

ELEC2208 Power Electronics and Drives

Transistor

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What is Transistor?

How many terminals?

- Three terminal device

What role in circuits?

- Transistors are operated as **switches** in power electronic circuits

Any consideration on gating?

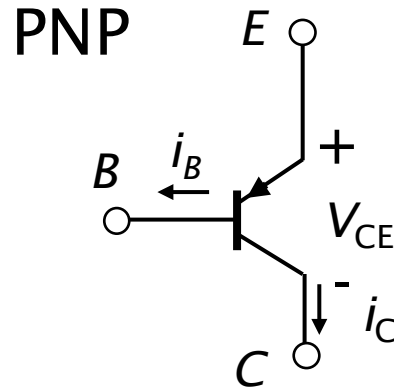
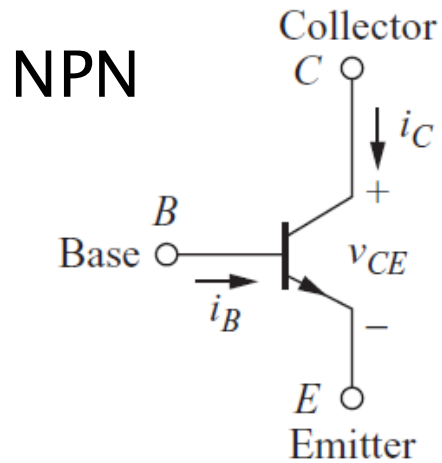
- **Gate driver circuits are designed to have the transistor either in the fully on or fully off state.**

Classification

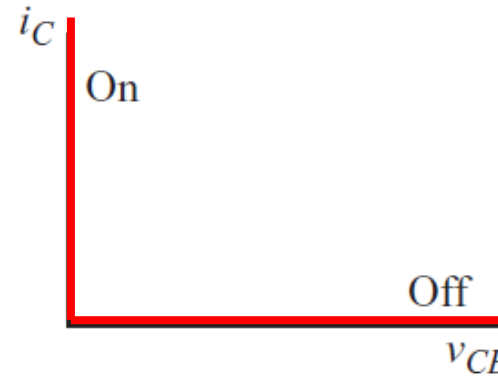
- Bipolar Junction Transistor (**BJT**)
- Metal Oxide Semiconductor Field Effect Transistor (**MOSFET**)
- Isolated Gate Bipolar Transistor (**IGBT**)

Bipolar Junction Transistor (BJT)

Symbol

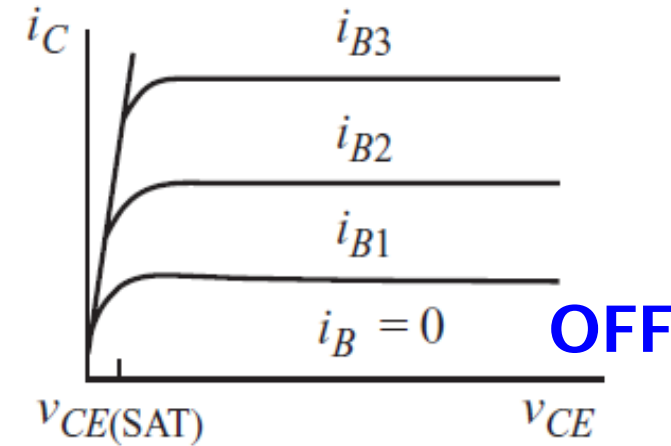


Characteristics Ideal



Practical

ON



i_C : Collector current
 V_{CE} : Collector-emitter voltage
 i_B : Base current

- **Current-controlled device.**

- On state is achieved by providing sufficient base current to drive the BJT into saturation.
- For high collector current, high base current is needed to drive BJT into saturation.

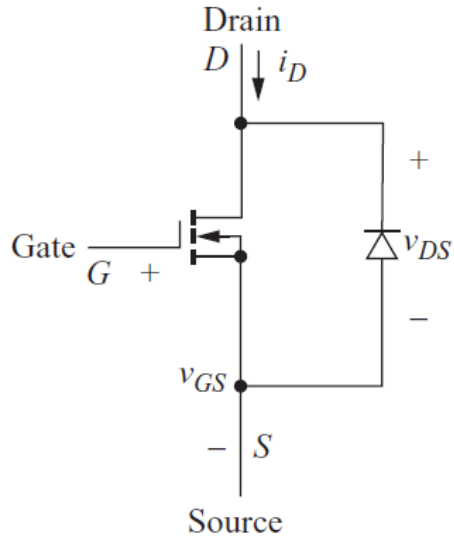
$$i_C = \beta i_B$$

β : Current gain (common-emitter)

