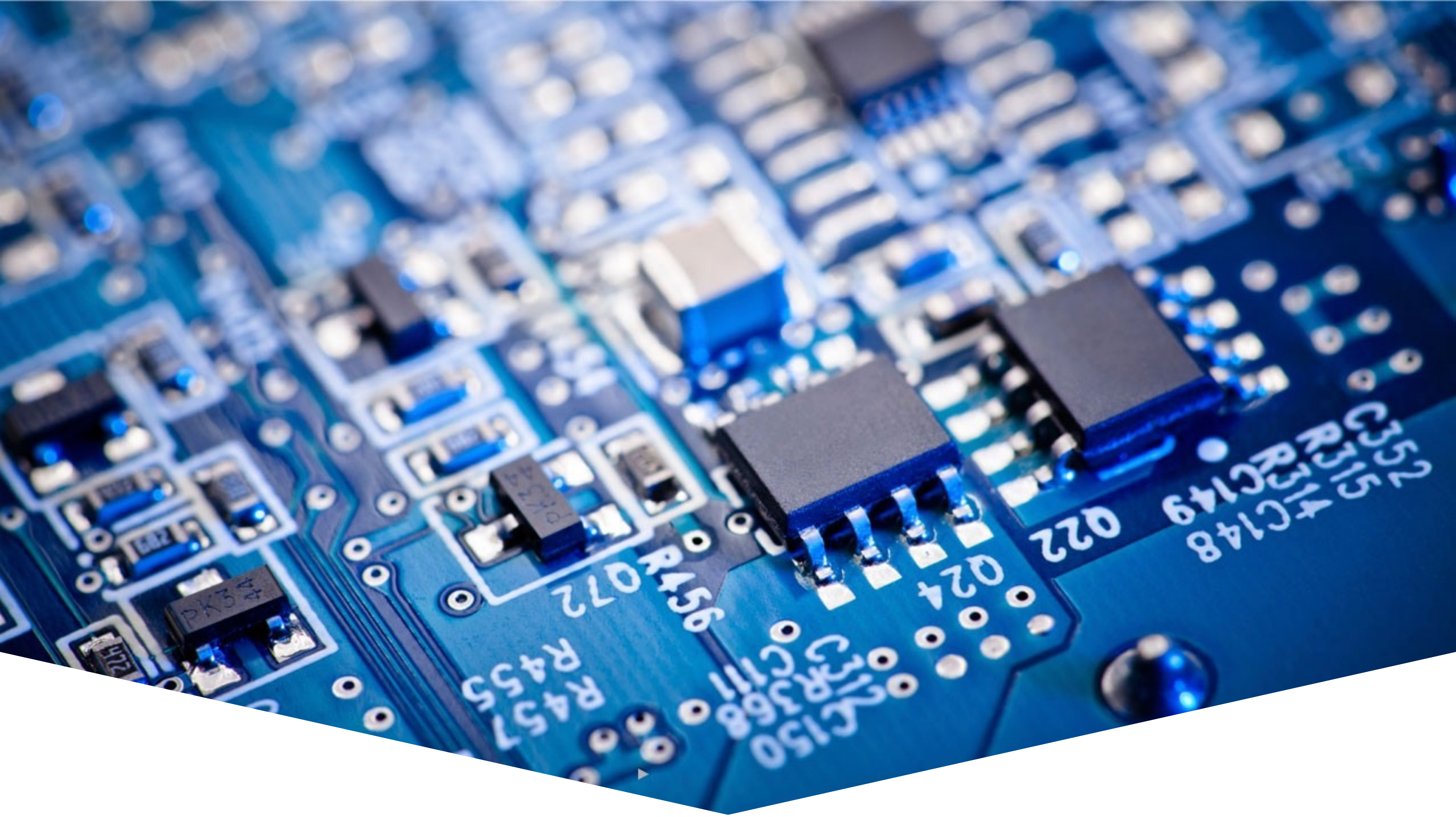

ANALOGE ELEKTRONICA 2

CLASS-D AMPLIFIERS

overtref jezelf

HOGESCHOOL ROTTERDAM

Overzicht

- Power Amplifiers
  - Power Transistors
  - Heat Sinks
- Classes of Amplifiers
  - Class A
  - Class AB
  - Class D
- Class D amplifier
  - RLC-Filter
  - Bootstrap Circuit Design

Power Amplifiers

- **Power Amplifiers**:
  - Deliver large amounts of power (> 100 W) to a passive load
  - Typically built with BJT-transistor or MOSFETs
- **Total harmonic distortion (THD)**:
  - RMS value of harmonic components of the output signal
  - Fundamental frequency excluded
  - Expressed as a percentage of the fundamental

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Power Transistors

- **Physical Transistor Limitations**:
  - Maximum rated current: typically I_C or I_{DS}
  - Maximum rated voltage: typically U_{CE} or U_{DS}
  - Maximum rated power: $P = U_{CE}.I_C$ or $\mathrm{P} = U_{DS}.I_{DS}$
- **Types of transistor: BJT and MOSFET**
- **Also to consider:**
  - Maximum allowed temperature: function of rate at which heat is removed
- **Example: MJ15003 (NPN) and MJ15004 (PNP)**
  - $U_{CE,max}$ = 140 V, P_{diss} = 250 W, $I_{c,DC}$ = 20 A, TO-3 case

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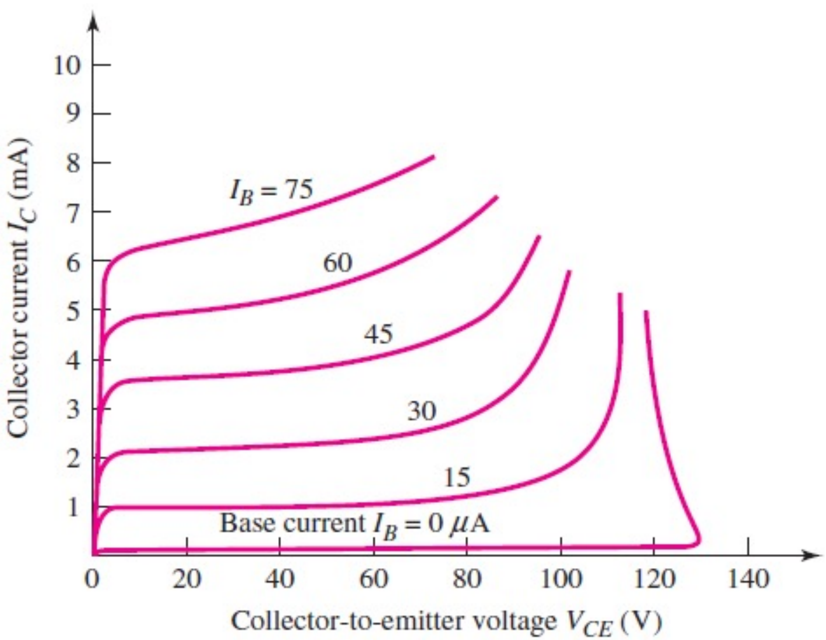
Power BJT Transistor

Table 8.1 Comparison of the characteristics and maximum ratings of a small-signal and power BJT

Parameter	Small-Signal BJT (2N2222A)	Power BJT (2N3055)	Power BJT (2N6078)
V_{CE}(max) (V)	40	60	250
I_C(max) (A)	0.8	15	7
P_D(max) (W) (at $T = 25\ °C$)	1.2	115	45
β	35–100	5–20	12–70
f_T (MHz)	300	0.8	1

- **DC current gain is not a constant**:
  - Drops at higher current
  - Much lower than a small-signal transistor
- **Watch the breakdown voltage mechanism:**



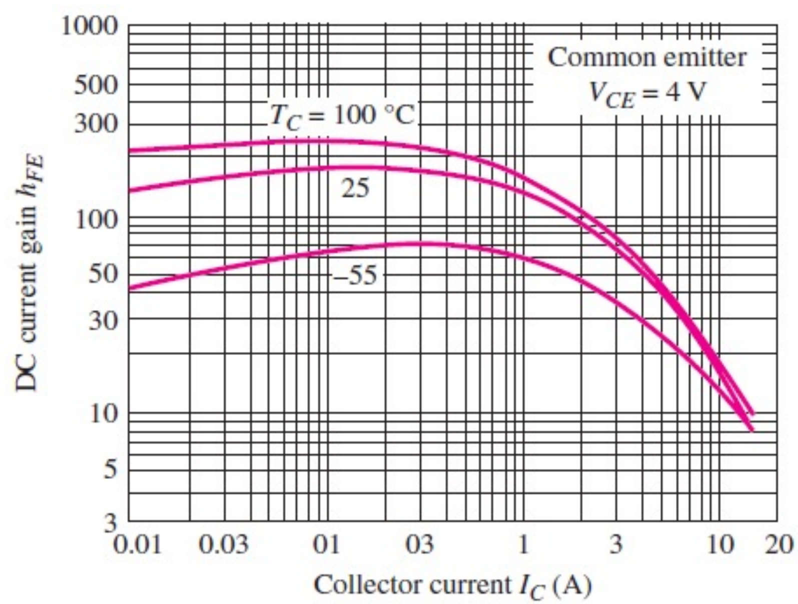


Figure 8.1 Typical dc beta characteristics (h_{FE} versus I_C) for 2N3055

Safe Operating Area (SOA)

