EE394V switches

Note Title 10/14/2007

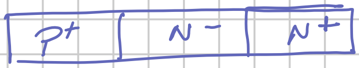
Objectives
→ Diode
→ MOSFET
→ IGBT
→ SCR & other switches fundamentals

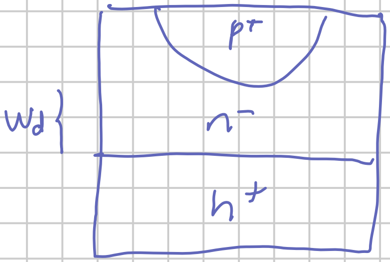
In most cases → behavioral model

Power diode (PiN diode)

Signal diode →

Power diode →





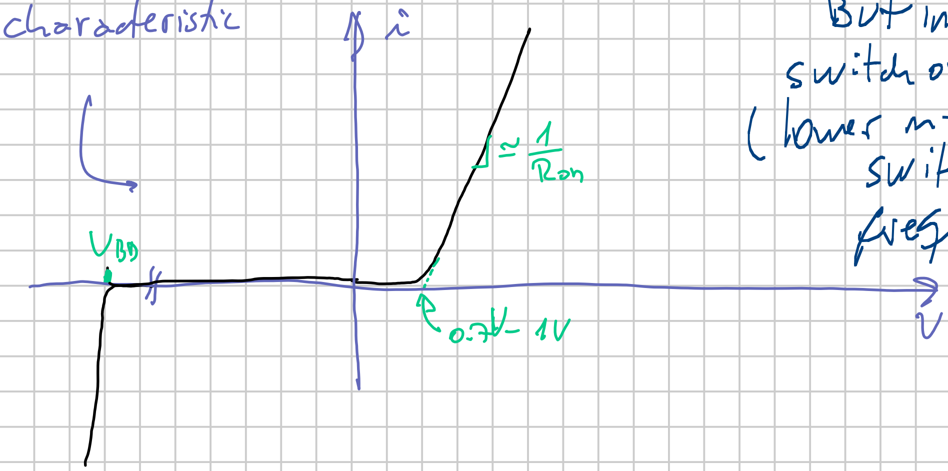
→ Blocking characteristics → drift region

lightly doped → "insulator"

↓ charge injection to the drift region reduces resistance while conducting current

↓ But increases switch on time (lower max. switching frequency)

Static characteristic



$$V_{BD} = \frac{\varepsilon E_{BD}^2}{2 q N_d}$$

$N_d \rightarrow$ drift region dopping density

$\varepsilon \rightarrow$ Dielectric constant ($1.05 \times 10^{-12} \frac{F}{cm}$ for Si)

$E_{BD} \rightarrow$ Electric field (breakdown) $\longrightarrow 2 \cdot 10^5 \, V/m$

$q \rightarrow$ electron charge $\longrightarrow \simeq 1.6 \cdot 10^{-19} C$

$$V_{Bd} \simeq \frac{1.3 \cdot 10^{17}}{N_d}$$ (The less dopped, the higher V_{BD} is)

$$W_d \geq W \Big|_{V_{BD}} \simeq \frac{2 V_{BD}}{E_{BD}} = 1 \cdot 10^{-5} V_{BD}$$

↳ cm

$$\underset{\downarrow \text{ meters}}{W_d} \geq 1 \cdot 10^{-7} V_{BD}$$

$$\underset{\hookrightarrow \mu m}{W_d} \geq 0.1 \, V_{BD} \longrightarrow \text{for } 1000V, \ W_d \simeq 100 \mu m$$

- Most of the losses occur when the diode is conducting
- $V_j \simeq 0.7 - 1V$ plays an important role in low power applications

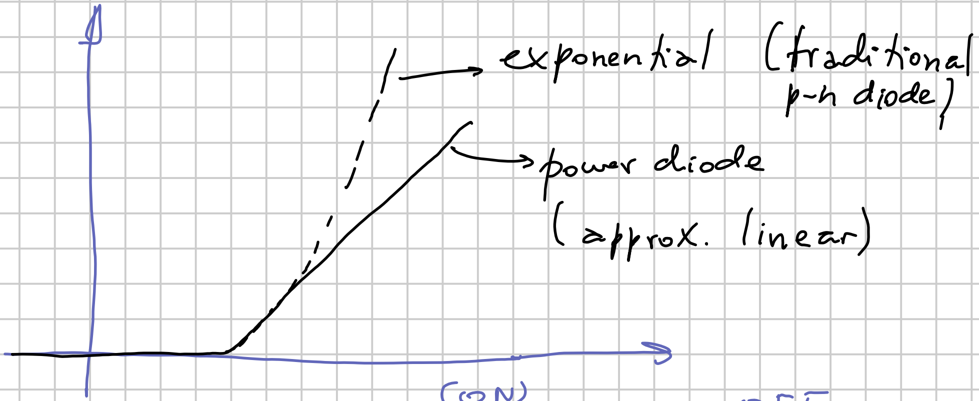
↳ At low current levels $P \simeq 0.7 \, I$

At high currents R_{on} plays a more important role
($R_{on} \rightarrow$ drift region resistance)

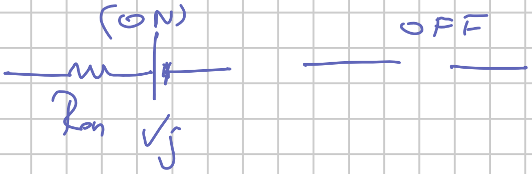
$$V \simeq V_j + \underbrace{k_1 J + k_2 J^{2/3}}_{V_d}$$

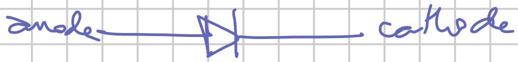
For high currents the term in J has more weight than the one in $J^{2/3}$ $\rightsquigarrow$

$$V \simeq V_j + R_{on} I$$

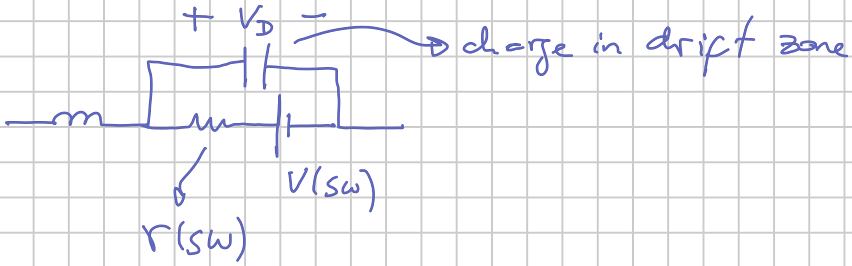


Diode static model →





Diode dynamic model (and behavioral)



$$r(sw) = \begin{cases} R_{on} & \text{if } sw = 1 \rightarrow R_{on} \text{ low} \\ R_{off} & \text{if } sw = 0 \rightarrow R_{off} \text{ high} \end{cases}$$

If $V_D > V_j$ → $sw = 1$, otherwise if $i = 0$ and $V_D \le V_j$ → $sw = 0$

Reverse recovery → see plot below

$S = \frac{t_s}{t_4} < 1$ (usually)