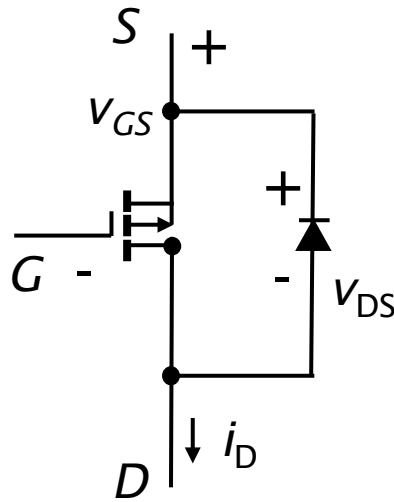
MOSFET

Symbol

N-channel



P-channel



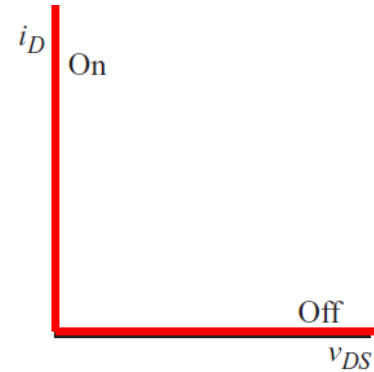
i_D : Drain current

v_{DS} : Drain-Source voltage

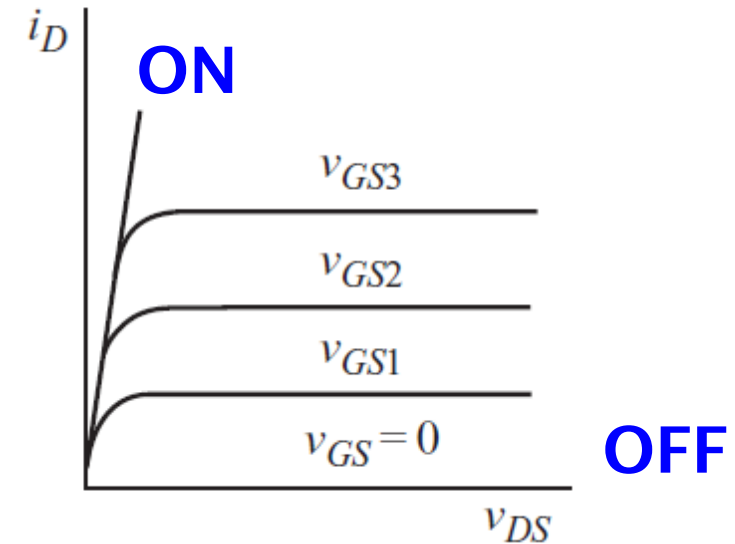
v_{GS} : Gate-Source voltage

- **Voltage-controlled device.**

Characteristics



Practical



- A sufficiently large gate-to-source voltage ($v_{GS} \sim 15V$) will turn the device on.
- During off condition, v_{GS} **should be zero or negative.**
- Fast switching transition used in converters up to MHz range.

MOSFET

Key specifications

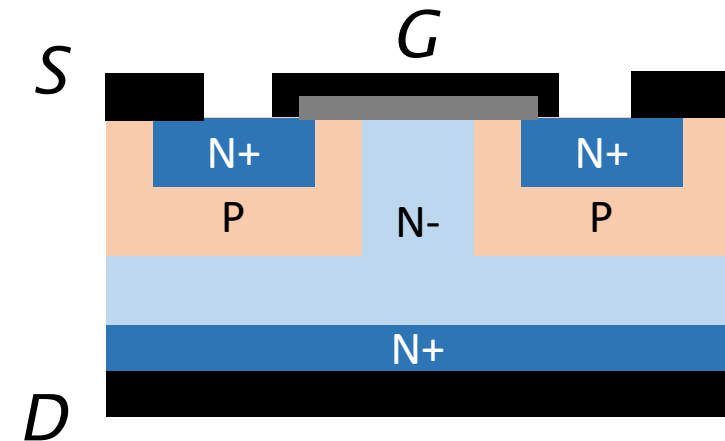
On-state Resistance R_{DSon}

- Drain to source resistance in on-state
- As low as a few $m\Omega$ which is significantly lower than BJT or diode (10- 1000 Ω)

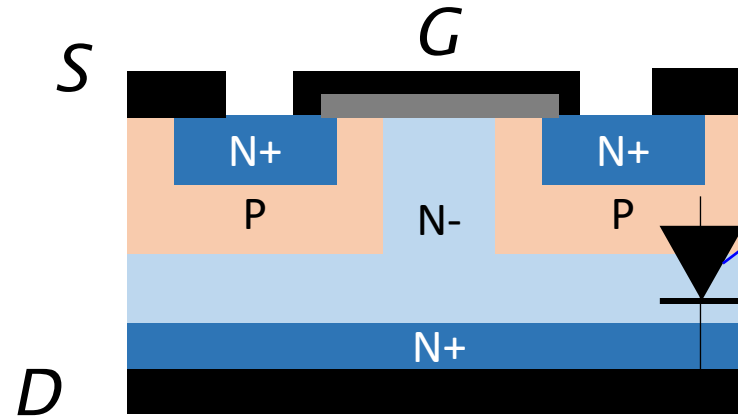
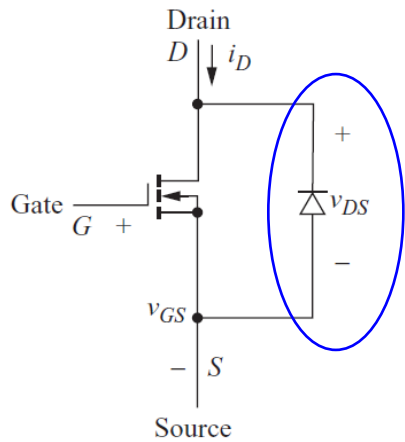
Breakdown voltage

- Breakdown of PN junction by S-D voltage
- Typically 100 – 600 V
- Trade-off against On-state resistance

Cross section of power MOSFET (VDMOS: Vertically-Diffused MOS)



MOSFET – Body diode



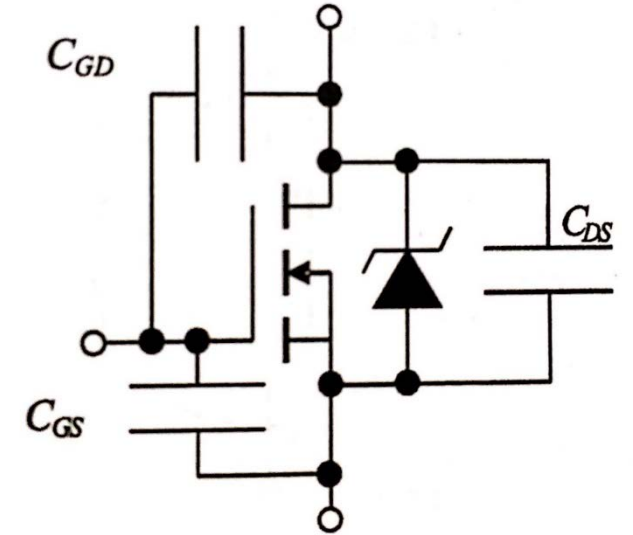
Body diode

MOSFETs have built-in diode called body diode.

