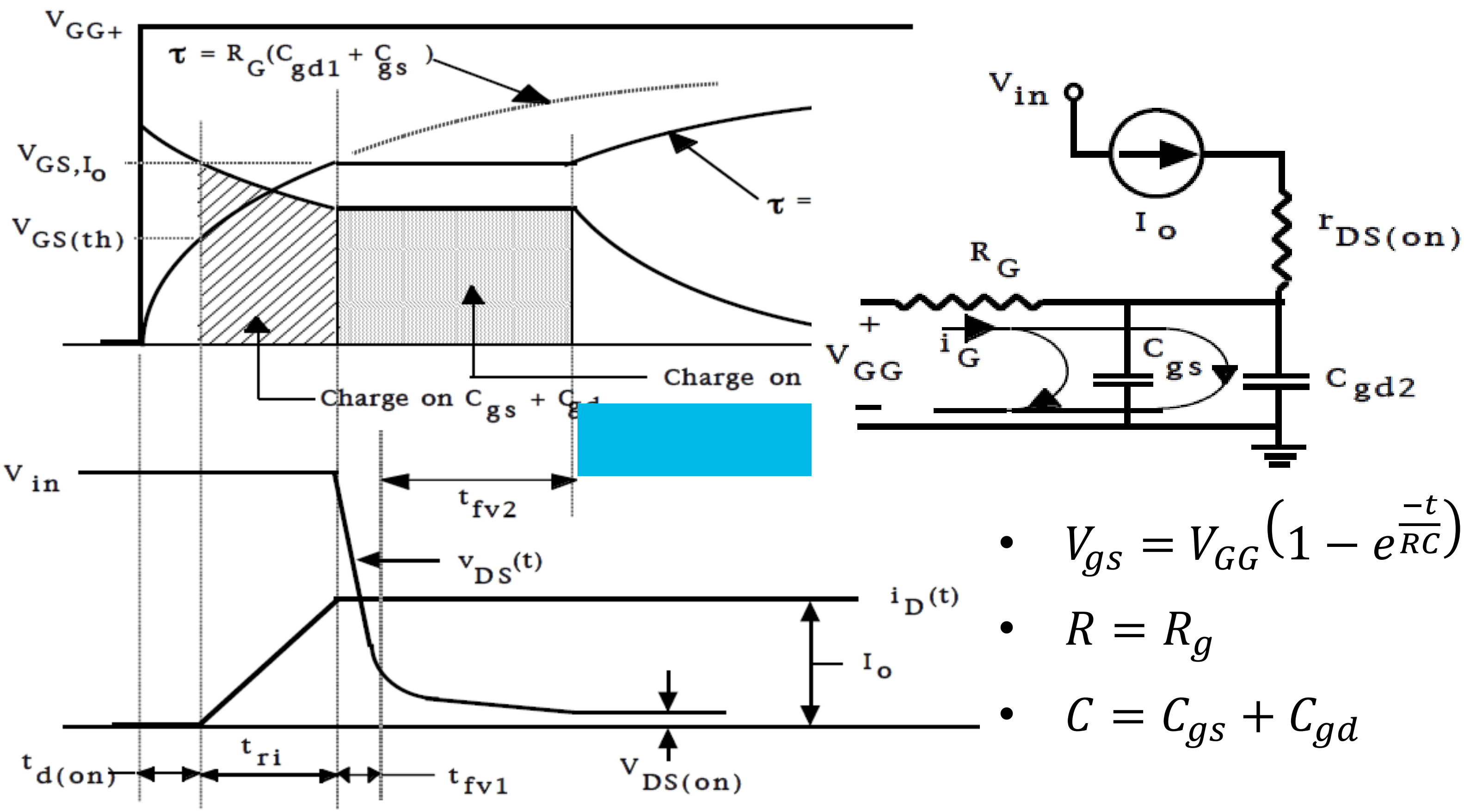


- Equivalent circuit during t_{fv1}.