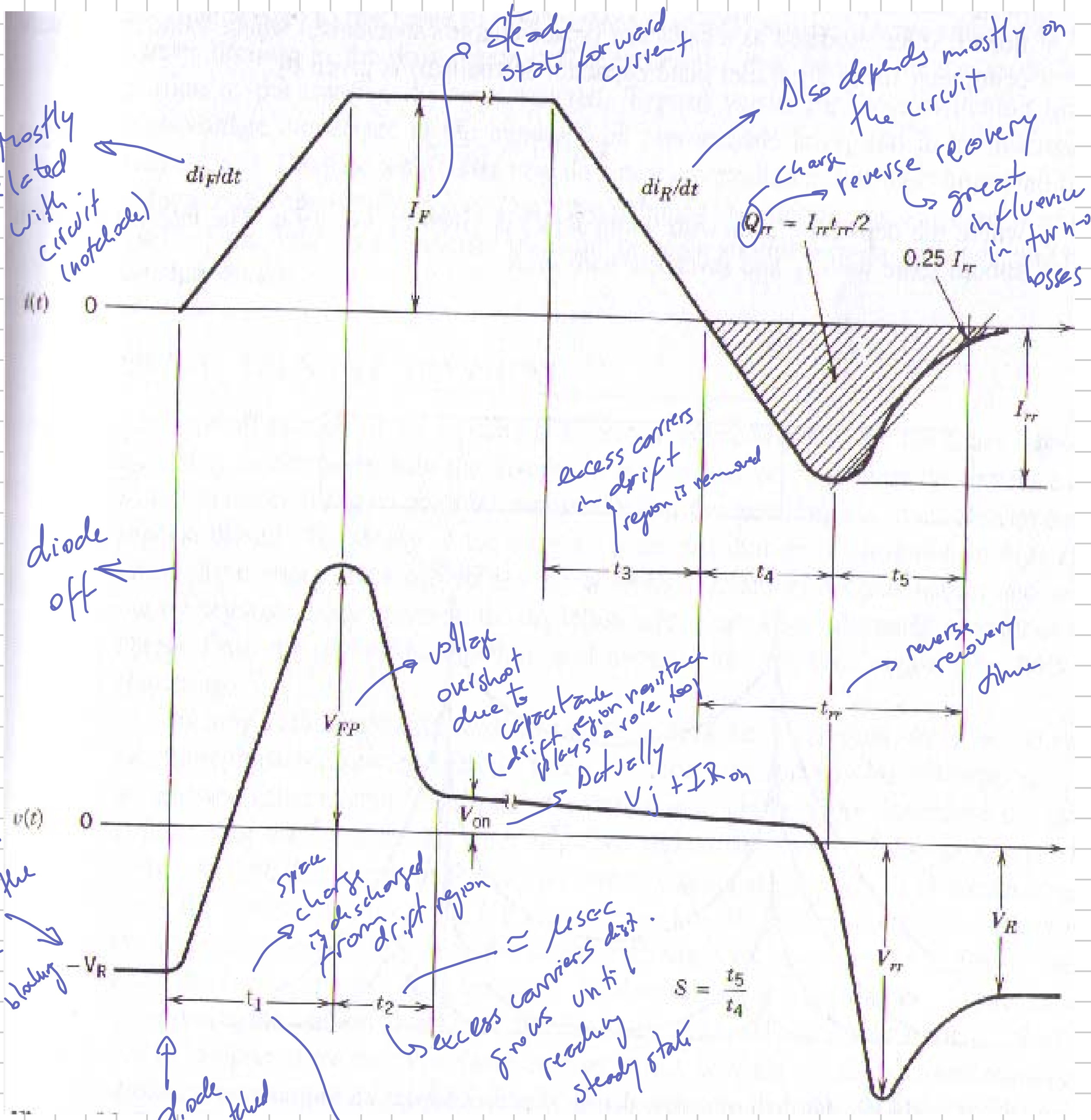
↳ snappines factor

$$\frac{I_{rr}}{t_4} \simeq \frac{di_r}{dt} \rightarrow I_{rr} \simeq \left|\frac{di_r}{dt}\right| \frac{t_{rr}}{s+1}$$

$Q_{rr} \simeq \frac{1}{2} I_{rr} t_{rr}$ (area of a triangle)

↳ $t_{rr} = \sqrt{\dfrac{2 Q_{rr}(s+1)}{di_r/dt}}$

$$I_{rr} = \sqrt{\frac{2 Q_{rr} (di_R/dt)}{s+1}}$$



Steady state forward current

mostly related with circuit (not diode)

Also depends mostly on the circuit

charge → reverse recovery → great influence in turn-off losses

excess carriers in drift region is removed

diode off

voltage overshoot due to capacitance (drift region resistance plays a role, too)

Actually $V_j + IR_{on}$

reverse recovery time

whatever voltage the diode is blocking

space charge is discharged from drift region

≃ μsec

excess carriers dist. grows until reaching steady state

diode is switched on

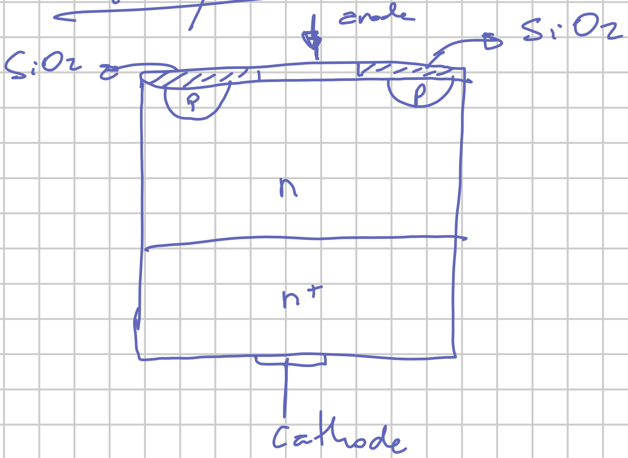
≃ 100's nsec.

In a very approximate way

$$t_{rr} \simeq 2.8 \cdot 10^{-6}\, V_{BD} \sqrt{\frac{I_F}{di_r/dt}}$$ (For higher V_{BD} higher t_{rr})

$$I_{rr} \simeq 28 \cdot 10^{-4}\, V_{BD} \sqrt{I_F \frac{di_r}{dt}}$$ (For higher V_{BD} higher I_{rr})

Schottky diode



$$I = I_s\left(e^{qV/kT} - 1\right)$$

or

$$I = I_s\left(e^{V/(nV_t)} - 1\right)$$

(like in traditional signal diodes)

- Schottky diodes are faster than power diodes because there is less stored charge (smaller capacitance)

$V_j \simeq 0.3\,V - 0.4\,V$ (For the same reason)

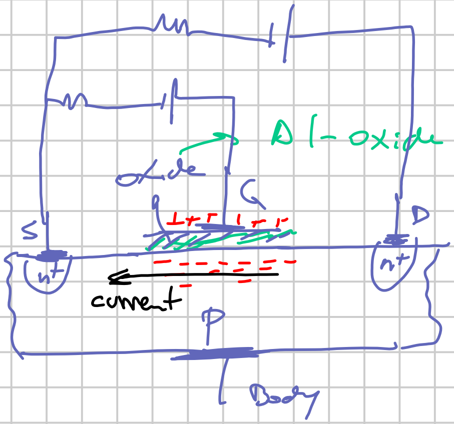
But → $V_{BD} \simeq 100V - 200V$.

Voltage overshoots are more prominent (b/c of))

MOSFET

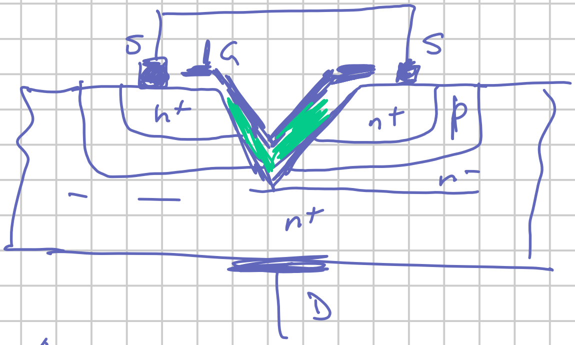
(Cross-section → see Mohan p. 572 for vertical MOSFET)

Lateral MOSFET

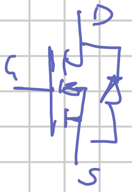


→ n-channel

VMOS

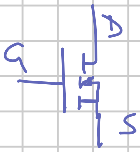


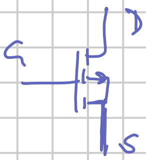
→ VMOS and vertical MOSFETS have diode



Use → "low" voltage
→ wide range of current

symbol





n-channel

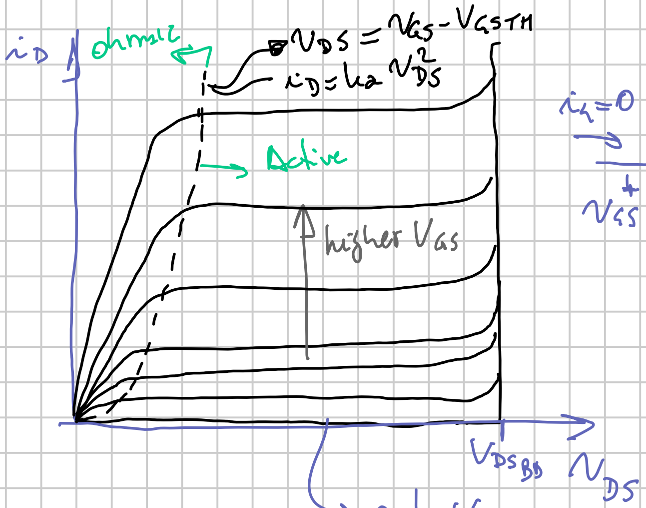
static behavioral model

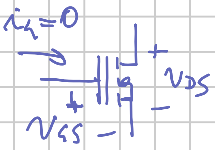
$$SW = \begin{cases} \text{ON} & \text{when } V_{GS} > V_{th} \\ \text{OFF} & \text{" } V_{GS} < V_{th} \end{cases}$$