- Body diode is not related to switching operation but useful for freewheeling to release energy from inductive load.
- When $v_{DS} > 0$, body diode is **reversed biased** and conducts zero current.
- When $v_{DS} < 0$, body diode is **forward biased** while MOSFET is not conducting if it is off (current flow through the diode only).

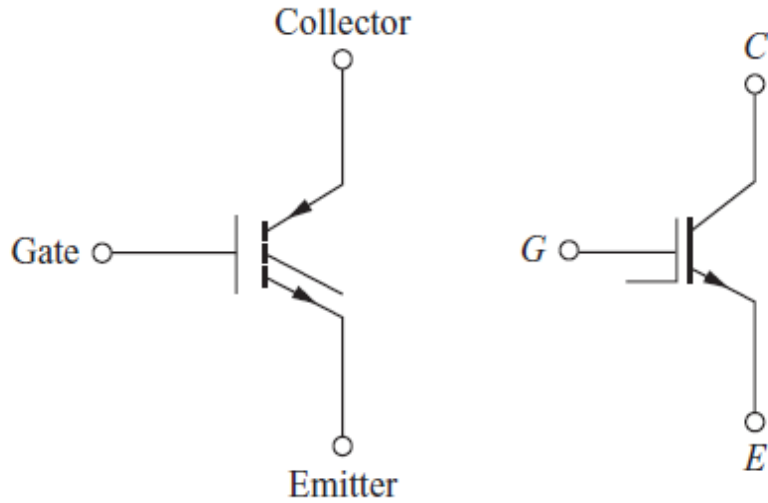
MOSFET – Parasitic capacitance

- In a practical MOSFET, **parasitic capacitance** exist between each of the three terminals.
- The drain-source or output capacitance is small and typically few hundred pF.
- Turning **on** and **off** the MOSFET requires **charging** and **discharging** the gate capacitance respectively.
- This gate capacitance with external gate resistance forms a RC circuit.
- **Gate charge** is an important variable for designing gate drive circuit, e.g. calculating the peak current for turning on a MOSFET.

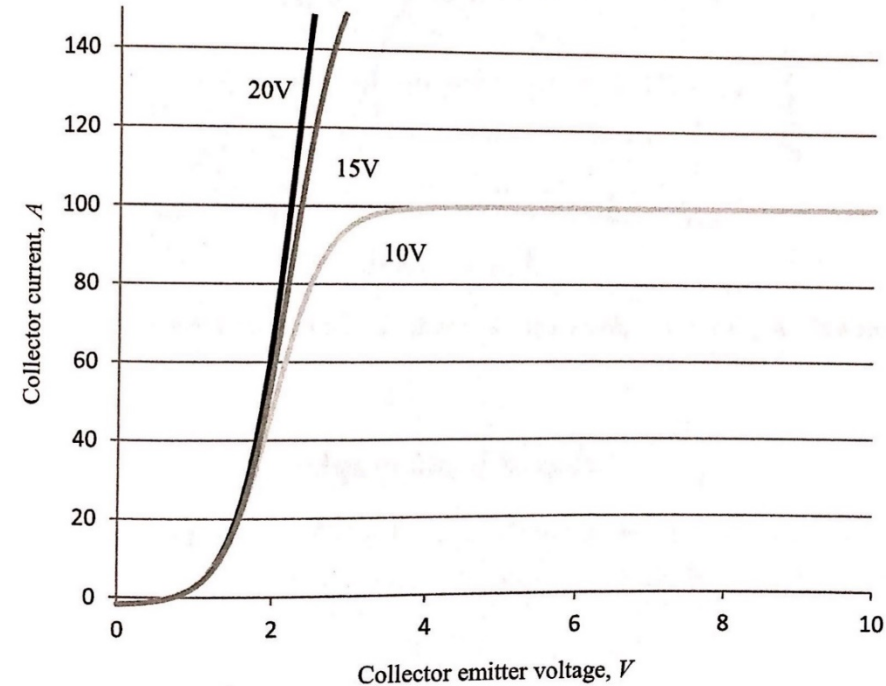


Isolated Gate Bipolar Transistor (IGBT)

Symbol (n-channel)



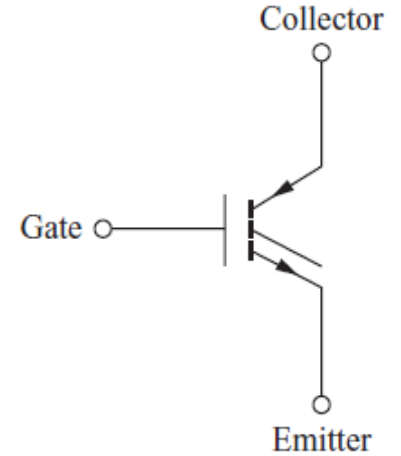
I_C - V_{CE} characteristics



- Integrated connection of a **MOSFET** and a **BJT**.
- **Voltage-controlled device**

Isolated Gate Bipolar Transistor (IGBT)