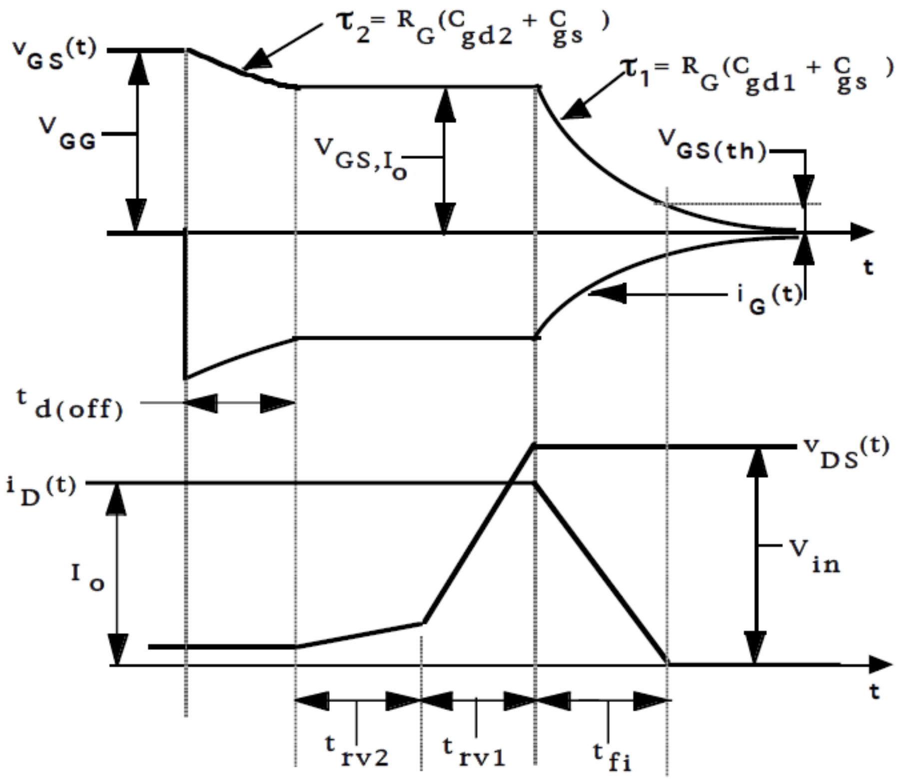
- $V_{gs} = V_{GP}$
- $i_g = \frac{V_{GG} - V_{GP}}{R_g} = C_{gd} \frac{dV_{ds}}{dt}$

MOSFET-based Buck Converter Turn-on Waveforms



- $V_{gs} = V_{GG}\left(1 - e^{\frac{-t}{RC}}\right)$
- $R = R_g$
- $C = C_{gs} + C_{gd}$

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

MOSFET data sheet

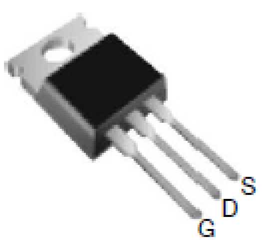
IRF540, SiHF540

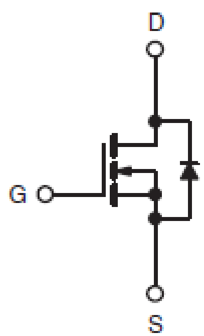
Vishay Siliconix

Power MOSFET

PRODUCT SUMMARY		
V_{DS} (V)	100	
$R_{DS(on)}$ (Ω)	V_{GS} = 10 V	0.077
Q_g (Max.) (nC)	72	
Q_{gs} (nC)	11	
Q_{gd} (nC)	32	
Configuration	Single	