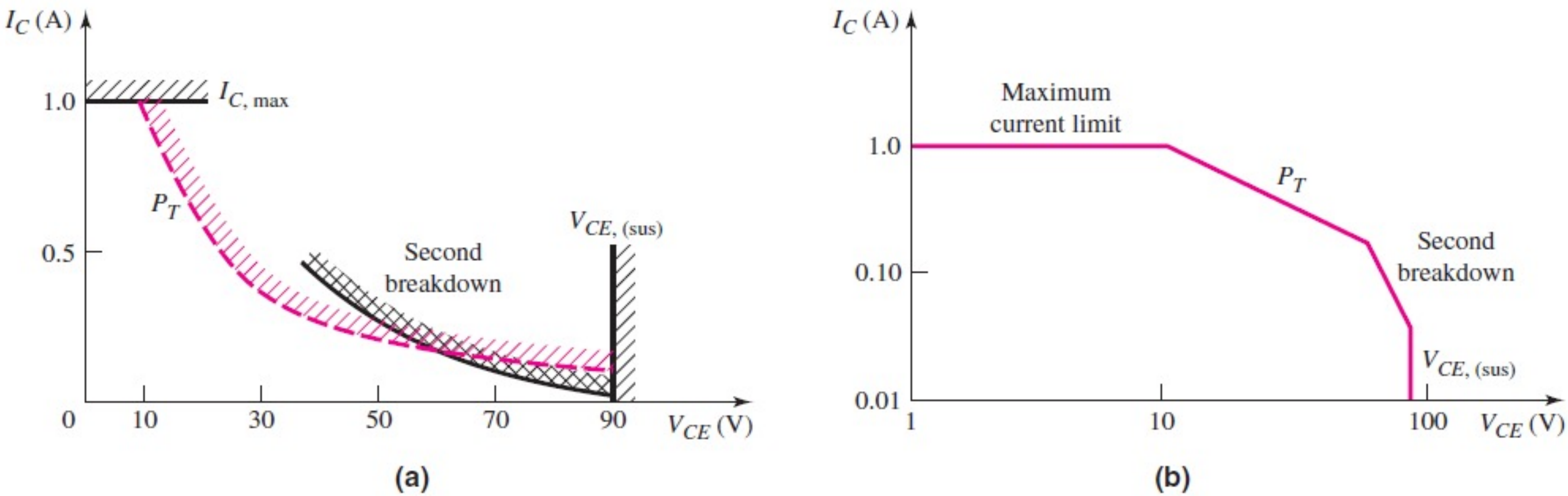


Figure 8.3 The safe operating area of a bipolar transistor plotted on: (a) linear scales and (b) logarithmic scales

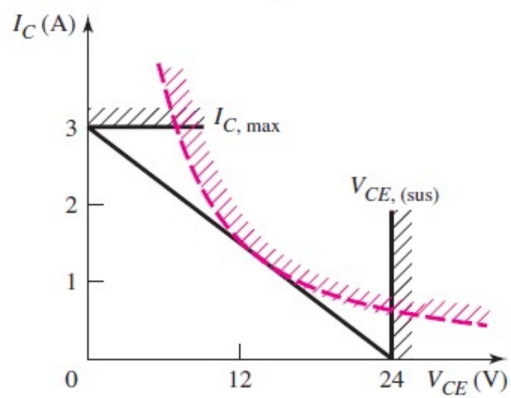


Figure 8.5 DC load line within the safe operating area

Power MOSFETs

Table 8.2 Characteristics of two power MOSFETs

Parameter	2N6757	2N6792
V_{DS}(max) (V)	150	400
I_D(max) (at $T = 25$ °C)	8	2
P_D (W)	75	20

No thermal runaway

- Transconductance decreases with temperature

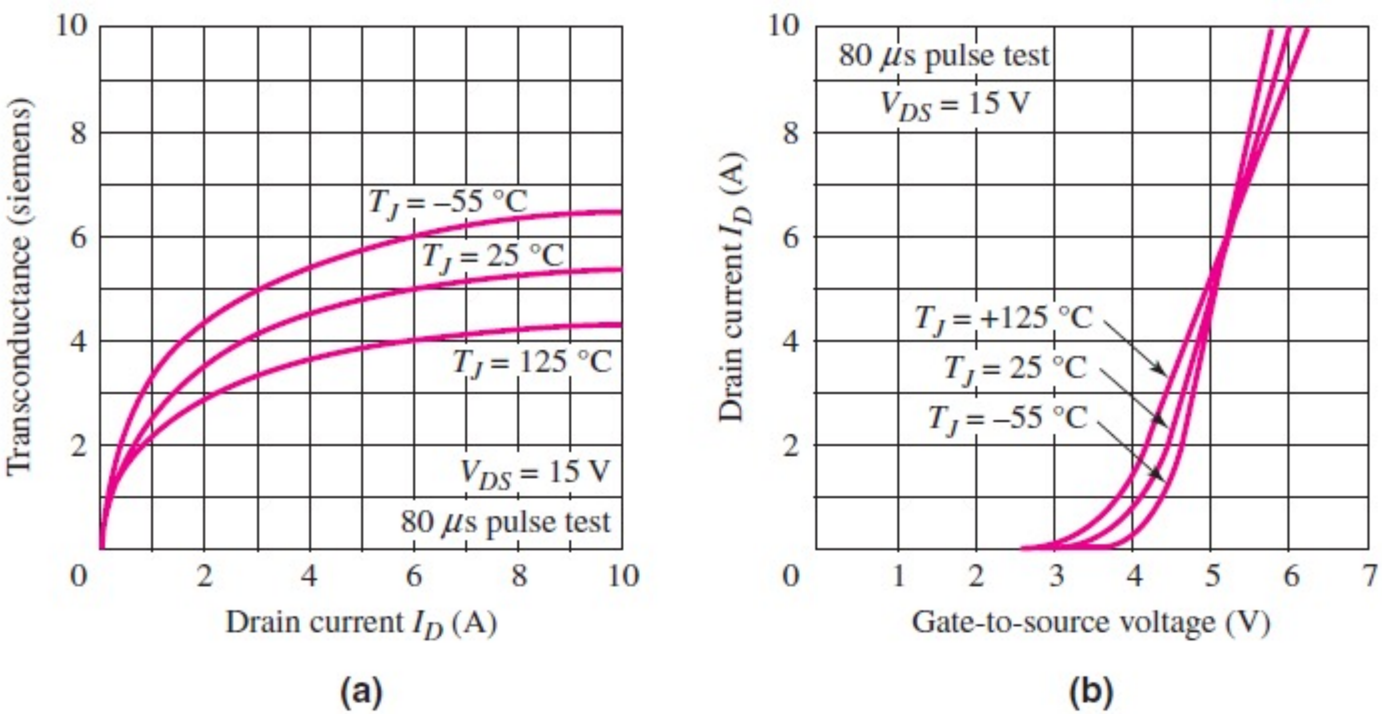
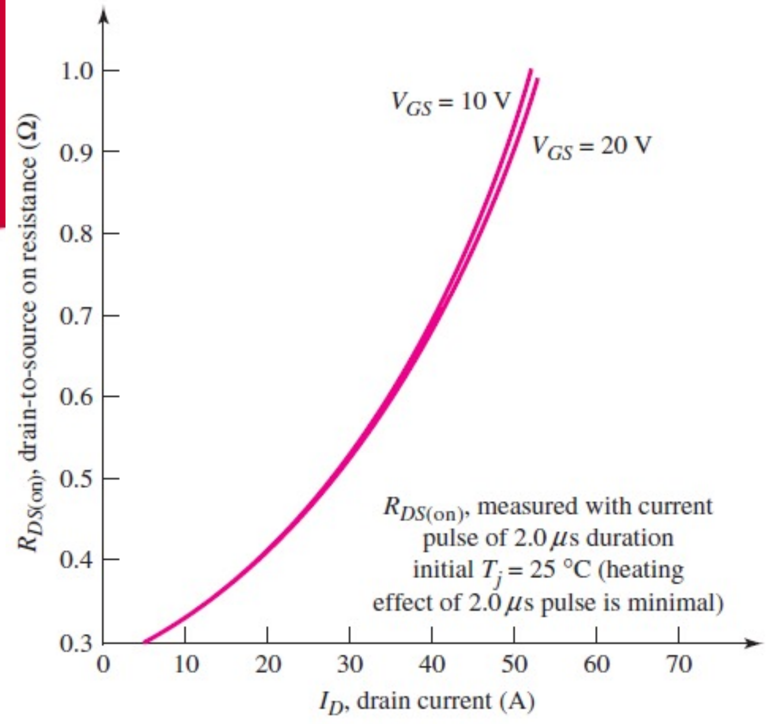