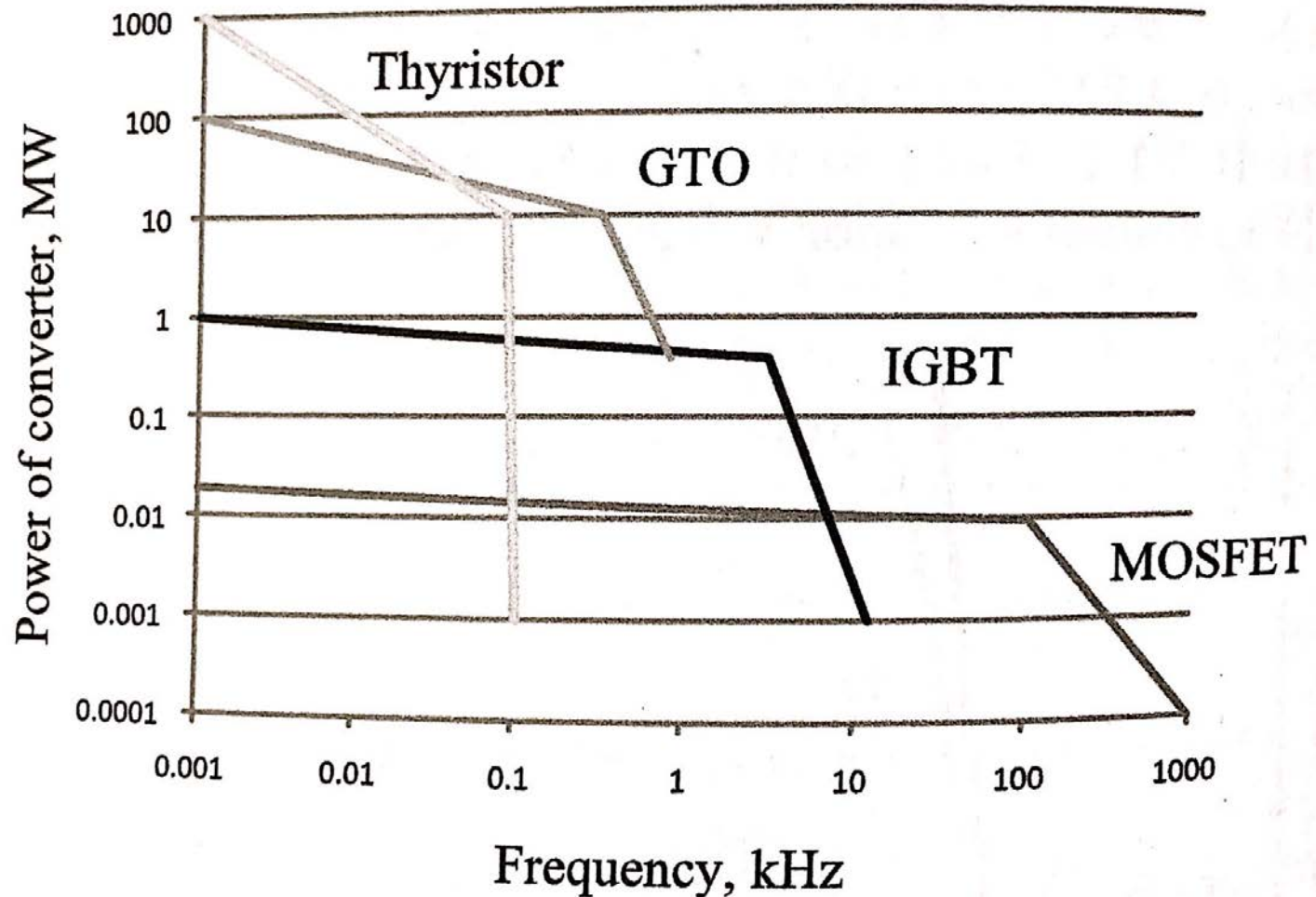
- Reason for integration: complement each other
 - BJT has **high current conducting capability** but it consumes large base current.
 - MOSFET has high gate input impedance and hence the gate drive circuit **consumes very low power**. In addition, the gate drive circuit is **simple**.
- Drive circuit for the IGBT is like that of the MOSFET, while the on-state characteristics are like those of the BJT.
- IGBTs have replaced BJTs in many applications.



Switch selection

- Based on power level and frequency.
- In selecting the proper device, we should know:
 1. The power rating (power that the load will put on the output of the converter).
 2. The switching speed required during operation of the converter.
 3. Voltage and current levels.
 4. Maximum switching and conduction loss, etc.