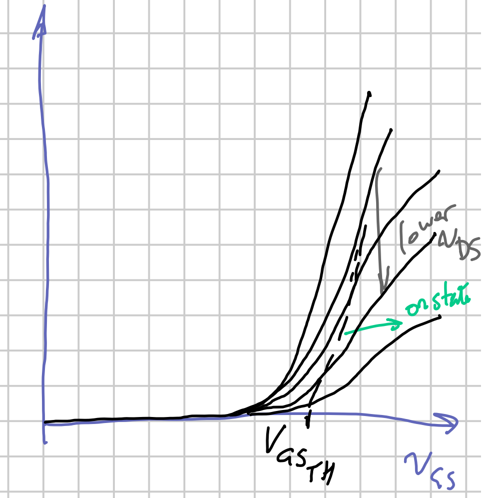
voltage controlled

Static characteristic

→ In power applications $V_{GS} \gg V_{GSTH}$







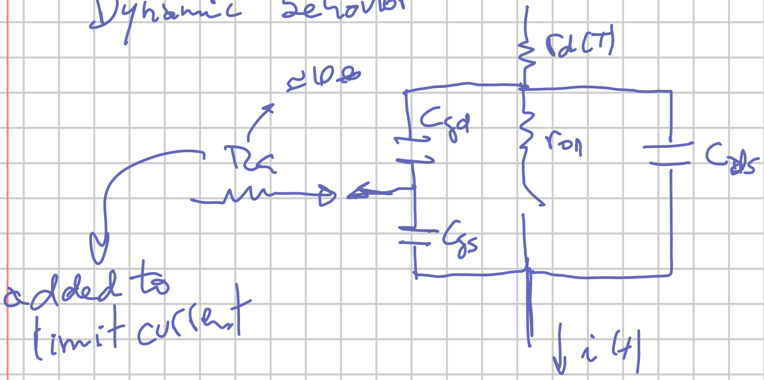
cutoff → $V_{GS} < V_{GSTH}$

Operation in ohmic region → $0 < V_{DS} < V_{GS} - V_{GSTH}$ ↳ ≈4V

$$i_D = k_o\left[(V_{GS} - V_{GSTH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

In active region → $i_D = k_a (V_{GS} - V_{GSTH})^2$

Dynamic behavior



$r_d(T)$ → additional resistance due to temperature

C_{gs} → ≃ constant for $V_{GS} > 0$

→ increase for $V_{GS} < 0$ up to C_{ox} ← oxide (g-substrate) capacitance → $C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$ → thickness of oxide layer

C_{gd} → $C_{gd} = C_{gd}(V_{gd})$ → varies up to 10 times

$$C_{ds}(V_{ds}) = \frac{C_0}{\sqrt{1 + \frac{V_{ds}}{V_0}}} \simeq C_0\sqrt{\frac{V_0}{V_{ds}}} = \frac{C_0'}{\sqrt{V_{ds}}}$$

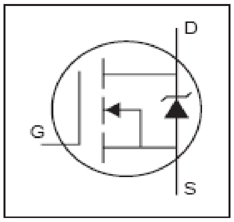
↳ C_0 and V_0 constants that depends on the device

Conduction losses → $I^2 R_{ds(on)}$

Switching losses
Safe operation area } → when we discuss dissipation

IRFPS3810

HEXFET® Power MOSFET

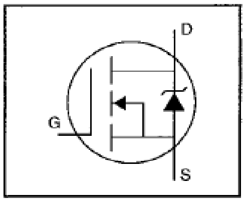


$V_{DSS} = 100V$

$R_{DS(on)} = 0.009\Omega$

$I_D = 170A$⑥

IRFP360



$V_{DSS} = 400V$

$R_{DS(on)} = 0.20\Omega$

$I_D = 23A$

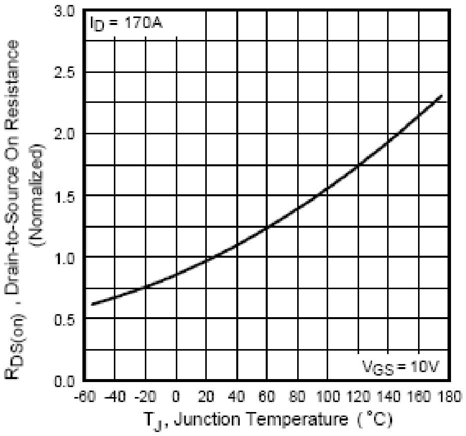
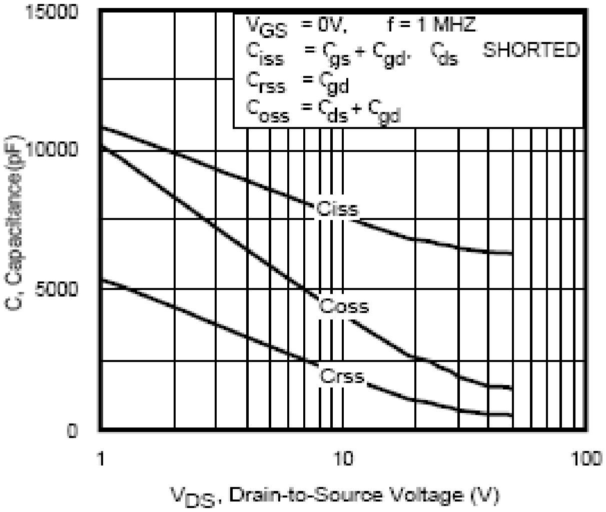