TO-220AB



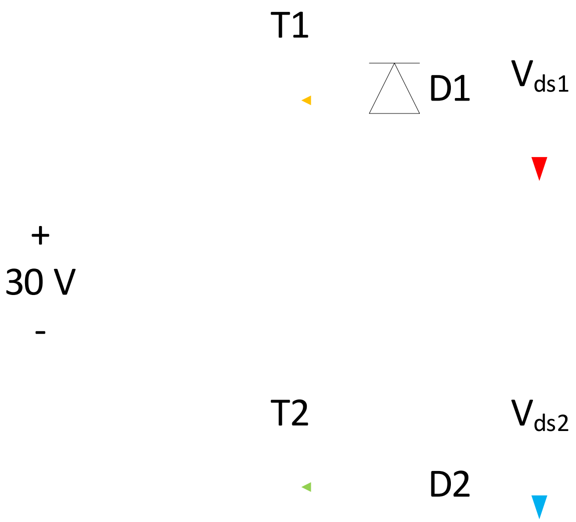


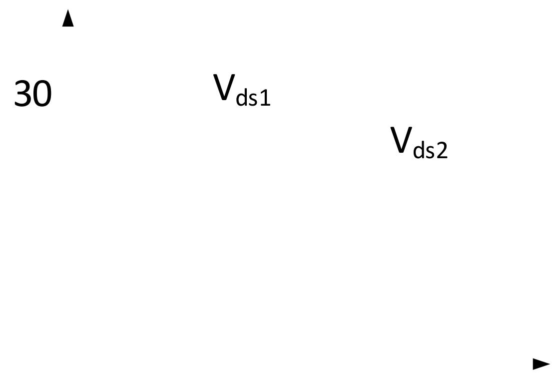
N-Channel MOSFET

Definitions of device capacitances.

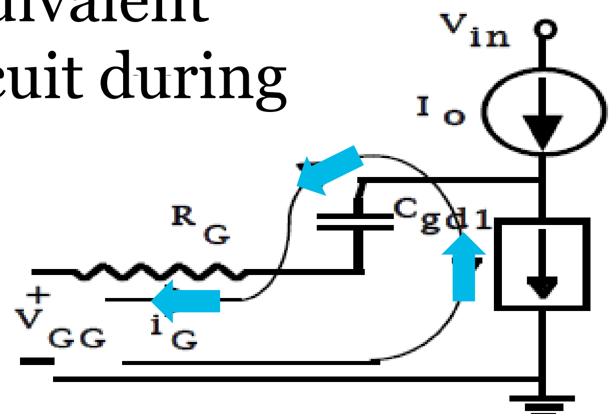
a. $C_{iss} = C_{GS} + C_{GD}$, C_{DS} shorted
b. $C_{rss} = C_{GD}$
c. $C_{oss} = C_{DS} + C_{GD}$

MOSFET T1 turn-on. Disturbance on T2 ??



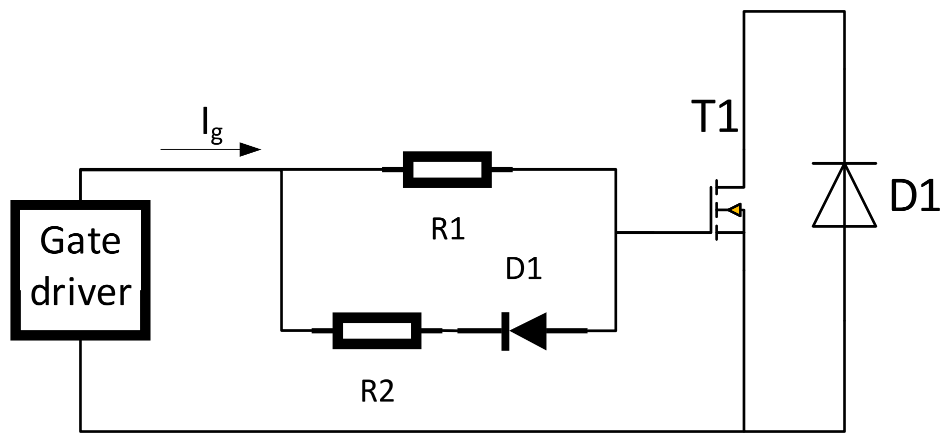


- V_{GG2}=0
- $i_{g2} = C_{gd}\frac{dV_{ds}}{dt}$
- $V_{gs2} = V_{GG2} + R_g\, i_{g2}$
  - $V_{gs2} > V_{gs(th)}$
  - **T2 TURN-ON**
- Equivalent circuit during t_{rv1}