Switch selection

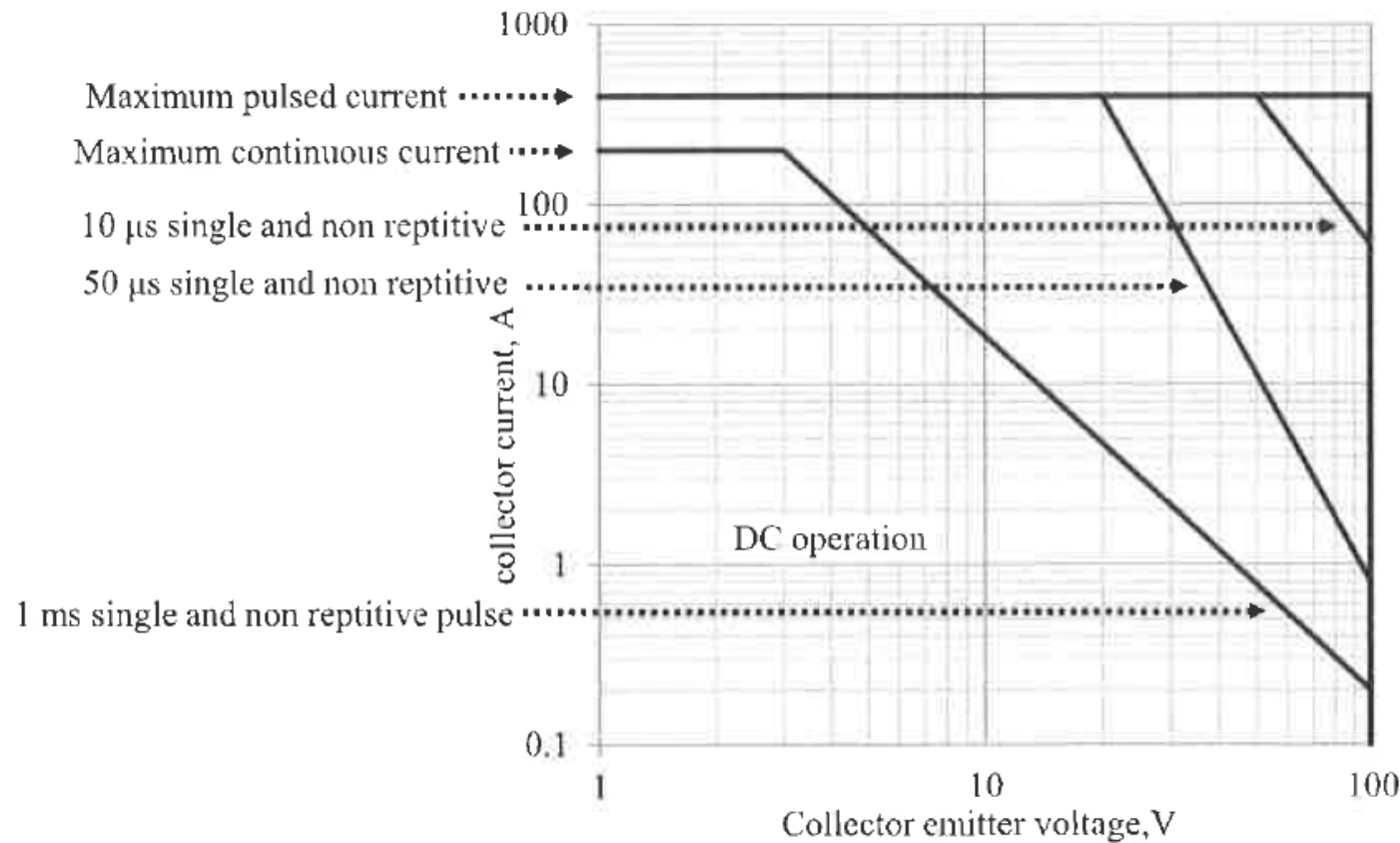


You can choose a suitable technology subject to primarily required specifications of the power and speed.

Safe operating area (SOA)

- SOA - the voltage and current conditions over which the device can be expected to operate without self-damage.

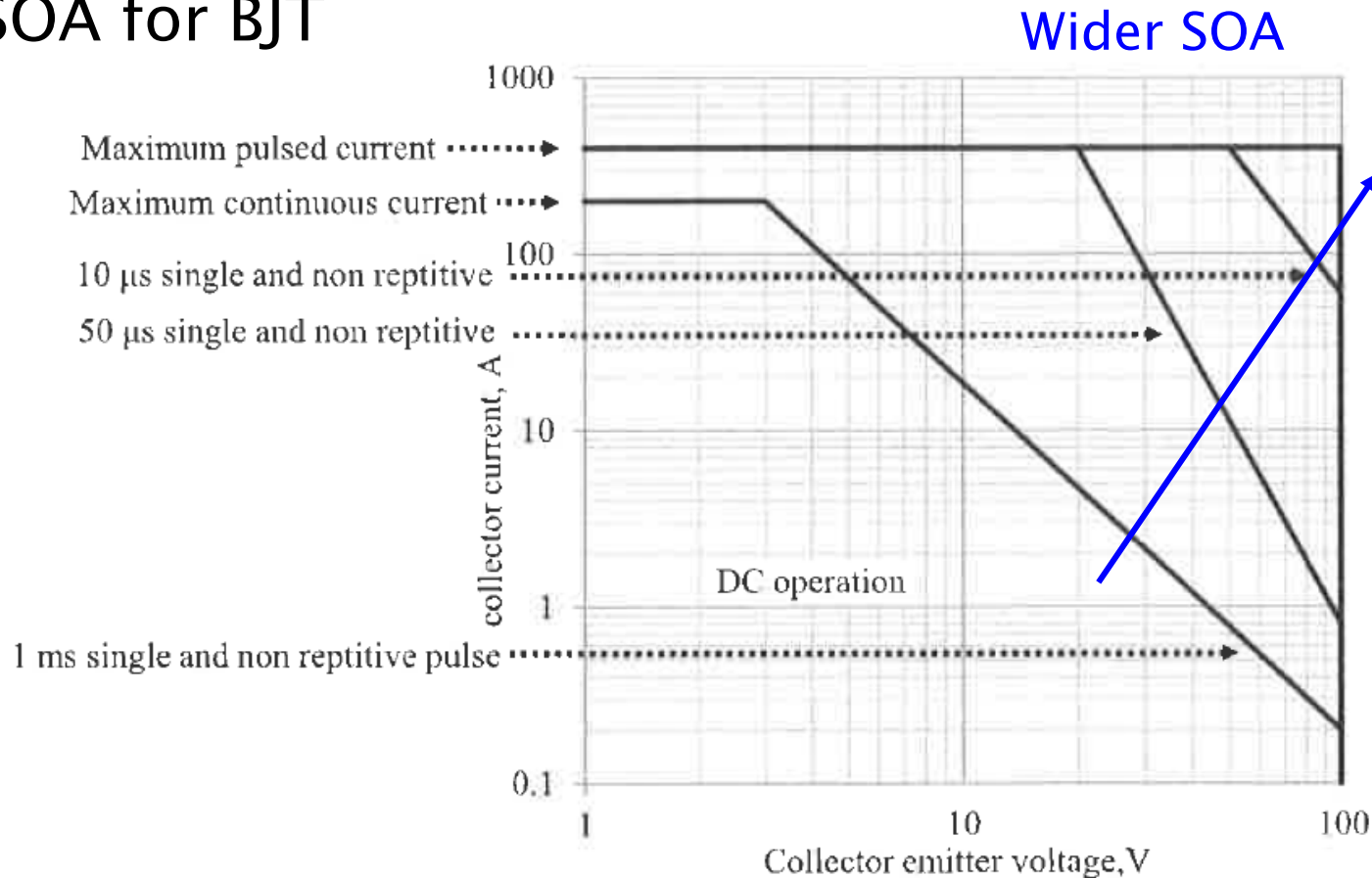
SOA for BJT



- SOA is under the solid lines depending on operational conditions.
- The limitation is related to power dissipation and device heating.