Figure 8.7 Typical characteristics for high-power MOSFETs: (a) transconductance versus drain current; (b) transfer characteristics

Power MOSFETs

Structure of MOSFETs

- HEXFET:
  - N-channel: IRF540
  - P-channel: IRF9540
- Normal FET:
  - N-channel: IRF530
  - P-channel: IRF9530



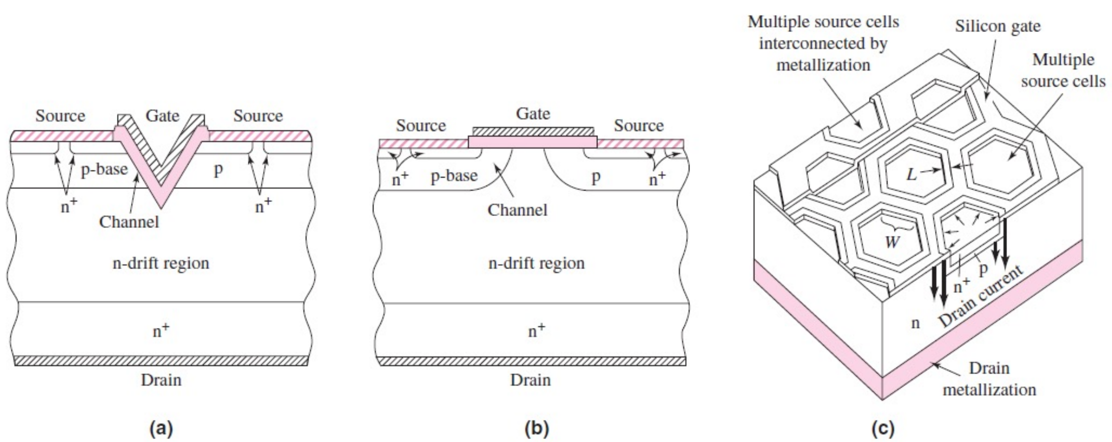
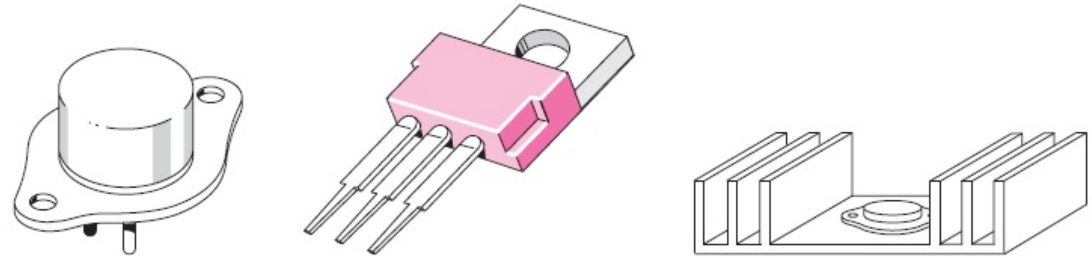


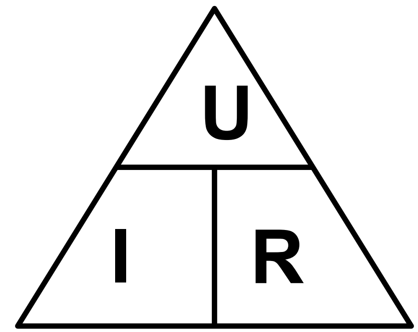
Figure 8.8 (a) Cross section of a VMOS device; (b) cross section of DMOS device; (c) HEXFET structure

Heatsinks



(a) (b) (c)

Figure 8.10 Two packaging schemes: (a) and (b) for power transistors and (c) typical heat sink



Max. Temp. Transistor (Silicium)

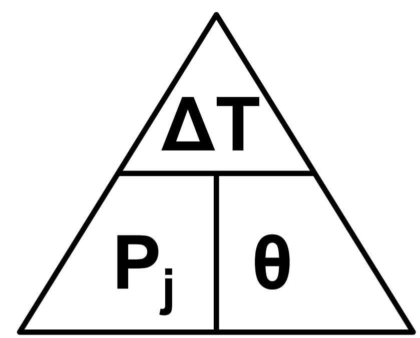
- 150 ^{0}C – 200 ^{0}C

Heatsink needed!

- What heatsink?
- **Θ** [^{0}C/W]: smaller = larger heatsink

Thermodynamics Law:

- Comparable to Ohm's law
- **ΔT**: Temperaturedifference [^{0}C]
- **Pj**: Power dissipation [W]
- **Θ**: Thermal Resistance [^{0}C/W]



Heatsink calculation

Example:

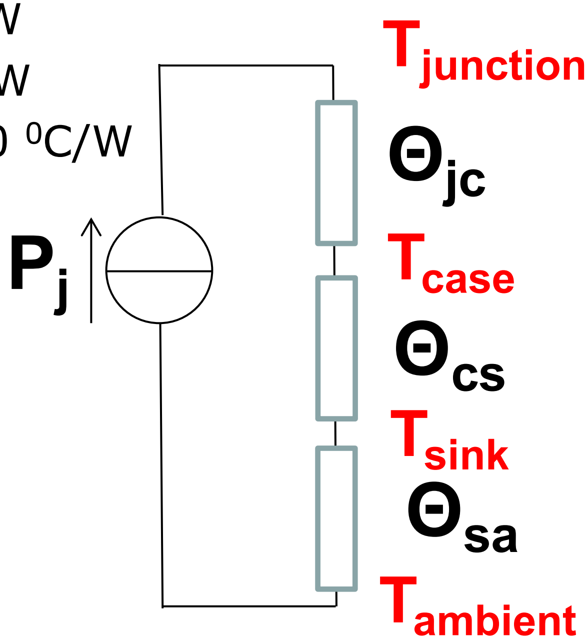
- Transistor Power Rating: 2 W
- Thermal Resistance Junction -> Case: 5 ^{0}C/W
- Thermal Resistance Case -> Heatsink: 2 ^{0}C/W
- Thermal Resistance Heatsink -> Ambient: 10 ^{0}C/W

Hoe groot zijn de temperaturen?

- What heatsink?
- $\mathbf{T}_a$ = 25 ^{0}C (omgevingstemperatuur)

Thermodynamica wet:

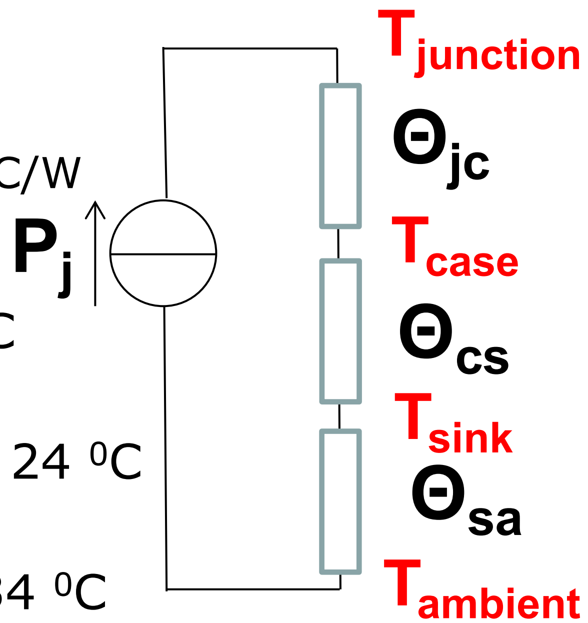
- Vergelijkbaar met wet van Ohm
- **ΔT**: Temperatuurverschil [^{0}C]
- $\mathbf{P_j}$: Power dissipation [W]
- **Θ**: Thermal Resistance [^{0}C/W]



Heatsink calculation

Example:

- Transistor Power Rating: 2 W
- Thermal Resistance Junction -> Case: 5 $^0C/W$
- Thermal Resistance Case -> Heatsink: 2 $^0C/W$
- Thermal Resistance Heatsink -> Ambient: 10 $^0C/W$