Fig 4. Normalized On-Resistance Vs. Temperature



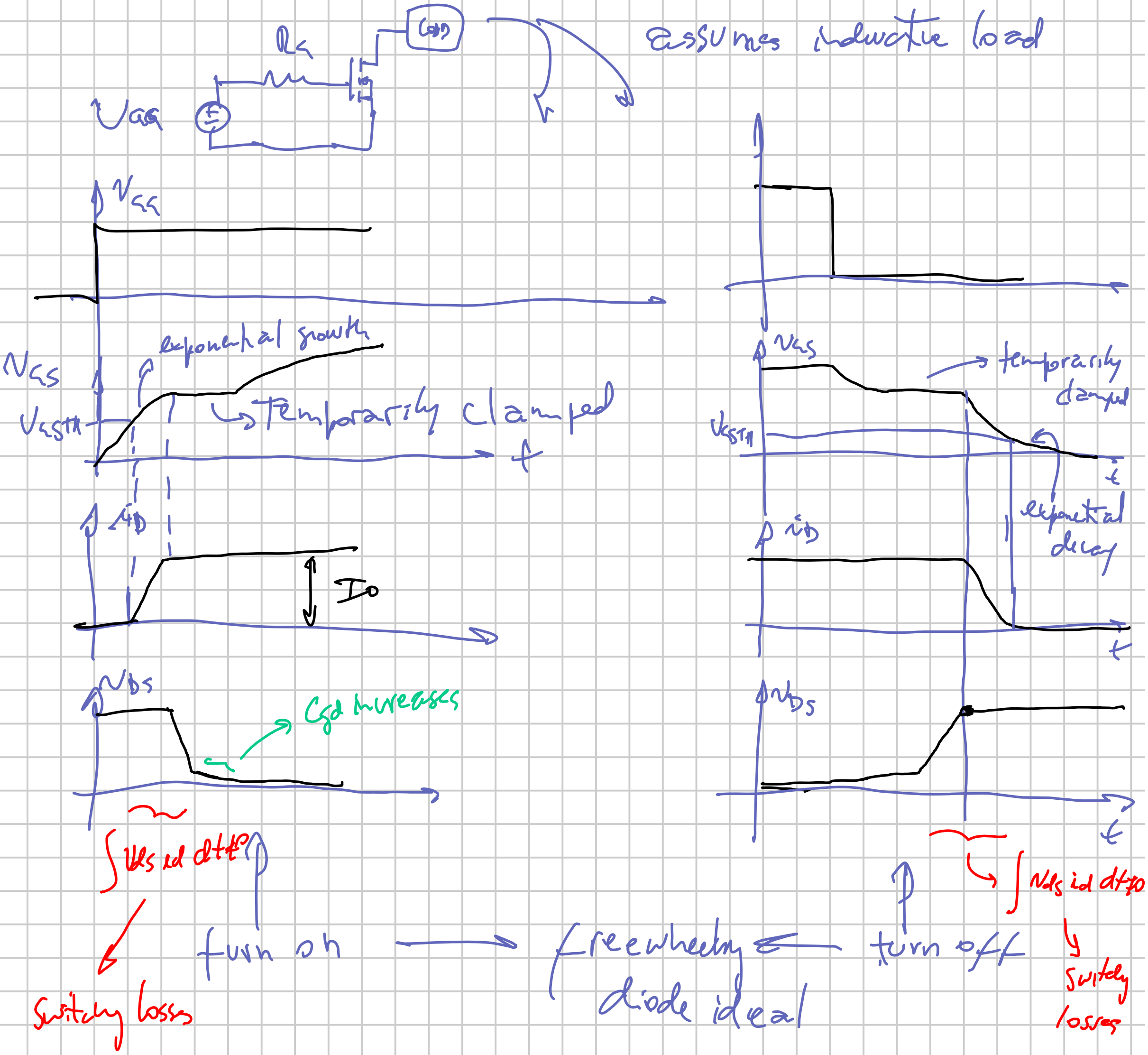
MOSFETs tend to be fast b/c there is not much charge stored in capacitances

- turn on and turn off curves tend to be complicated due to → varying capacitances
  → circuit used

↓ physics

Free wheeling diode (reverse recovery effect)

Important characteristics are:



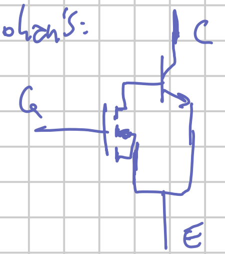
Ringing due to stray capacitances & inductors

IGBTs → Isolated gate bipolar transistor

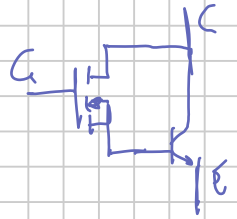
Tend to be used for higher power and votage (blocking voltage) than the MOSFETS. But IGBTs are slower than MOSFETS

Forward voltage drop is lower than equivalent MOSFETS

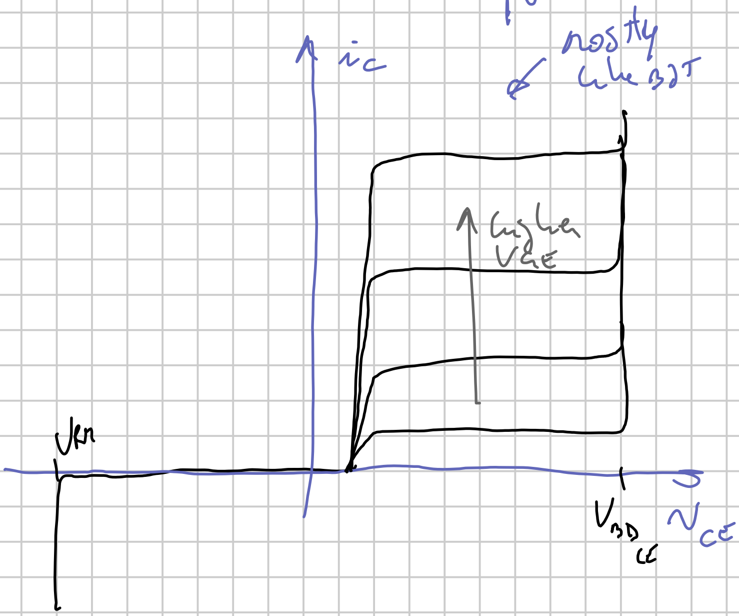
From Erikson's & Mohan's:

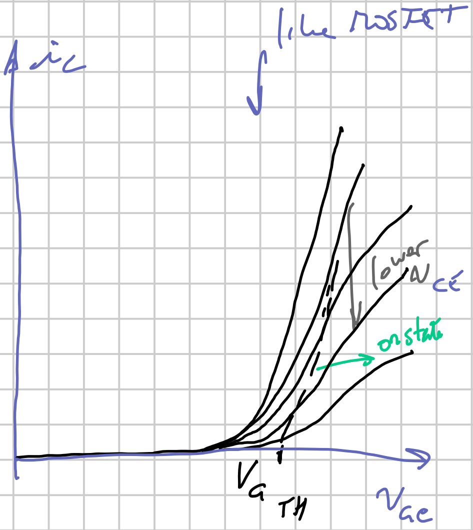


From Krein's



BJT: $\beta \simeq 10$ to 20





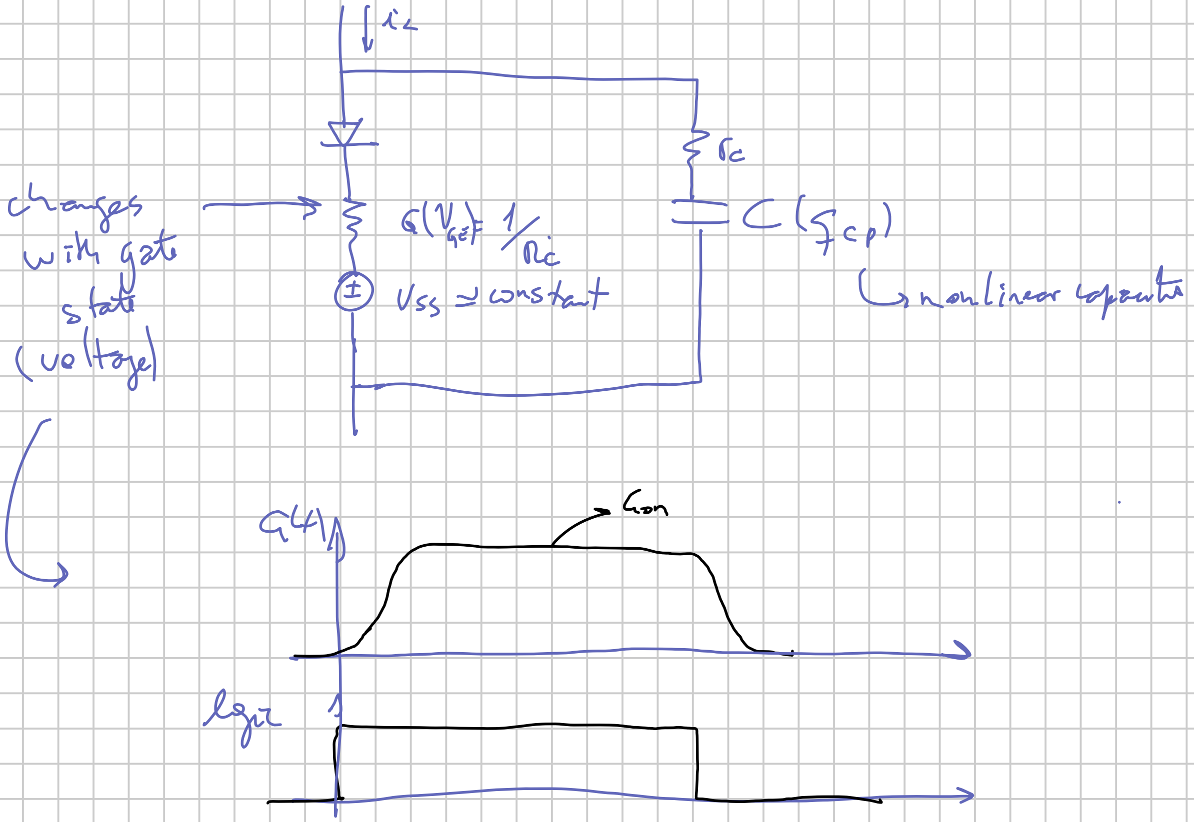
It's a votage controlled IGBT

$$V_{CE(on)} = \underbrace{V_{J1}}_{0.7-1V} + \underbrace{V_{drift}}_{small} + I_C R_{channel} \simeq \text{constant} \simeq 1.7 \text{ to } 2.5V$$