Safe operating area (SOA)

SOA for BJT



- The boundaries are determined by peak voltage, peak current, and power rating.
- With shorter and non-repetitive pulse, the maximum current available is higher.

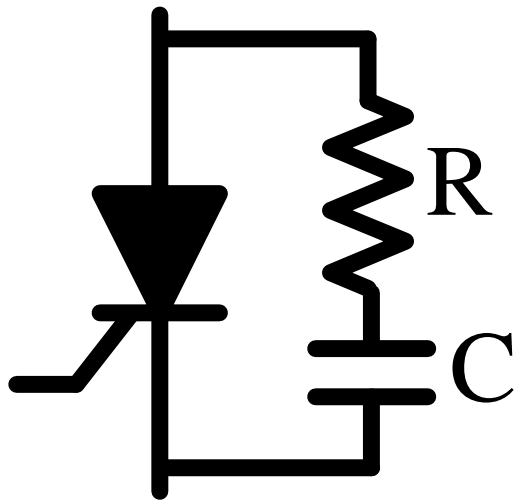
- **Breakdown will occur** if the devices are taken over the boundaries caused by excess heating and high current density.

Snubber

Snub (= Suppress)

A device to suppress transient phenomena in electrical circuits/systems

RC Snubber for Thyristor



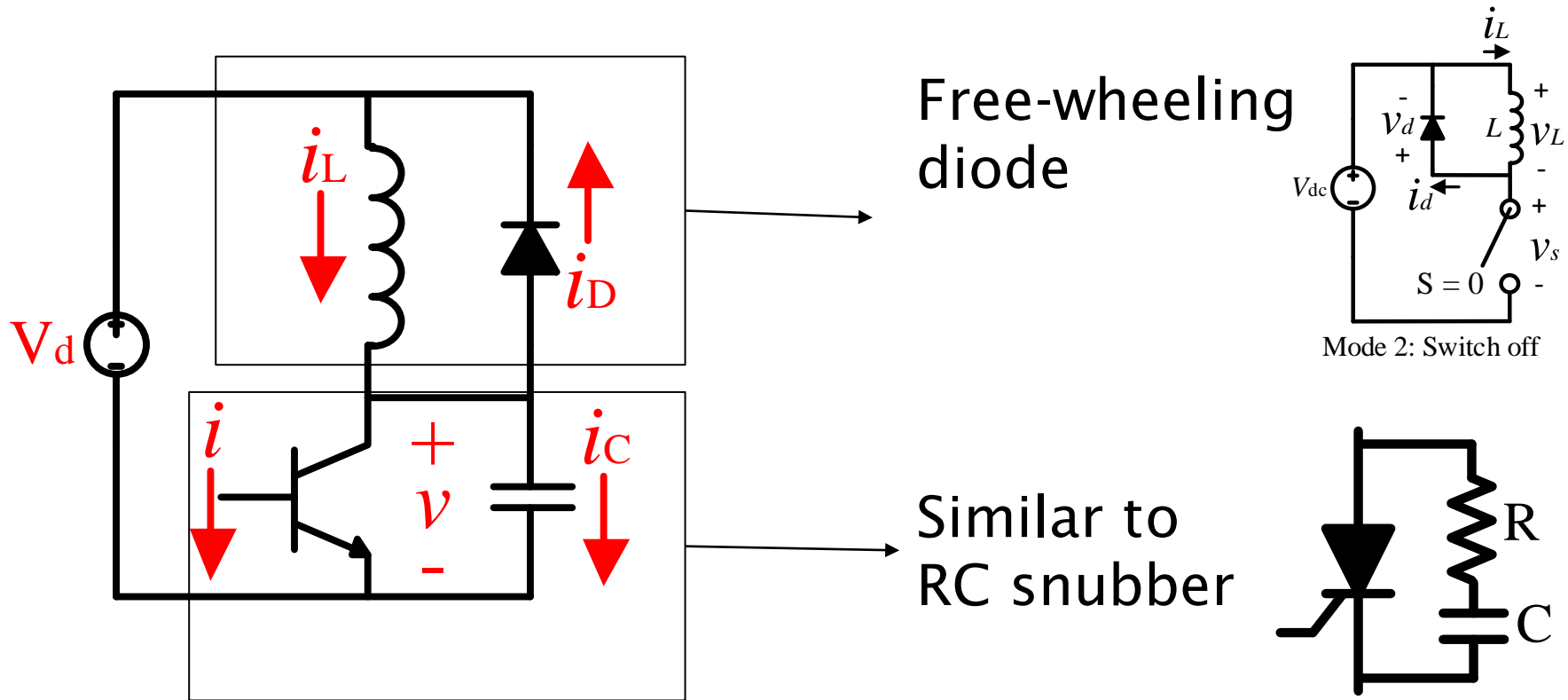
$(dv/dt)_{\max}$: Maximum critical rate of rise of off-state voltage

→ Sudden change of v_{AK} causes turn on

RC Snubber can limit the transient voltage dv/dt below the critical value.