Solution:

$\mathbf{\Delta T_{sink,ambient}} = T_{sink} - T_{ambient} = 2 \times 10 = 20\ ^0C$

$T_{ambient} = 25\ ^0C \Rightarrow T_{sink} = 45\ ^0C$

$\mathbf{\Delta T_{case,ambient}} = T_{case} - T_{ambient} = 2 \times (10+2) = 24\ ^0C$

$T_{ambient} = 25\ ^0C \Rightarrow T_{case} = 49\ ^0C$

$\mathbf{\Delta T_{junction,ambient}} = T_j - T_a = 2 \times (10+2+5) = 34\ ^0C$

$T_{ambient} = 25\ ^0C \Rightarrow T_{junction} = 59\ ^0C$

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Heatsink calculation

Example MJ15003 power transistor

- Power Transistor: P = 25 W ; $\boldsymbol{\Theta_{jc}}$ = 0.7 ^{0}C/W
- Assume $\boldsymbol{\Theta_{ca}}$ = 5 ^{0}C/W
- Ambient Temperature $\mathbf{T_a}$ = 50 ^{0}C
- Max. Junction Temperature: 150 ^{0}C
- Bepaal Junction-temperatuur zonder heatsink
- Welke heatsink is nodig?
  - Mica-washer: $\boldsymbol{\Theta}$ = 0.5 ^{0}C/W

Oplossing:

- $\mathbf{\Delta T_{ja}} = T_j - T_a = 25 \times (0.7+5) = 142.5\ ^0C$
  - $T_a = 50\ ^0C \Rightarrow T_s = 192.5\ ^0C$

- $\mathbf{\Delta T_{ja}} = T_j - T_a = 25 \times (0.7+0.5+ \boldsymbol{\Theta_H})$
  - $150 - 50 = 30 + 25.\ \boldsymbol{\Theta_H}$
  - $\boldsymbol{\Theta_H} = 70/25 = 2.8\ ^0C/W$

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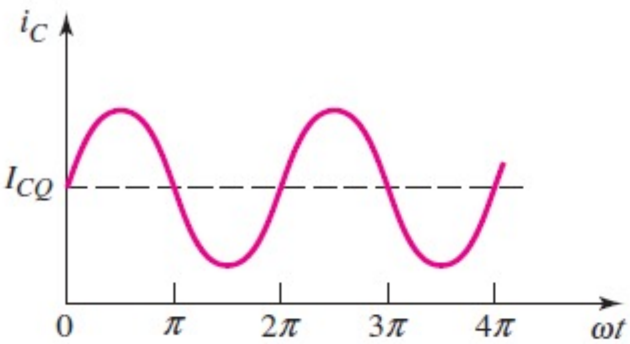
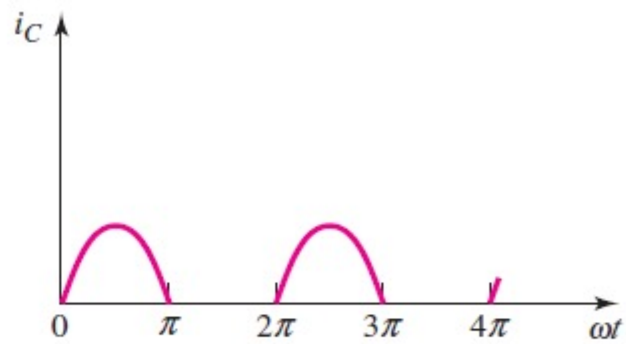
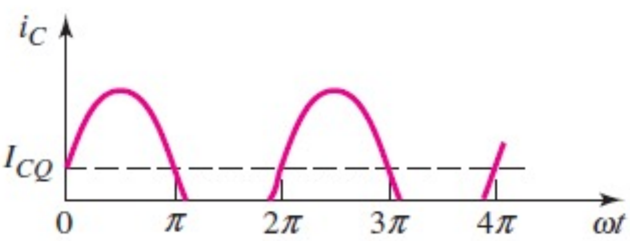
Classes of Amplifiers



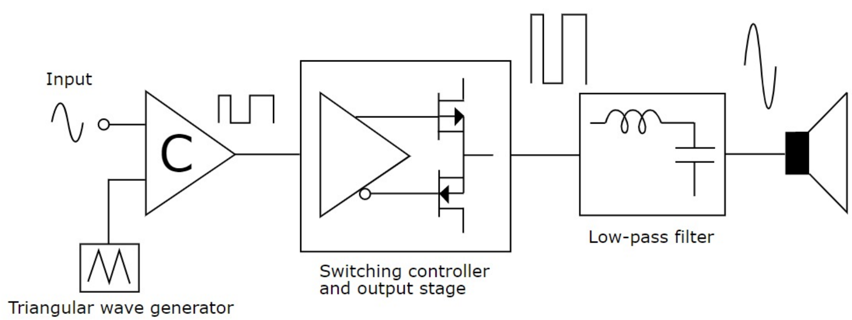
(a)



(b)



(c)



(a) Class A

(b) Class B

(c) Class AB

(d) Class D

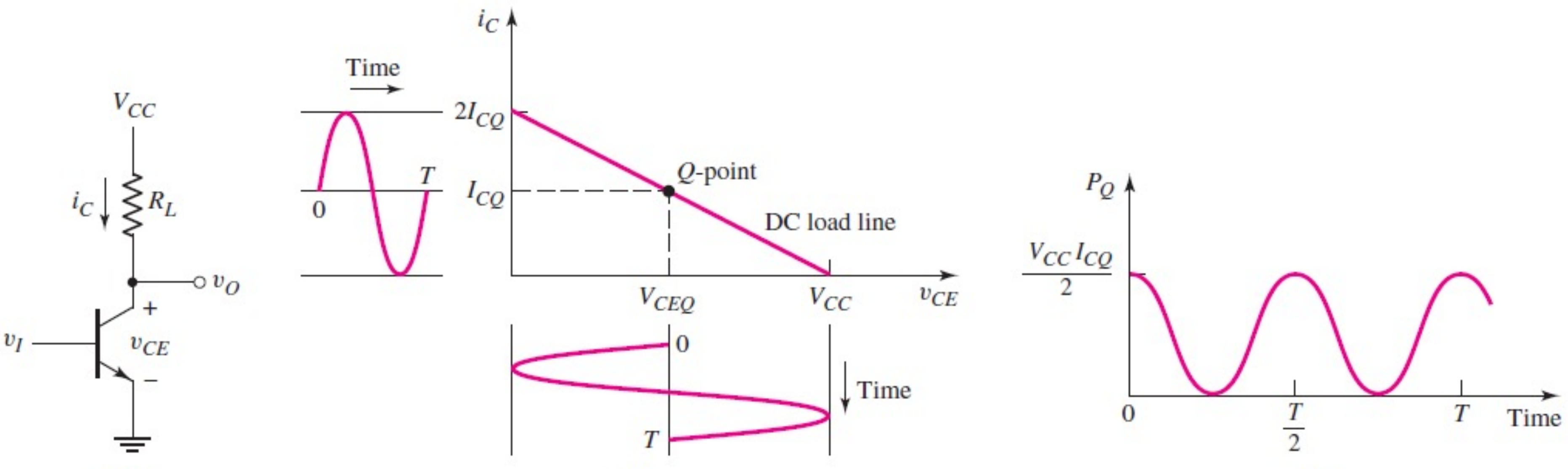
Class A amplifier

Advantage:

- Lowest distortion => high-quality amplifier

Disadvantage:

- Always on => low-efficiency (10-15 % max.)
- Large heatsinks



(a) (b) (c)

Class B amplifier

- Class B not a practical amplifer
  - Because of BJT imperfections
  - Crossover distortion as a result