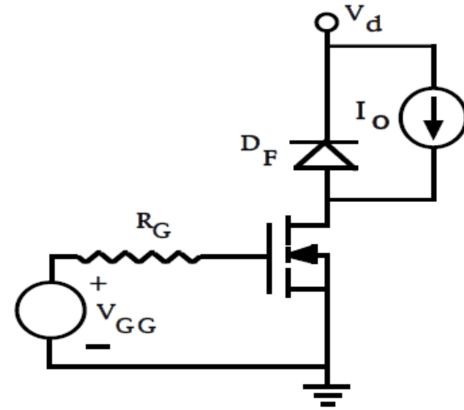


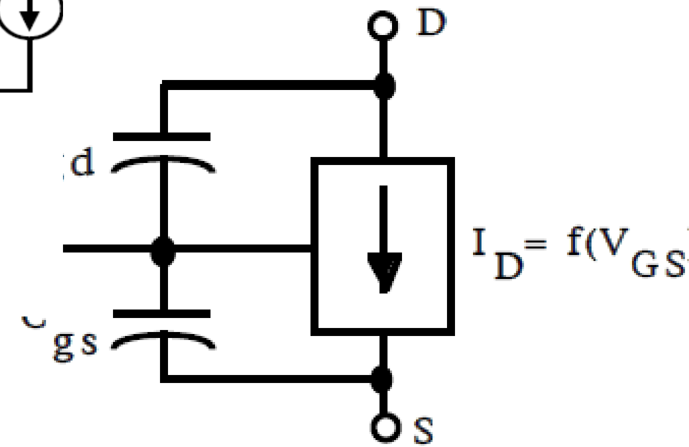
Gate resistance control

- Separate $R_{g(on)}$=R1 and $R_{g(off)}$=R2
- Diode D1 makes R1 active during turn-on and R2 active during turn-off
  R2<< R1
- Reduced $R_{g(off)}$ to prevent parasitic turn-on at high dv/dt

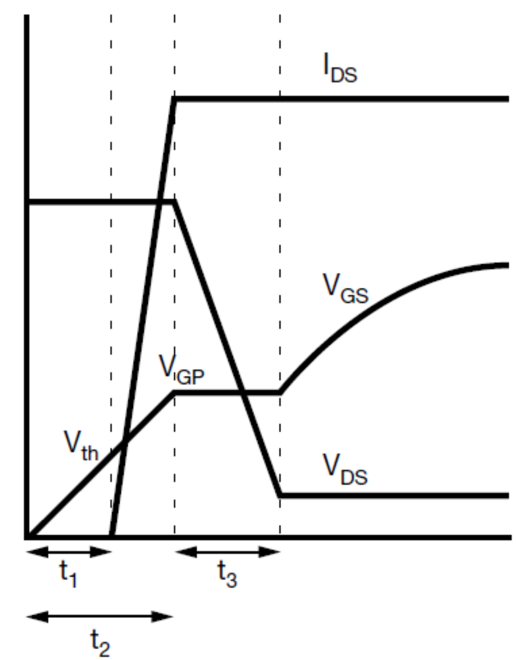


5-100



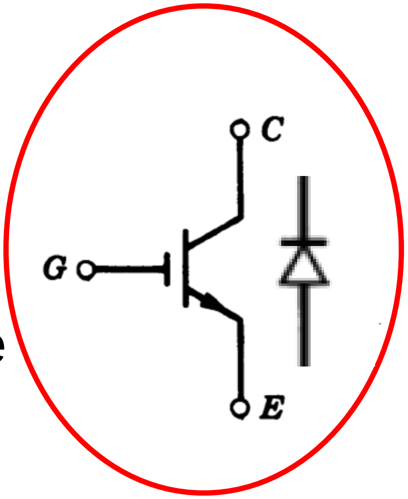


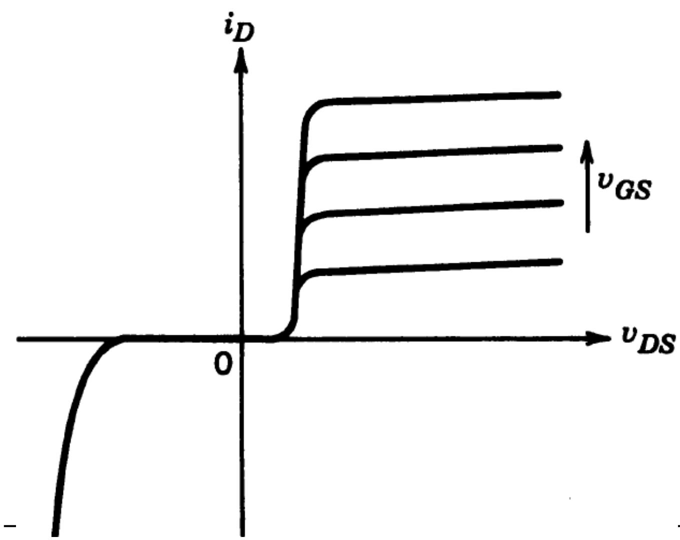
- For a step-down converter the dV_{DS}/dt of a MOSFET during turn-on is defined by V_d (assume V_{dson}=0) and t_{fv}.
- V_{ds} = 100 V, t_{fv} =t3= 200 ns
- The gate-drain capacitance, C_{gd} = 120 pF. The miller platteau voltage V_{GP} = 4V
- Calculate the gate resistance, R_G for a gate drive with V_{GG} = 10V which gives a dV_{DS}/dt as specified.

