Unit 2

Power Semiconductor Device

requirements, characteristics and application

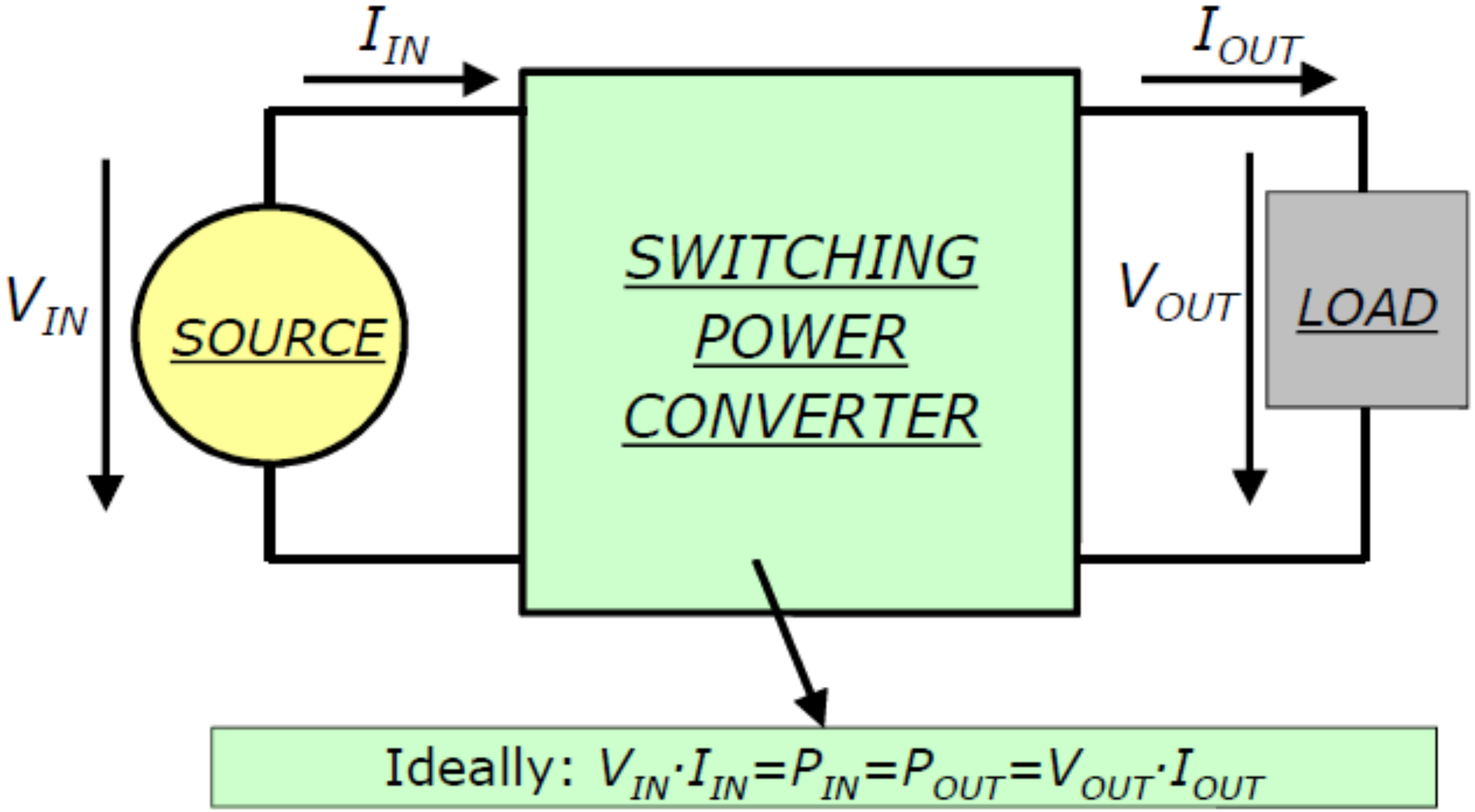
Power Semiconductor Devices

- Devices similar to the ones you already have heard of (MOSFET, BJT, Diodes etc) are used – but they are often much bigger – called "Power Devices"
- In many electronic circuits (e.g. amplifiers), devices are ***biased*** so that they operate in their ***linear region*** – not good for power electronics – too much heat generated in the device
- In power electronics, devices are either **OFF** (no base or gate drive) or **ON** (sufficient base or gate drive to "saturate" the device – see later)
- There are three basic classes of switching device:
  - *Controlled devices* ("transistors" of various kinds) – ON/OFF can be controlled by a gate or base terminal
  - *Uncontrolled devices* (Diodes) – ON/OFF is determined by external circuit conditions
  - *Latching Devices* (Thyristors and Triacs) – special devices with ON control via a gate, but OFF determined by external circuit conditions

Requirements

Power semiconductor devices

Power Electronic Conversion

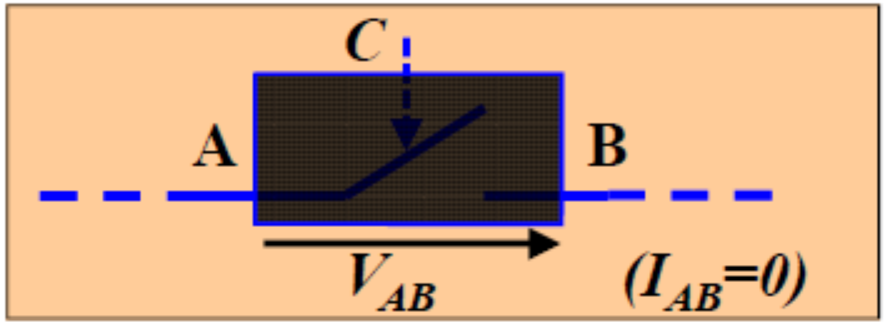


Power semiconductor devices

Ideal switches in Power Electronic Conversion

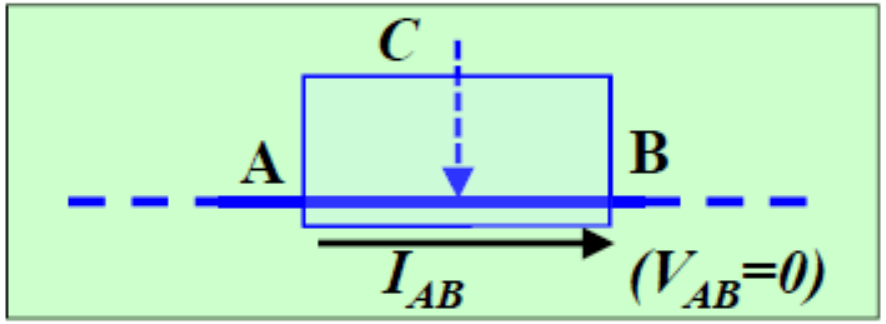
$$V_{AB} \cdot I_{AB} = P_{DISS} = 0$$

OFF-STATE



Block voltage with zero current flow

ON-STATE



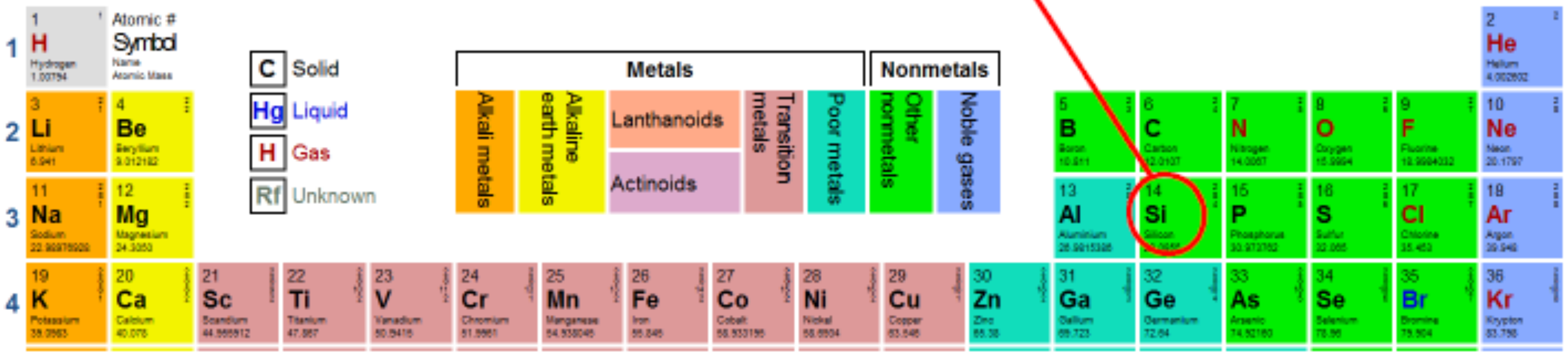
Allow current flow with zero voltage drop

Transition between ON and OFF states controllable, instantaneous and non-dissipative

Power semiconductor devices

Conductive properties of materials

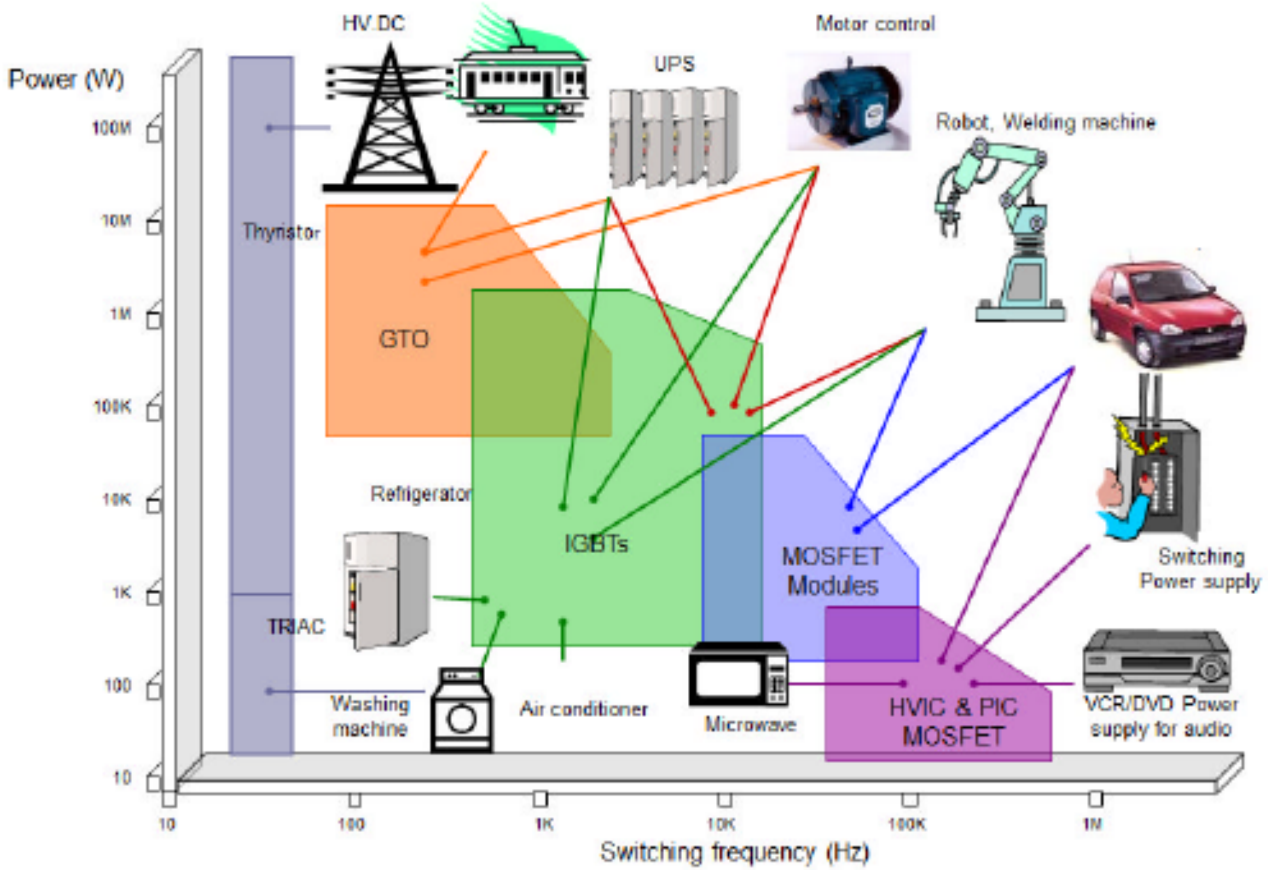
Metal	**Semiconductor**	**Insulator**
EXCELLENT CURRENT CONDUCTION PROPERTIES	TRADE-OFF ACHIEVABLE BY DESIGN	EXCELLENT BLOCKING CHARACTERISTICS



Application

Power semiconductor devices

Switches in power conversion circuitry



Higher switching frequency → smaller dimensions, better EMC, improved dynamics

Limit associated with power losses

Power semiconductor devices

Most relevant ratings

Voltage rating: withstand reverse bias without failure and with negligible leakage current (➔ off-state power losses)

Current rating: handle required current levels with good performance in terms of efficiency and switching speed

Temperature rating: ensure desired performance, prevent catastrophic failure, lifetime

Power semiconductor devices

Most relevant characteristics

Controllability: low-power control of transitions from ON to OFF and vice versa; low-power control of both ON and OFF states

Switching speed: fast, low-dissipation achievement of final states (either ON or OFF)

Power dissipation: device/system efficiency, thermal management (system size, weight, cost), reliability

Power semiconductor devices

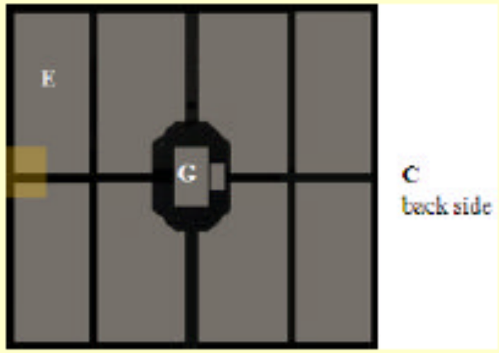
Device types and characteristics

Power semiconductor devices

Basic components

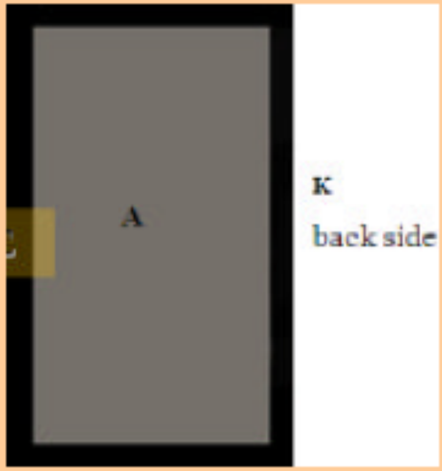
Transistor (IGBT):

3-terminal device (Collector, Gate, Emitter)

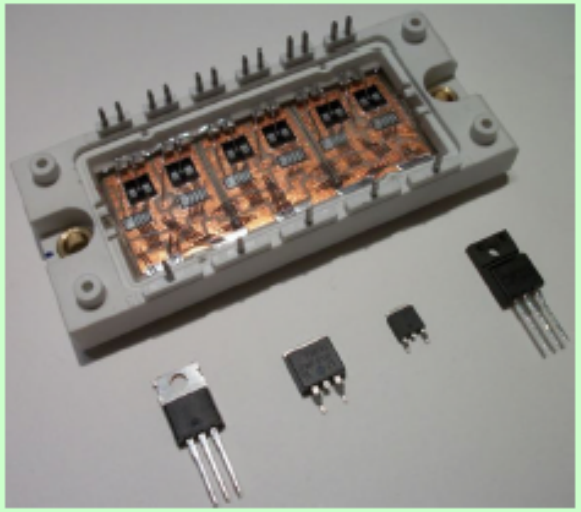


Diode (IGBT):

2-terminal device (Anode, Cathode)