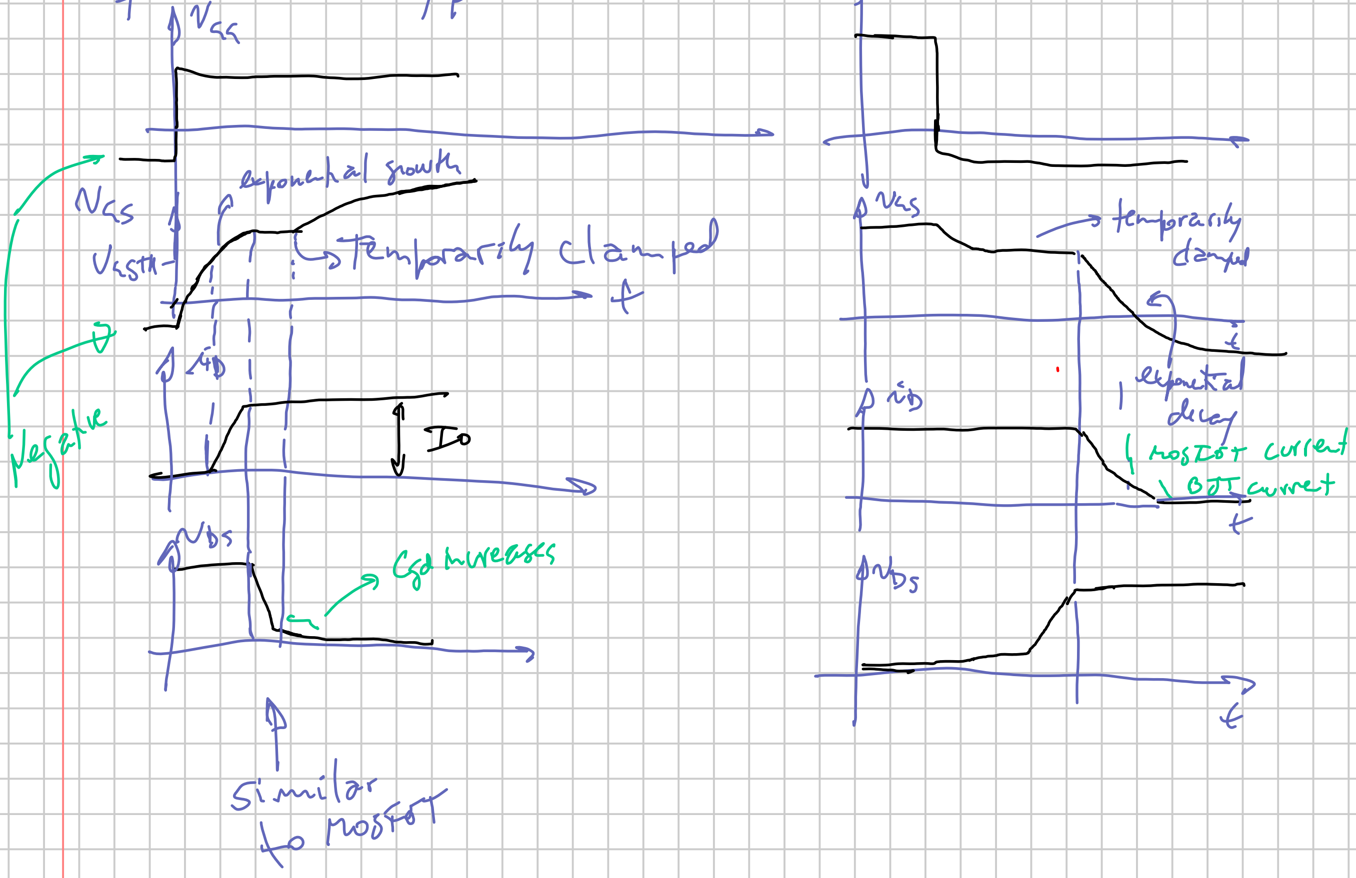
latch up → with large spike in i_C, it latches on even with gate = "0"

No diode in ||.

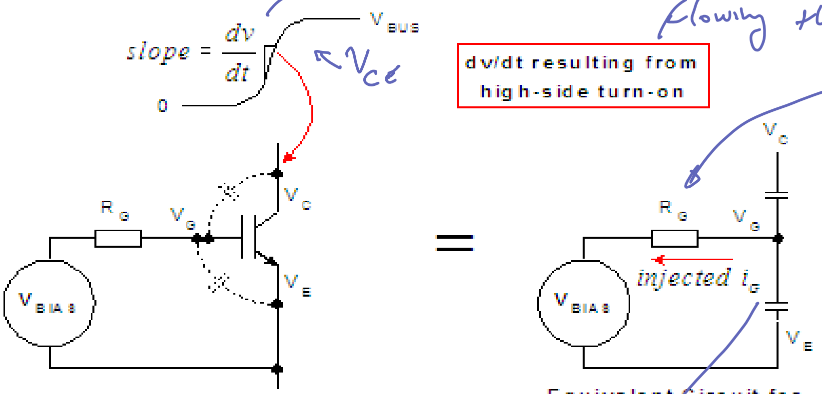
Behavioral model:



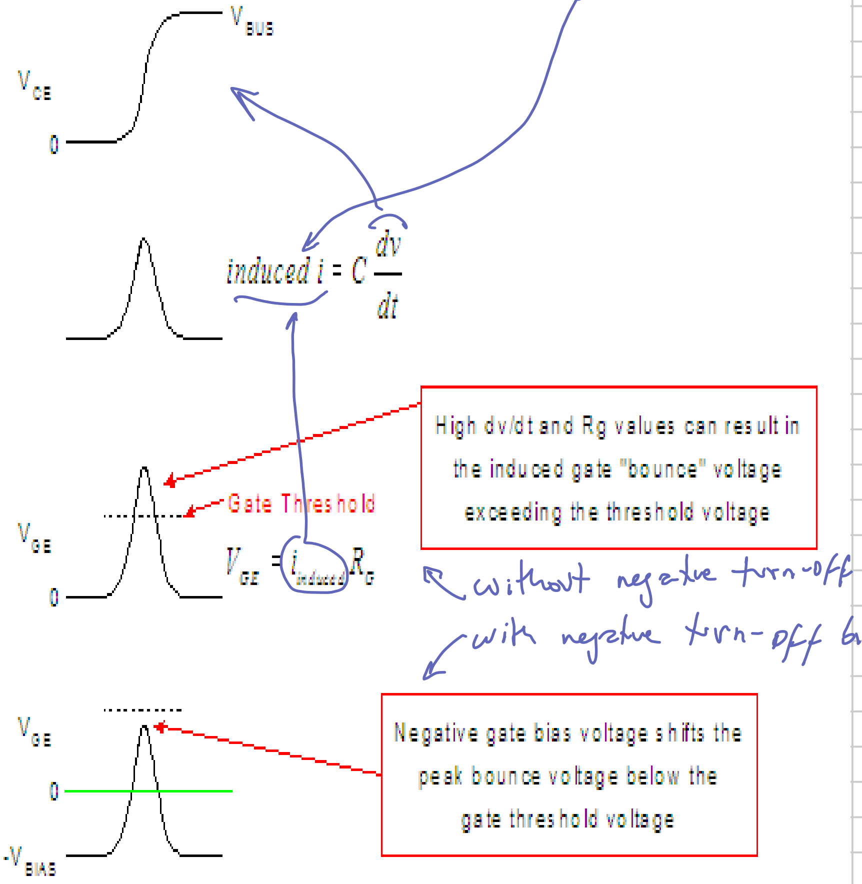
turn on and turn off curves



This dv/dt translates into a current flowing through R_G. The current appears because the capacitances are charge/discharg