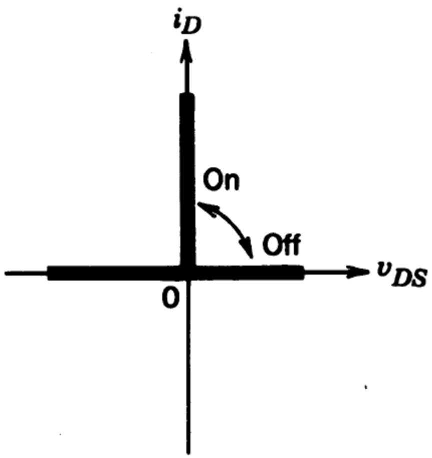


Insulated gate bipolar (IGBT)

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

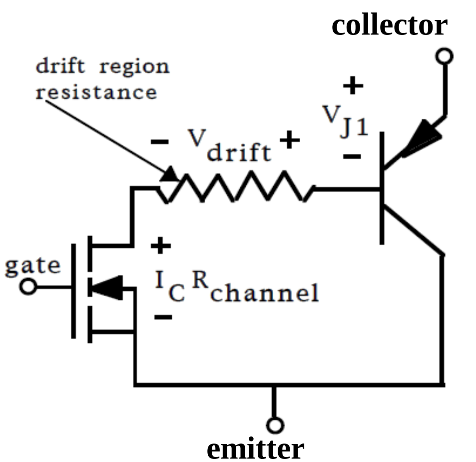


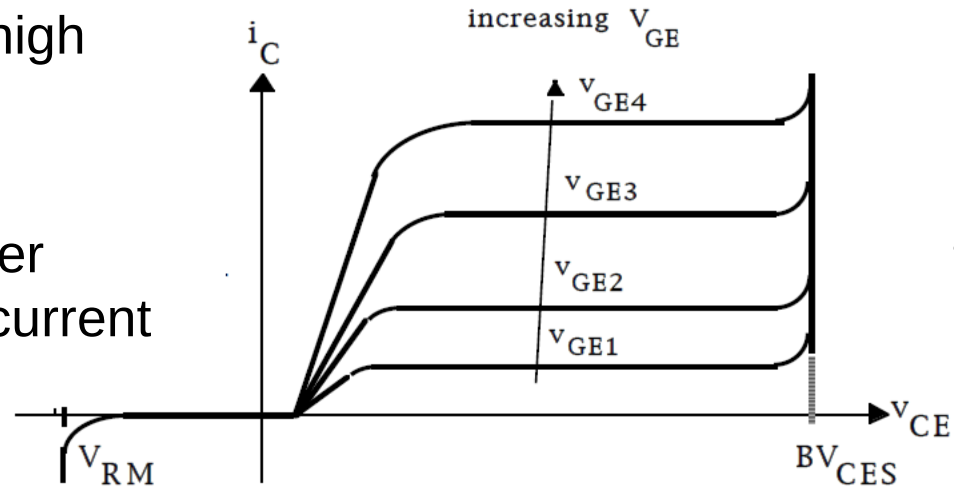


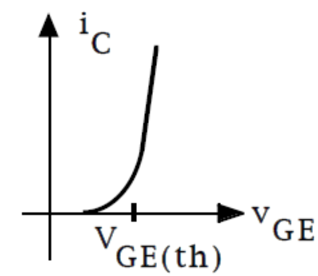


Insulated gate bipolar (IGBT) implementation

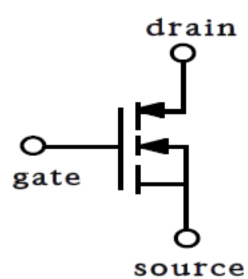
- Bipolar carrier conduction (electron & holes)
  low voltage drop at high current
- PN-junction in PNP transistor gives higher voltage drop at low current