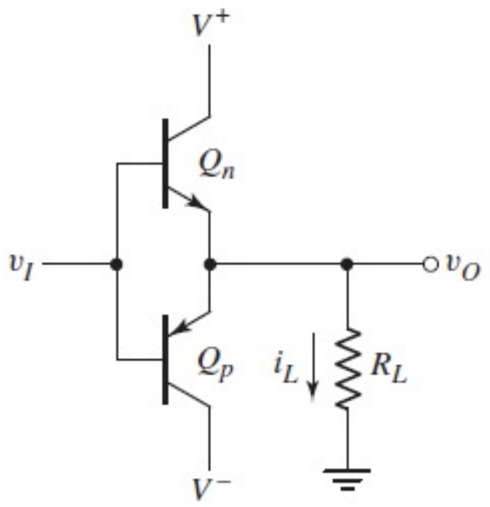


Figure 8.19 Basic complementary push–pull output stage

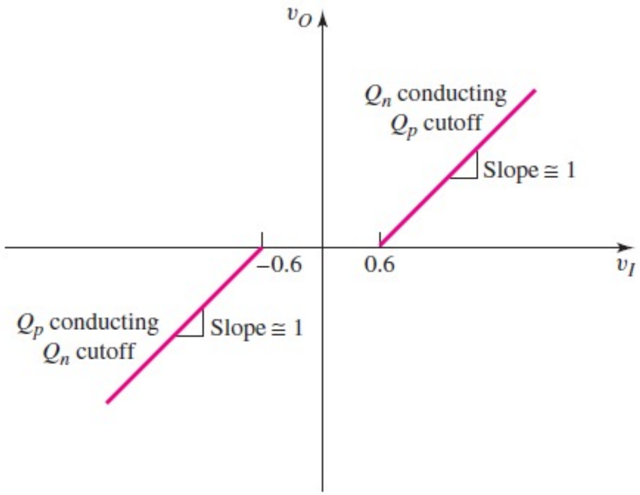


Figure 8.20 Voltage transfer characteristics of basic complementary push–pull output stage

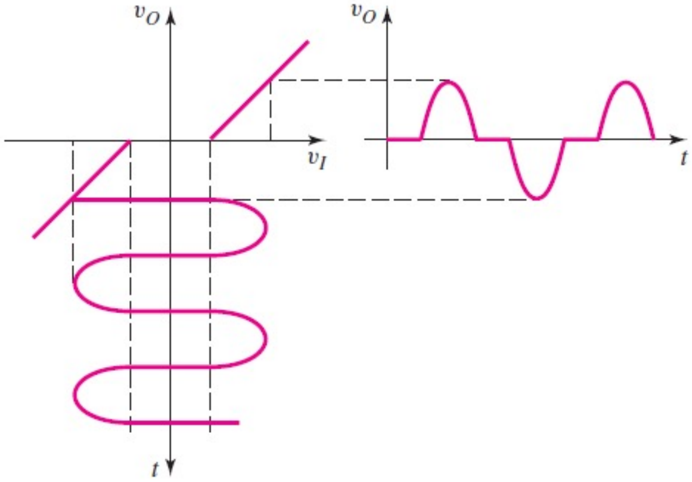


Figure 8.21 Crossover distortion of basic complementary push–pull output stage

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Class AB amplifier

Difference with Class B:

- Small bias current set
- Most practical amplifiers use this
- V_{be} multiplier (bias voltage) needed

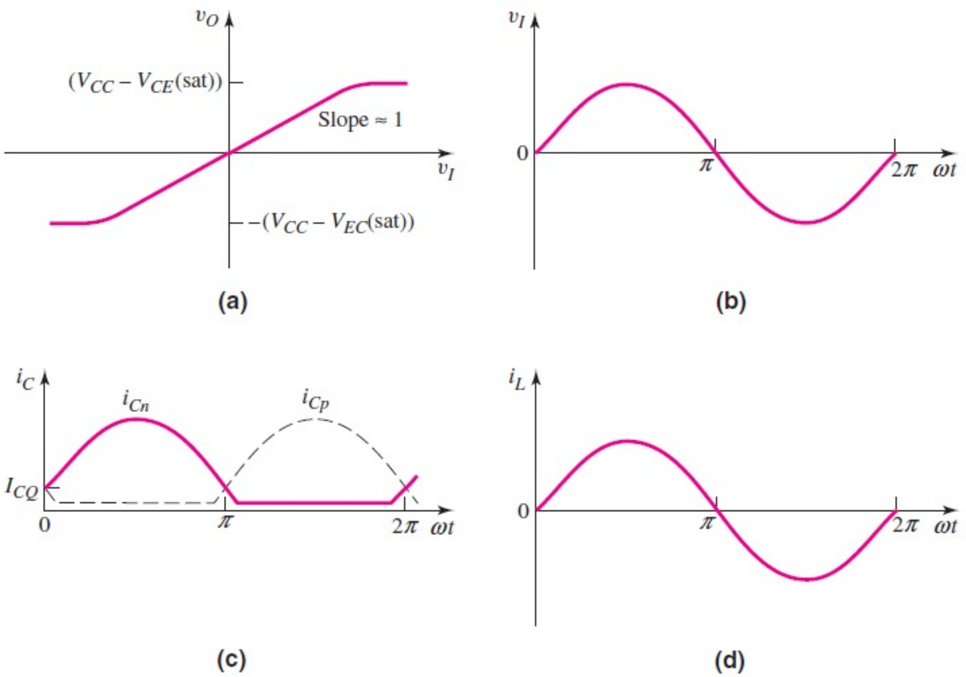


Figure 8.25 Characteristics of a class-AB output stage: (a) voltage transfer curve, (b) sinusoidal input signal, (c) collector currents, and (d) output current

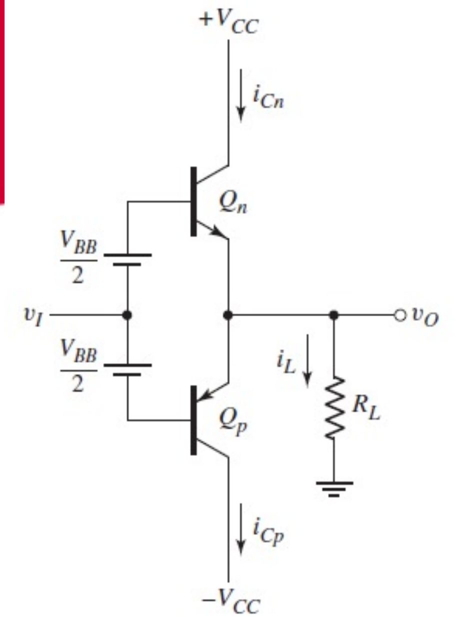


Figure 8.24 Bipolar class-AB output stage

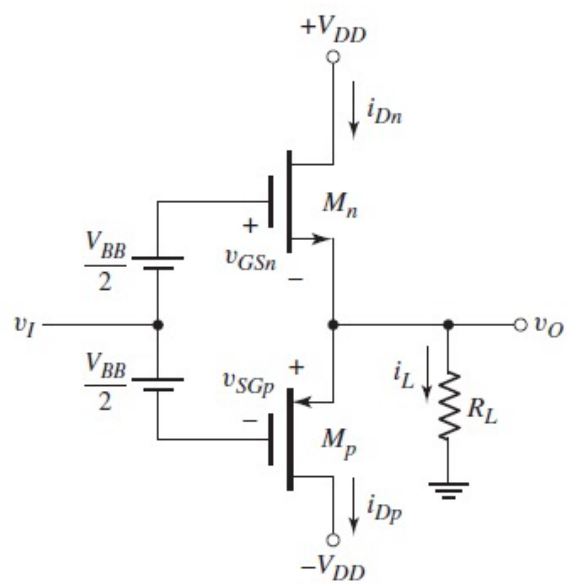
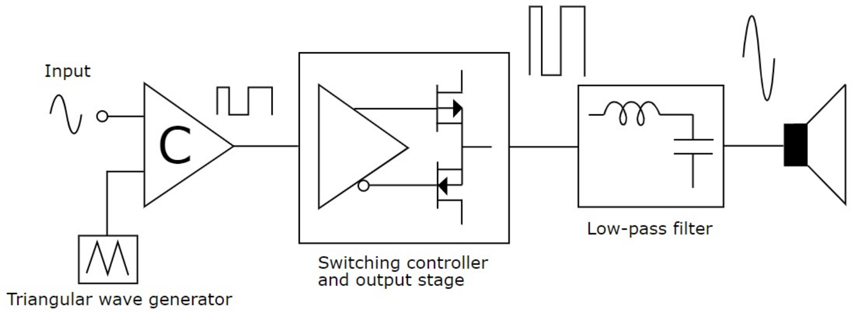


Figure 8.26 MOSFET class-AB output stage

Class D amplifier



Typical for a Class D amplifier

- Input converted to bitstream
- Bitstream switches MOSFETs push-pull stage
- High switching-frequency needed

Typical components used:

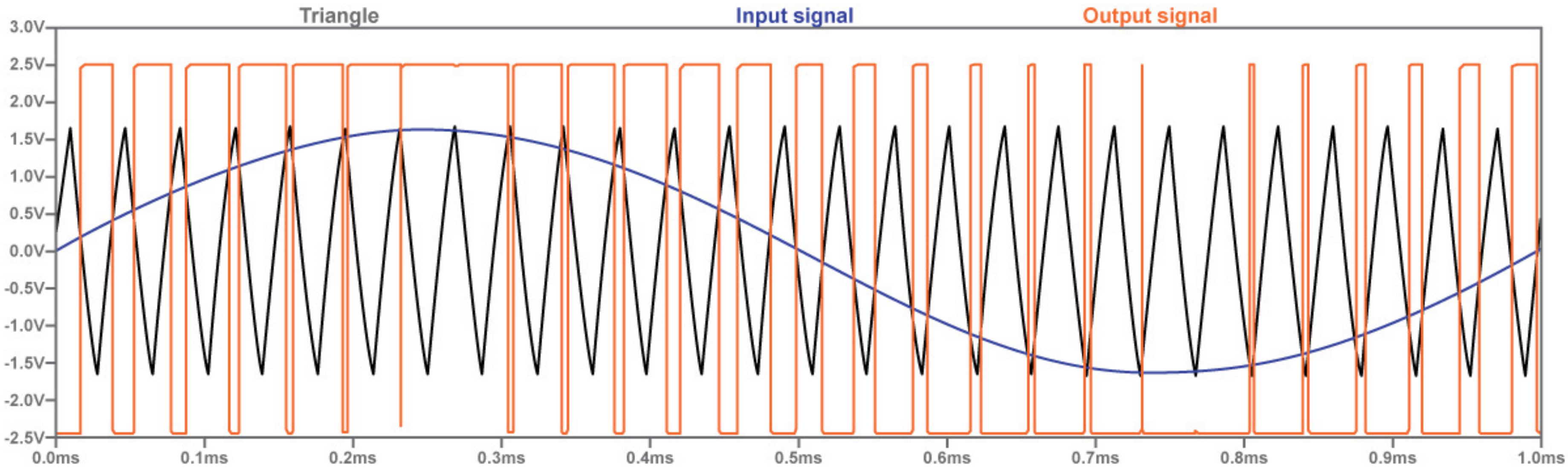
- ADC / sigma-delta converter
- Gate driver with bootstrap voltage
- MOSFET push-pull stage
- LC-filter to remove switching-frequency

500 W IRS2092

Class D amplifier

AD-conversion principle in our Class D-amplifier:

- Input signal compared with triangle-waveform signal



The triangle signal has much lower frequency for demonstration purposes

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Components used

LM393:

- Dual Comparator
- Open-Collector output

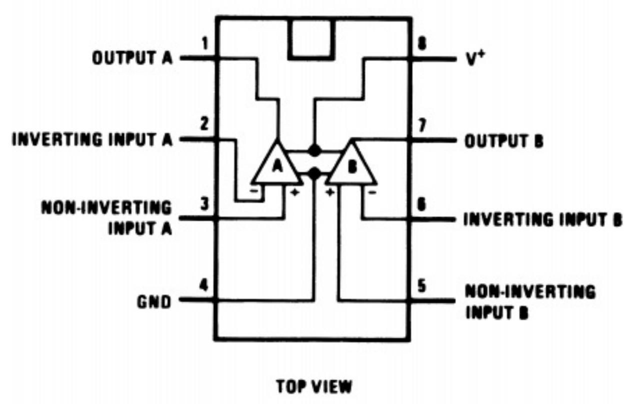
IR2110:

- High and Low side Driver
- Bootstrap voltage

IRF540N:

- N-channel Power MOSFET
- $R_{DS(on)}$ = 77 m Ohm
- $R_{th,JC}$ = 1.0 C/W
- $R_{th,CS}$ = 0.5 C/W
- Non-isolated: Case = Drain !!

P and D Package
8-Pin CDIP, PDIP, SOIC
Top View



$P_{audio} = 100\ W_{rms}$

$R_{speaker} = 4$ Ohm

$I_{peak} = ?$ A

$P_{IRF540} = ?$ W

Transfer function 2nd order LPF

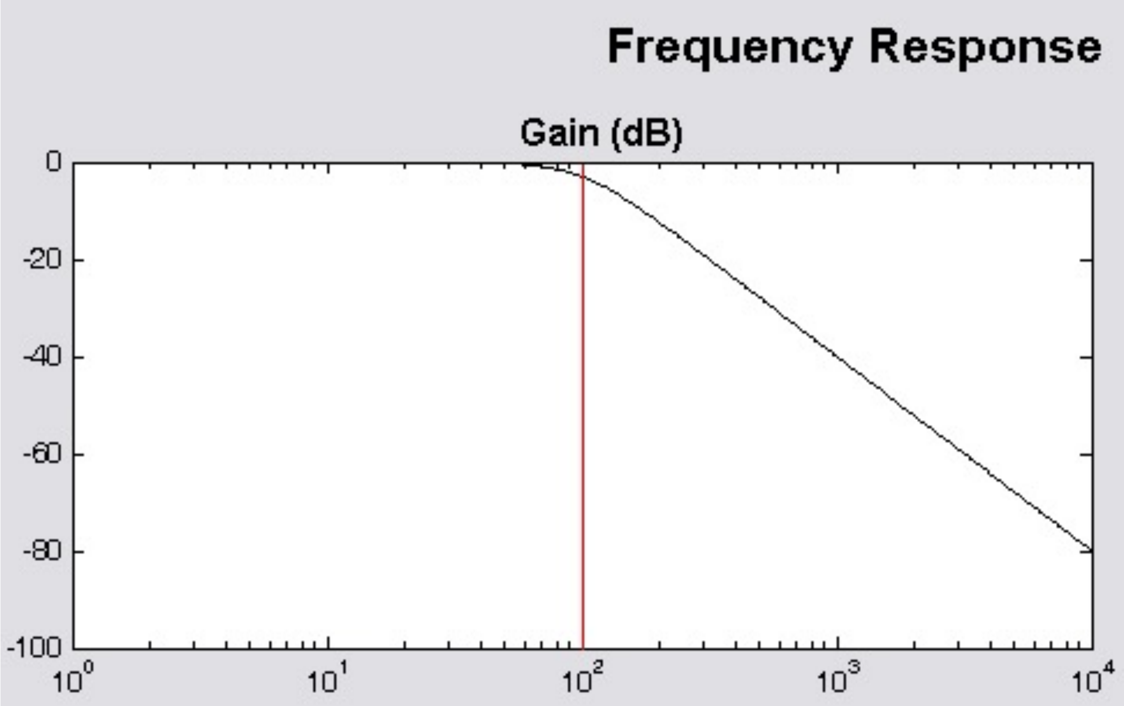
$$H(s) = \frac{k.\omega_c^2}{s^2 + \frac{\omega_c}{Q_c}.s + \omega_c^2}$$

- **Legend:**
  - **Q_c**: quality factor of the filter, determines ripple in passband
  - ξ : demping factor = $1/(2.Q_c)$
  - ω_c : the cut-off frequency of the filter (in rad/sec.)
  - **k** : filter gain
- **Note**
  - Numerator does not contain terms with s!

Example (from AFD Toolbox)

- **Butterworth, f_c=100 Hz, order N=2**
  - **$Q_c = \frac{1}{2}\cdot\sqrt{2}$**
  - **$\omega_c = 200.\pi$**
  - **k = 1**

$$H(s) = \frac{a_0}{s^2 + b_1.s + b_0} = \frac{394784}{s^2 + 888{,}577.s + 394784}$$




```
MATLAB:
f=100; k = 1
wc=2*pi*f
Qc=1/sqrt(2)
b = [0 0 k*wc^2]
a = [1 wc/Qc wc^2]
bode(tf(b,a))
```

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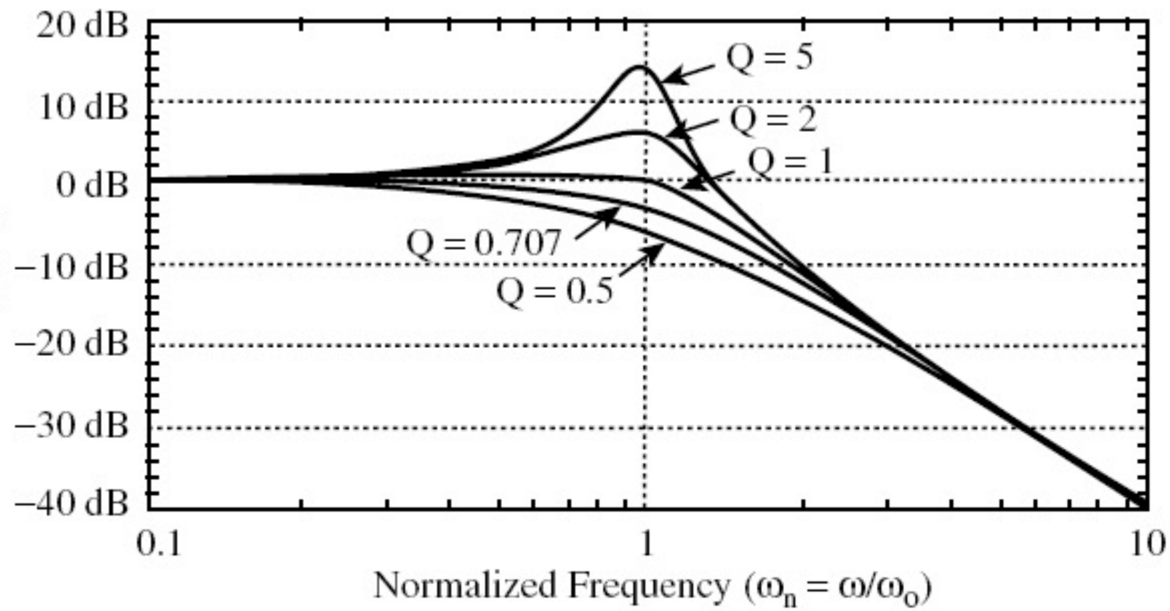
Quality factor Q_c