Packaged devices/module

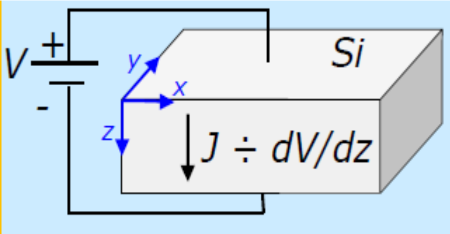


Power electronic devices are typically *vertical*, i.e. their power terminals are located on the top and bottom surfaces of the Si chip, respectively

Power semiconductor devices

Current transport mechanisms

Drift: current density proportional to the gradient of the electric potential (electric field)



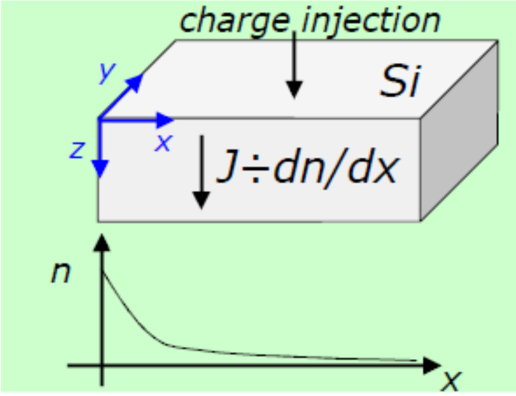
Drift currents:

- associated with power losses and heat generation (➔limits in ON-state performance)

+ can be initiated/terminated virtually instantaneously (➔ fast, relatively low dissipative switching transitions)

Power semiconductor devices

Properties



<u>Diffusion:</u> current density proportional to the *gradient of charge carrier density*

<u>Diffusion currents:</u>

\+ virtually non-dissipative
(➔enhanced ON-state performance)

\- Require non-instantaneous charge accumulation/extraction
(➔ limited switching performances)

Power semiconductor devices

Devices and applications

Both current conduction mechanisms can be combined and used within a single device

One of the two components can be made dominant to achieve specific target characteristics

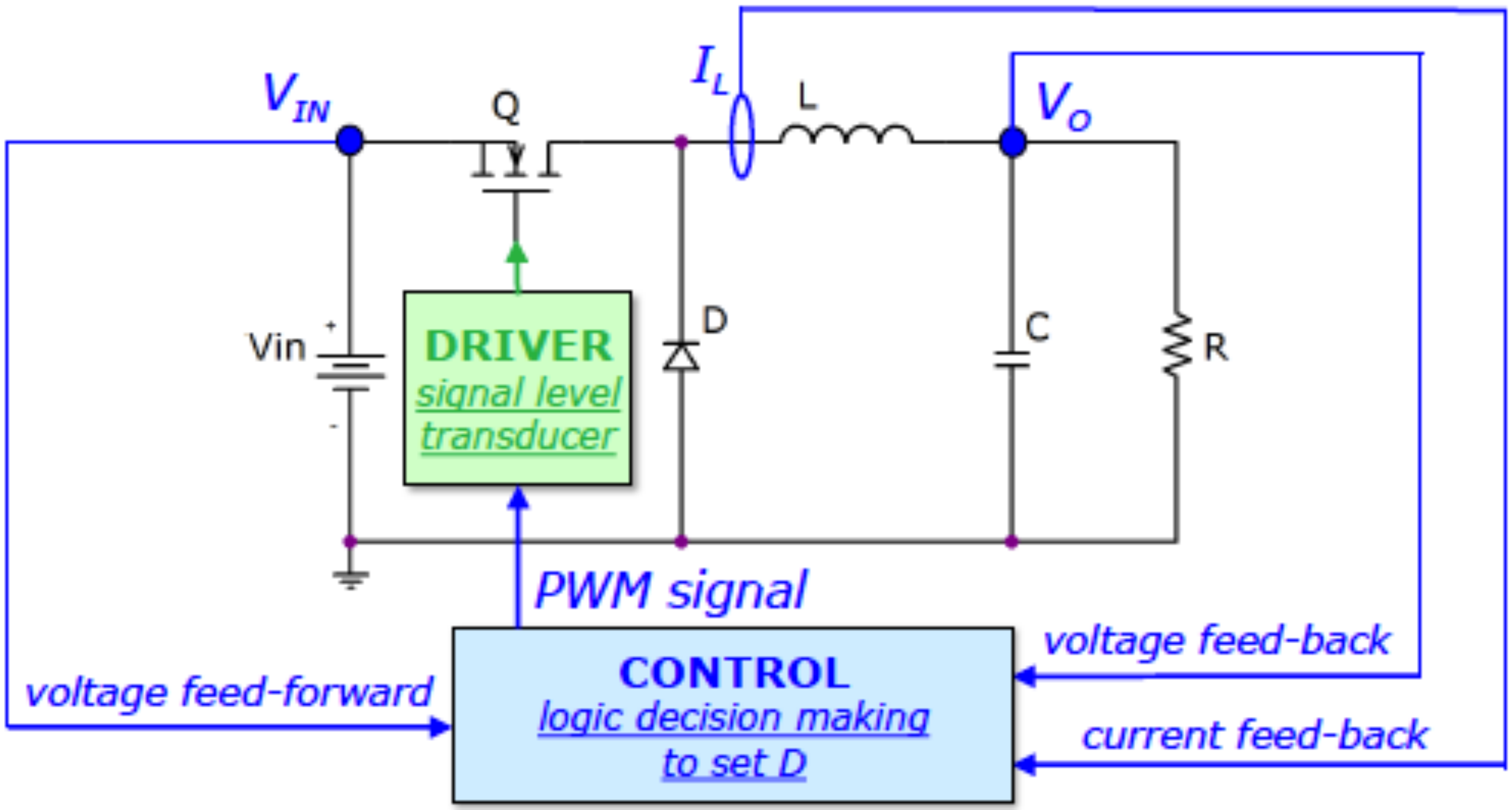
Current conduction mechanism is related to *controllability* of device switching: driving requirements/characteristics are also an important performance indicator

Power semiconductor devices

Driver function and types

Power semiconductor devices

Closed-loop converter operation



Power semiconductor devices

Driver types

Gate-drivers:

- ➢ Need to deliver current pulses to charge/discharge device input capacitance during switching
- ➢ Fast and low-dissipative

Base-drivers:

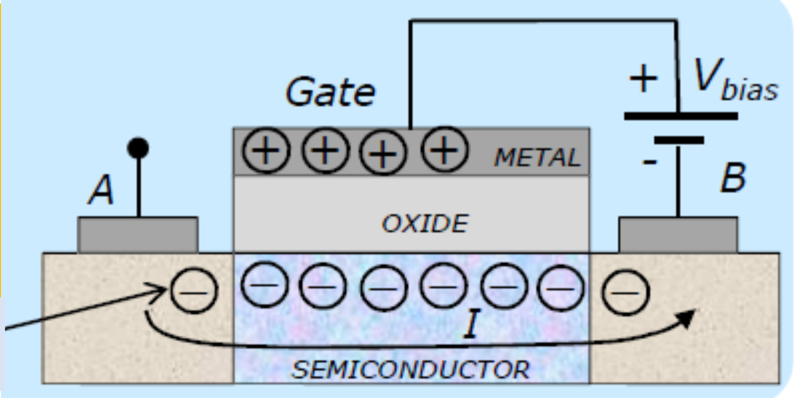
- ➢ Need to supply current during switching and during conduction
- ➢ Relatively slow and dissipative

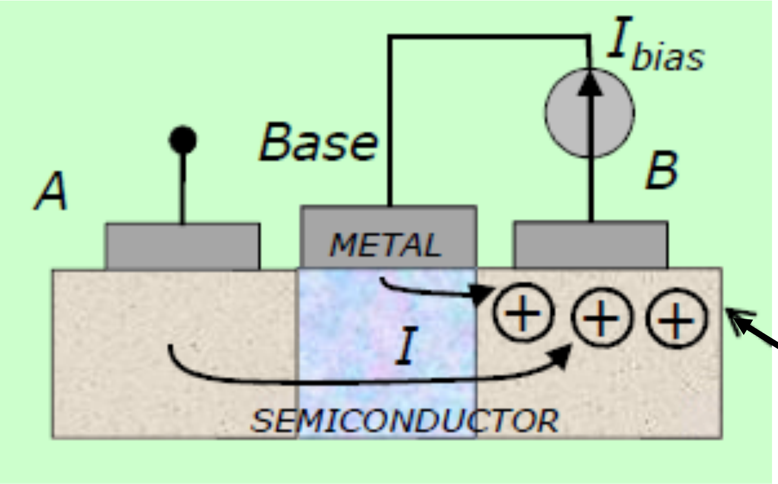
Power semiconductor devices

Driving mechanisms

Gate-drive: Metal-Oxide-Semiconductor (MOS) capacitive control terminal; device is voltage-driven

Creation of conductive channel





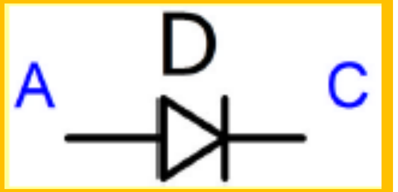
Base-drive: charge-injection control terminal; device is current driven

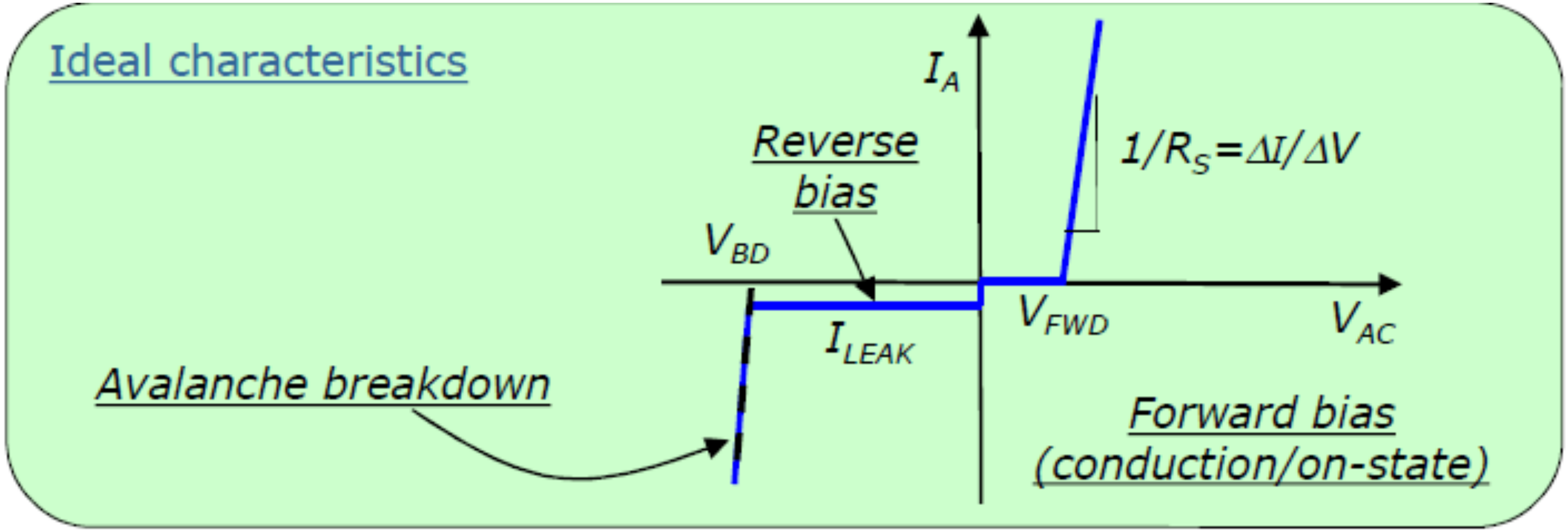
Creation of charge gradient

Power semiconductor devices

Diodes

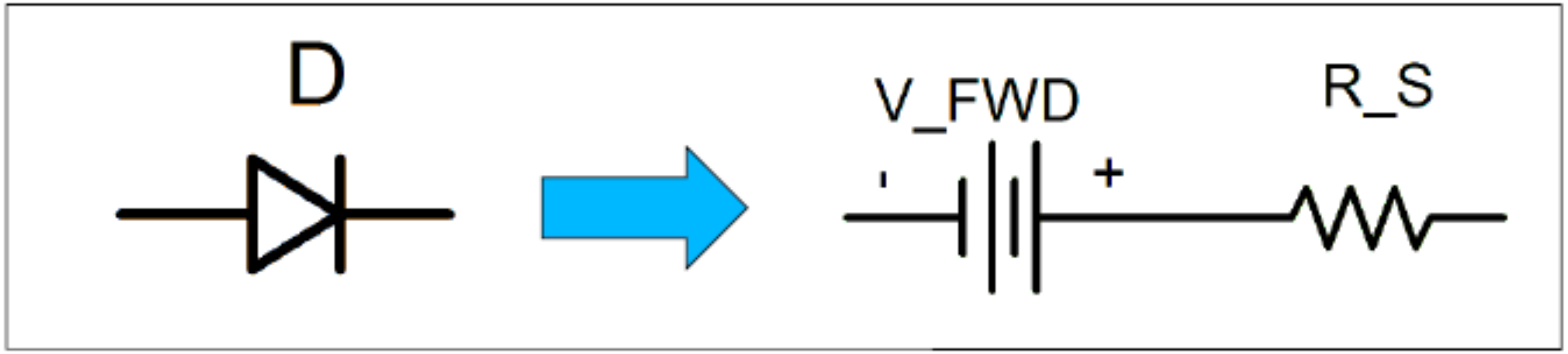
- ✓ Two terminal device (*Anode* and *Cathode*)
- ✓ All voltage ranges (from 1 V to 6.5 kV)
- ✓ Diffusion-current based
- ✓ Unidirectional current flow





Power semiconductor devices

Diode equivalent on-state model

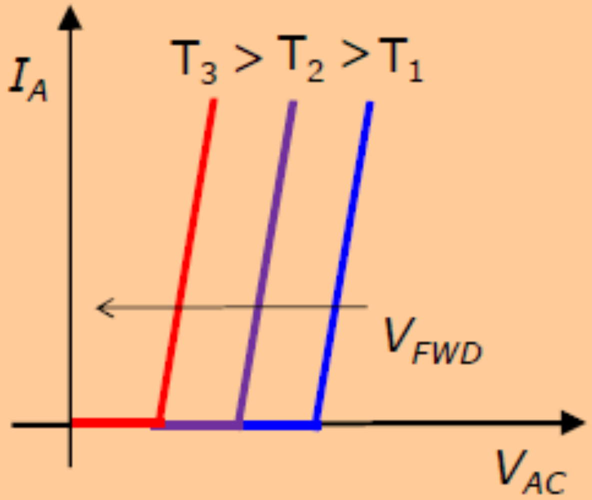


Temperature behaviour

V_{FWD} decreases with temperature

(ca. 2mV/K)

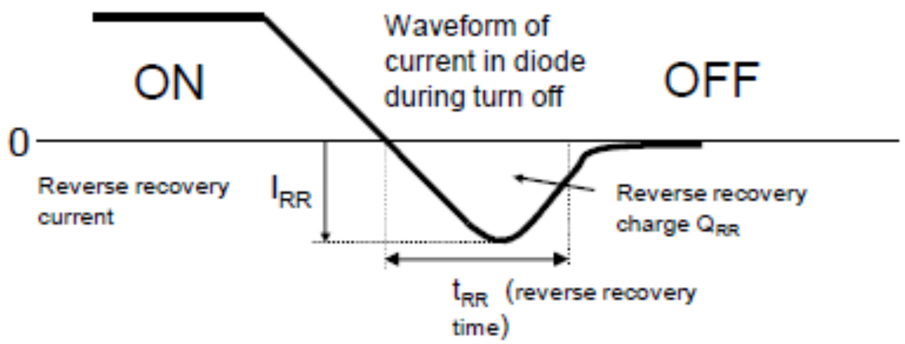
Diode not ideal for parallel operation!