Snubber for Transistors

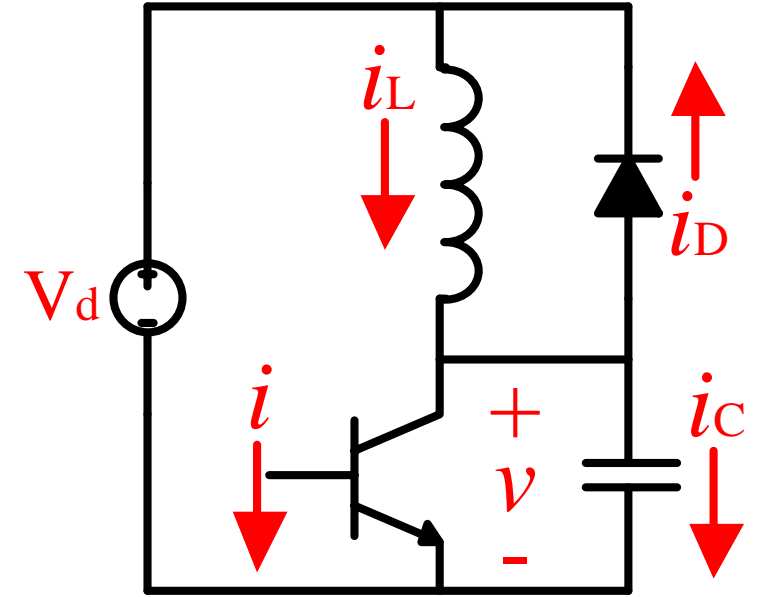
- Snubber circuit can improve the turn-off characteristic of transistors.



- This is important as in typical power electronics circuits the load is mainly inductive.

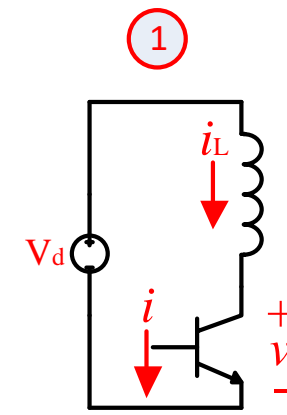
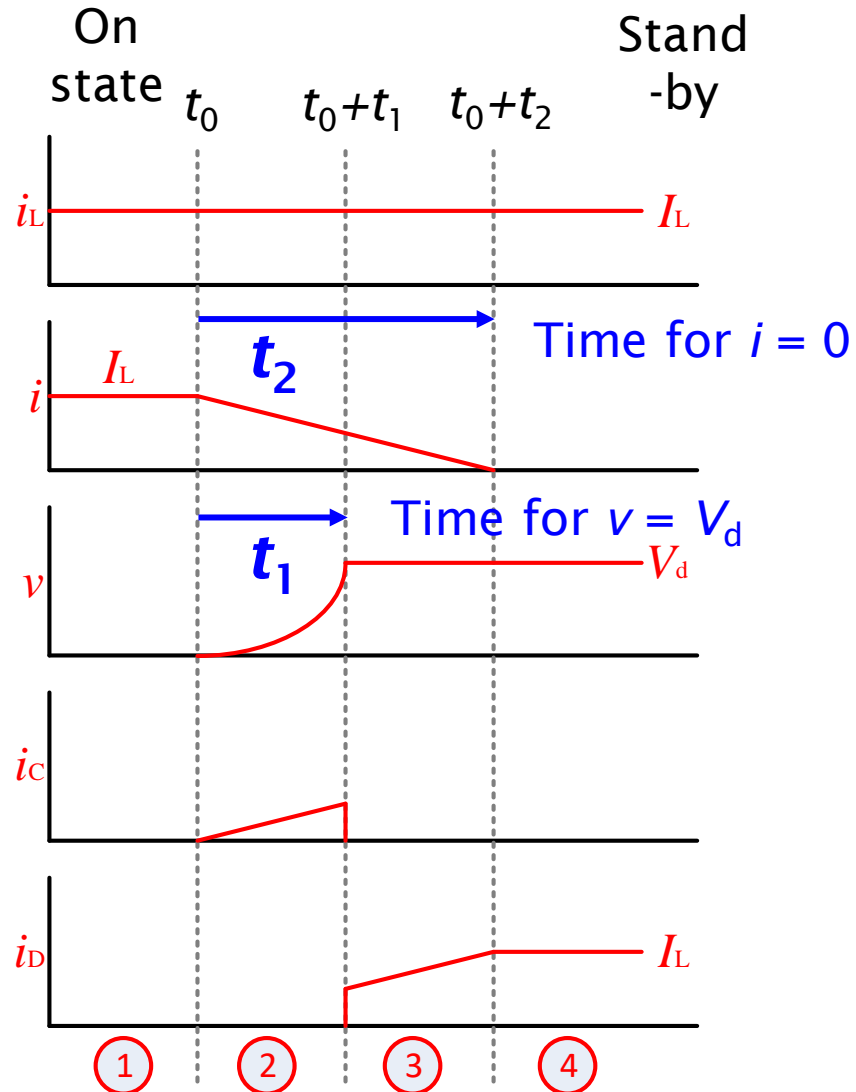
Snubber for Transistors

- During switching, the inductor current is varying slowly (maybe **milliseconds** depending on inductance) compared to the switching (**microseconds**) hence we can assume it to be constant.
- In the turn-off process, **the current in the inductor is transferred to the capacitor** (charges from 0V to supply voltage) **then to the diode** and falls linearly with time.

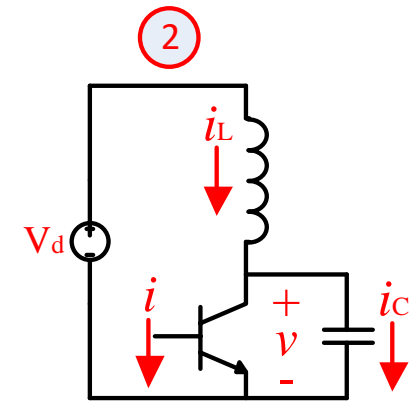


Snubber circuit analysis

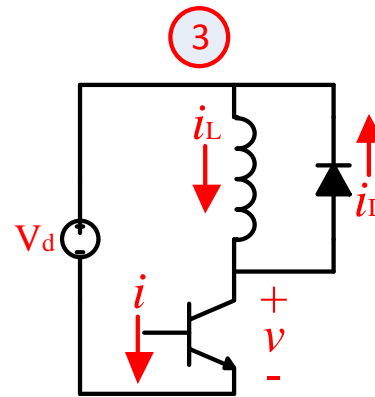
Turning off at $t = t_0$



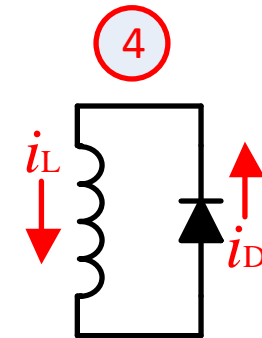
On state ($t < t_0$)