Equivalent Circuit for Gate-Emitter Voltage is Capacitive Divider



High dv/dt and Rg values can result in the induced gate "bounce" voltage exceeding the threshold voltage

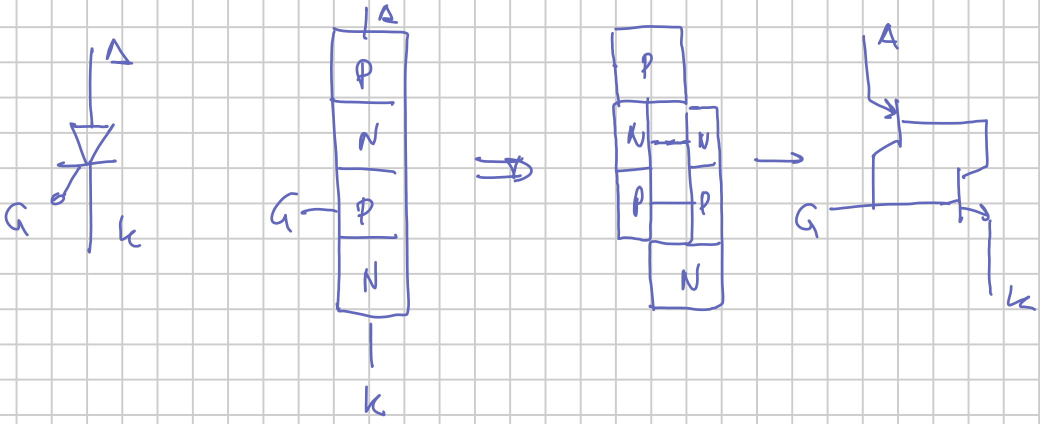
without negative turn-off bias

with negative turn-off bias

Negative gate bias voltage shifts the peak bounce voltage below the gate threshold voltage

Thyristor family

SCR — rectifier
↓ ↳ controlled
Silicon (old)
Semiconductor (newer — not all SCR are now Silicon)



Turn on: 1) Forward biass
+
NORMAL ⟶ 2) I_G that last enough time (to allow charge building) ↳ few μsec ⇒ SCR are slow but can handle large power

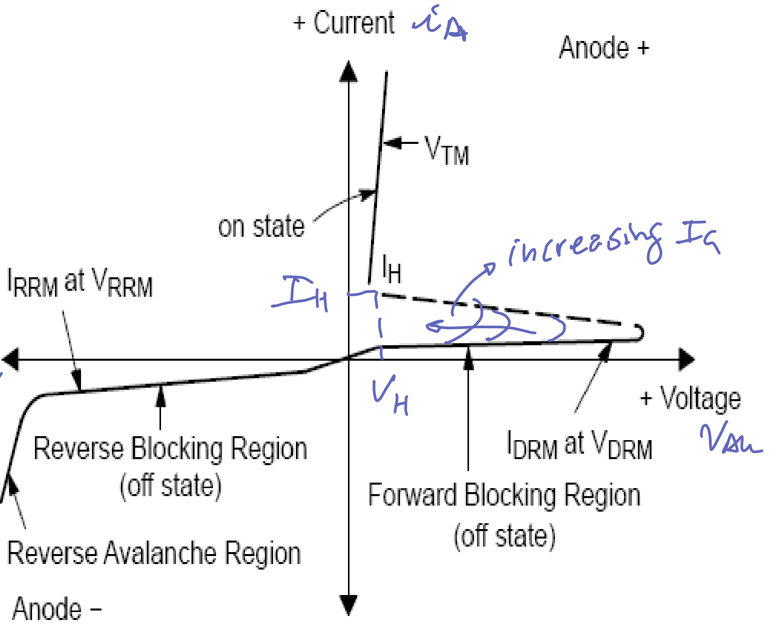
Alternatives to 2):
2') large V_{AK}
2'') $\frac{dV_{AK}}{dt}$ large

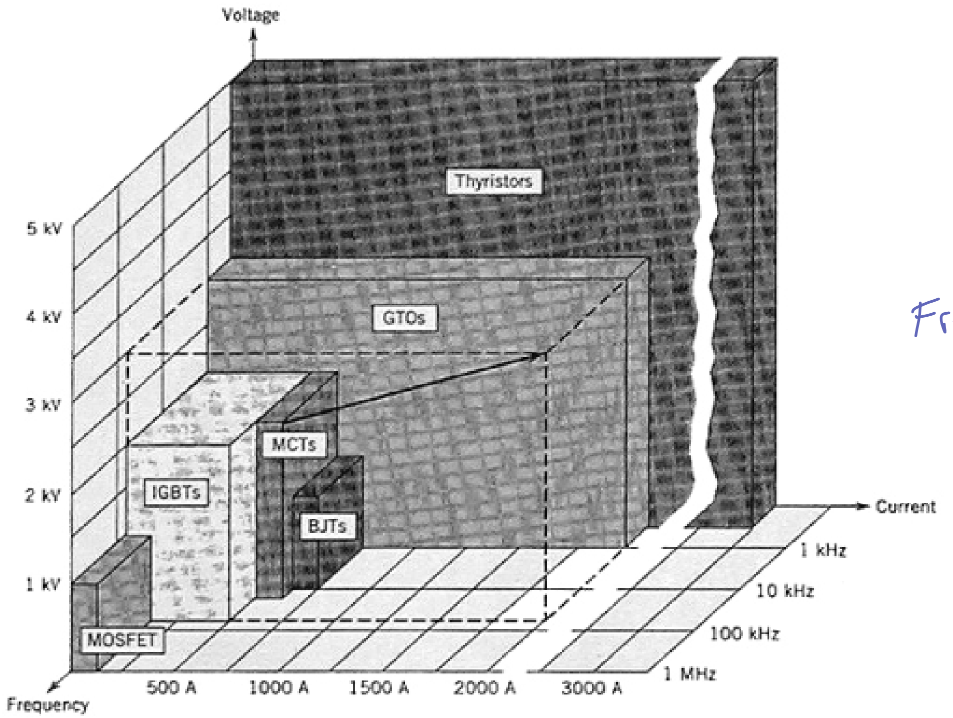
Increasing temperatures helps triggering

State characteristic:

SCRs conduct until
$i_A < I_H$

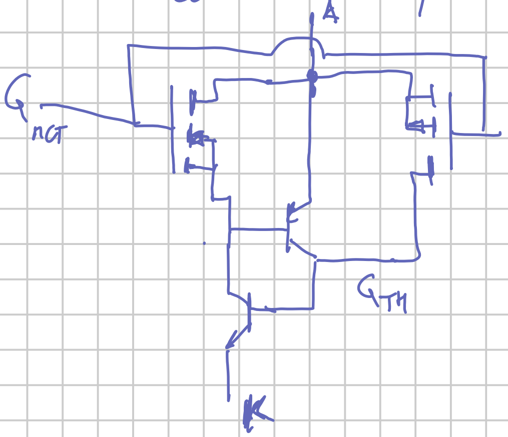
For ON 2N6504 — 09
Max rms current → 25A
V_{BD} → 50, 100, 400, 600, 800V
$I_H \simeq 30\ mA$
$t_{gt} \simeq 1.8\ \mu sec$
↳ turn on time

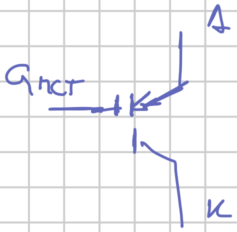


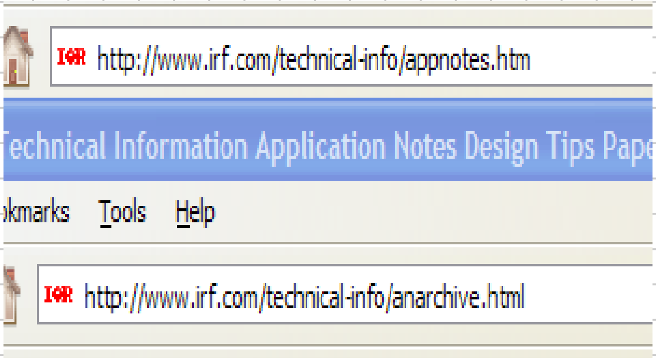


From Mohan's

MCT → MOS controlled thyristor



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Technical Information Application Notes Design Tips Pape