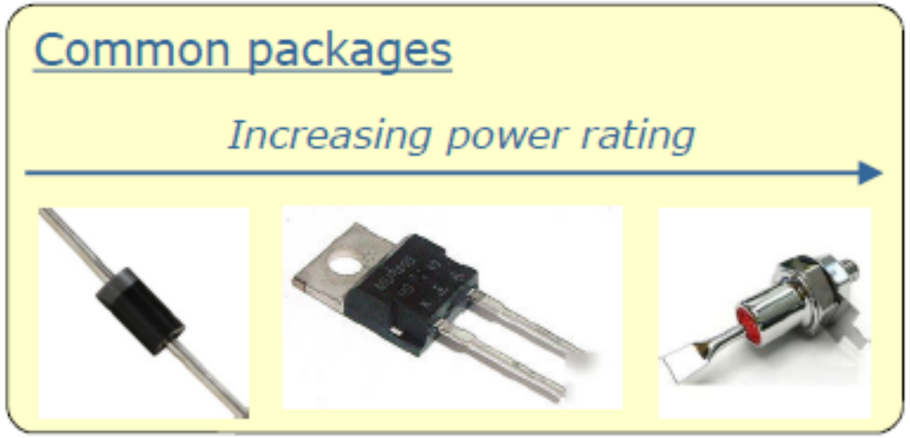
Power semiconductor devices

Diode switching performance

Real diodes characterised by *reverse-recovery* currents and switching delays due to charge extraction



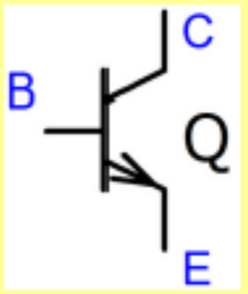
Schottky diodes are used for improved switching (but poorer on-state performance)

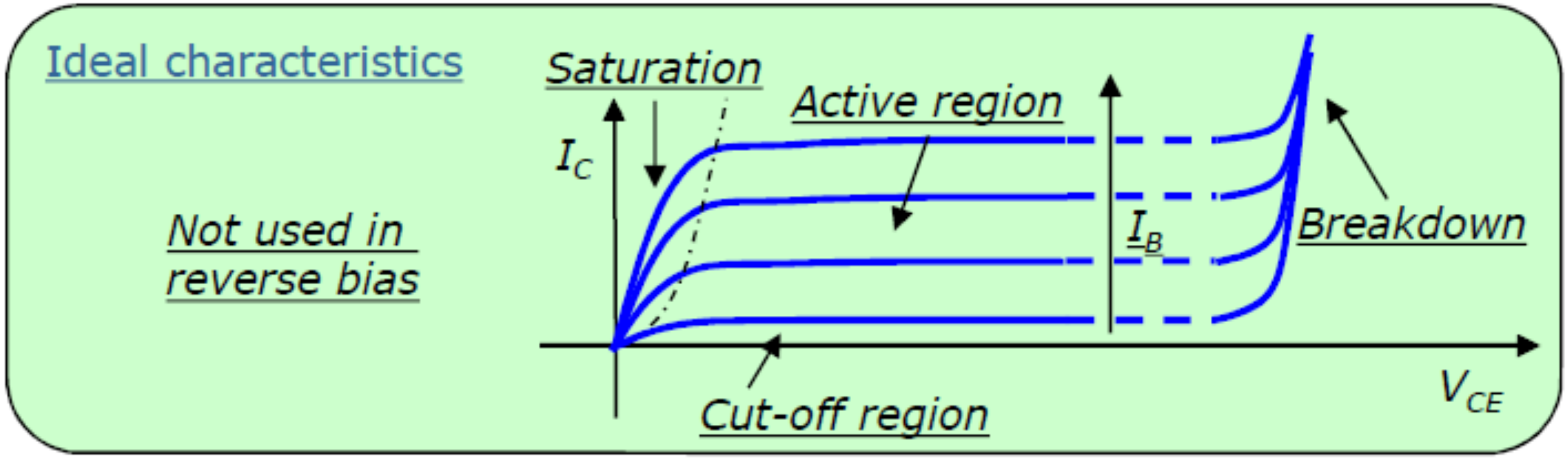


Power semiconductor devices

BJT (Bipolar Junction Transistor)

- ✓ Three terminal device (*Collector-Base-Emitter*)
- ✓ Diffusion-current based
- ✓ Current controlled (*base* is control terminal)
- ✓ Unidirectional current flow

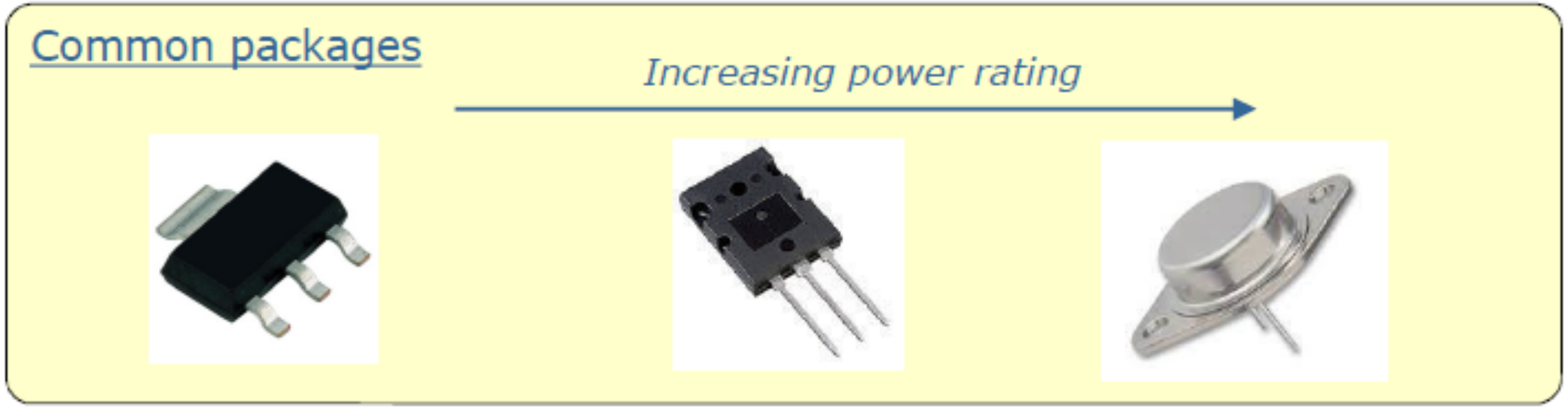




Power semiconductor devices

BJT (Bipolar Junction Transistor)

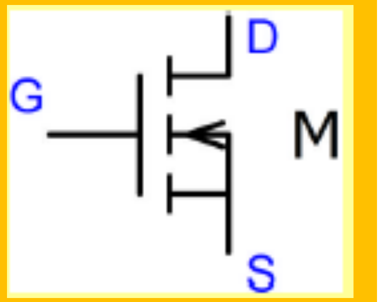
Ratio between I_C and I_B is the *current gain*. Power BJTs typically have poor current-gains, i.e. their driving can be very dissipative and limited in practical frequency.
They also suffer from current tails at turn-off, which limits their switching speed/frequency. Presently confined to niche applications. Used frequently in gate-driver design.

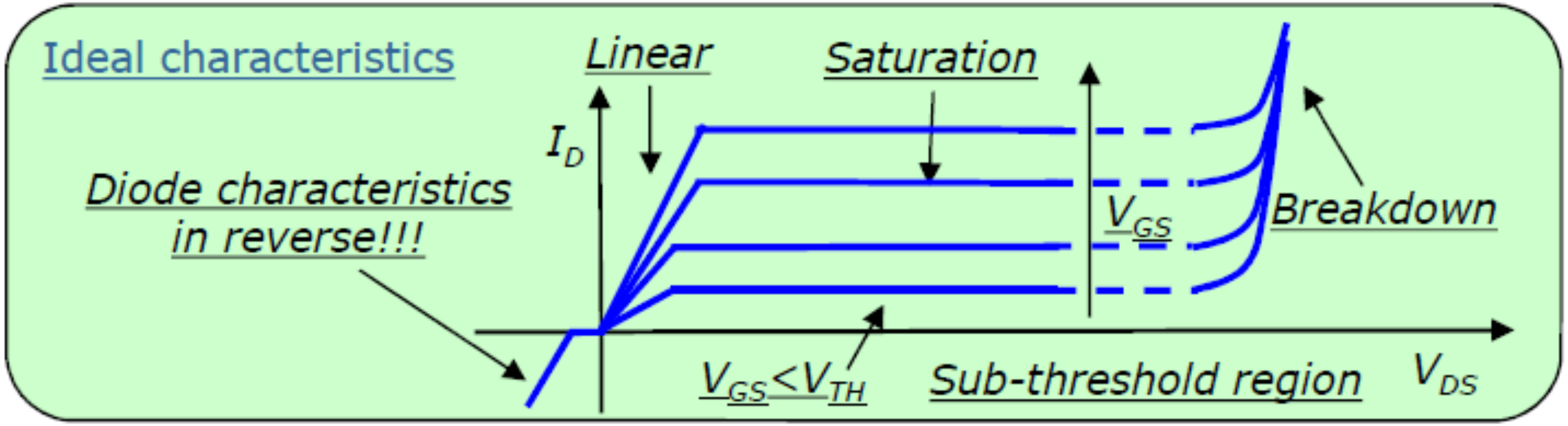


Power semiconductor devices

MOSFET (MOS Field-Effect Transistor)

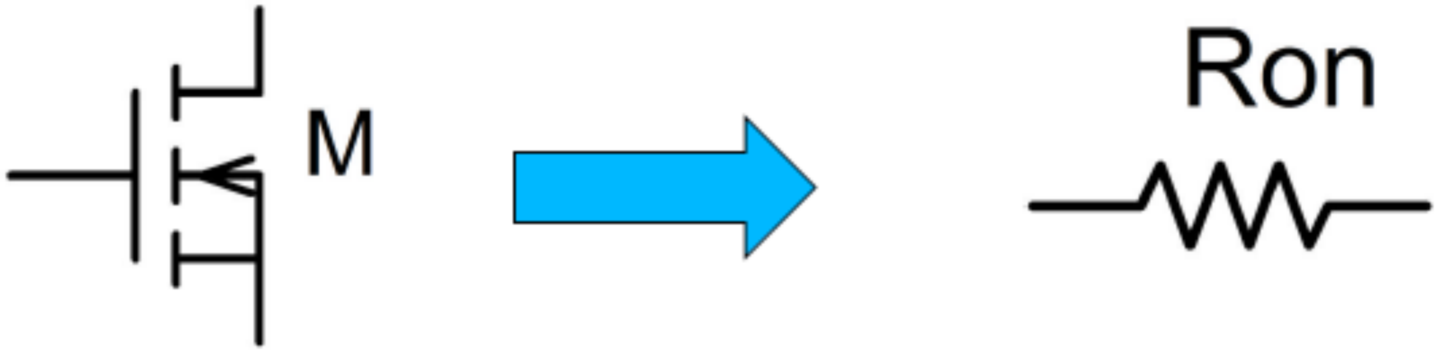
- ✓ Three terminal device (*Drain-Gate-Source*)
- ✓ Drift-current based
- ✓ Voltage controlled *with minimum threshold*
- ✓ Bi-directional current flow between drain and source
- ✓ Contains intrinsic (body) diode between *source* and *drain*





Power semiconductor devices

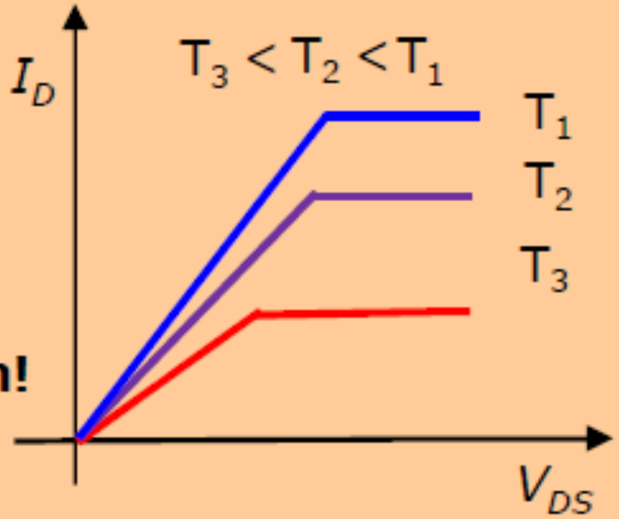
MOSFET equivalent on-state model



Temperature behaviour

R_{ON} increases with temperature

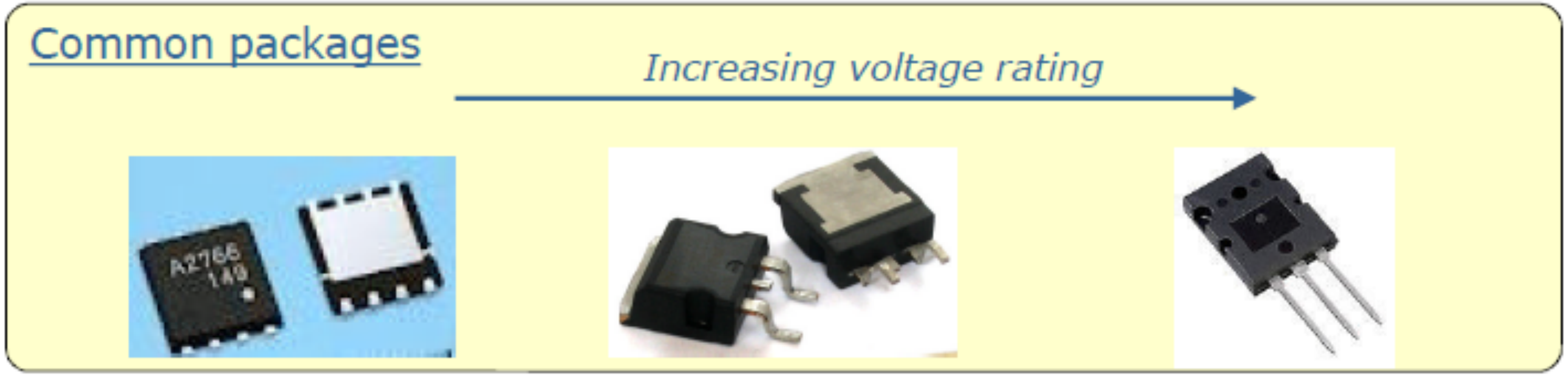
MOSFET ideal for parallel operation!



Power semiconductor devices

MOSFET

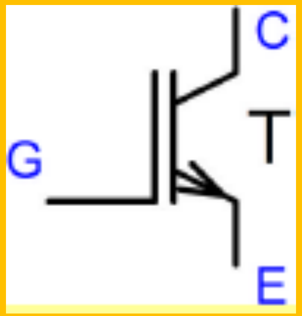
Dominating in the low-power range (<600V). Low-dissipative drive, but requires fast/high current peaks. Ideal for parallel operation (on-state performance similar to a resistor). Limited in voltage scalability due to $R_{DS,ON}$ (typically scales with 2.5 power of voltage rating). Intrinsic body-diode simplifies design of a number of power converter topologies.