$t_0 < t < t_0 + t_1$

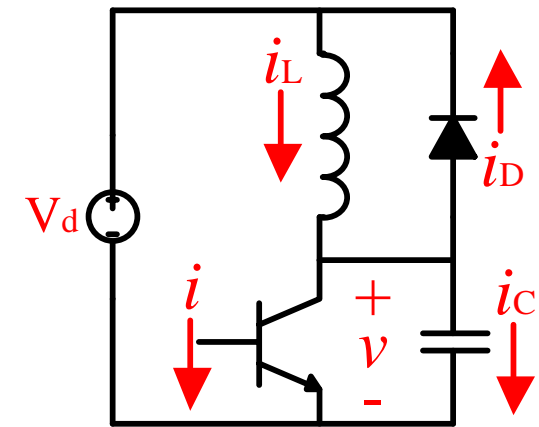
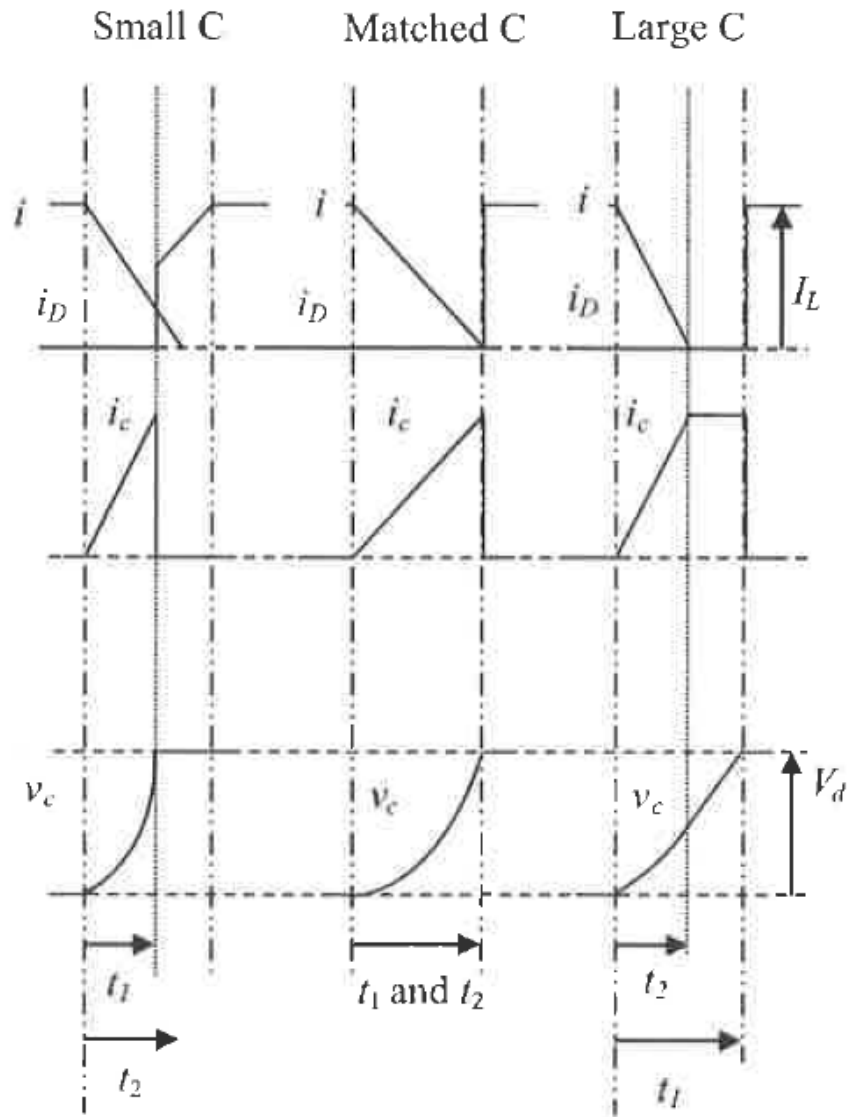


$t_0 + t_1 < t < t_0 + t_2$



Stand-by ($t > t_0 + t_2$)

Snubber circuit analysis



- Capacitance affects the turning off performance.
- Small C (charge quickly): v reaches V_d before i has reached zero ($t_1 < t_2$).
- Large C (charge slowly): v reaches V_d at a time after i is zero ($t_1 > t_2$).
- **Matched C (optimum charging rate)** : i is zero at the same time that v reaches V_d ($t_1 = t_2$).

State-of-the-art Power MOSFETs

- Conventional power MOSFETs are based on silicon.
- Wide band-gap semiconductors are considered to overcome the limitation of silicon to achieve higher speed and higher breakdown voltage at the same time.
 1. SiC (Silicon Carbide)
 2. GaN (Gallium Nitride)
 3. Ga₂O₃ (Gallium Oxide)
- Emerging materials

Further reading:

J Millan *et al.*, "A Survey of Wide Bandgap Power Semiconductor Devices", *IEEE Transactions on Power Electronics* **29**, 2155 -2163 (2014).

Summary – Power Transistors

- A three terminal switch, **transistor** is another key element in power electronics, and particularly useful for **high frequency operation up to MHz** range with **relatively low power handling** of up to 1 MW.
- SOA is a primary concern to avoid self-damage of the transistors by heating which is produced by the voltage and current applied at each operational condition.
- **Snubber** circuits are also very important for transistors to minimise switching loss.
- **MOSFET and IGBT** are two major transistors in use in current power electronics. Emerging **wide band gap materials** are in consideration for future power switches.