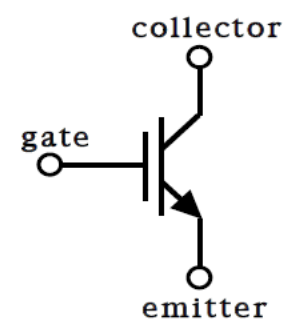




• Transfer curve



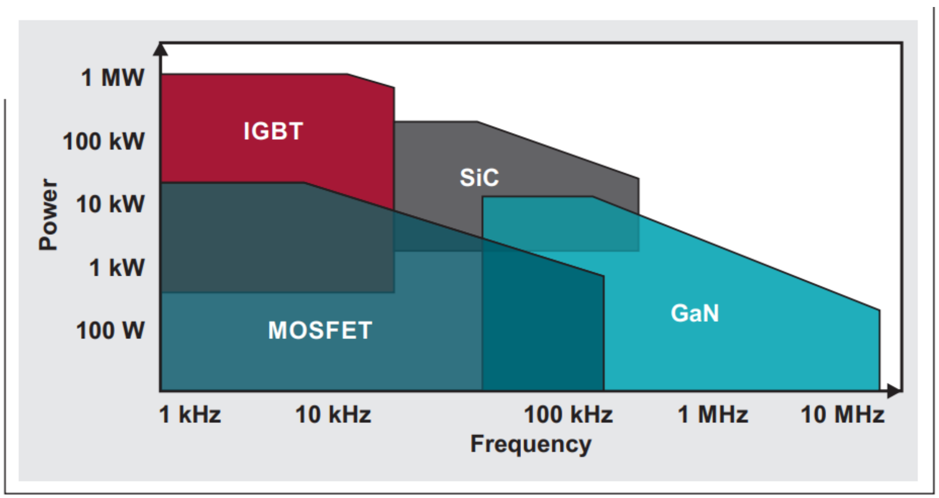
• N-channel IGBT circuit symbols



Semiconductor materials

- Silicon
  MOSFET & IGBT
- Silicon Carbide
  MOSFET
- Gallium Nitride
  MOSFET, HEMT

Parameter	GaN	SiC	Si
Electron mobility (cm^2 /V*s)	1800	900	1400
Energy gap (eV)	3.5	3.26	1.12
Breakdown electric field (MV/cm)	3.3	3	0.3
Thermal conductivity (W/cm*K)	1.3	4.9	1.5
Saturation drift velocity (Mcm/s)	27	27	10



Source: Wide-bandgap semiconductors: Performance and benefits of GaN versus SiC, Analog Design Journal, Texas Instruments 2020

Lecture 4

Thermal management

Cooling requirement motivation

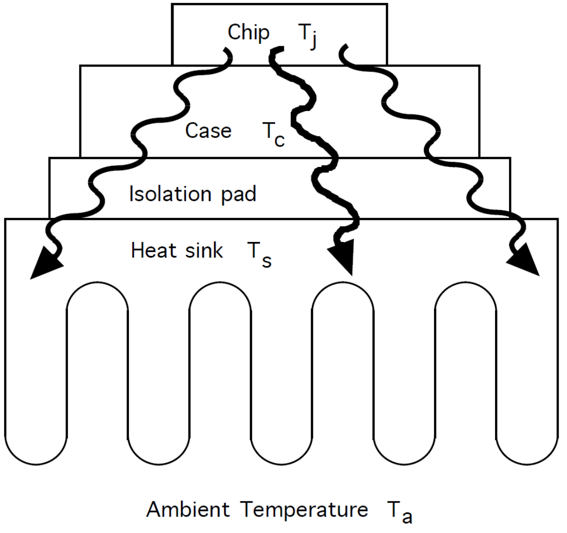
- Component failure rate increase with temperature increase
- Capacitors
  - Electrolyte evaporate reate increase with temperature
- Magnetic components
  - Losses in magnetic components increase when T > 100 degrees
  - Winding insulation degrades when T > 100 degrees
- Semiconductors
  - Breakdown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