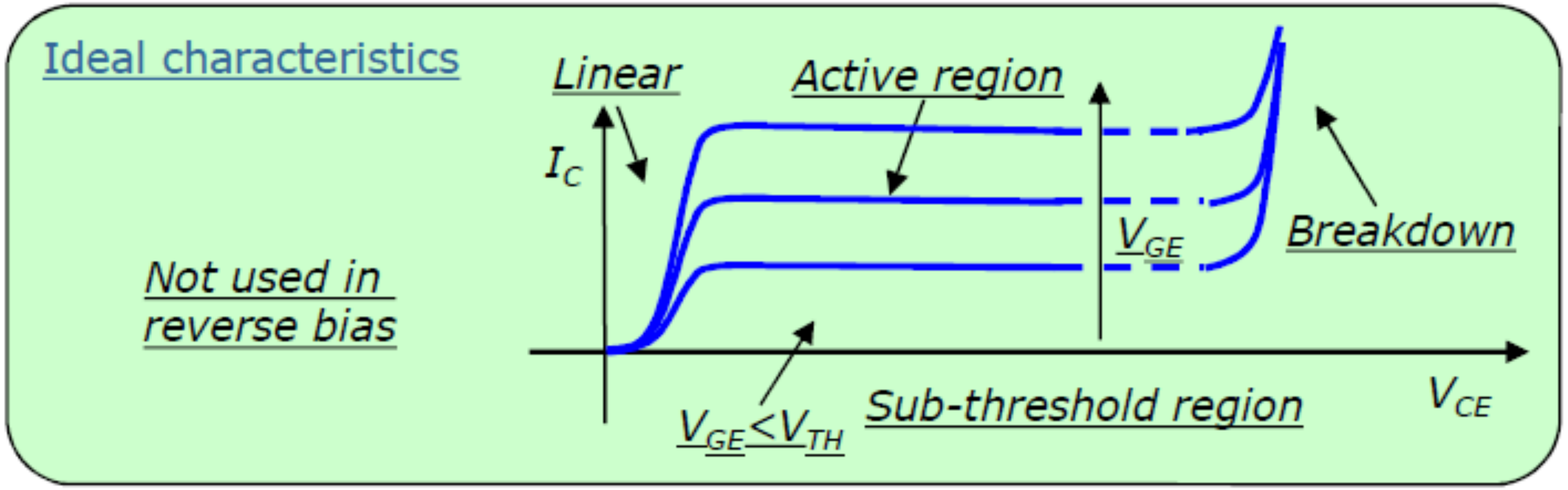


Power semiconductor devices

IGBT (Insulated Gate Bipolar Transistor)

- ✓ Three terminal device (*Collector-Gate-Emitter*)
- ✓ Uses both drift and diffusion current components (very high current density and versatile design)
- ✓ Voltage controlled (Gate)
- ✓ Unidirectional current flow

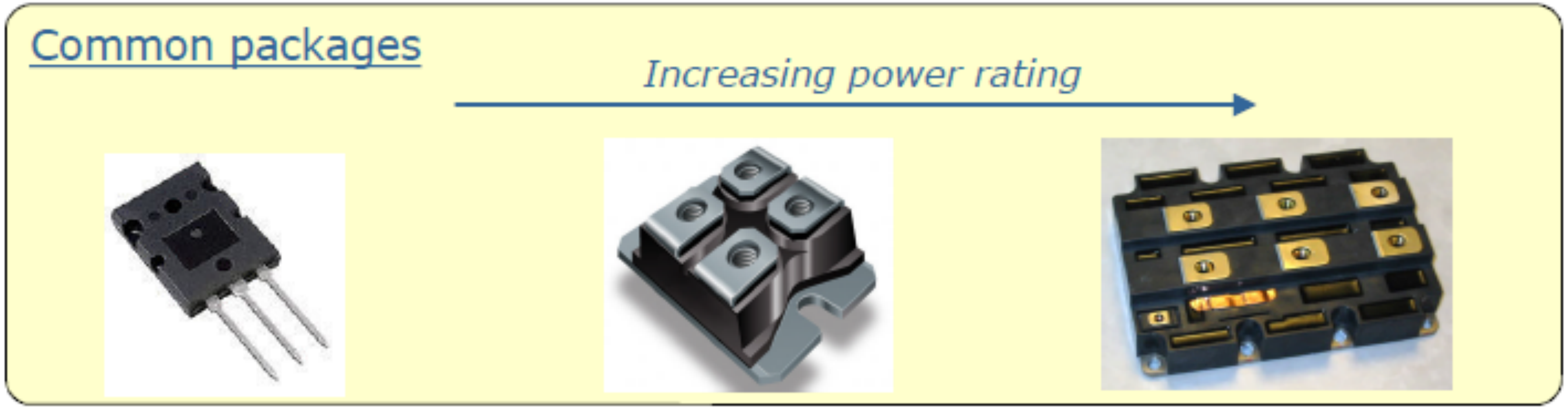




Power semiconductor devices

IGBT

Combines the positive features of BJT (low on-state voltage) and MOSFET (low-dissipation driving).
One of the most flexible devices from design point of view (design can be optimised/tailored for a vast number of different application requirements). Dominates the voltage range 1 – 6.5 kV.
Limited in switching speed (also affected by current tail at turn-off).



Power semiconductor devices

Other device types and developments

- Thyristor/Gate Turn-Off Thyristor (GTO)
- IGCT (Integrated Gate Commutated Thyristor)

Replacement of Silicon with so-called wide-band-gap (WBG) materials, such as Silicon-Carbide (SiC) and Gallium-Nitride (GaN) is extending the application range of consolidated device types opening up new scenarios

Power semiconductor devices

Typical key parameters range

parameter	*diode*	*MOSFET*	*BJT*	*IGBT*	*thyristor*	*GTO*
typ. min. voltage rating	30V	20V	60V	600V	100V	1000V
max. voltage rating	50kV	1500V	1800V	6000V	9kV	8kV
typ. min. current rating	1A	0.5A	1A	10A	10A	300A
max. current rating	6000A	1000A	1000A	400A	4000A	3000A
max. frequency	>1MHz	>1MHz	100kHz	50kHz	10kHz	1kHz
on-state loss	low	high	moderate	moderate	v. low	low
switching loss	moderate	low	moderate	moderate	high	high
drive requirements	none	v. low	high	v. low	low	moderate
ease of parallel connection	moderate	easy	moderate	moderate	hard	hard
ease of series connection	moderate	moderate	hard	moderate	hard	v. hard
cost/VA	v. low	moderate	low	low	v. low	moderate

Power losses

Power semiconductor devices

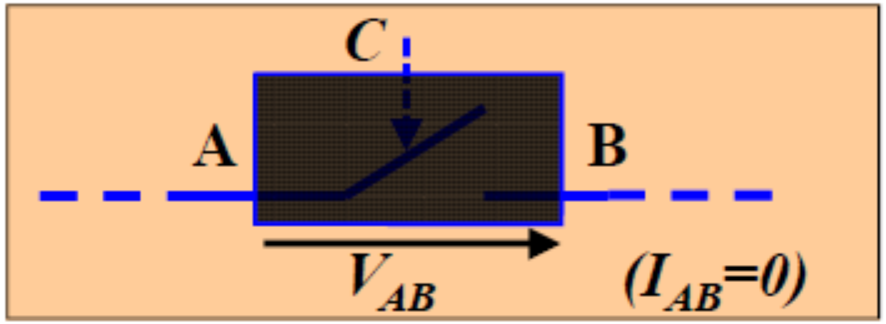
Introduction/recap

Power semiconductor devices

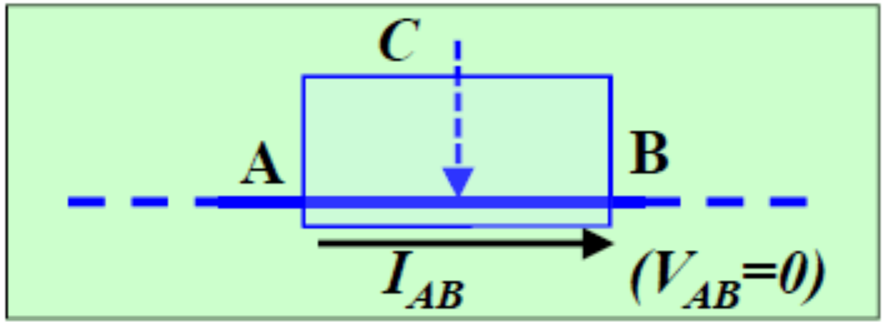
Ideal switches in Power Electronics

$V_{AB} \cdot I_{AB} = P_{DISS} = 0$

OFF-STATE



ON-STATE



Block voltage with zero current flow

Allow current flow with zero voltage drop

Transition between ON and OFF states controllable, instantaneous and non-dissipative

Power semiconductor devices

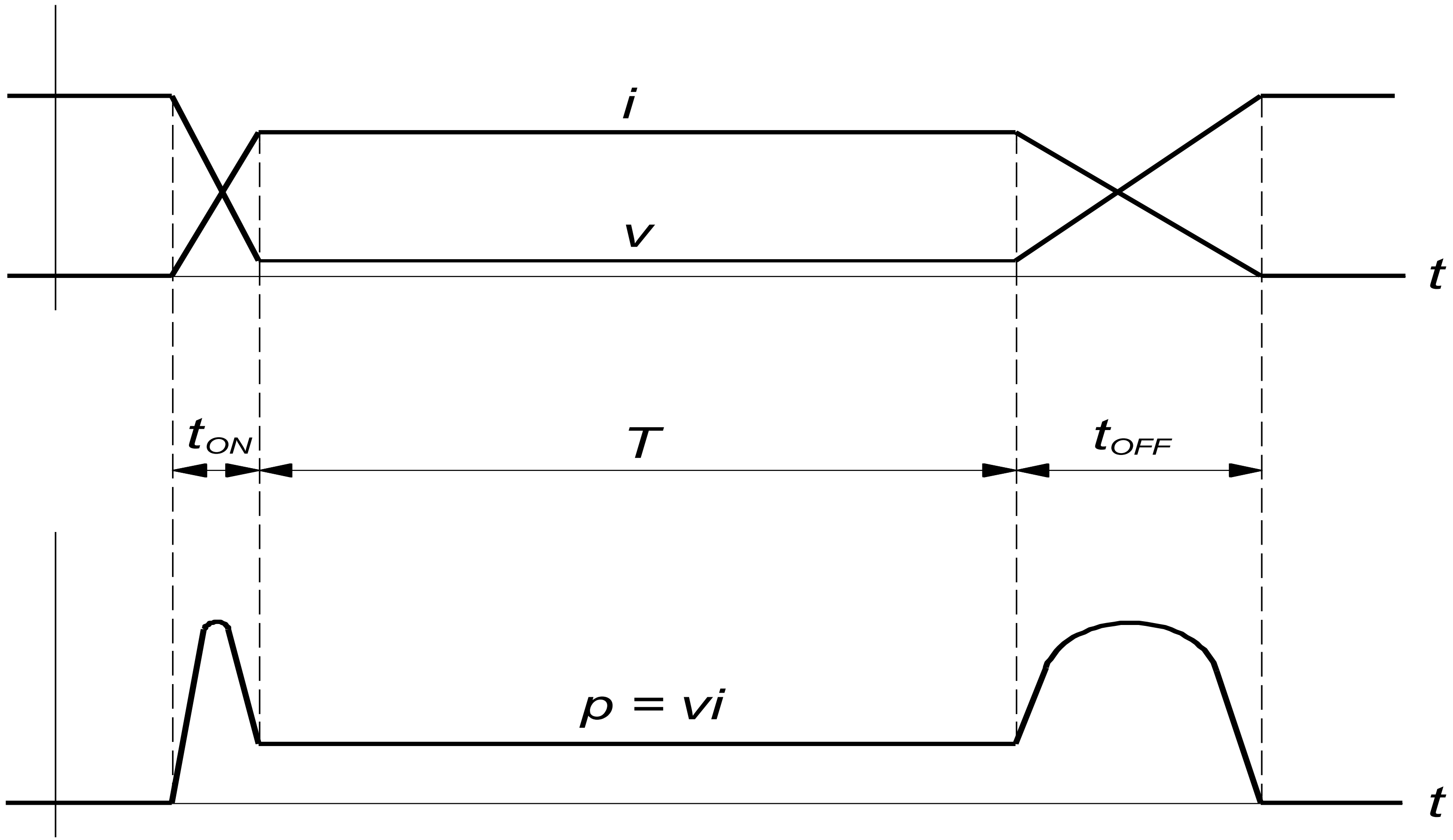
Real switches

Affected by power losses during operation:

- ON-state (conduction)
- Switching
- OFF-state (blocking)

Conjunct device design optimisation for all states is very challenging!!!

Power semiconductor devices



Waveforms of voltage, current, and power loss in a semiconductor power switch

Power semiconductor devices

Implication of power dissipation-I

- *waste of energy* (environmental impact; reduction of operational time of battery-powered systems; higher costs)

Exercise:

The average power consumption of a mobile phone is 0.5 W.

The phone is powered by a battery with 6.11 Wh rating, via a DC-DC converter.

How long can the phone be operated (in-between recharges) if the converter efficiency is:
a) 80 %; b) 90 %

Solution:

Efficiency =
$P_{OUT}/P_{IN} = P_{PHONE}/P_{BATTERY}$

a) $P_{BATTERY}$=0.5W/0.8= 0.625W;
b) $P_{BATTERY}$=0.5W/0.9= 0.55W.

So, the operation time is:

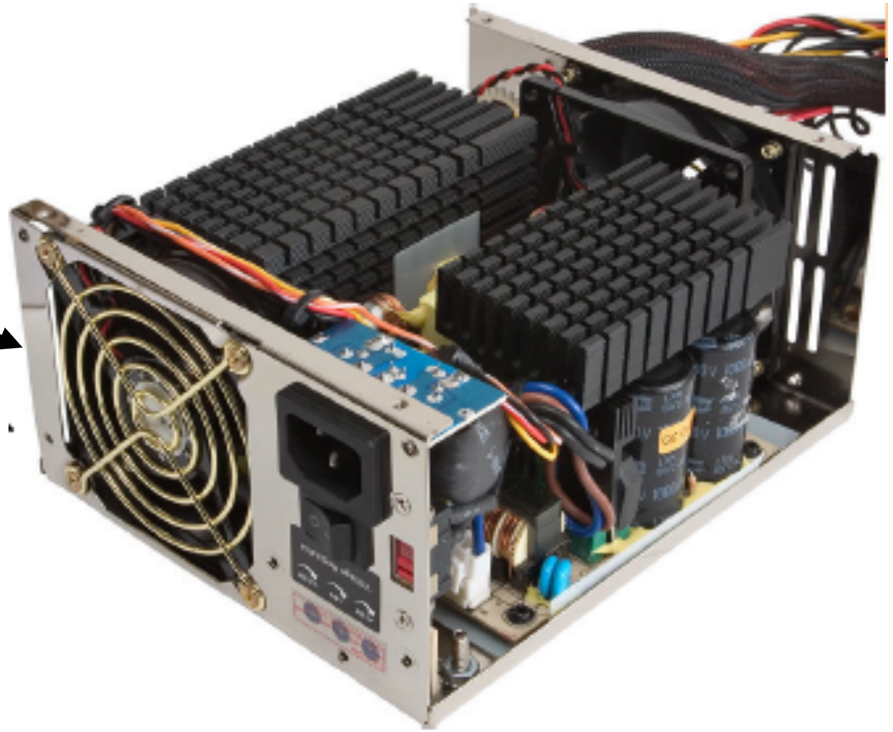
a) t_{OP}=6.11/0.625=9.8 h;
b) t_{OP}=6.11/0.55= 11.1 h.

Power semiconductor devices

Implication of power dissipation-II

- *Generation of heat* (requires additional thermal management components; negatively affects device performance; key factor in component/system degradation and failure)

Complexity, size and cost of typical power supply significantly affected by thermal management issues!