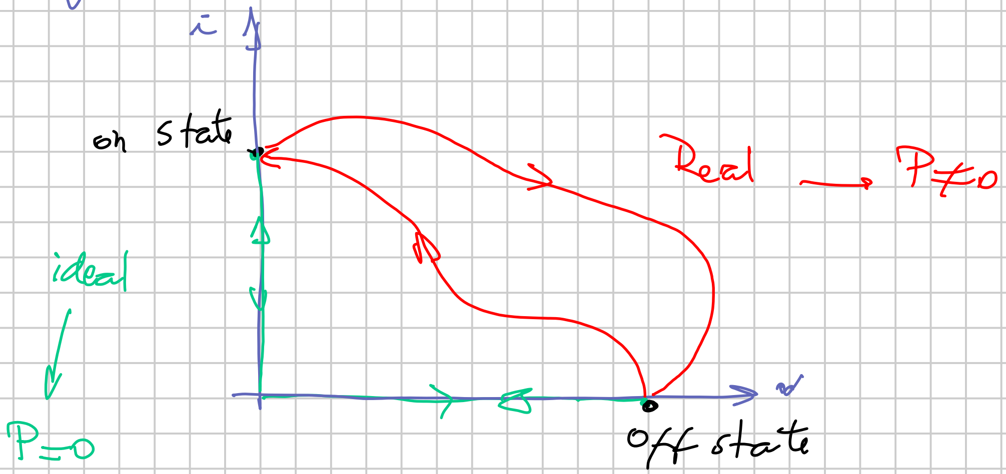
http://www.irf.com/technical-info/anarchive.html

Semiconductor losses

Conduction and switching losses

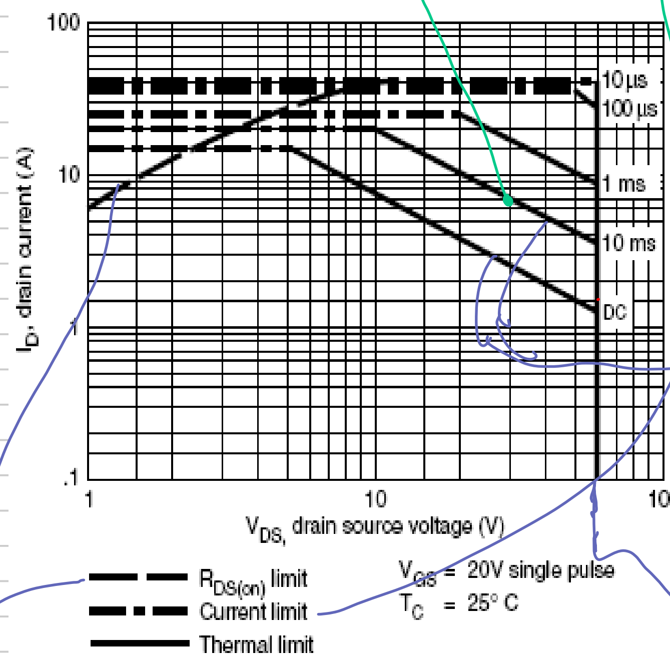
↳ $I_{RMS_{ON}}$ $V_{RMS_{ON}}$

Switching losses



↳ no losses

eg → I can have a current of 8 A and a voltage of 40V only for up to 10 msec



Current limit

→ Bond wires and surface metalization

- Nominal (dc or continuous) current can be exceeded for short times

Thermal limit (or power limit)

- It depends on how much power can be dissipated and how much the junction temperature increases
- Allowable currents are time dependent

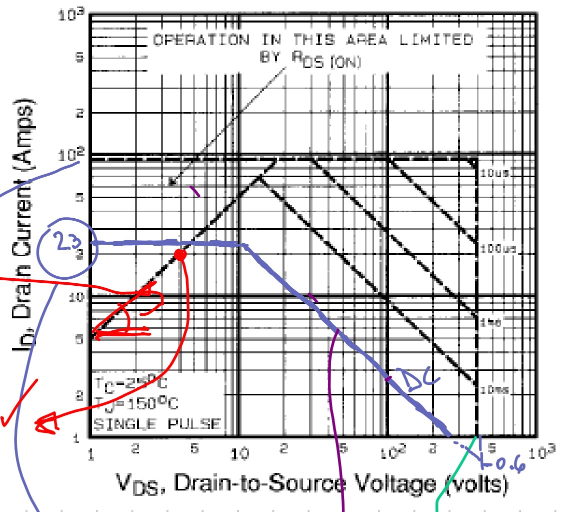
Self protecting → cannot be exceeded because I_D is limited by ohm's law

Voltage limit → Breakdown. Cannot be exceeded even for very short times.

IRFP360 $V_{DSS} = 400V$

$R_{DS(on)} = 0.2\Omega$

$I_D = 23A$

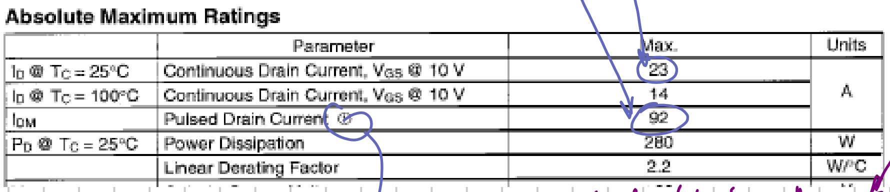


$\frac{1}{Rdson}$

$Rds_{on} = \frac{4V}{20A} = \frac{1}{5} = 0.2\Omega$

400V

Absolute Maximum Ratings



	Parameter	Max.	Units
I_D @ $T_C = 25°C$	Continuous Drain Current, V_{GS} @ 10 V	23	A
I_D @ $T_C = 100°C$	Continuous Drain Current, V_{GS} @ 10 V	14	
I_{DM}	Pulsed Drain Current ①	92	
P_D @ $T_C = 25°C$	Power Dissipation	280	W
	Linear Derating Factor	2.2	W/°C

Hyperbola $I_D = \frac{P_D}{V_{DS}} = \frac{280}{V_{DS}}$

Looks like line due to logaritmic scale

Duty cycle

$Z_{th\,jc}$

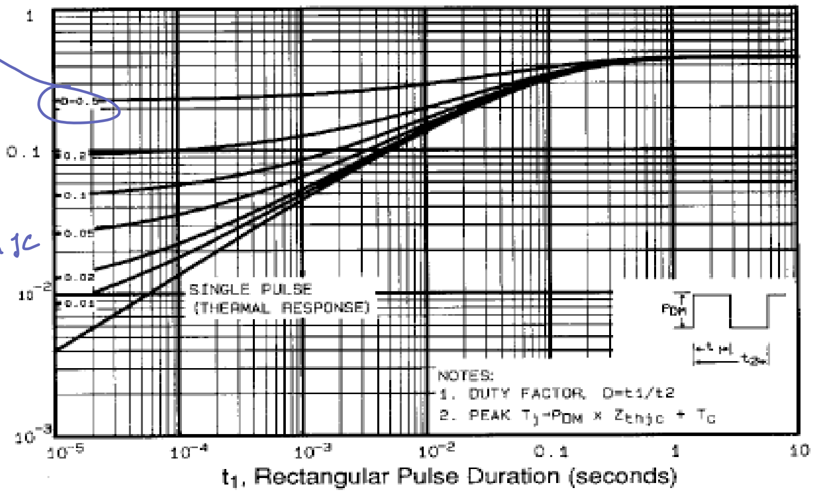


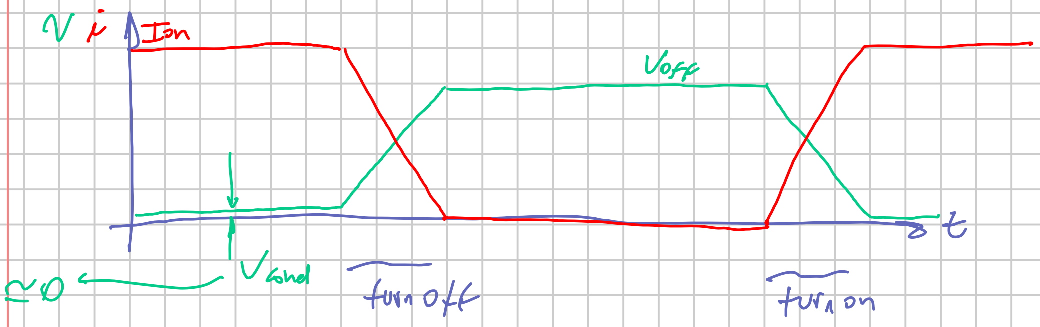
Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