Heat sinks

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

Thermal model with electric analogy

- Power corresponds to current,
- Temperature corresponds to voltage,
- Thermal resistance R_Θ (or R_{th}) corresponds to ohmic resistance



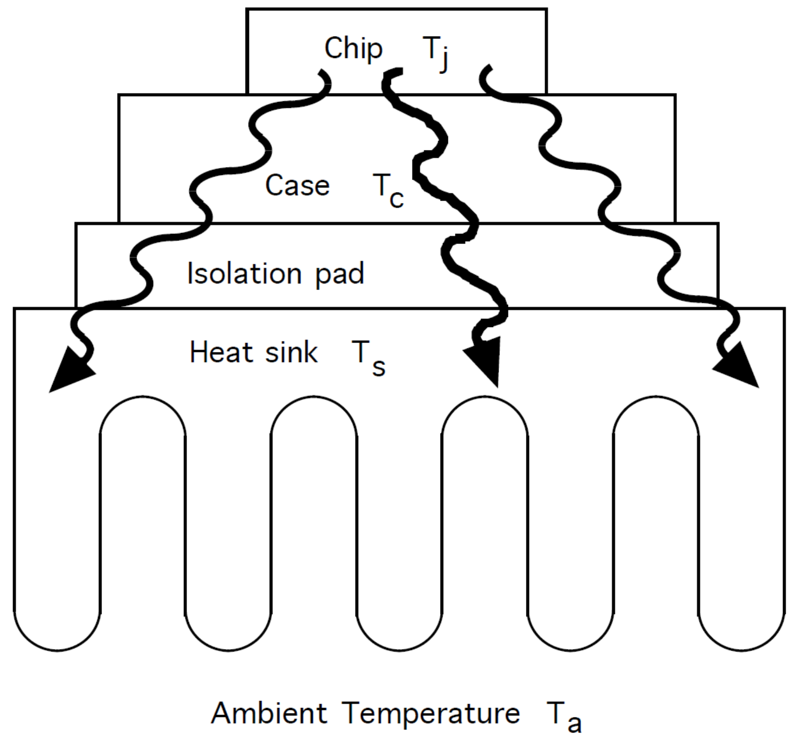
$$\Delta T = P \cdot R_\Theta \, [\mathrm{K}/W]$$

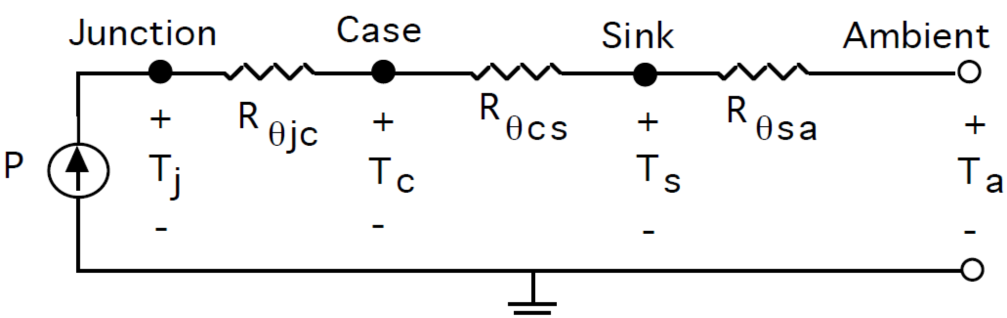
$$R_\Theta = \frac{\Delta T}{P} \, [\mathrm{K}/W]$$

Multiple layer structure model

$$T_j = T_c + \Delta T_{jc} = T_c + P \cdot R_{\Theta,jc}$$

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



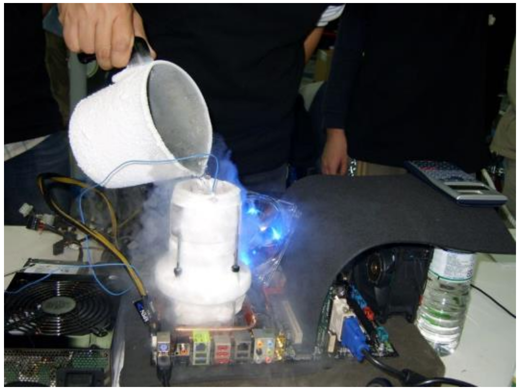


29-6

- 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.

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



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