Power semiconductor devices

Calculation of power losses

Power semiconductor devices

Power loss calculation

General equation:

$$P = \frac{1}{T}\int_0^T (V_{AB} \cdot I_A)dt$$

$$\boxed{1/T = f_s}$$

$\boldsymbol{V_{AB} = constant}$

Special cases:

$$P = V_{AB} \cdot \left[\frac{1}{T}\int_0^T I_A dt\right] = V_{AB} \cdot I_{A,AVG}$$

$$P = R \cdot \left[\frac{1}{T}\int_0^T (I_A)^2 dt\right] = V_{AB} \cdot (I_{A,\,RMS})^2$$

$\boldsymbol{V_{AB} = I_A \cdot R}$

with

$$I_{A,\,RMS} = \sqrt{\frac{1}{T}\int_0^T (I_A)^2 dt}$$

Power semiconductor devices

On-state power losses

Diode:

$$P_{ON} = V_{FWD} \cdot I_{FWD,AVG} + R_S \cdot (I_{FWD,RMS})^2$$

with R_S often negligible

MOSFET:

$$P_{ON} = R_{DS,ON} \cdot (I_{D,RMS})^2$$

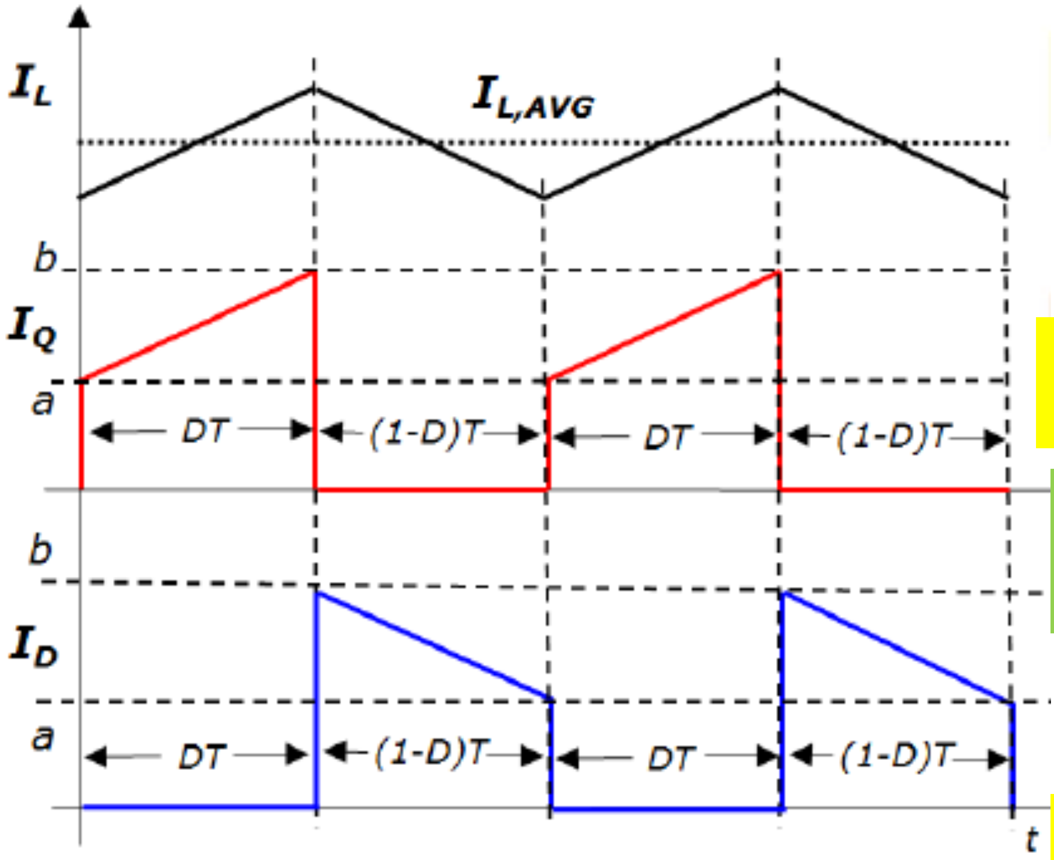
with $R_{DS,ON}$ *typically dependent on temperature and current*

BJT/IGBT:

$$P_{ON} = V_{CE} \cdot I_{C,\,AVG}$$

Power semiconductor devices

Common functions AVG and RMS values



$$I_{L,\,AVG} = \frac{a+b}{2}$$

$$I_{L,RMS} = \sqrt{\frac{(a^2+b^2+ab)}{3}}$$

$$I_{Q,\,AVG} = \frac{a+b}{2} \cdot D$$

$$I_{Q,RMS} = \sqrt{\frac{D}{3} \cdot (a^2 + b^2 + ab)}$$

$$I_{D,\,AVG} = \frac{a+b}{2} \cdot (1 - D)$$

$$I_{D,RMS} = \sqrt{\frac{(1-D)}{3} \cdot (a^2 + b^2 + ab)}$$

Power semiconductor devices

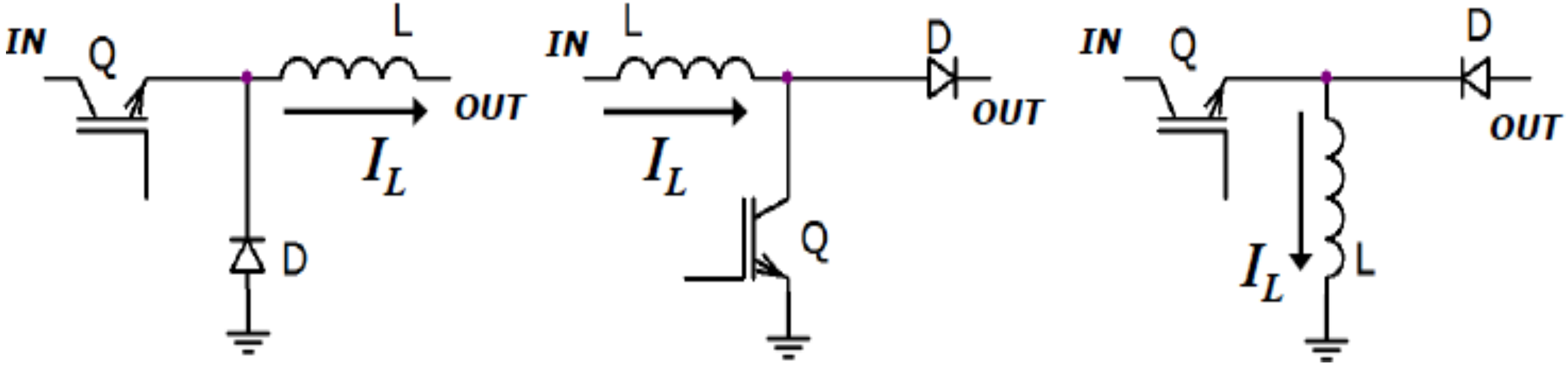
Switching losses

Representative commutation cells:

Forward type (step down)

Forward type (step-up)

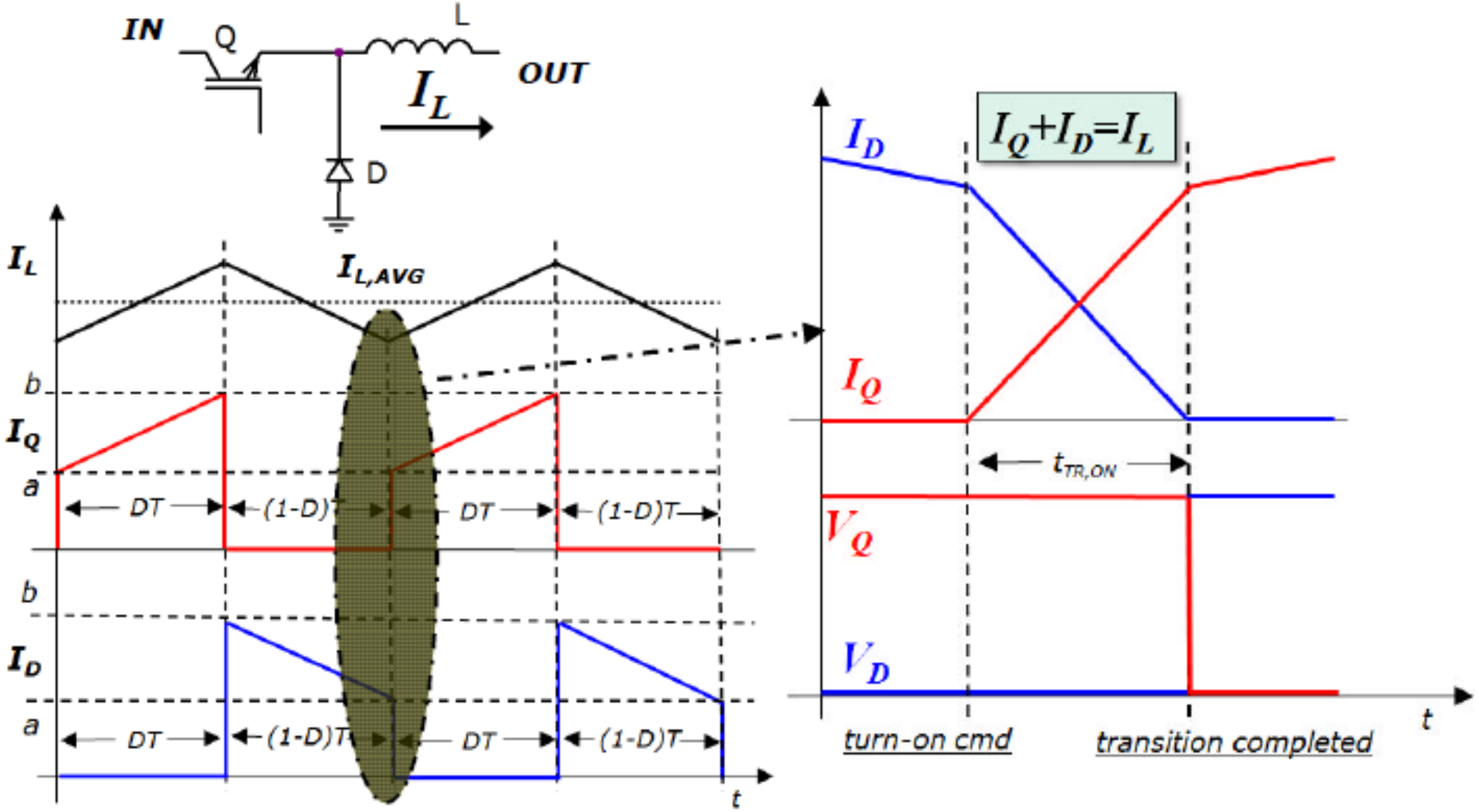
Fly-back type (step up or down)



Cell includes transistor and diode;
Switching transition *short* compared to characteristic period;
I_L assumed constant during switching transition!

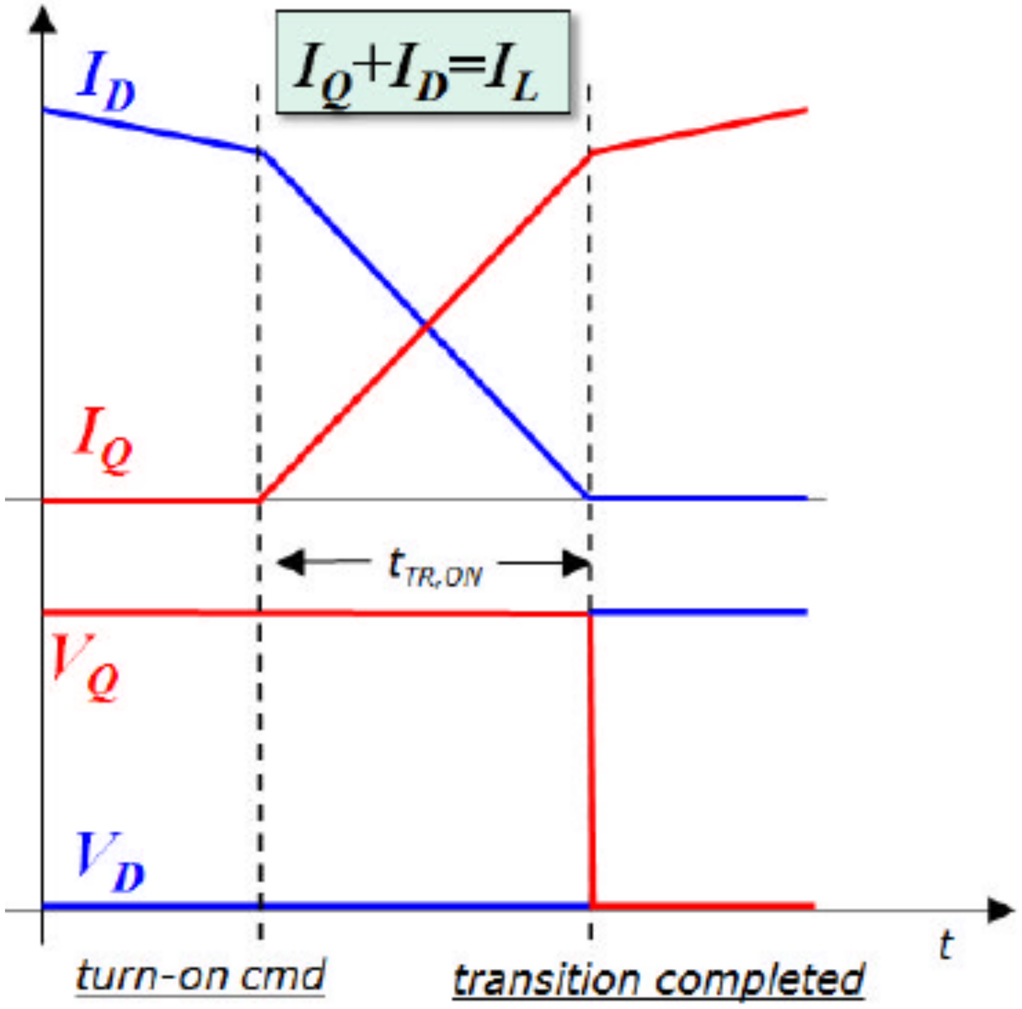
Power semiconductor devices

Switching transitions: turn-on (of Q)



Power semiconductor devices

Switching transitions: turn-on (of Q)



Diode:

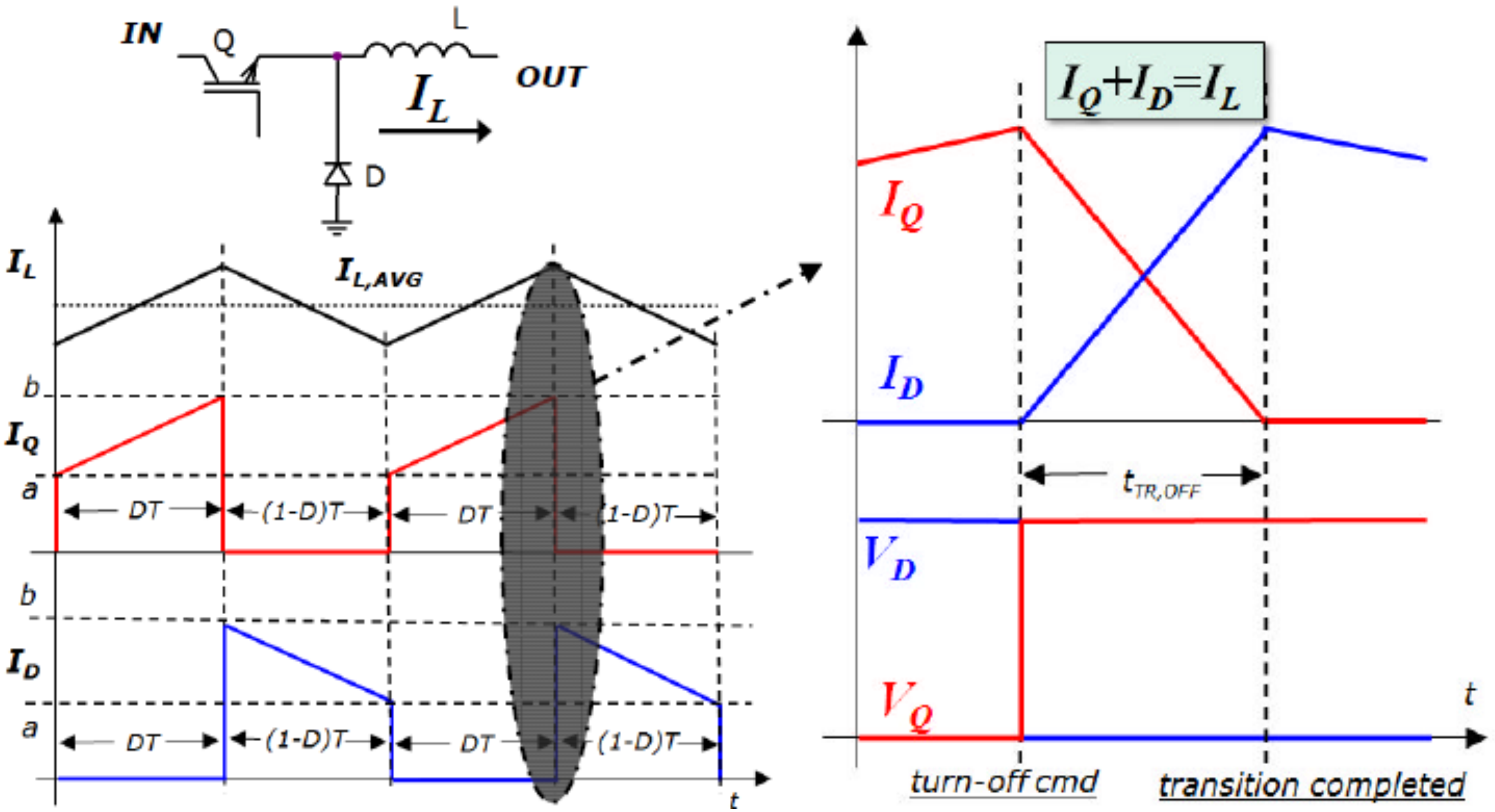
$$P_{LOSS} = 0$$

Transistor:

$$P_{LOSS} = V_Q \cdot I_{Q,AVG}$$
$$= 0.5 \cdot V_Q \cdot I_L \cdot t_{TR,ON} \cdot f_S$$
$$= E_{SW} \cdot f_S$$