IGBT ≃ same SOA than mosfet

Switching transitions with different loads:

Switching losses depends on external circuit

- Resistive load — linear commutation



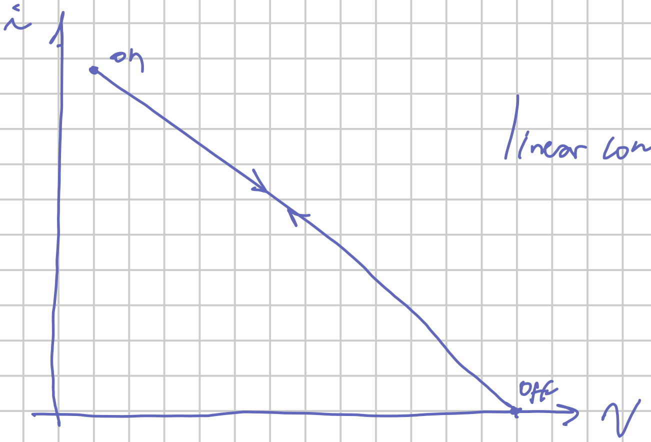
$$U_{S_{on}} = \int_0^{t_{on}} \underbrace{\frac{I_{on}}{t_{on}} t}_{\text{equation of a line with slope } \frac{I_{on}}{t_{on}}} \Big(\underbrace{V_{off} - \frac{V_{off}}{t_{on}} t}_{\text{eq. of a line}} \Big) dt = \frac{V_{off} I_{on} t_{on}}{6}$$

energy

$$U_{S_{off}} = \int_0^{t_{off}} \frac{V_{off}}{t_{off}} t \left(I_{on} - \frac{I_{on}}{t_{off}} t \right) dt = \frac{V_{off} I_{on} t_{off}}{6}$$

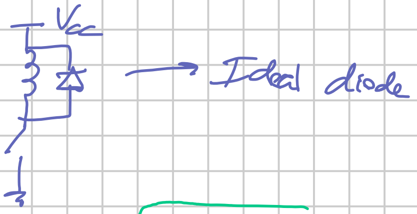
If $t_{on} + t_{off} = t_{sw}$ Then

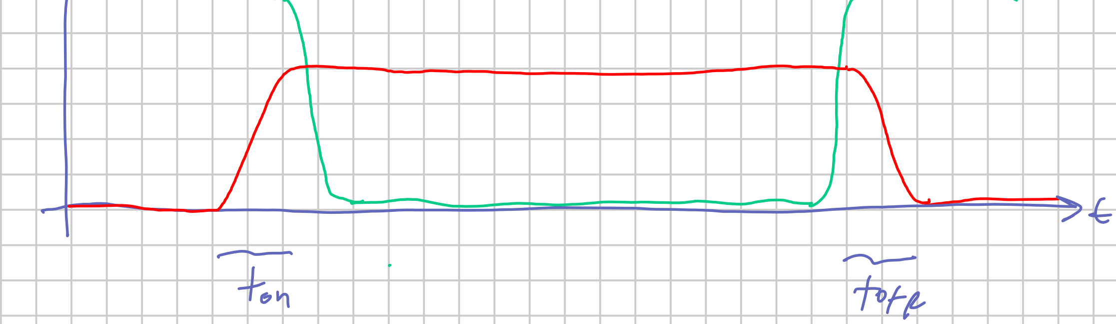
$$U_{sw} = \frac{V_{off} I_{on} t_{sw}}{6}$$



linear commutation

Clamped inductive load waveform





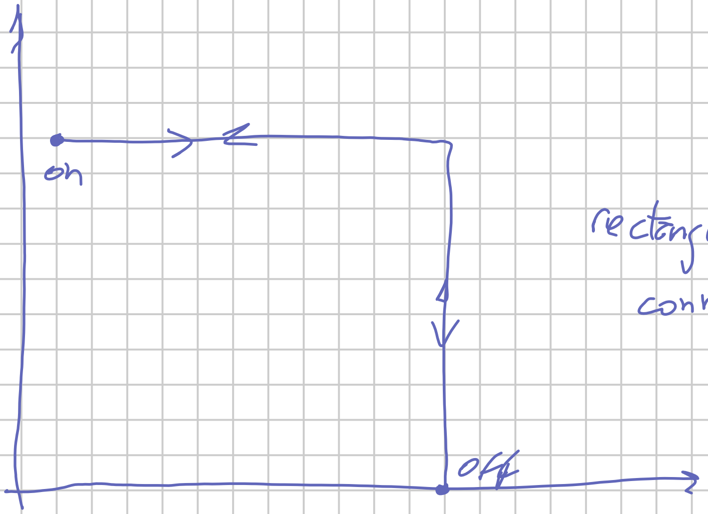
turn on → MOSFET is commanded to turn on but current takes time to rise. During that interval the diode conducts the remaining inductor current so it must be forward bias, Thus, Vds stays at ≈ Vcc. When the current through the switch reaches the inductor current then the diode can turn off. So it gets reversed polarized with V_{cc} so the switch voltage drops almost instantaneously.

turn off → Reverse process

$$U_{s\,on} = \int_0^{t_{on}} V_{off} \frac{I_{on}}{t_{on}} t \, dt = \frac{V_{off} I_{on} t_{on}}{2}$$

$$U_{s\,off} = \int_0^{t_{off}} V_{off} \left(I_{on} - \frac{I_{on}}{t_{off}} \right) t \, dt = \frac{V_{off} I_{on} t_{off}}{2}$$

$$U_{sw} = \frac{V_{off} I_{on} t_{sw}}{2}$$



rectangular commutation

With a real diode

↳ turn off → when the action is initiated the diode does not react immediately so the inductor reacts with a negative voltage that increases V_{ds} (above $V_{cc} = V_{off}$)

Hence, losses increases 50-100%

Situation agravates with unclamped commutation

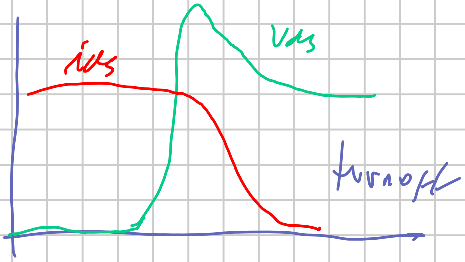
unclamped

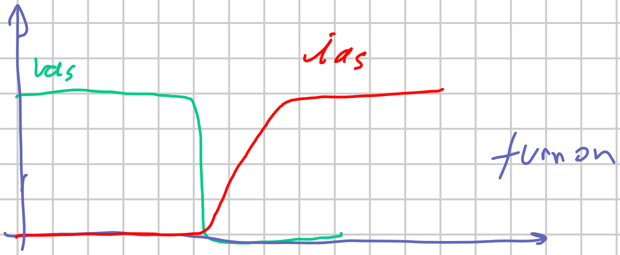
turn on →

→ the inductor voltage is as shown which makes $V_{ds} \simeq 0$ almost immediately while i_{ds} increases — So losses are

Big risk that trajectory gets out of SOA

less (maybe even less than with linear commutation





Unclamped

$$U_{s\,on} = \frac{I_{on} V_{on} t_{on}}{2} \longrightarrow \text{very low}$$

$$U_{s\,off} \simeq V_{off} I_{on} t_{off}$$

In general → $U_{sw} = \frac{V_{off} I_{on} t_{sw}}{a}$

Linear → $a = 6$

Rectangular → $a = 2$

Inductive (real diode) → $a = 1.5$