- **Quality factor Q_c vs frequency response:**



- **Peak:**
  - **Q_c = ½ : -6 dB**
  - **Q_c = ½.√2: -3 dB**
  - **Q_c = 1 : +1.25 dB**
  - **Q_c = 2 : +6.3 dB**

$$Piek(dB) = 20.\log\left(\frac{Q_c}{\sqrt{1-\frac{1}{4Q_c^{\,2}}}}\right)$$

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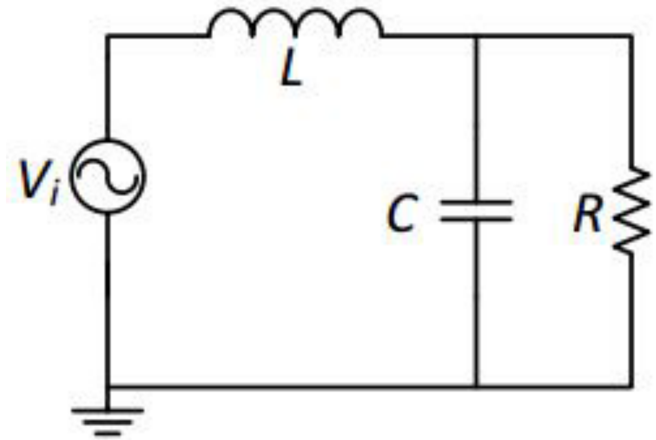
(R)LC filter in the Class D amplifier



- $R = R_L$ = speaker (4 Ω)
- C parallel with R gives ($s = j\omega$):

$$Z_{C//R} = \frac{R \cdot \frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{R}{1+j\omega RC} = \frac{R}{1+sRC}$$

- $H(s) = \frac{V_O}{V_I} = \frac{\frac{R}{1+sRC}}{\frac{R}{1+sRC} + sL} = \frac{R}{R+sL+s^2LRC}$
- $H(s) = \frac{\frac{1}{LC}}{\frac{1}{LC} + \frac{s}{RC} + s^2}$
- $\omega_c = \frac{1}{\sqrt{LC}}$
- $\frac{\omega_c}{Q_c} = \frac{1}{RC} \Rightarrow Q_c = R \cdot \sqrt{\frac{C}{L}}$

$$H(s) = \frac{k.\omega_c^2}{s^2 + \frac{\omega_c}{Q_c}.s + \omega_c^2}$$

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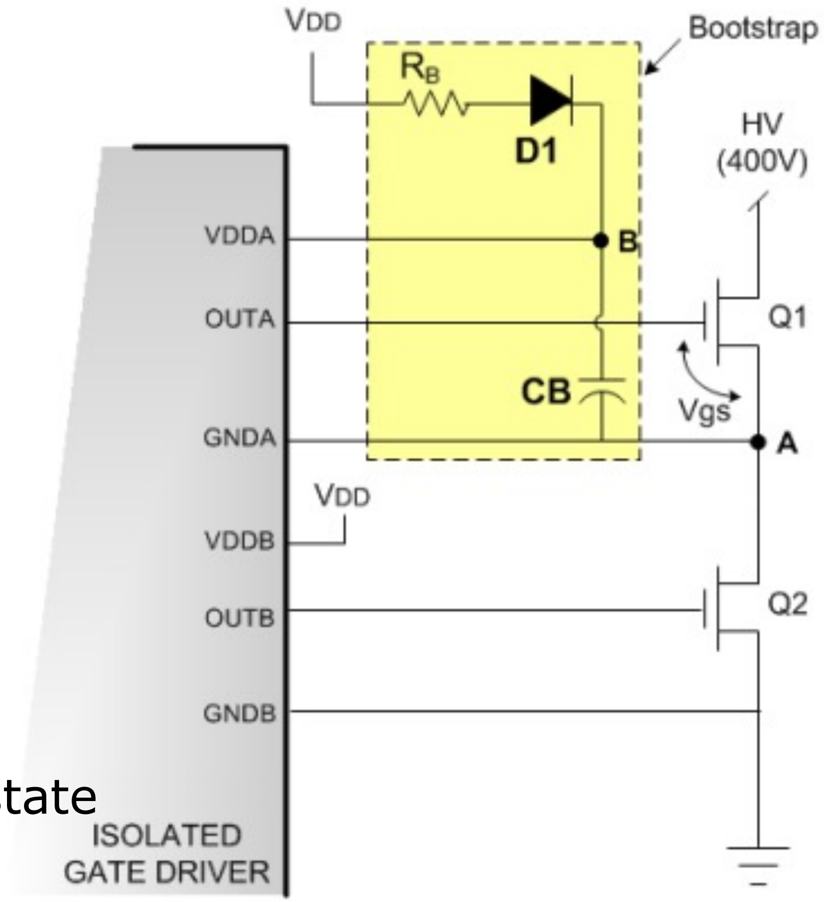
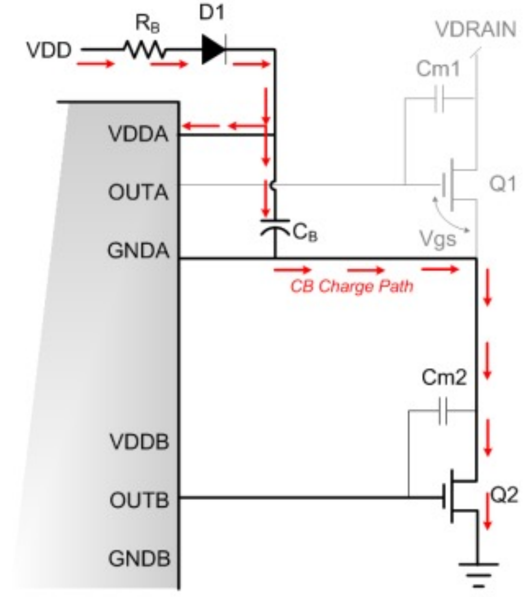
Bootstrap Design

- Mosfet half-bridge
  - High-side and low-side mosfets
  - V_{gs} voltage determines on/off state
  - Q_1 source jumps to HV when on
  - Q_1 gate voltage should be higher!
- Mosfet gate:
  - Basically a capacitor
  - Charge Q_G needed for on-state
  - Charge should be removed for off-state