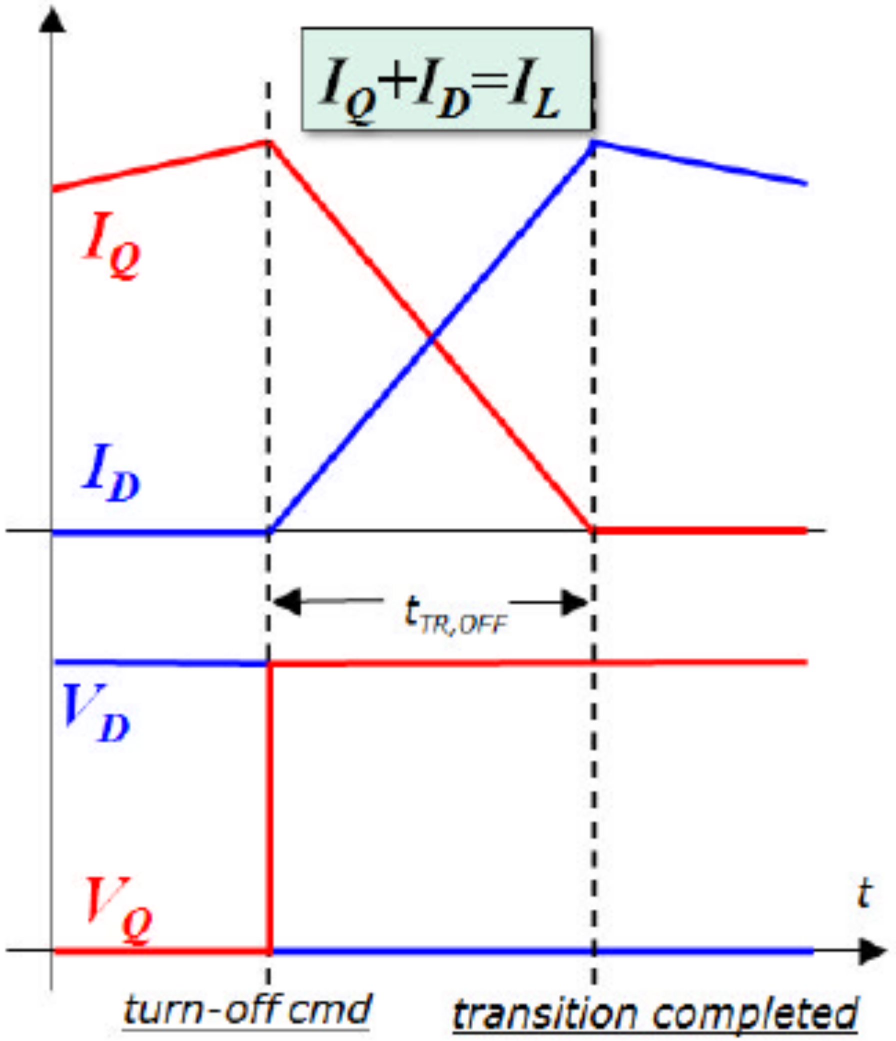
Power semiconductor devices

Switching transitions: turn-off (of Q)



Power semiconductor devices

Switching transitions: turn-off (of Q)



Diode:

$$P_{LOSS} = 0$$

Transistor:

$$P_{LOSS} = V_Q \cdot I_{Q,AVG}$$
$$= 0.5 \cdot V_Q \cdot I_L \cdot t_{TR,OFF} \cdot f_S$$
$$= E_{SW} \cdot f_S$$

Power semiconductor devices

Off-state power losses

Diode:

$$P_{OFF} = V_{REV} \cdot I_{LEAK}$$

MOSFET:

$$P_{OFF} = V_{BLK} \cdot I_{LEAK}$$

IGBT:

$$P_{OFF} = V_{BLK} \cdot I_{LEAK}$$

Typically, both voltage and current values are assumed constant, with

$$I_{LEAK} = f(V_{REV/BLK,}T)$$

For most device types, off-state power losses are negligible compared to conduction and switching losses in most applications/operational conditions.

Basics of thermal modelling

Power semiconductor devices

Heat transport

Conduction: heat propagates through matter

Convection: heat is transferred by relative motion of different parts of the system

Radiation: heat is transferred by electromagnetic waves

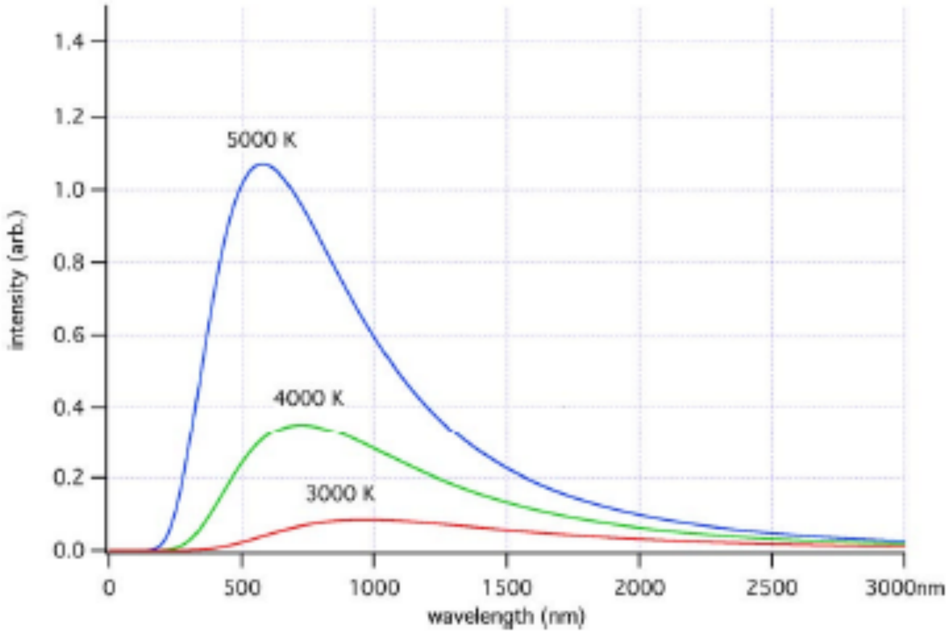
Heat is a form of energy. Propagation always takes place in the direction of decreasing temperature.

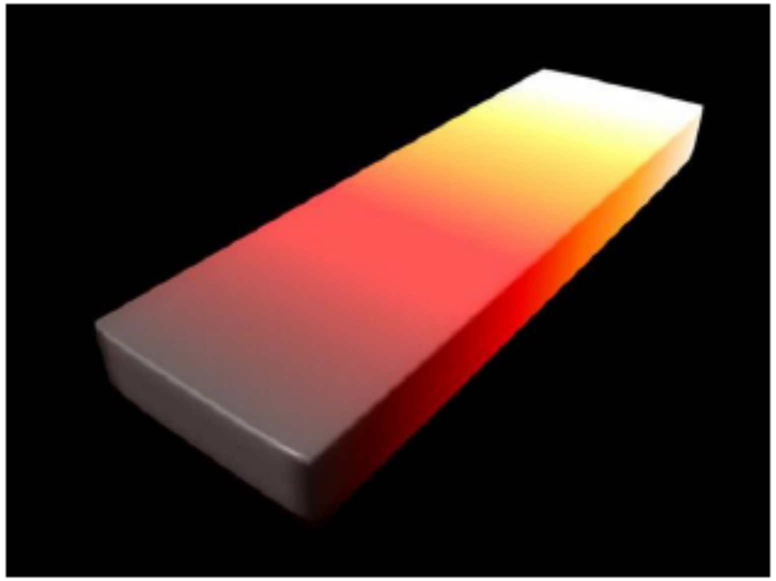
Power semiconductor devices

Heat radiation

Electromagnetic radiation is emitted by all substances at temperatures greater than zero due to molecular/atomic agitation

Black-body: ideal entity with continuous emission spectrum emitting maximum radiant energy (Planck' theory)





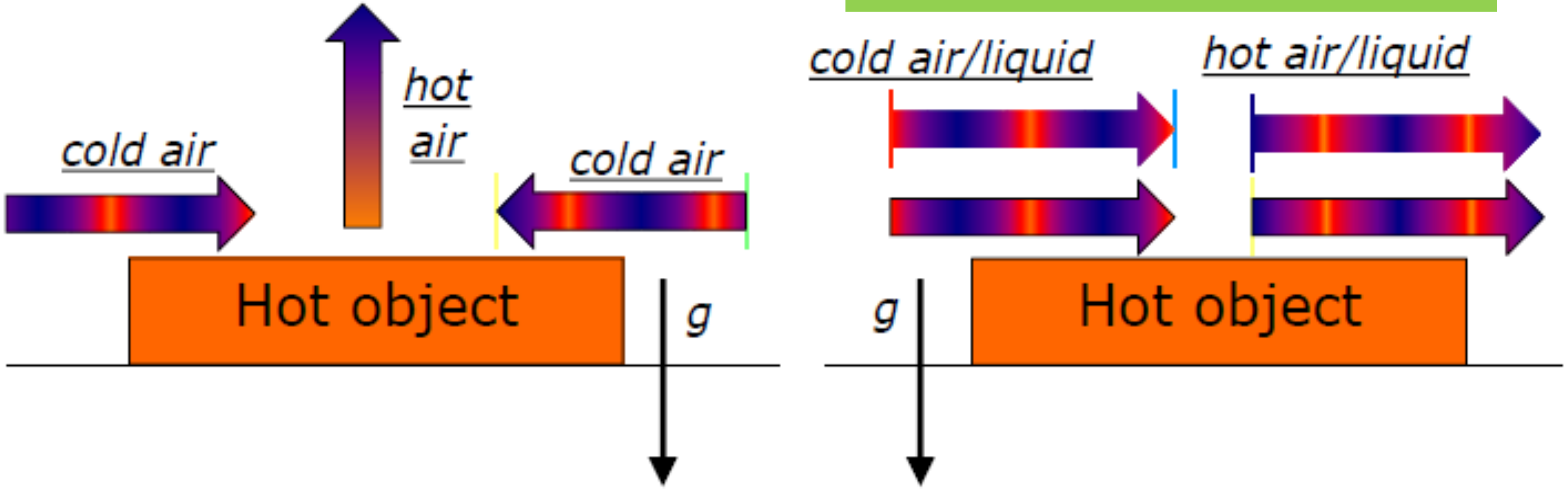
Power semiconductor devices

Heat convection

Cold air or liquid flow on a hot body will give rise to heat exchange by convection

Natural convection

Forced convection
(passive or active cooling)

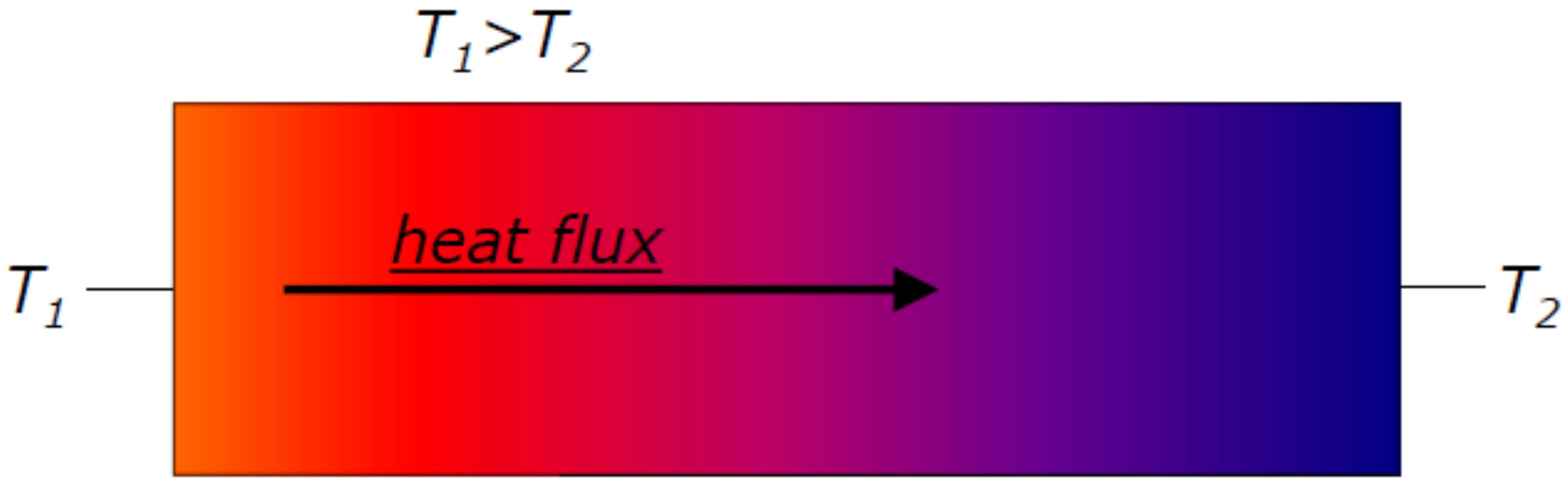


Power semiconductor devices

Heat conduction

Diffusion-based mechanism, driven by temperature gradient

Main mechanism of heat transport in solids



Power semiconductor devices

Cooling assemblies

Thermal management of power devices needed to ensure target performance and reliability

Thermal interface material between device and heat-sink to maximise conduction between the two

Finned and *fanned* heat-sink to maximise convection (increase heat exchange surface and turbulence of fluid)

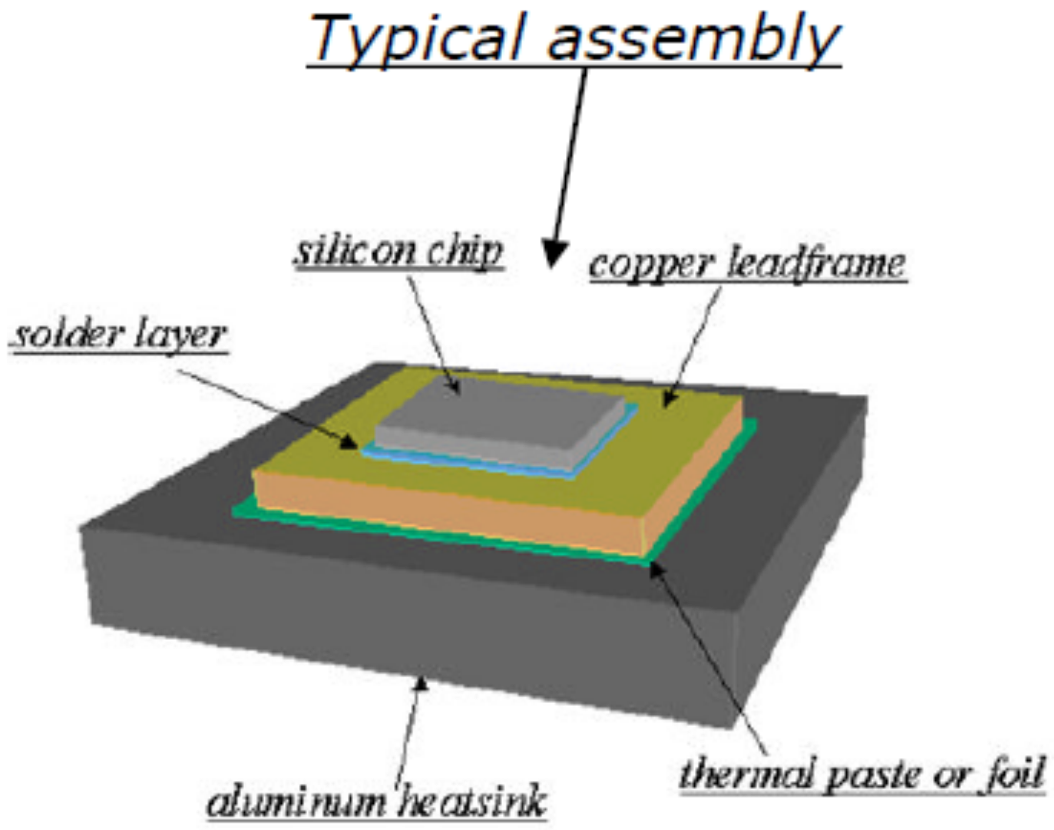
Black paint to maximise radiation

Power semiconductor devices

<u>Heat conduction analysis</u>

Power semiconductor devices

The thermal problem



Heat is generated on device top surface: *power density = heat generation rate*

3D problem reduced to *essentially* 1-D: heat flows in the vertical direction with a ca. 45° spread angle