Bootstrap Circuit



Bootstrap Circuit – C_B Charging

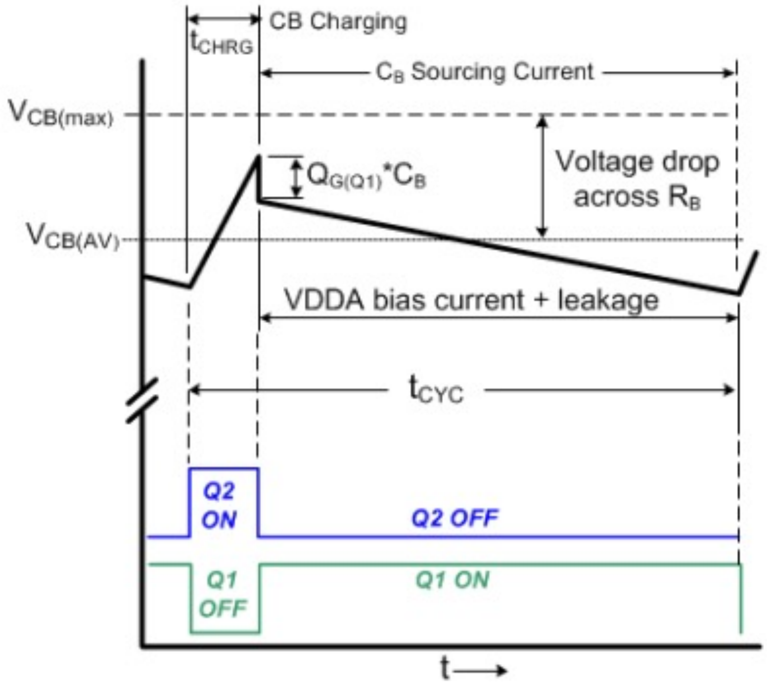
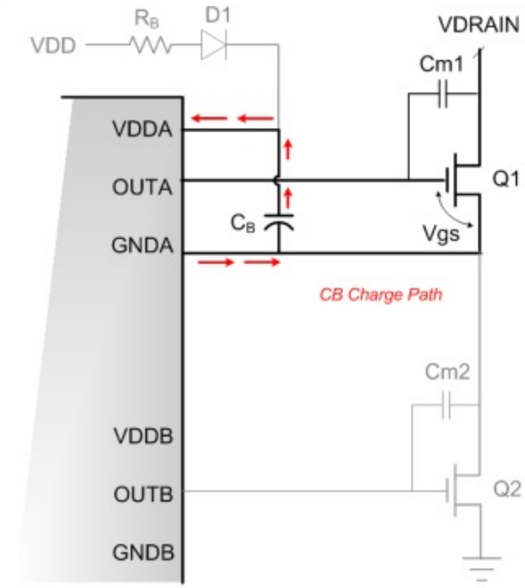


Figure 1.3. Typical C_B Ripple Cycle

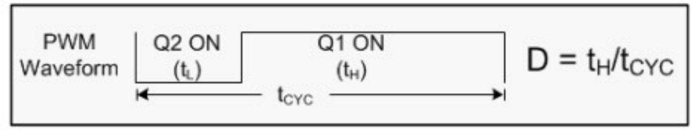


Bootstrap Circuit – C_B Sourcing

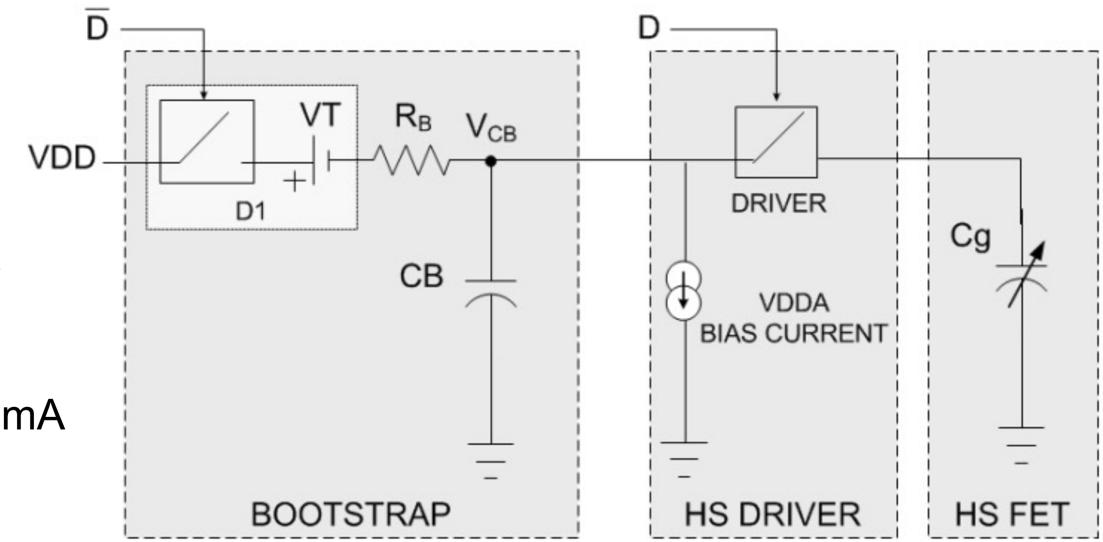
- Q_2 on
  - C_B is charged up to V_B Volts

- Q_1 on
  - C_B sources OUTA/Q_1

Bootstrap Equivalent Circuit



- IRF540N
  - Q_G = 94 nC
- IR2110 gate-driver
  - V_{BS} supply-current = 230 µA
- Class D design:
  - I_{Rgs} = (12-0.7) V/1 kΩ= 11.3 mA
  - f_{cyc} = 200 kHz => T_{cyc} = 5 µs
  - D between 10% and 90 %
    - V_{in} between -1.5 V and +1.5 V



- Total charge Q_{CB}:
  - To be delivered by C_B during max. duty-cycle (90 %)

$$Q_{CB} = Q_G + D \cdot t_{cyc} \cdot (230\,\mu\text{A} + 11.3\,\text{mA})$$
$$Q_{CB} = 94\,\text{nC} + 0.9 \cdot 5\,\mu\text{s} \cdot 11.53\,\text{mA} = 146\,\text{nC}$$

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Bootstrap Equivalent Circuit: C_B calculation

- Total charge Q_{CB}:
  - To be delivered by C_B during max. duty-cycle (90 %)

$$Q_{CB} = Q_G + D \cdot t_{cyc} \cdot (230\,\mu\text{A} + 11.3\,\text{mA})$$
$$Q_{CB} = 94\,\text{nC} + 0.9 \cdot 5\,\mu\text{s} \cdot 11.53\,\text{mA} = 146\,\text{nC}$$

- Max. allowable ripple (ΔV_{CB}) set to 5 % of V_{DD}
  - IR2110 undervoltage threshold = 9.4 V
- C_B calculation:

$$C_B \geq \frac{Q_{CB}}{\Delta V_{CB}} = \frac{146\,\text{nC}}{0.6\,\text{V}} = 243\,\text{nF}$$

  - Use 330 nF to be safe
- R_B calculation:
  - Eliminated from design
  - Only needed for low-frequency applications

$$5 \cdot R_B \cdot C_B \leq (1 - D_{MAX}) \cdot t_{CYC}$$
$$R_B \leq \frac{0.1 \cdot 5\,\mu\text{s}}{5 \cdot 330\,\text{nF}} = 300\,\text{m}\Omega$$

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Coil calculations

- Magnetic flux in a coil:
  - $\Theta = B.A$
  - B = flux density, with $B = \mu . H = \frac{\mu . N.I}{l}$
  - A = area of coil, l = length of coil (in datasheet: $\mathbf{A_E}$ and $\mathbf{L_E}$)
  - $\mu = \mu_0 . \mu_R$, met $\mu_0 = 4\pi . 10^{-7}$ H/m

- Inductance of a coil:
  - $L = \frac{N.\Theta}{I} = \frac{N.B.A_E}{I} = N.\frac{\mu . N.I}{l_E . I} . A_E = \boxed{\mu . \frac{N^2 . A_E}{l_E}}$

Part Number:	T106-2

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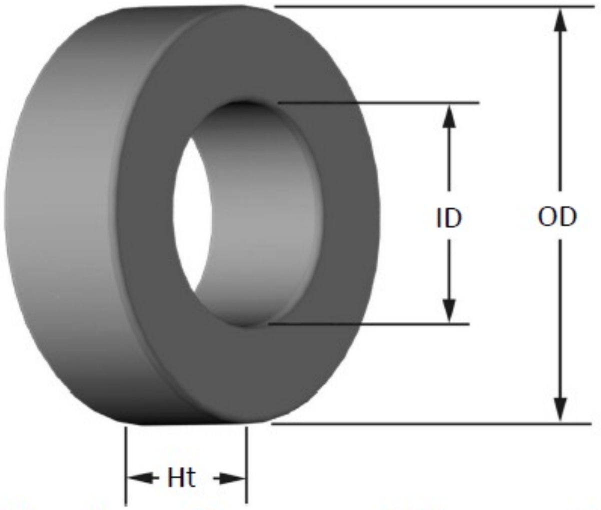

OD	(nom. - bare core)	26.92 mm	1.060 in
	(max. - after coating)	27.43 mm	1.080 in
ID	(nom. - bare core)	14.48 mm	0.570 in
	(min. - after coating)	13.97 mm	0.550 in
Ht	(nom. - bare core)	11.10 mm	0.437 in
	(max. - after coating)	11.73 mm	0.462 in
Mass	(approximate)	21 grams	
Magnetic Dimensions	A_e - Eff. Mag. Cross Section	0.659 cm²	
	L_e - Eff. Mag. Path Length	6.49 cm	
	V_e - Eff. Core Volume	4.28 cm³	
	WA - Min. Eff. Window Area	1.53 cm²	
	sa - Surface Area	28.1 cm²	
	mlt - mean length per turn	4.39 cm	
	μ_i(reference)	10	

HOGESCHOOL ROTTERDAM

Class D amplifiers