Thermal properties of all components are assumed constant (*linear problem*)

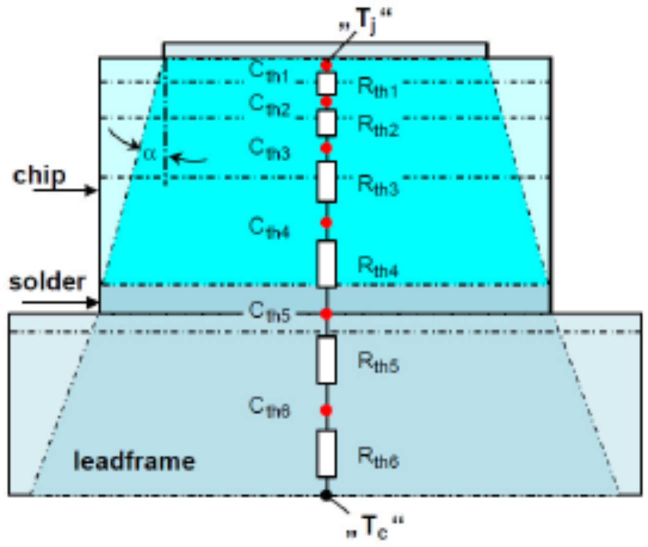
Power semiconductor devices

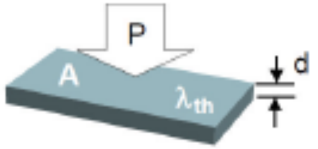
Packaged device thermal model

ρ → material density

c→ specific heat

λ_m → thermal conductivity





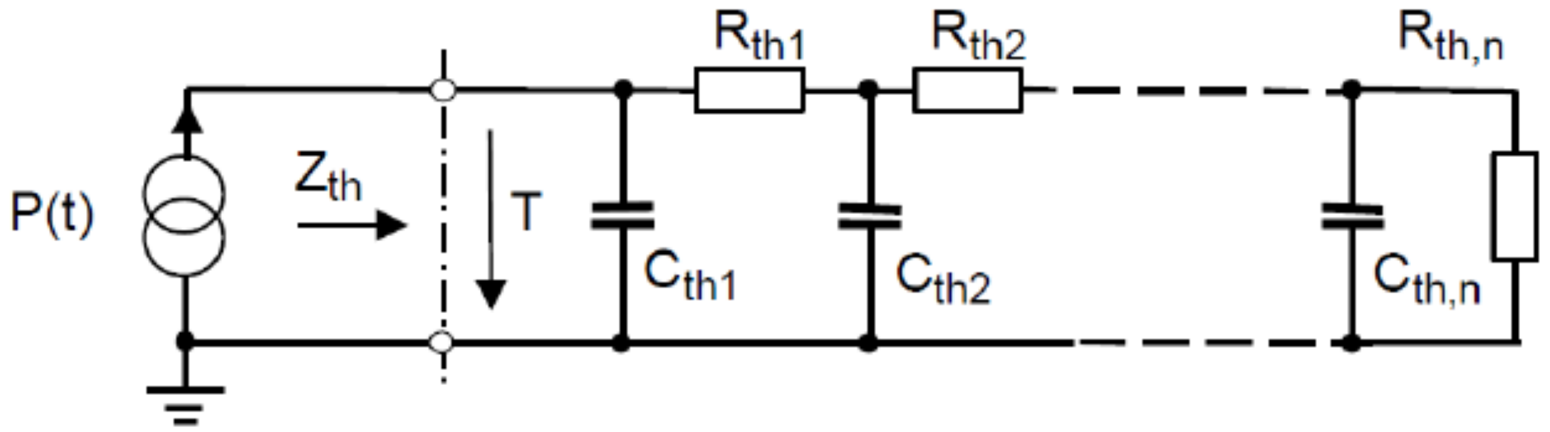
$$R_{th} = \frac{d}{\lambda_{th} \cdot A}$$

$$C_{th} = c \cdot \rho \cdot d \cdot A$$

Thermal resistance R_{th} and capacitance C_{th} can be associated with each element in the thermal path

Power semiconductor devices

Equivalent thermal model



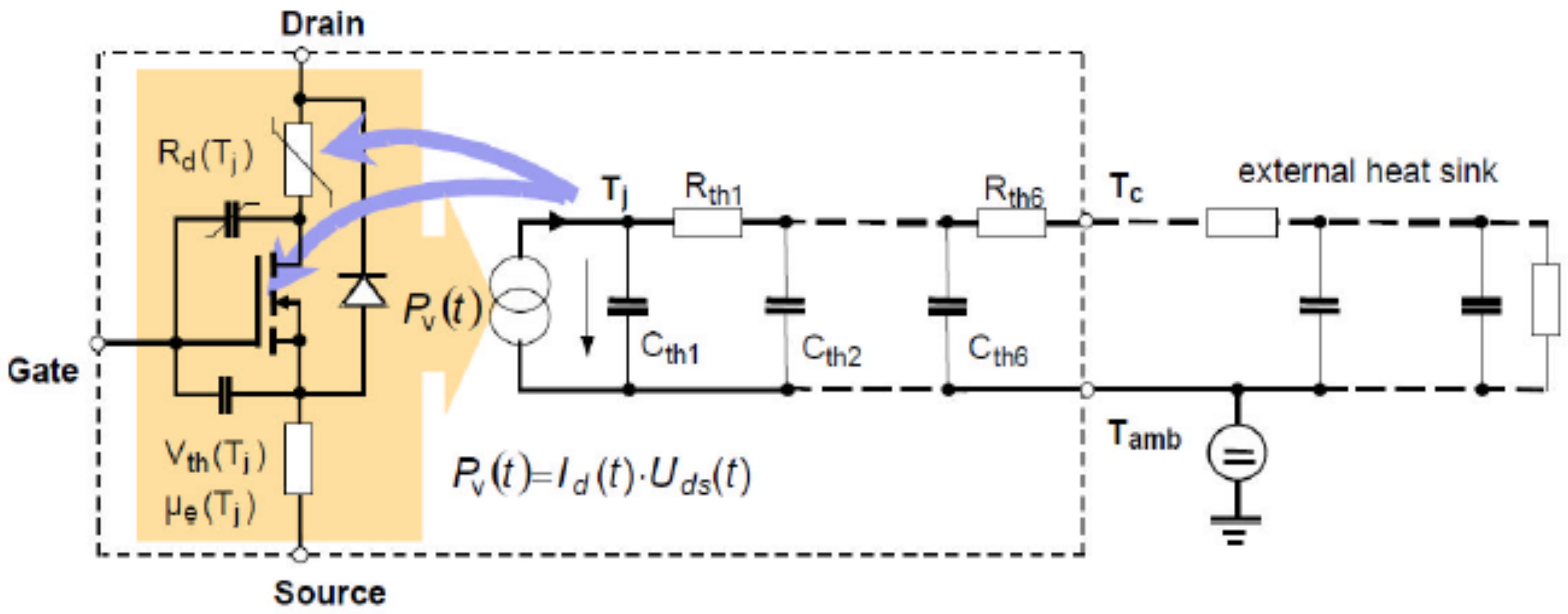
Power losses are the input to the thermal network

Straightforward implementation into standard circuit simulation tool

Electrical	Thermal
V [V]	T [K]
I [A]	P [W]
R [Ω]	R [K/W]
C [F]	C [J/K]

Power semiconductor devices

Coupled electro-thermal model



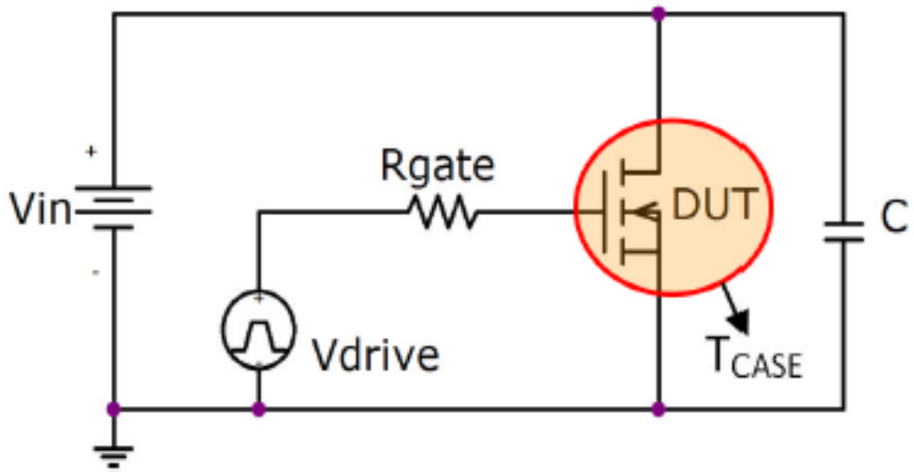
Device parameters/equations temperature dependent: performance and efficiency temperature dependent

Temperature is circuit variable, depending on thermal model and power losses

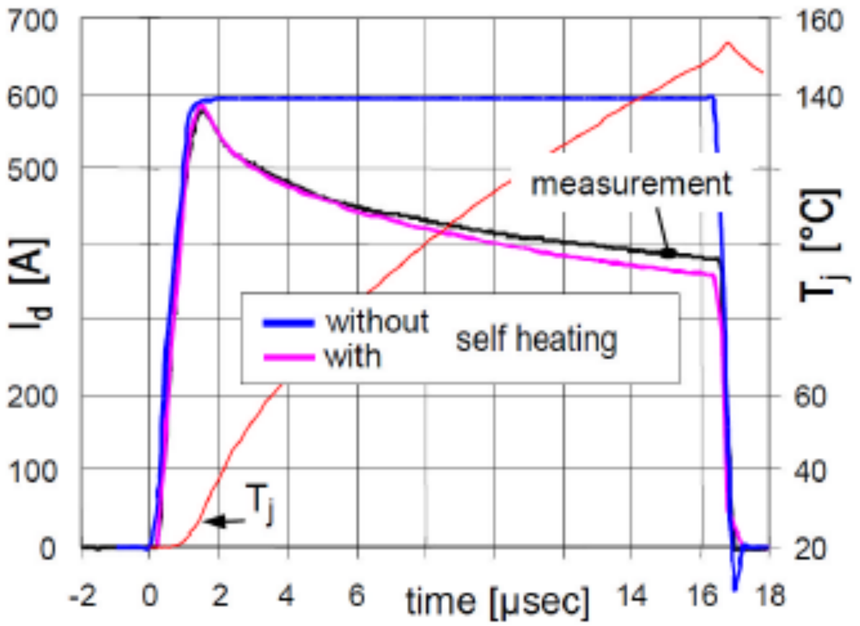
Power semiconductor devices

Importance of thermal modelling

Test circuit schematic



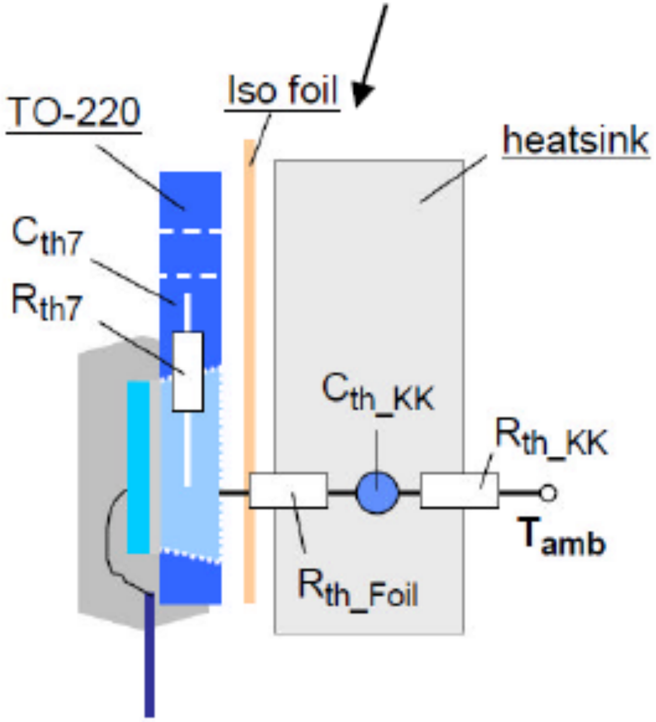
Experimental and simulation results



Power semiconductor devices

Typical problem

Packaged device mounted on heat-sink



Steady-state analysis: thermal network contains resistors only

$$P_{DISS} \cdot R_{th} = \Delta T$$

$R_{th,JH}$ → Junction-to-Case

$R_{th,CH}$ → Case-to-Heatsink

$R_{th,HS}$ → Heatsink-to-Ambient

Power semiconductor devices

Worked Examples on
Power Device Losses

Power semiconductor devices

Q1.

A switching transistor energises a series R-L load from a 200 V supply. A freewheeling diode is connected across the load. The transistor switches at 2 kHz with a duty cycle of 60 %. The load resistance is 20 Ω and the load inductance is such that the peak to peak ripple in the load current is 2 A. It may be assumed that the load current rises and falls linearly.

(a) Draw the circuit

(b) Calculate the mean load current and sketch the load current waveform.

Power semiconductor devices

Q1 cont.

The components are now considered in more detail to calculate the power losses. The transistor turn-on and turn-off times are 10μs and 5μs respectively. The voltage across the transistor when it is conducting (V_{CE}(sat)) is 2 V and may be assumed to be independent of the current. The diode may be approximated by a threshold voltage drop of 0.7 V in series with a resistance of 0.1 Ω when it is conducting.

(c) Draw the transistor current waveform

(d) Determine the conduction loss in the transistor

(e) Draw the transistor current and voltage waveforms at turn-on and turn-off

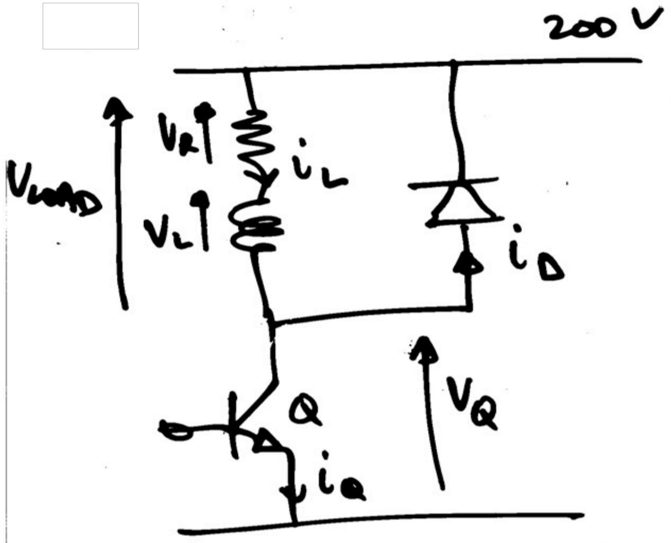
(f) Calculate the switching loss in the transistor

(g) Draw the diode current waveform

(h) Calculate the conduction loss in the diode

Power semiconductor devices

Q1



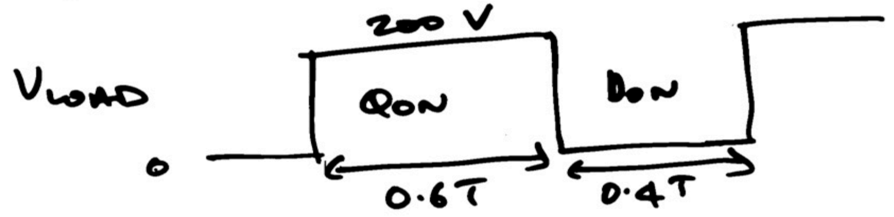
$R = 20\Omega$

$f = 2KHz$

$d = 0.6$

$\Delta I_L = 2A$

ΔI_L is linear.



The $\overline{V_{LOAD}} = 200 \times 0.6 = 120V$

$\Rightarrow \overline{I_L} = 6A$

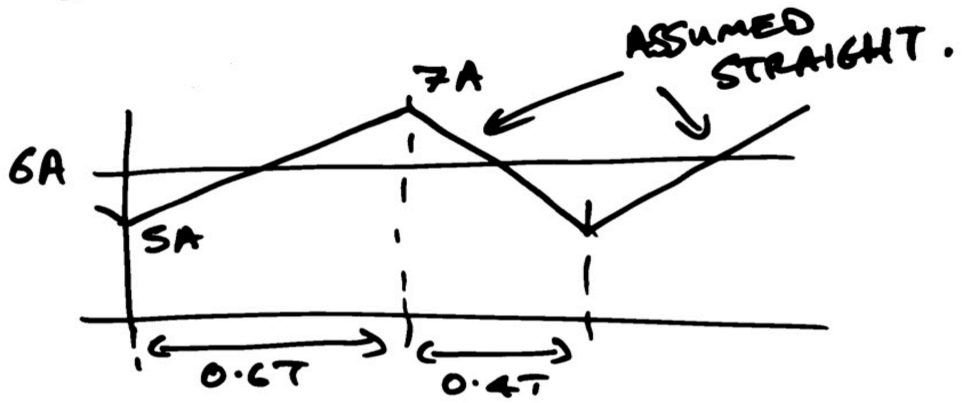
$\Rightarrow 0$

Because $\overline{V_{LOAD}} = \overline{V_L} + \overline{V_R}$

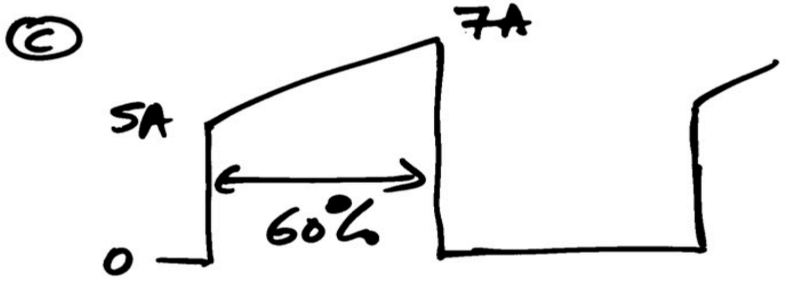
$\Rightarrow \overline{V_R} = 120V \Rightarrow \overline{I_L} = \frac{\overline{V_R}}{R} = 6A$

Power semiconductor devices

i_L looks like:



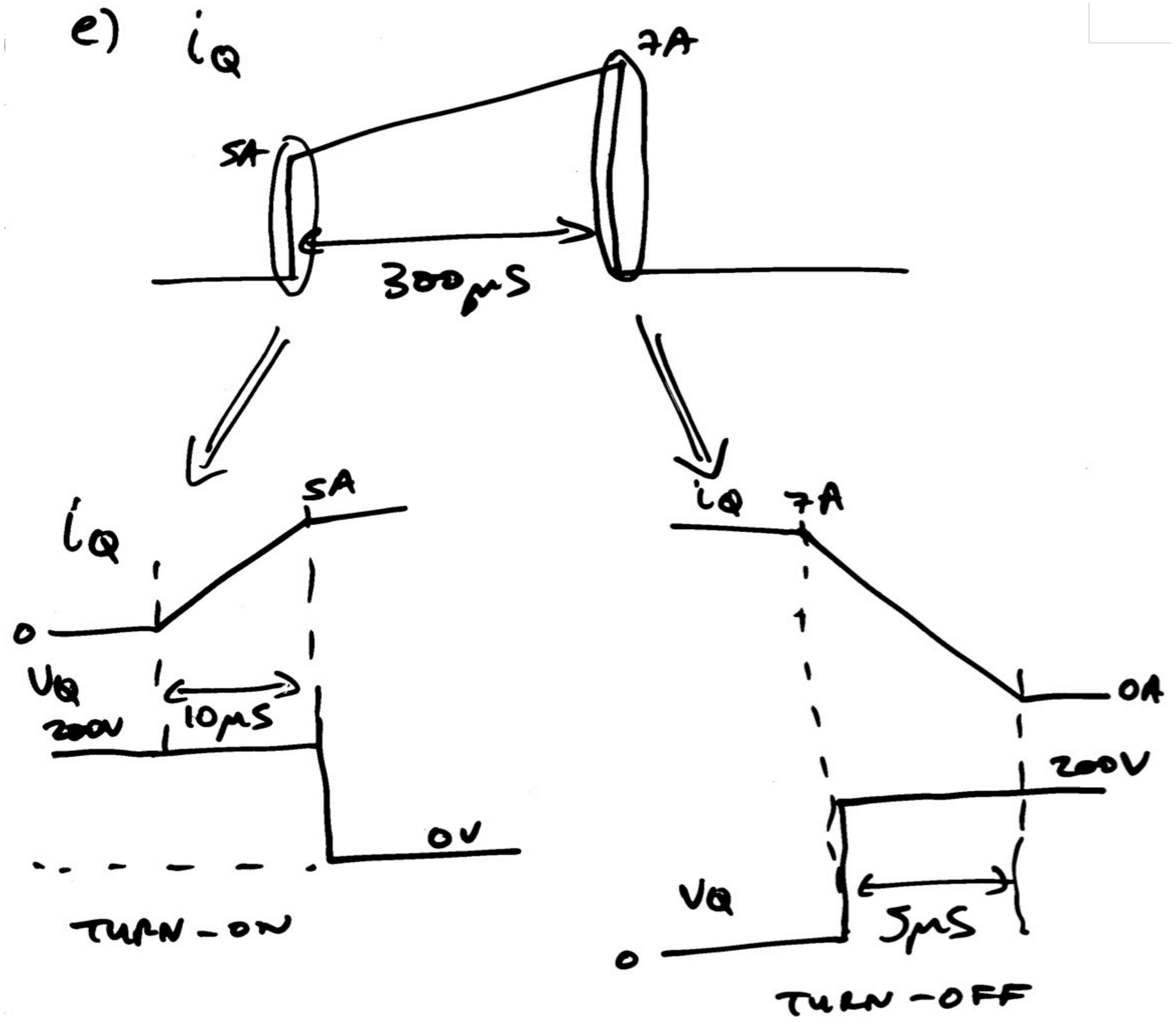
(c)



Conduction loss $= V_{CE}(SAT) \times \bar{I}_Q$

$$= \underbrace{2}_{V_{CE}(SAT)} \times \underbrace{\left(\frac{5+7}{2}\right) \times 0.6}_{\bar{I}_Q} = \underline{\underline{7.2\,W}}$$

Power semiconductor devices



Power semiconductor devices

f)

Energy loss @ TURN-ON

$$= \frac{1}{2} \times 200 \times \underset{\Downarrow}{5} \times 10\mu S = \underline{\underline{5mJ}}$$

I @ turn-on

@ TURN-OFF

$$= \frac{1}{2} \times 200 \times \underset{\Downarrow}{7} \times 5\mu S = \underline{\underline{3.5mJ}}$$

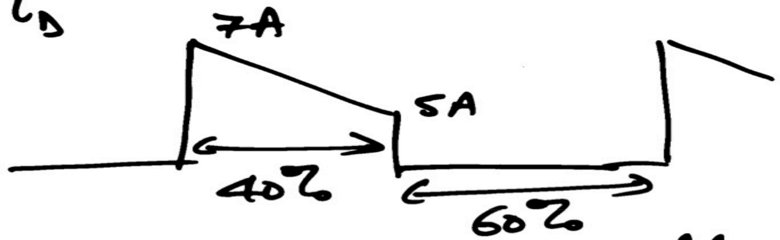
I at turn-off

Power loss = Energy × frequency.

$$(5mJ + 3.5mJ) \times 2kHz = \underline{17W}$$

Power semiconductor devices

g) i_D



h) Conduction loss in the DIODE

DIODE "MODEL"

Power loss

$$= \underbrace{\bar{i}_D \times 0.7\ V} + (i_{Drms})^2 \times 0.1$$

$$0.7 \times \left(\frac{7+5}{2}\right) \times 0.4$$

$$\underbrace{\left[\frac{(7^2+5^2+7\times5)}{3} \times 0.4\right]}_{\text{MEAN SQUARE CURRENT}} \times 0.1$$

Power semiconductor devices

⇒ DIODE CONDUCTION LOSS

= $\underline{3.13\ W}$

Power semiconductor devices

Q2

The transistor and freewheeling diode in Q1 are attached to the same heatsink. The thermal resistances between the device junctions and the devices cases are 1 °C/W (Transistor) and 6° C/W (Diode) respectively. The thermal resistance between the device case and the heatsink is 1 °C/W for both devices. Neglecting switching losses in the diode determine the:

(a) power losses in the transistor and diode,

(b) device with the hottest junction,

(c) heatsink rating (in °C/W) if the junction temperature of the hottest device is to be limited to 120 °C and the ambient air temperature is 40 °C,

(d) case temperatures of both devices and the junction temperature of the cooler device.

Power semiconductor devices

Q2

D & Q in Q1 have parameters

$\theta_{JC} = 1°C/W$ for Q

$\theta_{JC} = 6°C/W$ for D

$\theta_{CS} =$ ~~~~ $1°C/W$ for both

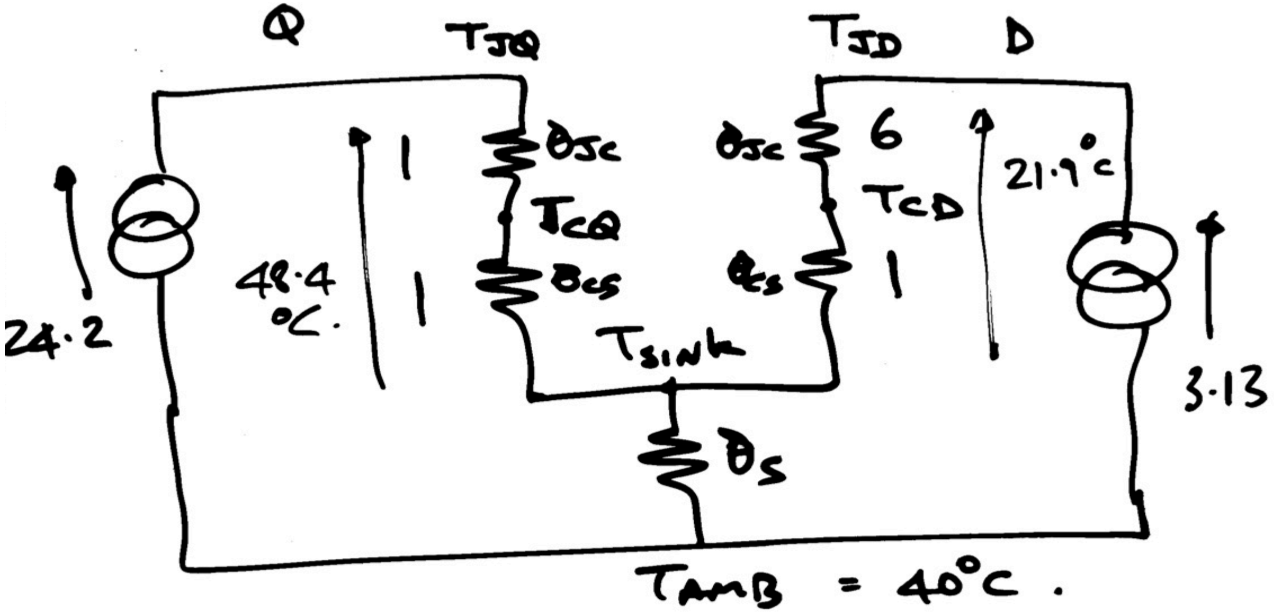
Find θ_S so that hottest Junction $= 120°C$ at $T_{AIR} = 40°C$.

Losses from Q1

$Q_{TOTAL} = 17 + 7.2 = 24.2\,W$

$D_{TOTAL} = 3.13\,W$

Power semiconductor devices



$\Rightarrow$ T_{JQ} is the hottest

c) $\Rightarrow$ Set $T_{JQ} = 120^\circ C$

$\Rightarrow$ $T_{sink} = 120 - 48.4 = \underline{71.6^\circ C}$

$\Rightarrow$ $\theta_{sink} = \dfrac{(71.6 - 40)}{(24.2 + 3.13)} = \underline{\underline{1.16^\circ C/W}}$

Power semiconductor devices

d) From diagram

$$T_{CQ} = 71.6 + 24.2 \times 1 = \underline{\underline{95.8^\circ C}}$$

$$T_{CD} = 71.6 + 3.13 \times 1 = \underline{\underline{74.7^\circ C}}$$

$$T_{JD} = 71.6 + 3.13(1+6) = \underline{\underline{93.5^\circ C}}$$

Power semiconductor devices

Q3

Consider the IRFZ34 MOSFET (datasheet given separately). It has the following “headline” ratings:

60 V, 30 A, R_DS (ON)=0.05 Ω

Determine the actual RMS current we can use the device at if we fix it to a heatsink rated at 3 °C/W (a very large piece of metal compared to the size of the device).

Neglect switching loss

Assume ambient temperature is 40 °C (this is probably low for a real design)

Assume we allow the junction to get to 150 °C (very hot! – 175 °C means certain destruction).

Determine also the device case temperature and the heatsink temperature.

Power semiconductor devices

Q3

IRFZ34 MOSFET

What RMS current will it handle when bolted to a 3°C/W heatsink? Neglect switching loss.

Headline Ratings 60V, 30A

$R_{DS(ON)} = 0.05\,\Omega$

Assume we allow the "Junction" to reach 150°C (175°C → destruction)

Assume Air temp = 40°C

At 150°C T_J $R_{DS(ON)}$

$$= \underbrace{0.05 \times 1.8}_{\text{See datasheet Fig 4.}} = 0.09\,\Omega$$

Temp difference = Power × Thermal Resistance.
$\Downarrow$
θ

Total θ

$$= \theta_{JC} + \theta_{CS} + \theta_{SINK}$$

Power semiconductor devices

$$= \underbrace{1.7 + 0.5}_{\text{DATASHEET}} + 3 = 5.2\,°C/W$$

$$\text{Power} = \frac{(150 - 40)}{5.2} = \underline{\underline{21W}}$$

$$\Rightarrow I_{rms}^2 \times R_{DS(ON)}$$

$$\Rightarrow I_{rms} = \sqrt{\frac{21}{0.09}} = \underline{\underline{15A}}$$

$\Rightarrow$ 50% of HEADLINE VALUE!!

Heatsink is @ $40 + 21 \times 3$

$$= \underline{\underline{103°C}}$$

CASE is @ $103 + 21 \times 0.05$

$$= \underline{\underline{114°C}} \quad !!$$

Need ~~Fan~~ Fridge to operate at 30A!!

See curve Fig 9